University of Colorado, Boulder
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4028

SIMBA

Final Report

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PAB Advisor: Zachary Sunberg

Customer Info

Name: Hagen Lyle
Address: 0182 Copper Circle, Lower Patrol Room Copper Mountain, CO 80443
Phone: 970-471-6175
Email: hlyle@coppercolorado.com

Team Info

Dickinson, Lucas ludi1754@colorado.edu (303) 717-8681 *Sensor Lead*	**Fidler, Max** mafi3354@colorado.edu (301) 801-5436 *Safety Lead*
Gourmos, Adam adgo3141@colorado.edu (303) 875-6407 *Financial Lead*	**Griffin, Travis** trgr7253@Colorado.EDU (864) 640-7692 *ADCS Lead*
Papenfuss, Brett brpa7743@colorado.edu (719) 238-1118 *Lead Software Engineer*	**Peng, Stephen** stpe2093@colorado.edu (817) 247-3248 *Project Manager*
Ricken, Devon deri9928@colorado.edu (720) 299-7200 *Electronics Lead*	**Sesnic, Aidan** aise1051@colorado.edu (720) 212-6533 *Modeling Lead*
Syed, Saad sasy1838@colorado.edu (720) 515-6110 *Systems Engineer*	**Walters, Jordan** jowa4870@colorado.edu (303) 898-2856 *Mechanical Lead*
Yevak, Kevin keye3825@colorado.edu (303) 656-3724 *Thermal Lead*	**Yoo, Sean** seyo3517@colorado.edu (720) 684-8948 *Manufacturing Lead*

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Acronyms

.csv	:	Comma-Separated Values
.txt	:	Text File
3D	:	Three Dimensional
ADC	:	Analog-to-digital Converter
AIAA	:	American Institute of Aeronautics and Astronautics
API	:	Application Programming Interface
BOM	:	Bill of Materials
CAD	:	Computer-Aided Design
CD	:	Conceptual Design
CP	:	Cost Plan
CONOPS	:	Concept of Operations
CORS	:	Continuously Operating Reference Station
COTS	:	Consumer Off-the-shelf
CU Boulder	:	University of Colorado Boulder
DD	:	Detailed Design
DR	:	Design Requirements
DSLR	:	Digital Single-Lens Reflex
EM	:	Electromagnetic
FAR	:	Federal Aviation Regualtion
FBD	:	Functional Block Diagram
FFR	:	Final Fall Report
FOV	:	Field-of-View
FR	:	Functional Requirements
GCP	:	Ground Control Points
GNS	:	Global Navigation System
GPIO	:	General Purpose Input/Output
GPS	:	Global Positioning System
GIS	:	Geographical Information System
GUI	:	Graphical User Interface
HDPE	:	High-Density PolyEthylene
INS	:	Inertial Navigation System
IR	:	Infrared
LIDAR	:	Light Detection and Ranging
LiPo	:	Lithium-ion Polymer Battery
LVDS	:	Low-Voltage Differential Signaling
NOAA	:	National Oceanic and Atmospheric Administrations
OC	:	Organizational Chart
PAB	:	Project Advisory Board
PM	:	Project Manager
PO	:	Project Objectives and Functional Requirements
PP	:	Project Purpose
PPK GNSS	:	Post-Processed Kinematic Global Navigation Satellite System
PPl	:	Project Planning
RA	:	Risk Assessment and Mitigation
RAM	:	Random Access Memory
RD	:	Requirements Development

RPN	:	Risk Priority Number
RS-232	:	Recommended Standard 232 (type of serial cable)
RTK	:	Real-Time Kinematic
SIMBA	:	Snow Depth Information and Mitigation Before Avalanches
SFM	:	Structure from Motion
STP	:	Standard Pressure and Temperature
UAV	:	Unmanned Autonomous Vehicle
USA	:	United States of America
USB	:	Universal Serial Bus
UV	:	Ultra Violet
VDC	:	Volts Direct Current
VV	:	Verification and Validation
WBS	:	Work Breakdown Structure
WP	:	Work Plan

Nomenclature

$d\phi$	=	Pointing accuracy error, deg
τ	=	Torque, Nm
δ_{dist}	=	Angular distance
δ	=	Inertia, $\frac{kg}{m^2}$
I	=	Inertia, $kg.m^2$
θ_{pot}	=	Potentiometer azimuth value, $\frac{kg}{m^2}$
ϵ_{pot}	=	Potentiometer elevation value, $\frac{kg}{m^2}$
m	=	Mass, kg
N_r	=	Number of repositings required
P	=	Pressure at altitude, Pa
P_o	=	Pressure at sea level, Pa
r	=	Pointing resolution requirement
R	=	Earth radius, m
S_w	=	Wetted area, m^2
t	=	Time, s
T	=	Absolute pressure, Pa
z	=	Altitude, m
Ω	=	Initial system bearings, $^\circ$
λ	=	Longitude, deg
ϕ	=	Latitude, deg

Part I.

Project Purpose

Authors: Stephen Peng, Lucas Dickinson

With 12.6 million annual skiers and snowboarders, Colorado represents 4% of worldwide avalanche fatalities. With this in mind, ski resorts have a responsibility to keep their patrons and their employees safe of avalanche dangers. Current avalanche prediction methods require researchers to spend hours digging 1-2 m deep snow pits on the side of avalanche prone areas. The purpose of digging these holes is to learn the layered snow pack density that is present, as well as accurate measurements of snow depth. This presents an inherent safety risk to those digging, as snow pit locations are in or near the avalanche zone being evaluated. The locations for these pits can also be difficult to decide, as snow depths can have high variability due to changing environmental conditions and terrain features. This method is inefficient for collecting snow depth over a wide area. The situation surrounding avalanche mitigation presents the need for an instrument that can measure snow depth from afar without creating any risks for the user.

Currently, there are few instruments available on the market that can measure a single snow depth point remotely and almost none that can measure snow depth over a larger area. The difficulty in being able to autonomously collect snow depths stems from achieving accurate snow depth measurements (within centimeters), as well as the unpredictability of the snow density pack. Because these instruments would need to be able to read snow depth values so accurately, a change in snow density can propagate large errors, rendering the snow depth measurements inaccurate. There are only a handful of instruments and algorithms that are currently available that do not consider snow density in its measurement, but still cannot collect snow depth values over a large area.

SIMBA's mission aims to provide the ability to remotely access and monitor snow depth in high risk areas of the Copper Mountain Ski Resort to help maximize safety by minimizing the time spent digging these pits. We also aim to provide a method to accurately acquire snow depth measurements over a large area and present this data in a user friendly way. Snow depth data that is collected over a given area for several months would assist ski patrol in deciding where to dig. Accurate and regularly updated snow depth data sets can also enhance current avalanche prediction models and provide information for explosives planning, boot packing, and ski cutting. Equipped with more data, ski patrol will be safer and more efficient when maintaining the mountain resort, making it safer for everyone.

Part II.

Project Objectives & Functional Requirements

Authors: Stephen Peng, Sean Yoo

1. Specific Objectives

The objectives of this project are found in Table 1, which contains four levels of success determined for our remote sensing platform. Tier one is a basic level of success. It focuses on measuring just one point of snow depth, and to a relatively low degree of accuracy. The next level of success involves increasing the amount of data being taken to improve the field accuracy and provide more useful information. The third level of success focuses on taking the data and presenting it in a useful manner. This level also includes greater sensor accuracy and more precise pointing data. The final level of success, level four, again improves the accuracy of the system to meet our customers requirement.

It also adds the requirement of a 1 meter spatial resolution and a topographic map of the snow depth. Performance parameters will be tested are accuracy, scan time, scan resolution, and maximum scan area. The team's ultimate goal is to meet the highest level of success in each category, but the strict accuracy requirements may not be able to be met within the course of the class and with our budget. For this reason the team aimed for a more realistic level 3 success. The team conducted in depth analysis on the performance of our system to determine its constraints for the Spring 2021 semester.

Level	Sensor Package	Software	Pointing Accuracy and Control	Data Visualization
1	Snow depth accurately measured within ±50 cm at 1 location at 400 m	Data of one distance measurement by sensor is saved	Laser pointing is able to be determined to 0.01 degrees. No feedback present. Motors within ±1 degrees of desired position	Compile data to form a plane to serve as origin for height measurements
2	Snow depth accurately measured within ±25 cm at 1 location at 400 m	Distance and attitude of each measurement is recorded for attitude control	Feedback is present allowing the motors to readjust as needed	Display snow depth calculated for one location
3	Snow depth accurately measured within ±15 cm at 400m with 2 m spatial resolution	Distance, attitude, time and temperature of each measurement is recorded	Motor initial movement is within ±0.1 degrees of desired position. Feedback allows for ±0.01 degrees accuracy	Produce map displaying snow depth
4	Snow depth accurately measured within ±10 cm at 400 m with 1 m spatial resolution		Motor initial movement is within ±0.01 degrees of desired position. Feedback allows for ±0.001 degrees accuracy	Produce topographic, color code snow depth map which is easy to interpret for the user

Table 1 Levels of success

2. Concept of Operations

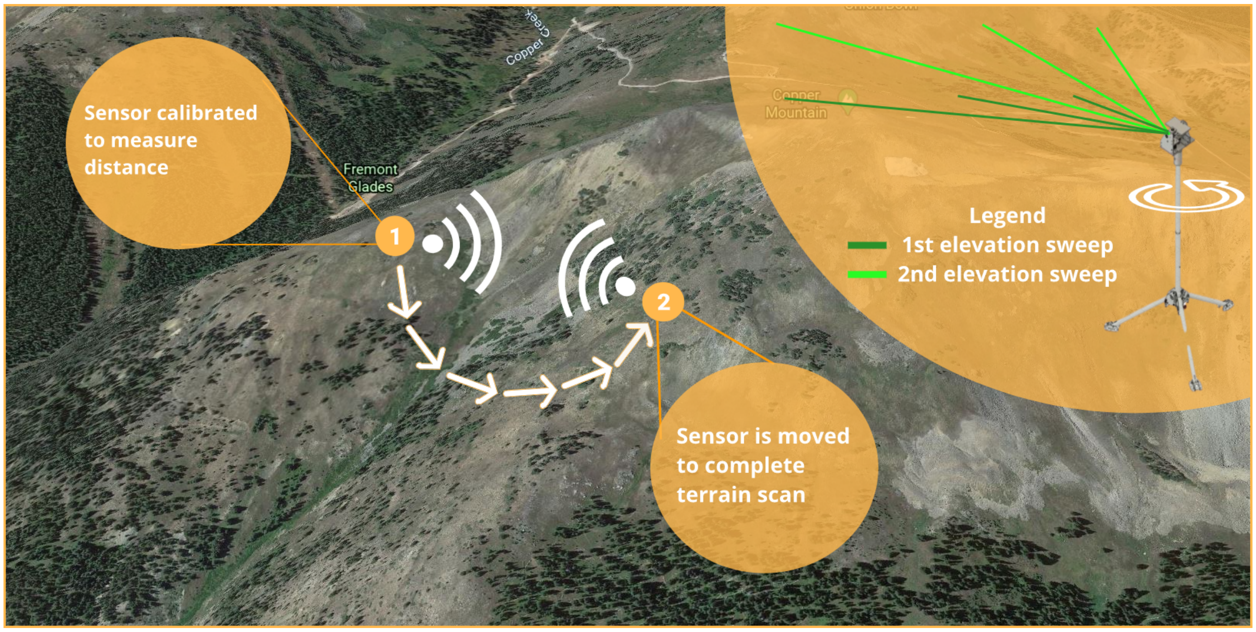


Fig. 1 Concept of Operation for project SIMBA

The Concept of Operations illustrates the end implementation of the system for Copper Mountain for the following year. Due to time constraints, testing of the system will be done locally, replicating similar environmental conditions found at Copper Mountain. The ski patrol will have tripods firmly staked to the ground at predetermined locations overlooking the area of interest. They will then attach the sensor package to the tripod via a quick release pin. The patrol will then perform a calibration check using a designated starting point and the sensor will proceed with the scanning process. The patrol team does not need to be present after the scan is initiated. A scan of the terrain will need to occur when the area is free of snow (during the summer) and then after snowfall (during the ski season). When the wet (winter) scan is complete, the range values scanned will be compared to the range values taken during the dry (summer) scan of the same area. The difference between these two values at the same location will output the snow depth. Scan times will take up to 2 hours during the wet scan and up to 20 hours during the dry scan. The sensor will then be moved to the opposite side of the bowl for an additional scan due its limited range. The data will then be transferred from the sensor package into ArcGIS via USB, where a topographical map will be generated. The map will be generated by creating a surface from the array of snow depth measurements calculated from the scan, giving the user an easy way to interpret the snow depths in the given region. The deliverables to the customer include a sensor package which is mountable on the tripods currently in use at Copper Mountain and a software package in ArcGIS, capable of processing and displaying the information collected by the sensor package. The deliverables to the course include an in depth analysis on the performance of the system which fully defines the maximum accuracy that the system can achieve.

3. Functional Block Diagram

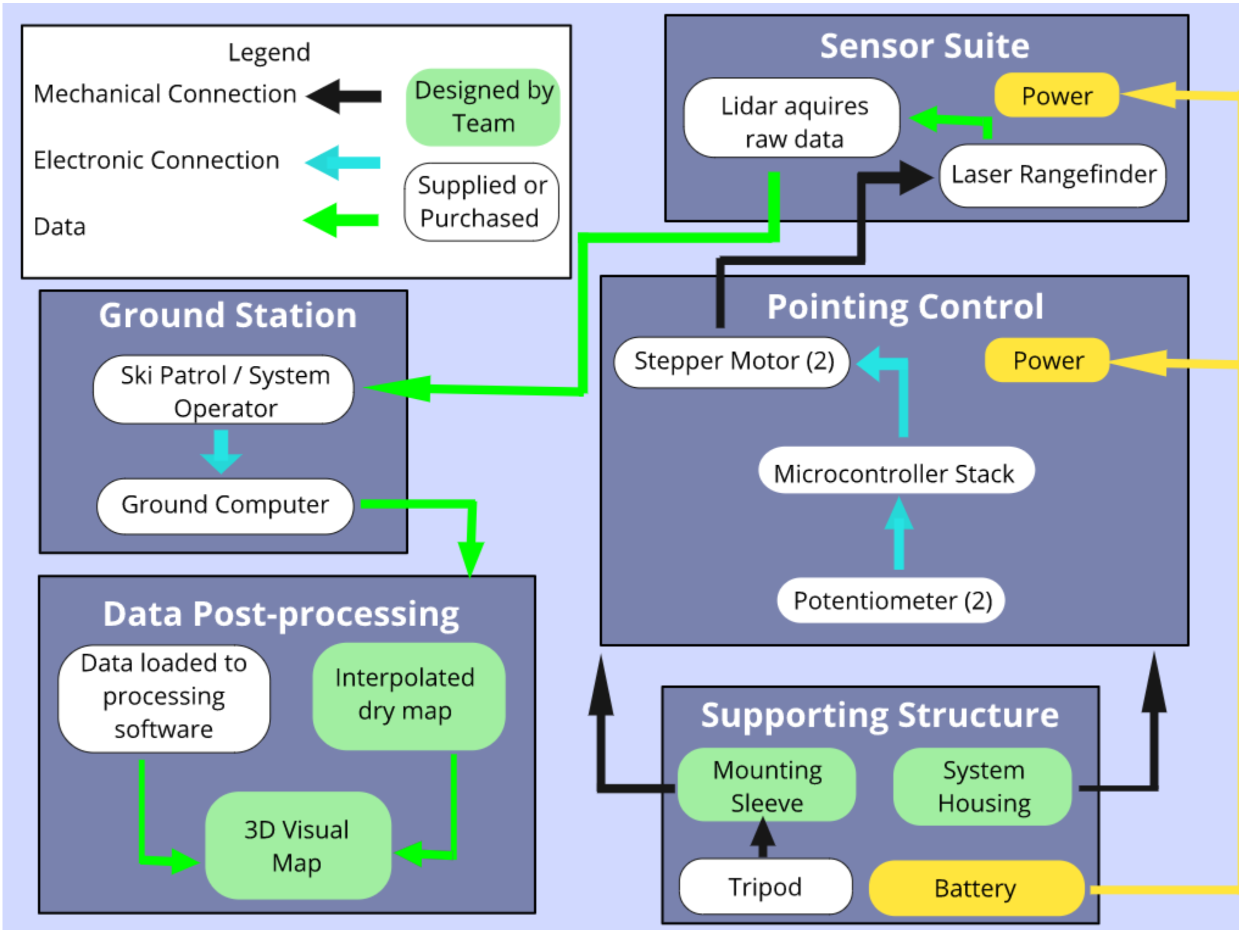


Fig. 2 Functional Block Diagram for SIMBA

The Functional Block Diagram groups the project into five major elements: the supporting structure, pointing control, sensor suite, ground station, and data post-processing. The supporting structure consists of the CM 106b Galvanized Steel Tripod owned and operated by Copper Mountain, the payload sleeve that mounts the sensor housing to the tripod, as well as a battery. The battery is needed to supply power both to the motors for pointing control as well as the sensor suite. The mounting sleeve and the housing for the system will be manufactured by the team while the tripod and battery are commercially available products.

The pointing control consists of the microcontroller stack, two potentiometers, and two stepper motors. The pointing control will allow the system to turn in elevation angle and azimuth angle to make sweeping measurements. The microcontroller contains a Raspberry Pi 4 that runs the software, an ADC that reads the voltage outputs of the potentiometer, and a custom designed PCB that helps regulate voltage inputs from the battery. The stepper motors will drive the platform that the laser rangefinder rests on which will, in turn, collect raw data. The potentiometers will record the angular displacement of the system as the motors actuate so we can tell where the system is pointing. This data is then transferred via USB by the system operator to the ground station at Copper Mountain. The Raspberry Pi, ADC, potentiometers, and stepper motors are all commercially available products with the exception of the PCB, which will be designed by the team and manufactured by Digikey.

ArcGIS will be the software program used for the data post-processing. Scan data will be inputted into ArcGIS, which includes pointing data to locate the data points and range data acquired with the range finder. This data will be used to create a 3D surface of the snow, and the difference between this 3D surface and the one created before snowfall will give us the snow depth. ArcGIS will then be used to create a visualization of the snow depth for interpretation by Copper mountain ski patrol. ArcGIS is provided free of charge to the team by the Office of Information Technology.

The sensor suite includes the laser range finder used to acquire range data. As the system actuates through the scan area, data is taken from the range finder. The range data from the same location before snowfall and after snowfall is used to compute snow depth. This data is transferred to ground station at Copper Mountain via USB. The range finder is commercially available and will be purchased by the team.

The ground station consists of a computer with ArcGIS installed, where the data will be transferred by an operator from the sensor via USB. ArcGIS is already owned by the Copper Mountain ski patrol, so no purchase will be necessary. The Functional Block Diagram above shows how these components interact with each other and whether they are physically connected or operate through an electric connection.

4. Functional Requirements

FR 1	**Depth Detection**: The system shall implement a snow depth detection system to assist Copper Mountain ski patrol in avalanche mitigation
FR 2	**Data Collection**: The system shall be able to operate with acceptable endurance such that data collection will occur in a reasonable amount of time
FR 3	**Operation Conditions**: The system shall be able to operate in the typical weather conditions found on the top of Copper Mountain
FR 4	**Data Storage**: The system shall be able to collect the required data, store the data, and transfer the data to Copper Mountain ski patrol through available interfaces
FR 5	**Data Processing**: The system shall process the data collected and present snow depth data to Copper Mountain ski patrol in the software found at their facilities
FR 6	**System Control**: The system shall collect pointing data accurately to control the sensor's pointing.

Table 2 Functional requirement details

The functional requirements for the system can be found above. They are outlined to characterize the system design based on design requirements. Functional Requirement 1 describes the overall measurement deliverable needed by Copper Mountain for avalanche mitigation.

The second functional requirement ensures that the sensor can make measurements autonomously and in a timely manner. The system will have a limited power supply so this requirement ensures that data collection can be completed quickly enough so it does not need to be recharged mid-scan. It ensures that the scan process will be viable for Copper Mountain Resort.

The third functional requirement ensures that the system will operate in the adverse conditions that can occur at the top of Copper Mountain. Temperatures can fall well below the freezing point and it is important that all components of the system can operate at a minimum temperature of -20 °C in order to remain serviceable throughout the ski season.

The fourth functional requirement ensures that the data collected by the sensor can also be stored on board. The motivation behind this is that the system operator may return to transfer the data well after the collection process is complete. In order to facilitate a viable scan process for ski patrol, data storage is a must The data must also be easily transferable by the system operator to be useful.

The fifth functional requirement describes the necessary software and processing in order to produce a meaningful snow depth visualization. Without processing the data, the data collected will just be an array of numbers that will be hard to visualize over the region. This will not be useful information for decision making about avalanche mitigation. Copper Mountain Resort must also be familiar with the software and own the software to facilitate the post processing.

The final functional requirement discusses pointing accuracy. The system must be able to determine where it is pointing extremely accurately in order to collect snow depth data which is useful. Error in pointing correlates to snow depth measurement error. If the system cannot determine where it is pointing, then the error in the snow depth measurements will be too big and the data will not be useful for avalanche mitigation.

Part III.

Final Design

Authors: Luke Dickinson, Adam Gourmos, Travis Griffin, Brett Papenfuss, Stephen Peng, Aidan Sesnic, Jordan Walters, Sean Yoo

5. Requirements Flow-Down

Snow Depth Detection

FR 1: The system shall implement a snow depth detection system to assist Copper Mountain ski patrol in avalanche mitigation.

Motivation: The customer calls for accurate measurements of snow depth.
Validation: Multiple fully integrated system tests are performed to quantify the distance measurements precision and accuracy between the system and a snowy surface.

DR 1.1: The snow depth measurements shall be accurate to ±10cm.

Motivation: Customer choice, snow depth measurements must be this accurate in order to be useful for avalanche mitigation.
Validation: A test is performed to determine the statistical spread for the distance measurements for the sensor package for a given, known distance.

DR 1.2: The snow depth data shall have a maximum spatial resolution of at least 6m by 6m.

Motivation: This was the accuracy determined by the customer for the collected information to be useful.
Validation: To account for varying terrain within the 1m by 1m area such as a steep cliff, careful mission planning must be conducted or smaller spatial resolution must be achieved.

DR 1.3: The system shall be able to meet requirements in areas clear of foliage.

Motivation: The mission requires coverage of clear areas only as most areas of concern are above tree line.

Validation: A system test is performed in a clear open area to confirm snow depth accuracy can be reliably achieved.

DR 1.4: The dry mountain terrain data shall have a spatial resolution of at least 1m by 1m.

Motivation: This was the accuracy determined by the team for precise measurements and easier map integration.
Validation: A test is performed with the sensor package from 0 to 122m away from a snowy surface. The test is a pass if the instrument is able to determine the required accuracy for some location during the testing.

FR 2: The system shall be able to operate with acceptable endurance such that data collection will occur in a reasonable amount of time.

Motivation: It will not be possible for the system to collect snow depth measurements in a timely manner if the system has to be recharged multiple times during a measuring session.
Validation: A fully integrated scan test is performed to determine if the system is able to collected measurements for the required area.

DR 2.1: The system shall collect snow data on an area of at least 0.15 km^2.

Motivation: This was determined by the customer through an estimation of the size of average avalanche areas at Copper. This results in a half circle of radius 309 meters.
Validation: The laser can measure out to 309 meters and there is enough data storage to handle 150,000 separate points.

DR 2.2: The system shall be able to complete snow data collection in two hours or less for a wet scan.

Motivation: Our goal is collect snow depth data within a time less than it takes to dig one snow pit (2-3 hours).
Validation: An endurance test of the system will provide validation that the system can complete full scans.

DR 2.3: The system shall have enough battery life to complete at least one scan (dry) in summer.

Motivation: Efficiency and error reduction by not having to pause/recalibrate the system in the middle of mapping.
Validation: The battery can supply 7.4 Watts of power for 1.7 days at a minimum temperature of 10°C.

DR 2.4: The system shall have enough battery life to complete at least one scan (wet) in winter.

Motivation: Efficiency and error reduction by not having to pause/re-calibrate the system in the middle of mapping.
Validation: The battery can supply 7.4 Watts of power for 70 minutes at a minimum temperature of -20°C.

Operating Conditions

FR 3: The system shall be able to operate in the typical weather conditions found on the top of Copper Mountain.

Motivation: A typical day is considered the average weather condition calculated from multiple days of weather data for the peak of Copper Mountain during the Winter.
Validation: Parts will be chosen to withstand minimum temperatures found at Copper Mountain.

DR 3.1: The system shall be able to operate and collect data in temperature as low as -20 degrees Celsius.

Motivation: The system should not fail in designed operating temperatures.
Validation: Test system components in cold conditions such as during winter or freezer.

DR 3.2: The system shall be able to endure 40 mph wind gusts.

Motivation: If the tripod tips over or moves, erroneous data is collected and the mission, as well as the system, could fail.
Validation: Test tripod in wind/test how much force it can withstand.

DR 3.3: The system should be water resistant, at least IP34 (protected against objects larger than 12.5 mm and splashing water for 5 minutes).

Motivation: Protect from weather/outdoor related failure such as snow, small animals, and other debris.
Validation:The system should be able to withstand direct contact with water and small objects (pine needles, pebbles, branches, etc).

Data Storage and Processing

FR 4: The system shall be able to collect the required data, store the data, and transfer the data to the Copper Mountain ski patrol through available interfaces (Data Storage).

Motivation: This will allow users to collect, process, and visualize data with ease.
Validation: During system testing, we test how easy the data can be transferred from the on board system to the PC analyzing the data.

DR 4.1: Data storage must be large enough to store 15MB of data until the sensor package has completed its scan.

Motivation: This is the estimated size of the data that will be collected during a single dry-scan and to ensure a reasonable data storage option is available.
Validation: The data storage space is measured and compared against the required space to store 15MB of data.

DR 4.2: Data must be able to be transferred to a computer for post-processing using a USB drive.

Motivation: This system cannot process the data it collects as more processing power is required.
Validation: After every test run, data will move from the system to a separate computer to verify it is complete and not damaged.

FR 5: The system shall process the data collected and present snow depth data to Copper Mountain ski patrol in the software found at their facilities.

Motivation: This will allow the staff at Copper mountain to run a good quality, efficient, and accurate analysis of any avalanche threats with the current software they are using.
Validation: Collecting data from test runs and analyzing it using software will provide evidence of our systems ability to display data.

DR 5.1: System must be able to interpolate a "dry" map from a scan during the summer.

Motivation: Points from "dry" and "wet" scans will not line up with each other, but if we create a solid sheet for the dry map using interpolation, then we can relate any point from the "wet" scan to the point on the "dry" map required to get snow depth.
Validation: Collect dry data and attempt to create a dry layer of the map. Compare these values to geogprahic maps given.

DR 5.2: System must be able to calculate snow depth from raw data (Distance, Azimuth, Elevation).

Motivation: Data will be received from the sensor system in the form of raw measurements that do not directly give snow depth. Some calculation will have to be made to actually derive the snow depth.
Validation: A full data set from the full-system test is required to to check this part of the code for any errors.

DR 5.3: System must be able to process data type received from USB.

Motivation: Cannot use data if its in an incompatible data type
Validation: ArcGIS accepts the data type we plan to use in tandem with the Raspberry Pi 4 (.txt).

DR 5.4: System must be able to display processed data using ArcGIS.

Motivation: This is customer preference because they believe this type of visualization will provide the most information to them and their team.
Validation: Check if the software can output a readable map or graph of the data.

DR 5.5: System must be able to input and display processed data into a computer or other device owned by the ski patrol quickly.

Motivation: This allows for easier integration into the staff's (at Copper Mountain) computer systems.
Validation: If the software can run on a Mac or a Windows, this would be sufficient for the software.

DR 5.5.1: Post-processing must be easy enough for a non-technical employee to use

Motivation: This allows for wide usability.
Validation: Test this by allowing a staff member at Copper Mountain to use the system and we will analyze the difficulty in use of it.

DR 5.5.2: Data visualization must be easily read and understood by our customer.

Motivation: Provides quality data without the user having any background information on the post-processing.
Validation: Check to see if the output has good quality visuals as well as data. Also make sure that the output is easy enough to read (graphs are labeled, legends and keys are present, etc.)

DR 5.5.3: Data processing must be quick (a few minutes not a few hours).

Motivation: The staff needs to analyze the data as quickly as possible to highlight any threats from avalanches. Therefore the data they will analyze needs to be processed quickly.
Validation: Record the time it takes for the software to compile its output.

Sensor Attitude Determination & Control

FR 6: The system shall collect pointing data accurately and then use that data to control the sensor's pointing

Motivation: In order to build a map of snow depth, accurate depth measurements and accurate locations of those measurements are needed.
Validation: The software package must be able to fully integrate with sensor package and have accurate pointing and reading.

DR 6.1: The system shall be able to locate its elevation pointing direction with an accuracy of $0.001[\text{ deg}]$**.**

Motivation: This minimum pointing accuracy is required in order to obtain data that is within our error budget
Validation: Use a graph paper and rotate a laser pointer situated on a potentiometer to test its accuracy.

DR 6.2: The system shall be able to locate its azimuth pointing direction with an accuracy of $0.001[\text{ deg}]$**.**

Motivation: This minimum pointing accuracy is required in order to obtain data that is within our error budget.
Validation: Same validation as DR 6.1

DR 6.3: The system will be able to use the location and angles measured during initialization to control sensor pointing to within the measured tolerance.

Motivation: This will allow for some control system to assure accuracy and prevent buildup of any error.
Validation: The accuracy of this step will be the result of the final systems test.

6. Final Design

The final design is shown in figures 3 and 4. It stands up to ten feet tall. It's main components include the tripod and sensor enclosure. Inside the sensor enclosure sits our sensor assembly, stepper motors, potentiometers, microcontroller stack, and laser range finder. These components are divided into the sensor package subsystem, actuator subsystem, and microcontroller subsystem and will be discussed in depth below.

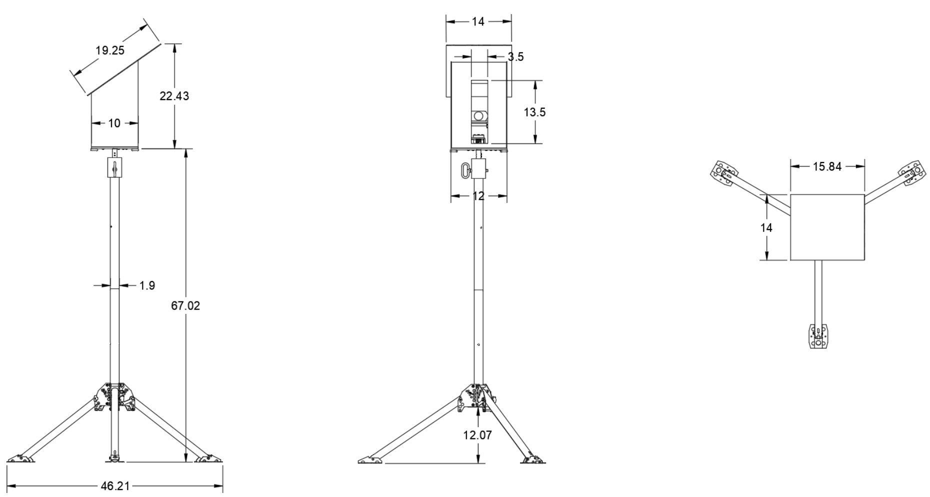


Fig. 3 CAD Drawing of Full System w/ Dimensions

Fig. 4 Full System

A. Sensor Package Subsystem Overview

The sensor package includes the laser range finder and two potentiometers. The laser range finder determines how far away the target is with very high accuracy. The potentiometers detects the angular displacement of the system, which allows the geographic location of the the target to be calculated. The location of the sensor package, the exact pointing direction of the target, and the range of the target allows us to calculate the snow depth at that point.

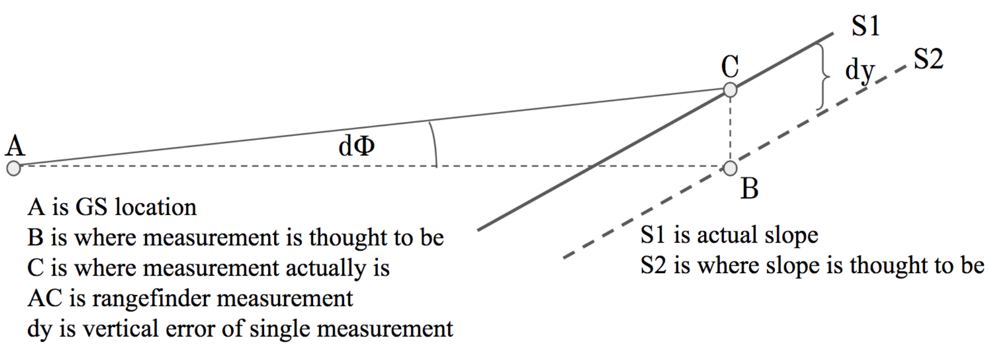


Fig. 5 Basic example of 2D error calculation for a single measurement

The pointing error for a single measurement is found by using the error in pointing accuracy ($d\phi$) to compare where the sensor package thinks it is pointing (AB) and where it is actually pointing (AC).The vertical error between S1 and S2 represents the error in height of a single point caused by the pointing error ($d\phi$). The pointing accuracy is the main factor that contributes to this error but the rangefinder accuracy also contributes in the variable dAC. The angle the sensor is pointing compared to the slope angle is also a key factor that changes the error.

$$dy = (AC + dAC) * (sin(\phi + d\phi) - [sin(\phi) * sin(\theta - \phi - d\phi)/sin(180 - \theta + \phi)]) \tag{1}$$

The equation above explains how vertical error, or height between S1 and S2 in the diagram, is calculated for one measurement, for example a single point during a dry map scan. This error is again calculated during each point of the wet scans that occur later in the season. These two errors are added in quadrature to get the total error of a single snow depth measurement.

1. Rangefinder

The TruPulse 200x Laser Rangefinder is a range sensor that has an accuracy of ±4 cm at a range of 400m and allows us to take measurements of highly reflective surfaces. These were the main constraints of our project which made the TruPulse 200x a viable option It allows measurements to be taken quickly and frequently from a variety of modes which change the characteristics of the laser. We used the gate mode in operation to ensure the laser would not return any measurements less than a specific difference so we would not get interference from our enclosure. We were able to connect the laser range finder via RS-232 cable to the Raspberry Pi to command measurements autonomously. This was facilitated by the RS-232 hat which was connected to the Raspberry Pi. The performance of the laser range finder did not appear to degrade significantly with increases in distance measurements which was advantageous for the system since it would be scanning at ranges of 100m - 400m. Surfaces with higher reflectivity increased the performance of the laser which was also advantageous since are intended target, snow, has high reflectivity. This sensor also works in cold climates and has basic water and weather proofing features to protect it from moisture from snow.

2. Potentiometer

The 6187R10KL1.0LF are single turn potentiometers with ability to rotate a full 360 degrees. These potentiometers can read turns of 0.036 degrees per ohm with a small 1% independent linearity. This gives an error value of 0.00036 degrees per ohm allowing us to take accurate measurements of azimuth and elevation angle. The potentiometer has a operating range of - 40 °C which is well within operating conditions at Copper Mountain. It has a power rating of 1 W at 70 °C derating to 0 at 125 °C. The potentiometer is capable at measuring azimuth and elevation angle at a cheaper price, eliminating the need for the inclinometer. They function as a voltage divider, and the user measures the voltage output of the potentiometer over the volage inputted to the potentiometer to detect angular displacement. Internally, the potentiometer has a wiper which rotates over a resistor with the external rotation of the potentiometer. The output of the potentiometer is connected to that wiper and the voltage output changes as the resistance internally increases or decreases depending on the direction of rotation. A diagram can be found below.

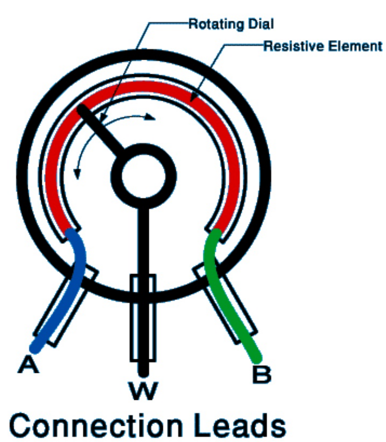


Fig. 6 Diagram of the Internals of a Potentiometer

In the diagram, the A connection would be grounded, the B connection would be connected to the positive lead of the supply voltage, and the W connection would be the output voltage. The potentiometers chosen have a linearity tolerance and resistance tolerance which translate to systematic error. In order to achieve the accuracy needed by the system, the potentiometers would have to be calibrated in order to mitigate these errors.

B. Microcontroller Subsystem Overview

The Microcontroller Subsystem is responsible for controlling the sensor packages pointing direction and storing the data from the various sensors in the sensor package. More broadly, this system is the communication hub for the sensor package as a whole. All of the electronic elements in the sensor package have different communication methods, so the microcontroller needs to handle various data inputs. See Figure 7 for an overview of the data connections.

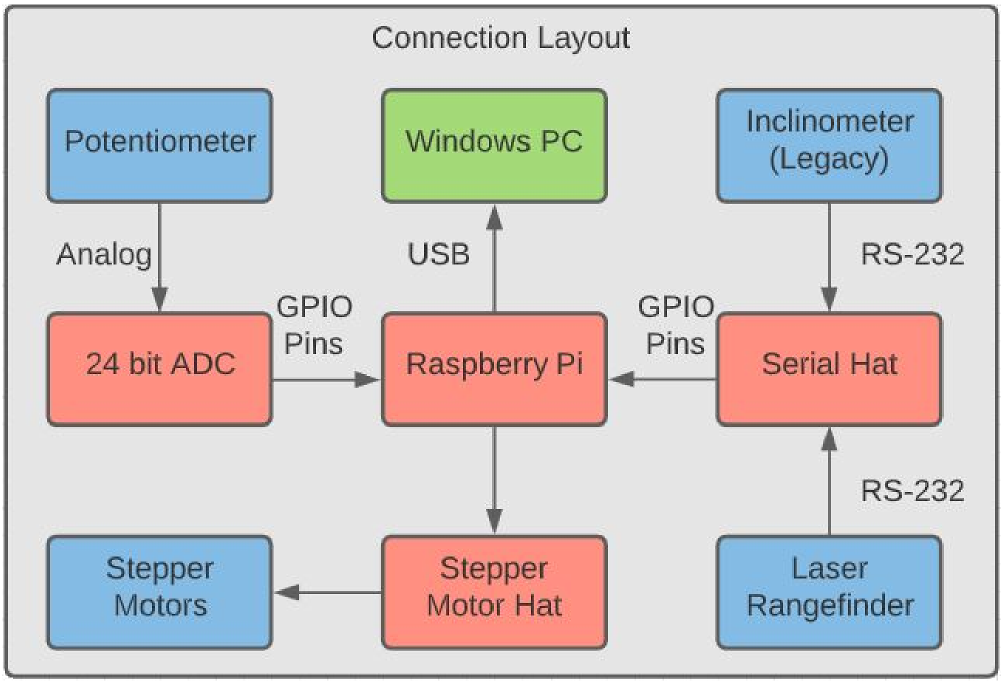


Fig. 7 Overview of required data connections for microcontroller subsystem

The subsystem is able to store at least one "dry" scan (a dry scan is the summer scan of snow-less terrain) estimated to be 15MB of data in text format with the capability to hold more depending on USB drive size. Finally, the microcontroller is able to operate actively in cold conditions, and be stored in even colder temperatures.

1. Raspberry Pi

An 8GB Raspberry Pi 4 was chosen as the "microcontroller". Microcontroller is in quotes because the Raspberry Pi is actually a mini computer, capable of much more than just a traditional microcontroller. The Pi was chosen because of its cheap price ($75), hardware capabilities, flexibility, and wide use. The Raspberry Pi is cheaper than most other small computers available, and is comparable in price to many microcontroller development boards for sale, even though its processing power is much more. Another important criteria was hardware capabilities. The Raspberry Pi has quad core processors that will provide more than enough processing power for intended purposes, as well as 8GB of RAM (which again should be more than enough for its intended purpose). The Raspberry Pi is also very flexible, coming with a wide array of input/output ports, a 40 pin general purpose (GPIO) header, and many commercially available accessories and attachments (often called "hats" because they fit right on top of the Pi easily). The Raspberry Pi is also widely used for development and research, and there are many support articles and forums for working with the Raspberry Pi. In fact, there are forums and commercially available products to assist with all planned operations for the Raspberry Pi. These attachments are shown below in Figure 8 and are covered in detail in the next few sections.

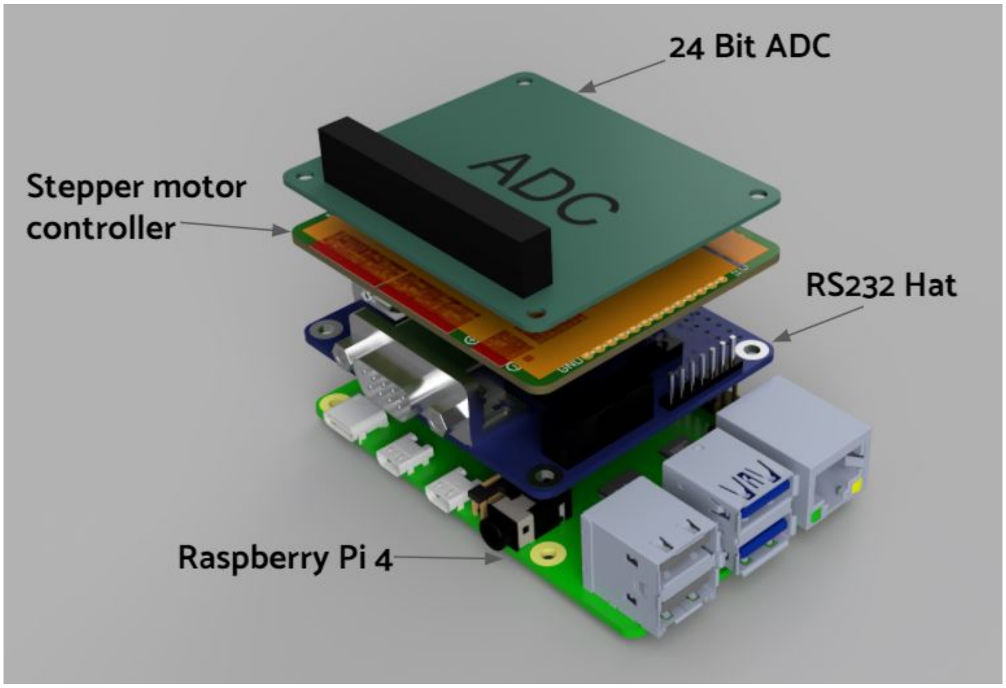


Fig. 8 CAD Model of Microcontroller Stack

2. RS232 Serial Hat

Raspberry Pi has no native support for RS-232 communication, so this component is necessary to handle RS-232 communication between the Raspberry Pi and the laser rangefinder sensor. The board is manufactured by Waveshare (part number: 2-CH RS232 HAT) for express use with the Raspberry Pi, and converts between RS-232 and SPI communications interfaces (SPI is native to the Raspberry Pi). The serial hat connects to the Raspberry Pi via the 40 pin GPIO header. The cost is \$22. Originally, when the project was set to include an inclinometer, this device would also be responsible for communication with the inclinometer. Later in the project, once it was decided that the inclinometer was not needed, the RS232 Serial Hat was replaced with an RS-232 to USB adapter cable that plugged into the USB ports on the Raspberry Pi (as only one RS-232 port was needed now as opposed to two previously). This simplified the design and took up less space and weight.

3. 24 Bit ADC

While the Raspberry Pi has a built-in 12-bit analog to digital converter, the team desired a higher resolution ADC. Assuming the potentiometer spans 360 degrees and the ADC is set up such that 0V and Vcc are at the extremes of the potentiometer range, a 12-bit potentiometer would digitize the angle measurement with an error of $\approx 0.088^o$. This is significant given the scales of errors that this project is dealing with - a few hundredths of a degree is a significant amount of error. Using a 24-bit ADC, the potentiometer value is digitized accurate to $2.1 \times 10^{-5^o}$ - introducing a negligible amount of error. Furthermore, a 24-bit ADC is quite inexpensive - a PCB with a 24-bit ADC onboard costs only on the order of \$30.

The final design choice for a 24-bit ADC is the Raspberry Pi High-Precision ADC/DAC Board manufactured by Seeed Technologies (part number 114990831). It is a commercially available accessory specifically designed and manufactured to work with the Raspberry Pi 4. Like the serial hat, it connects via the Raspberry Pi's 40 GPIO header and adds 24 bit ADC capability to the Raspberry Pi. It costs \$30.

4. Stepper Motor Hat

Finally, the last hardware attachment for the microcontroller subsystem is a stepper motor hat. This board assists with controlling the stepper motors that point the sensor package. The board is manufactured by Adafruit (PRODUCT ID: 2348) and adds dedicated PWM driving capabilities for stepper motors. Adafruit also provides a free Python library of PWM and associated motor control functionality. The board connects via the Pi's 40 pin GPIO header and costs $22.50.

C. Actuator Subsystem Overview

The actuator system is responsible for taking the pointing command from the Raspberry Pi and moving the laser such that it points at the desired target. The laser system needs a field of view of ±67.50° azimuth (horizontal) and ±30° pitch (vertical). The neutral location of the laser system is 0°, 0°. The azimuth and pitching axis is controlled by an independent stepper motor and gearing system. This allows the azimuth and pitch of the laser to be controlled individually.

The azimuth control system pushes against the stationary tripod. The pitch control system is mounted to the azimuth control system. Therefore, when the azimuth system moves, the pitching system moves, but when the pitching system moves, the azimuth system does not move.

The actuating structure is responsible for keeping the system rigid and providing space for the laser, motors, instruments and microcontroller. The system is built from aluminum for lightness and ease of machining. The entire system must be capable of pointing the laser in 0.11° increments about both axis. To keep measuring times down, the actuator system is able to rapidly change pointing directions and then hold the system stable while a measurement is being made.

1. Actuator Structure

The key design features of the actuator structure is structural stiffness and decreased moment of inertia. Therefore, the structure is made from aluminium 5/16 plate and 1/4 angle iron. Most of the angle iron is built from 2 inch flanges however two parts are built from 3 inch flange angle iron. All axles are made from 1/2 inch aluminium rod. All bolt holes are threaded to avoid the need of bolts and every bolt is 1/4-20 except for the mounting bolts for the stepper motor and set screws which are 8-32. Any connection that are not a bolted are press fit. The actuator structure is built around two plates: the azimuth plate and the pitching plate. All parts that will rotate about the z axis are mounted to the azimuth plate and all parts that rotate about the x axis are mounted to the pitching plate.

All parts of the assembly follow a naming convention. Parts that begin with an "A" refer to angle iron. Parts beginning with a "P" stand for plate and all parts beginning with a "B" are a bar. Lastly, parts beginning with a "C" are chunks or blocks of metal. There is no order to the numbering of the parts. Figure 9 below shows each part and its label on the actuator structure.

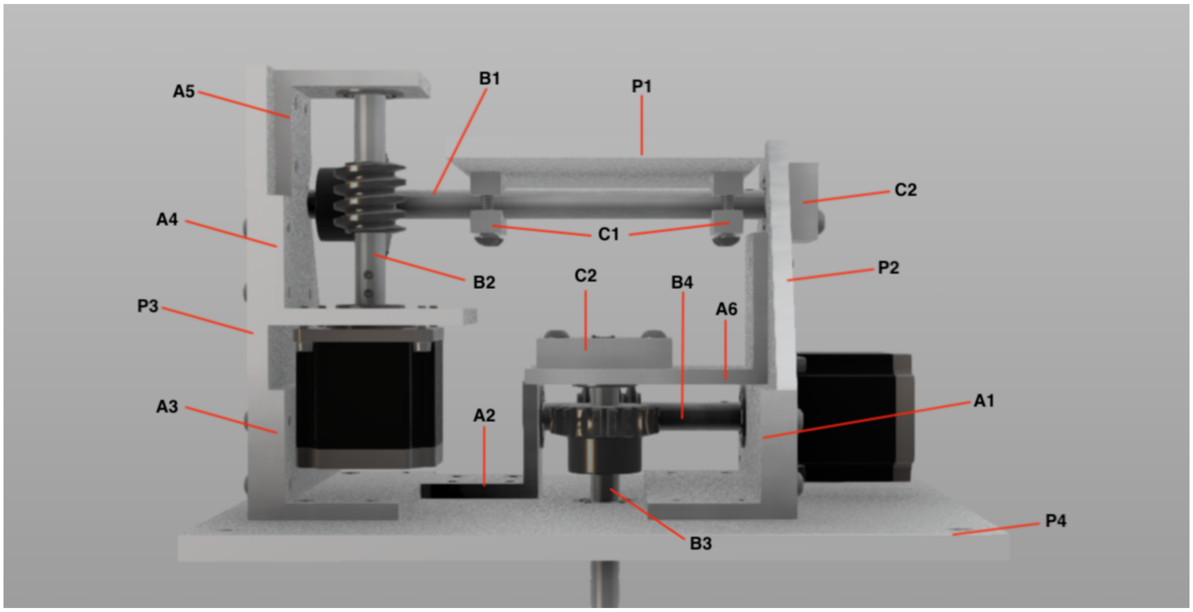


Fig. 9 Actuator part labels and locations

The azimuth plate (P4) is the "foundation" of the structure and the only plate that is 3/8 inches thick. Figure 51 in the appendix shows the bolt pattern from the bottom of this plate. In the center of the plate drilled from the top side of the plate is a 1.13 hole, 5/16 inches deep for the press fit bearing that fits on the azimuth axle (B3). The azimuth axle is fixed with respect to the tripod. Therefore, the azimuth plate rotates about this axle. The azimuth stepper motor will be fixed the azimuth plate and pushes against the fixed azimuth axle. Surrounding the 0.51 inch hole for the axle to pass through is a 0.55 inch groove upon which the thrust bearing for the azimuth plate sits. Running across the shorter length of the plate are two piece of 2 inch, 1/4 inch thick angle iron (A1 & A3) . These angle iron pieces are used to mate the vertical plates that support the pitching plate to the azimuth plate. These angle iron pieces are shown in figures 53 and 54. The first angle iron piece (A1, fig 53) has a 1.13 inch hole for the press fit 1/2 bearing. The azimuth stepper motor is connected to the back side of this angle iron using 8-32 bolts. Also mounted to the azimuth plate is a third piece of angle iron (A2) shown in figure 55. This piece supports the far end of the azimuth driving axle (B2). Therefore, a 1.13 inch hole is required for 1/2 press fit bearing.

The vertical plates (P2 P3) shown in the appendix in figures 56 and 57 connect to the two angle iron pieces discussed above and hold the pitching plate upon a 1/2 in axle (P1). Therefore, each plate has 1.13 inch holes drilled near the top to hold the 1/2 press fit bearing. Attached to second vertical plate (fig 57) are two pieces of angle iron (A4 & A5) shown in the appendix in figures 58 and 59. These two angle iron pieces hold and support the pitch driving axle (B4). Therefore, both pieces have 1.13 inch holes for the 1/2 inch press fit bearings. The pitching stepper motor is mounted beneath the lower plate (fig 58) with 8-32 bolts. Attached to P2 is another piece of angle iron (A6) shown in figure 60 in the appendix. This piece of angle iron holds one end of the azimuth axle (B3). The angle iron also holds the azimuth potentiometer mount (C2).

The pitching plate (P1) is mounted to the pitching axle (P1). Since the final position of the TruPulse 200 on the pitching plate is to be determined, the bolt pattern for the pitching plate shown in figure 61 is not complete. The TruPulse 200 will attach to the front of the plate leaving room to the back of the plate for the micro controller and hats. An plastic printer enclosure will also surround the TruPulse 200 which will need to be bolted to the pitching plate. Currently, the only bolt holes are for the pitching plate clamps (C1) shown in figure 10 in the appendix. Two of the these clamps are fitted on either side of the pitching axle and bolted to the pitching plate. This is very similar to how pipe clamps work. When the pitching axle rotates the clamps force the pitching plate to rotate.

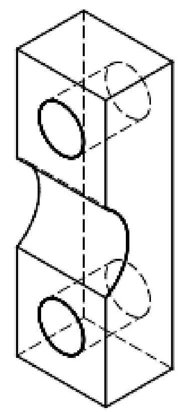


Fig. 10 Pitching axle clamp

Again the pitching axle is B1, the azimuth axle is B3, the pitching driving axle is B4 and the azimuth driving axle is B2. Bars B2 and B4 shown in the appendix in figures 64 and 66 are connected directly to the stepper motors. This is done by reaming out the inside of the bar to a 1/4 inch and a depth of 1 inch. A 8-32 set screw is then drilled perpendicular to the reamed out hole. When the axle is attached to the stepper motor, the motor shaft slides into the reamed out hole and the set screw holds everything in place. Bars 1 and 3 shown in figures 63 and 65 are rotational axles. Potentiometers which are used to measure angular position are also mechanically fixed to these bars in a similar way the stepper motors motors where attached to the previous bars. A 0.13 inch hole is reamed 1 inch deep into the end of a bar. A 8-32 set screw is then drilled and tapped perpendicular to the reamed hole.

The last part of the actuator structure are the potentiometer mounts (C2) shown in figure 67 in the appendix. The potentiometer mounts hold the potentiometer stationary with respect to the structure while the axle rotates. For lack of a better way to fix the potentiometer, the potentiometer will be epoxied into the hole drilled out in the mount. It is important the potentiometer is first mounted with the set screw and then epoxied into place.

It's worth describing in more detail how the shafts are connected. The large aluminum shafts will be fit loosely into the bearings, since there is no need to restrict axial movement of the shaft. Further, the bearings will be press fit into the aluminum structure in which they are mounted. These shafts also need to interface with the potentiometers and the stepper motors. The stepper motors have a flat milled into the shaft, and the team will grind a flat into the potentiometer shaft. In the larger aluminum shaft, a set screw is used to transfer torque between the larger and smaller shafts.

The azimuth shaft (B3) is rigidly attached to the tripod through an interface sleeve. The weight of the actuator system is supported with a thrust bearing:

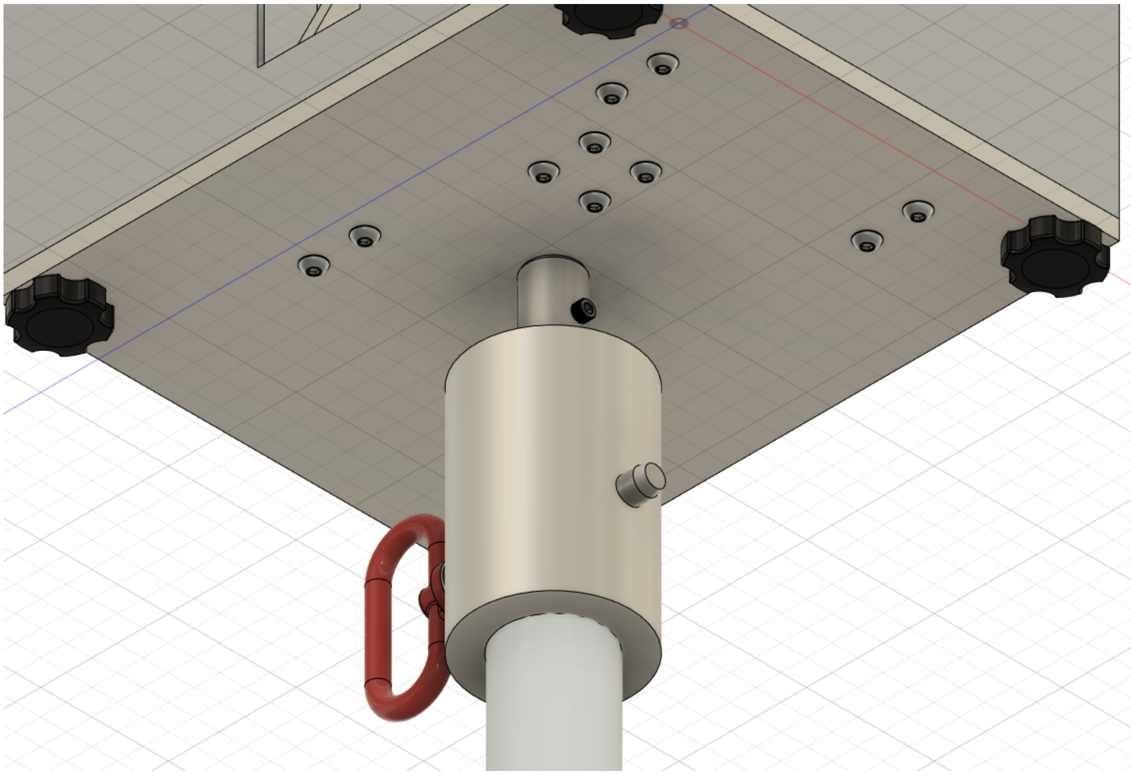


Fig. 11 Tripod mount interface with thrust bearing and sleeve

2. Stepper Motor-Worm Gear System

The stepper motors are responsible for providing the torque necessary to move the system. The worm gears take the stepper motor position inputs and divided it down to improve resolution and holding torque.

The azimuth and pitch axis each are driven by a QSH5718-56-28-126 stepper motors. Each motor has 200 steps per revolution or a pointing resolution of 1.8°. This is 16.4 times courser then the required pointing resolution for the system. Therefore, the motor employs 8 substep microstepping. Microstepping is where each step of the stepper motor is divided into smaller substeps. Therefore, using 8 microsteps on the QSH5718 stepper motor results in 1,600 steps per revolution or a pointing resolution of 0.225°. The remaining required pointing resolution comes from the gearing system.

A draw back to microstepping is that the holding torque per step is divided by the number of microsteps used. The QSH5718-126 stepper motor has a holding torque of 1.26 Nm. However, with 8 microsteps the holding torque becomes 0.1575 Nm. If the holding torque placed on the motor is greater then 0.1575 Nm, the motor will begin the skip steps which will result in the laser moving while the system is trying to hold the laser steady. This could result in failed measurements, but was not experienced during testing as a 20:1 worm gear was used on each axis to improve the holding torque and step resolution

The worm gear takes the stepper motor 1,600 steps per revolution input and increases it to 32,000 steps or 0.01125°. Also, the holding torque is increased to a theoretical maximum of 3.15 Nm. Assuming a 50% loss due to the worm gears, the final holding torque is 1.575 Nm.

The stepper motor has an accuracy of ±5%. This means that if the user commands a 200 steps movement, the motor can stop from step 190-210. Therefore, the smaller the distance traveled, the less error the stepper motor will produce. With this in mind, the actuator system will be driven the smallest distance possible per measurement. However, the largest possible motion from the system is 135°. With this command driving the stepper motor and worm gear system, the error is ±6.75°. Microstepping does not change the accuracy. This error is not concerning since the potentiometers detect this pointing error and the system will reposition.

3. System Performance

Again, the entire actuator system has a pointing resolution of 32,000 steps or 0.01125°. From the CAD model, the moment of inertia about the azimuth axis is I=0.133 kg m^2 and the pitching axis is I=0.002 kg m^2. Stepper motors perform the best below 10% of the holding torque. Therefore, by limiting the stepper motors to a shaft torque of τ=0.1575 Nm, the time to move the system some $\Delta\theta$ is found in equation 2. Measuring points six meters apart at 400 meters represents a $\Delta\theta$=0.15°. Given a 0.25 second settling time, positioning at this angle requires 0.971 seconds per motion in the azimuth direction and 0.338 seconds in the pitching direction. If the points being measured are 1 meter apart 10 meters away, $\Delta\theta$=5.71° and the positioning time for the azimuth system is 4.968 seconds and the pitching axis is 0.795 seconds. Since the majority of the points being measured are further from the sensor location, the average measurement per motion is 1.5 seconds for the dry scan resulting in 4.36 days of operation, however, faster scanning is required. Therefore, by driving the stepper motors at 40% maximum torque load and decreasing the scan time to 0.75 seconds average per motion results in a dry scan of 2.18 days. Assuming a linear relationship between amperage and holding torque, at 10% torque, the system would consume 0.138 watts for a total energy consumption of 14.5 watt hours or 36.25 amp hours. If running at 40% holding torque the power increases to 0.55 watts 29.00 watt hours or 72.5 amp hours.

$$t = 2\sqrt{\frac{\Delta\theta I}{\tau}} \tag{2}$$

Since the system has a pointing error of 5%, larger stepping commands require repositioning to make the pointing direction usable. Equation 3 below is used to calculate the worst case number of repositions N_r needed to get the laser pointed in the correct direction where r is the resolution requirement and $\Delta\theta$ is the change in pointing angle. For the actuator system, the pointing resolution must be ±=0.055°. With the largest repositioning angle of $\Delta\theta$=135°, the system would require 2 repositionings. Table 3 shows the number of repositionings required for a given $\Delta\theta$.

$$N_r = log_{0.05}\left(\frac{r}{\Delta\theta}\right) \tag{3}$$

Repositioning for a Given Travel Distance

.

$\Delta\theta$	0°-1.1°	1.1°-22°	22°-135°+
N Repositions	0	1	2

Table 3 Repositioning required for $\Delta\theta$

D. Enclosure & Platform

1. Overall approach and sizing

To protect the components from adverse weather such as snow accumulation, an enclosure is designed to go around the actuator system. The enclosure is made of high-density polyethylene or HDPE. This material is commercially available and commonly used for milk containers. HDPE is selected due to cost, manufacturability, and weight considerations.

The enclosure is made of 5 flat sheets of 1/8 inch thick HDPE. In the following view of the left side of the enclosure, the side panel can be seen. It's trapezoid shape will be cut from 12x24 in. sheets. The roof of the enclosure is 19.25 inches long, extending 6 inches out in the direction of the measurement. It is at an angle of 35° to encourage any snow accumulation to slide and melt towards the rear end of the enclosure.

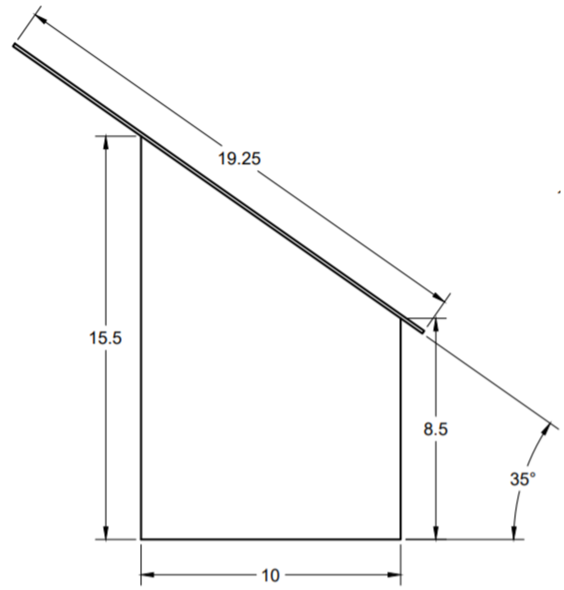


Fig. 12 Sensor Enclosure: Side

From the back of the enclosure, the large rectangular roof is visible.

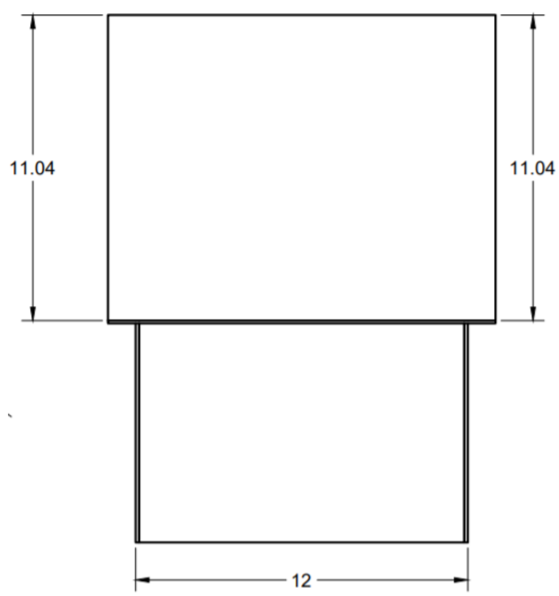


Fig. 13 Sensor Enclosure: Back

The bottom of the enclosure is the previously discussed azimuth plate. The enclosure is reinforced along each vertical edge 1 inch thick bars, also made of HDPE. The bars are screwed on to the azimuth plate with oversized thumb screws, allowing the customer to access the internal assembly as needed, even while wearing gloves. These bars also used to reinforce the connection between the roof and the two side sheets. Connecting the enclosure to the azimuth means the laser rotates with the enclosure and does not interfere with its operation in the yaw direction. This view also shows the roof as it overhangs each side by an inch. This prevents any precipitation from slowly dripping on to the sides of the enclosure and becoming difficult to remove. The extra inch on each side means icicles that form can be broken off with ease.

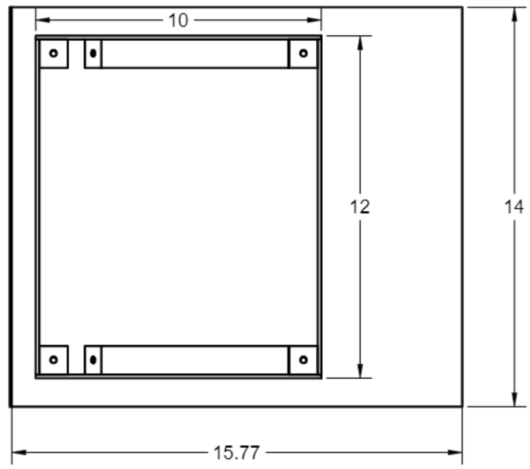


Fig. 14 Sensor Enclosure: Bottom

The front of the enclosure is also a sheet of HDPE, but has a tall slit cut into it. As the laser changes elevation angle, the enclosure does not move. Refraction due to changing incidence angle of the laser introduces significant error. Thus, a gap of height 13.5 inches is cut into the front sheet. This allows the laser to pass outside the enclosure and measure distance without interference. The width of the gap in figure 15 is 3.5in wide.

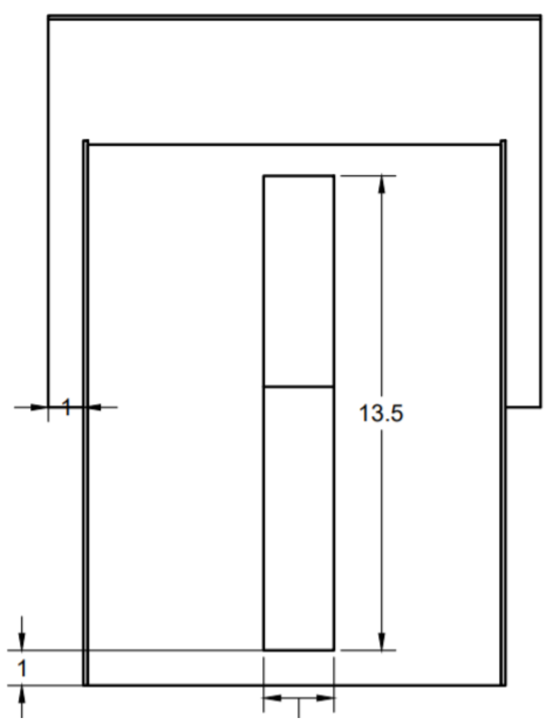


Fig. 15 Sensor Enclosure: Front

E. Software

1. System Control Software

The system control software helps satisfy Functional Requirements 1 and 6 and their associated Design Requirements. This software is responsible for autonomously controlling the sensor platform, coordinating communication and feedback from the various sensors, and storing the collected data until it can be transferred for post-processing. All system control code is written in Python 3. Python 3 was chosen for its flexibility, widespread use, and functionality with the various subsystems. All of the system control code runs on a single script on the Raspberry Pi 4. The script controls both stepper motors using an Adafruit Python library for electric motors. The scan pattern is currently set up to be a snake pattern scan over a rectangular area, but this pattern can easily be changed by simply changing the amount of steps each motor takes. The code also communicates with the laser rangefinder and potentiometers, commanding them to take data and storing the response. Finally, the script writes the collected data to a text file in an easy-to-use format for transfer to a Windows PC for data processing (it is also theoretically possible to do the data processing on the Raspberry Pi, but it is very slow).

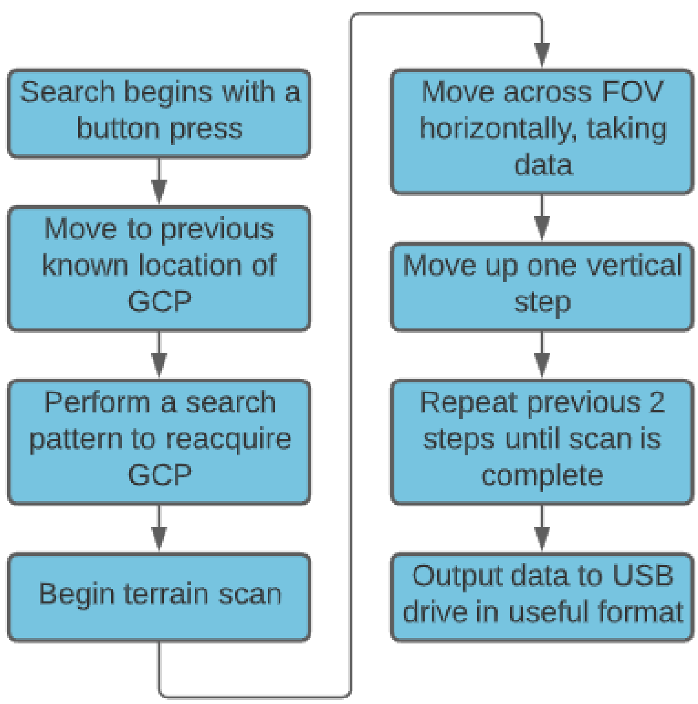


Fig. 16 Simple Code Flowchart

2. Data Visualization: ArcGIS

This portion of the design satisfies DRs 5.1, 5.2, 5.3, 5.4, and 5.5. ArcGIS is capable of calculating values using math packages from Python. There is also a Python API available that can provide a smoother transition into a new coding interface. To satisfy requirements to create a dry map and a wet map, there are tools on ArcGIS that can compute

2D interpolations as well as provide different methods to overlay data, analyze data, and determine proximity of data based on geolocation. Ease of use for the customer will be difficult to apply using this application; however, the staff at Copper Mountain has experience with this program and we will also provide steps on uploading and prepping .txt files as well as data.

Part IV.
Manufacturing

Authors: Aidan Sesnic, Jordan Walters, Brett Papenfuss

7. Manufactured vs Purchased Parts

The total station is made up of multiple subsystems. Following is a list of the parts the team had to manufacture/assemble and those that where purchased.

Manufactured:

- Weather proofing HDPE enclosure
- Actuating structure
- Assembly of custom PCB
- All software

Purchased:

- Laser range finders
- All electrical components: potentiometers, LM-35 temperature sensors, components used to populate PCB
- Stepper motors
- Worm gear
- Micro-controller components: ADC, Raspberry Pi, stepper motor controller, RS-232 communications
- Mounting tripod

8. Manufacturing

The first round of manufacturing was completed at the aerospace engineering machine shop. This required manufacturing the following parts:

- Enclosure parts: front face, rear face, side faces, and roof of HDPE enclosure. These were laser-cut.
- Pitch and azimuth assembly: this consists of a multitude of parts machined from the following stock: plates, bars, and round stock. This was machined using a milling machine and lathe.

However, there were several changes that needed to be made. In order to do so, one of the team members utilized his grandfather's machine shop. A summary of the required changes are as follows:

- The potentiometer shafts were of a larger diameter than the team anticipated based on the manufactuturer-provided CAD models. This required several changes:
  - The potentiometer shafts are inserted into a large shaft whose rotation is being measured. Accordingly, the diameter of this bore was increased in order to accommodate these larger shafts.
  - The potentiometers are mounted in blocks which bolt to plates. This requires that the potentiometer shoulder fit within the 1/2-inch diameter hole in the bearings. Because of the larger shoulder on these potentiometers, the shoulder was not able to fit through the bearings as intended. In turn, the potentiometer mount blocks had to be mounted on standoffs and offset. The hole in the potentiometer mounting block was also widened to accomodate this change.
  - Because the potentiometers were now mounted further outboard, the set screws used to transfer torque

between the shafts needed to be moved further outboard.

- The potentiometer mount blocks contain asymmetrical bolt holes. One of the potentiometer mount blocks had the incorrect bolt pattern, but this was corrected easily on a mill.
- The team had planned on press fitting all components onto the axles, including worms, worm gears, and bearings. This proved prohibitively difficult. In turn, several changes were made:
  - The axles are press-fit only into one bearing. The remainder of the axle was turned down by several thousandths of an inch to allow for the other components to slip onto the axle with ease.
  - To mount the worm gears, threads for a set screw were drilled and tapped into the gears on a milling machine. Then a set screw can be used to transfer torque between the gear and shaft.
  - A Woodruff key was used to transfer torque between the axle and the worm. This required milling a shallow slot into the axle so that the Woodruff key can interface to both the shaft and worm. The team used an oversized Woodruff key to minimize backlash.
  - To keep the worm located appropriately along the shaft, the team added spacers and shaft collars.
- Due to loose tolerances in the tripod mass, the tripod interface sleeve needed its bore widened to a larger diameter.

9. Structure Assembly

With the aforementioned machining fixes made, the structure could be very easily assembled; no major issues were faced during assembly.

The enclosure proved more difficult in assembly. The team believed that cyanoacrylate would bond the HDPE panels of the enclosure. However, these glued joints were extremely weak, so the team instead fastened the enclosure panels together with small screws.

10. Printed Circuit Board

The PCB circuit board was designed by the team and then printed by Oshpark board house. The next step was to solder the electrical components ordered through Digikey to the board. This required a soldering iron, solder, hot air, flux and solder wick. Populating a board took 1.5 hours to complete. The primary challenge was soldering the 8 pin DC-DC converters to the board and avoiding cold solder joints. The PCB uses a standard 2x20 header pin block which plugs directly into the Raspberry Pi header stack.

11. Software

The software was developed specifically for this project by the team. The software is written in Python 3 and Matlab, and is split into three main components: system control software, test scripts and analysis, and data post-processing. The system control software is all in Python 3 and was developed directly on the Raspberry Pi 4. The test scripts are also in Python 3, and the test analysis is written in Matlab and Python 3. Finally, the data post-processing is written in Python 3 using Jupyter Notebooks and the associated ArcGIS plugin. Software was developed using a typical programming development cycle. First, the code was laid sketched out using rough pseudocode not specific to a particular programming language. After determining via trade study and research to use Python 3 as the primary tool for the project, the pseudocode was updated to be more Python-like (see Figure 17). The next step was to create a Github repository to be used for backup and version control. Next, simple test scripts for each critical component were created. These scripts were iteratively tested and debugged until they functioned correctly. Finally, the individual test scripts were combined into a main script for controlling the system and a main script for post-processing the data. The control software is run on the Raspberry Pi 4 micro-controller and the post-processing is done on any Windows PC.

```
motorsObject = MotorKit(i2c=board.I2C()) # create object for motor input
# for now, motor 1 is the horizontal plane and motor 2 is vertical plane

def stepper_function(motornum, direction, step_type): # function to step motor once
    print('step') # debug purposes
    motornum.onestep(direction=direction, style = step_type)
    time.sleep(0.1) # quick delay to let things settle, may be able to decrease this



searchRangeSize = # yet to be determined, probably about 1 degree
minimumStepSize = 0.0056 # degrees, needs to be confirmed

if GCP.txt not blank:
    step until at previous known coordinates of GCP
    currentAngle - previousGCP_angle = turnAngle
    numberSteps = turnAngle/motorStepSize
    stepper_function(motorsObject.stepper1, STEPPER.FORWARD, STEPPER.SINGLE)
    # repeat for other plane
```

Fig. 17 Segment of Python-like pseudocode

One of the greatest challenges faced during the software development process was the nature of the project leading to the software and hardware being intrinsically linked. To fully test most of the software, the associated hardware had to be setup and working correctly. At various points, software was developed far ahead of the associated hardware being completed, and the software could not be fully tested for some time. Also, this led to a couple software tests where the system did not work as expected, and it was difficult to tell if it was software or hardware components (or both) that was causing the issues.

Part V.
Verification & Validation

Authors: Luke Dickinson, Max Fidler, Adam Gourmos, Brett Papenfuss, Jordan Walters, Kevin Yevak, Sean Yoo

12. Laser Rangefinder Accuracy

A. Test Setup
The laser rangefinder is a key component to developing an accurate scan of the mountain slope. Its accuracy directly impacts the snow pack error calculation geometries. From the manufacturer, the rangefinder is said to have an accuracy of ±4cm at any range below 400m. To test this, the straight of a running track was used for its level surface and known distance (100m). Using a 100ft tape measure, the team measured the track to be 100.07m with an uncertainty of 0.5cm. The range finder was set up on a tripod at a known height and measurements were taken to determine the distance to a wooden board on the other end of the track. The point measured was at the same height as the sensor to ensure a level and accurate reading.

B. Results
At the 100.07m distance, the laser rangefinder repeatedly measured a distance of 100.09m. This leads to an error in the laser rangefinder of 2 cm ±0.5cm. This is better than the ±4cm given by the manufacturer, however, that accuracy is given for a maximum of 400m range. This concludes that the rangefinder performed as expected and is accurate enough to meet the needs of the system error budget.

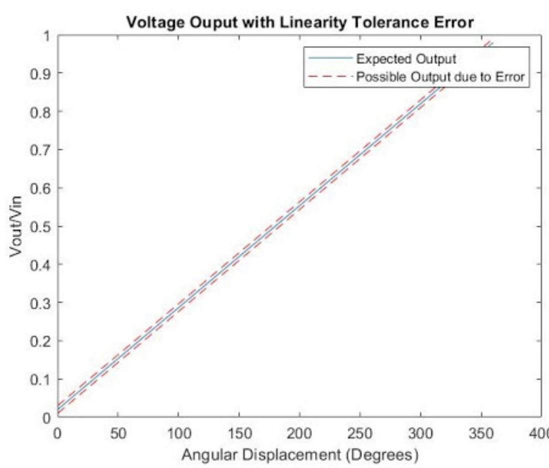
13. Potentiometer Accuracy Determination

A. Test Setup

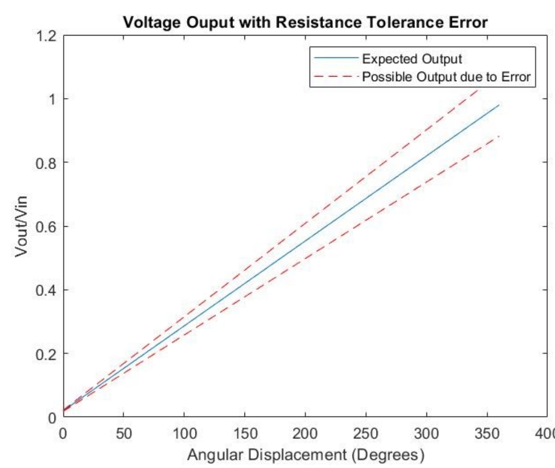
The goal of this test is to quantify the potentiometer's accuracy in predicting the actual angle our system turns in the azimuth and elevation. The team began by modeling what the potential error of the potentiometer is by using the given datasheet. The values that the teams uses to determine this error is the independent linearity as well as the resistance tolerance give as ±1% and 10% respectively. The independent linearity describes the error in the input voltage which will impact the voltage ratio that we would use to measure the mechanical rotation of the potentiometer. We can translate this into error bounds by using the current of the circuit given the input voltage and the ratio range of the potentiometer. For the team's tests an input voltage of $5V$ was used as well as a resistance range of $49k$. The step size between different resistance values was found by dividing the resistance range value by 360. An array was developed using these this step size form the minimum resistance value the potentiometer would see $(1k)$ to the maximum value $(50k)$. This is then multiplied by the calculated current in order to determine the output voltage values the test would yield. By dividing this number by the input voltage and its given error range, the team is then able to calculate the error bounds of the expected signal given the independent linearity. This can be represented in equation form:

$$V_{error} = \frac{I * (R_{min} : R_{step} : R_{max})}{V_{in} \pm \%1} \tag{4}$$

Similarly, the error due to resistance tolerance can also be calculated. However, the resistance tolerance error is applied to the resistance values opposed to the input voltage. The resulting graphs of the resulting error bounds are given here:



(a) Error due to linearity tolerance



(b) Error due to resistance tolerance

Fig. 18 Potentiometer models

Because the error bounds due to the resistance tolerance had the widest margins, this is model the team decided to use in evaluating the potentiometer's accuracy.

Because the potentiometer was the most accurate component of the team's whole system, its error had to be determined through a large test setup. In other words, the system would turn over a single step and this stepping angle would be determined using the law of cosines. In order to do this, the team used the laser rangefinder to measure the legs of the triangle and marked points on a wall ahead of the visible laser attached to the system. A diagram of the test setup can be seen here:

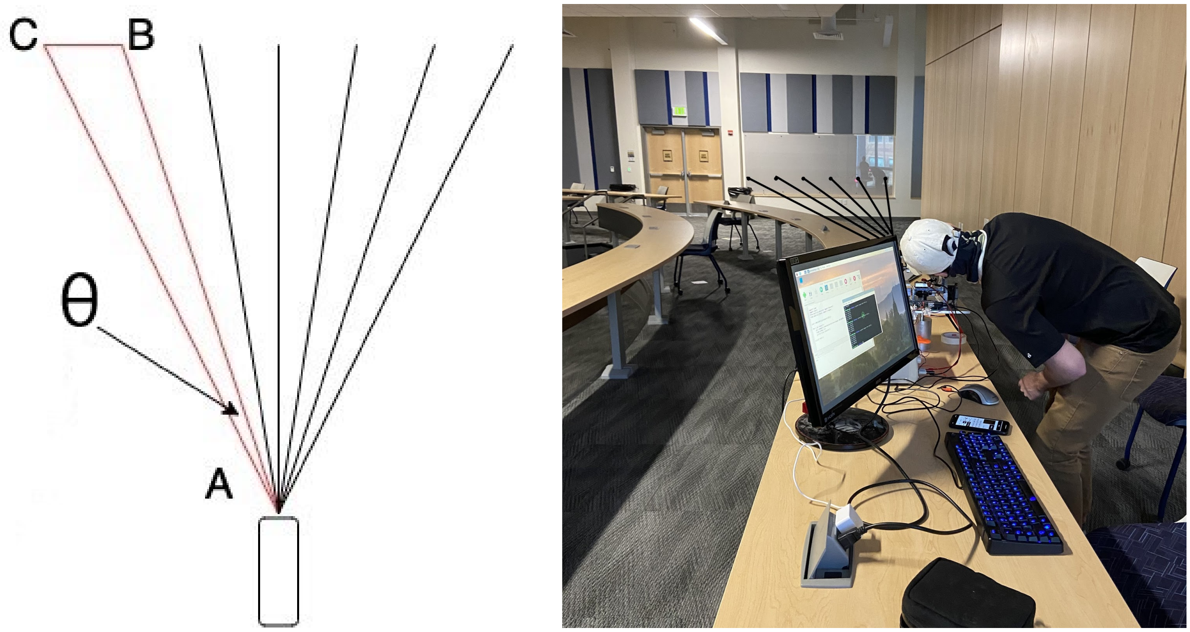


Fig. 19 Complete potentiometer test setup

The exact equation for finding angle θ is derived straight from the law of cosines:

$$\theta = arccos\left(\frac{\overline{AC}^2 + \overline{AB}^2 - \overline{BC}^2}{2 * \overline{AC} * \overline{AB}}\right) \tag{5}$$

By physically measuring the distance $\overline{CB}$ the team is able to accurately plot the actual distance the system turns in the azimuth direction. Once this is characterized for one of the potentiometers, the test would be repeated for the other. Another goal of these tests was to determine whether or not the signal we received each time would replicable, especially between the two different potentiometers.

Another interesting aspect of this test is being able to determine how accurately the team would be able to measure this physical system. The laser rangefinder is able to read distance with an accuracy of ±2cm. The small leg of the triangle was measured using a ruler which allowed the team to measure at an accuracy of ±0.cm. Combining these two errors allowed our team to measure the turning for each step to an accuracy of approximately 0.02°. This was found using equation 5 and using the errors to calculate the extremes given actual test data from the dimensions of the area the team used. Longer legs of the triangle were on the order of $10 - 12$m while the smaller legs would range between $5 - 10$cm.

Another final note on this test setup is that the surface that the laser rangefinder project onto needed to be flat. Not because it directly impacts the accuracy of the laser rangefinder, but because the teams ability toe measure marked points through terrain would cause large errors. Take the actual setup shown in figure 19. If the marked points happened to be on the door and the next point was on an elevated surface relative to point on the door, the team would need to measure through the obtrusion in order to retrieve an accurate measurement pf that leg. For this reason, only flat walls output substantial results.

B. Results

After running the experiments over the total of eight tests, only five yielded substantial results (results with more than 10° of range) and only three of those five yielded results within our model. The signal from the these five tests are plotted with the model of resistance tolerances to initially visualize the errors:

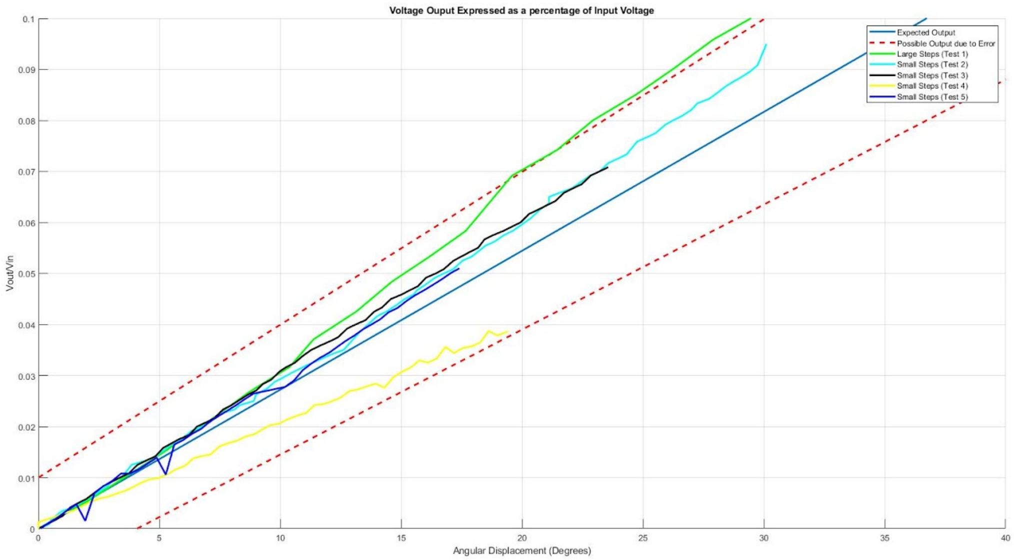


Fig. 20 Potentiometer signal from accuracy tests

Immediately in the post analysis, the team had determined that the signal is replicable between different tests. This means that the signal can be predicted in order to determine an accurate signal when pulling voltages from the potentiometer. Test 1 was the only test where the team had doubled the step sizes to see if it would be able to replicate a similar signal. A lesson that was learned from this test is that even though larger step sizes may allow for more testing (shorter testing times), an error in measuring large step sizes will have a larger propagation on the predicted tuned angle. Hence why the green signal trends outside of the error bounds in the above figure. So for the following tests, only small steps sizes over flat walls were used. The only difference between the last four tests was that and ADC was used to measure the potentiometer voltage in tests 4 and 5. Test 4 shows the other negligible tests. Once that data was plotted, it was evident that there was an error in how the ADC was configured with other components. This was fixed before the final test. Therefore, the tests that are used for the team's analysis of the system's accuracy in measuring turning angles are tests 2, 3, and 5.

These test signals were then plotted with the expected voltage output as well as a linearly interpolated line to each signal. The team's new predictive output line then became the average of the all the interpolated lines. Another line that is plotted with each of the valid tests are their predicted outputs of each signal. This is done by taking the voltages read from the potentiometer, turning them into a ratio of the total voltage, and plotting the degrees as a function of the voltage ratio (just multiplying each ratio value by 360). Interesting enough, this line would help determine the validity of each test. If there was an error with how the potentiometer was reading the voltage during the test, the predicted output's would not line up with the original expected output shown in figure 20. This is how the team determined that Test 4 was not a valid test.

Because the difference in these lines can be so small, plotted below will be a graph of the three tests and their analytical lines as well as a enlarged version to see those differences:

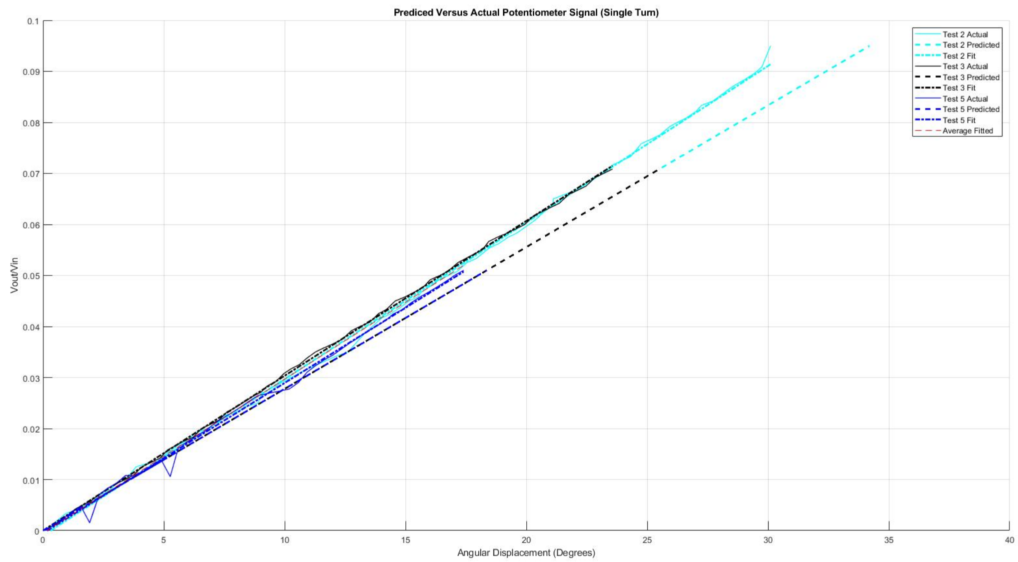


Fig. 21 Potentiometer signal analysis

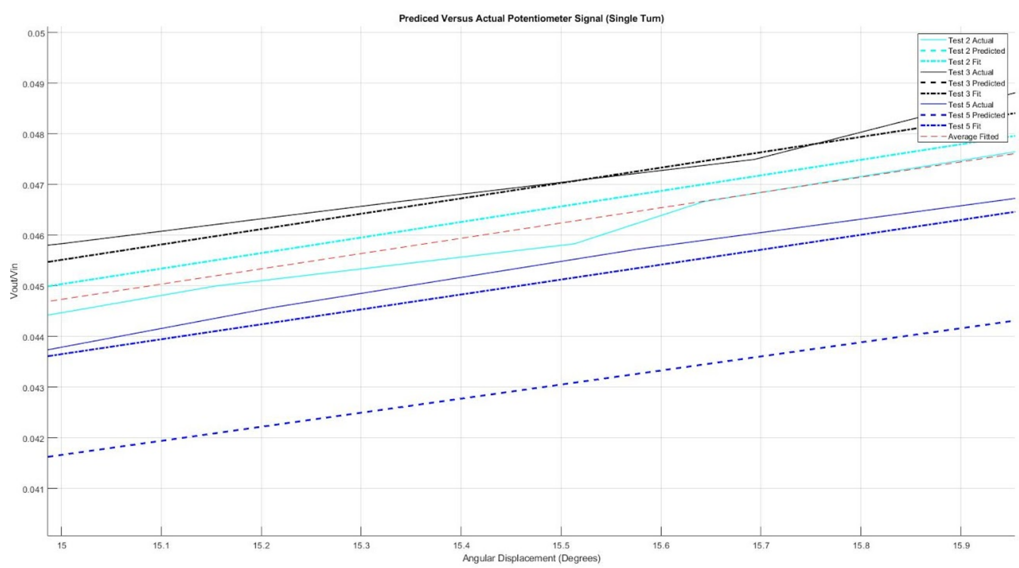


Fig. 22 Potentiometer signal analysis (enlarged)

To reiterate some of the features mentioned above, all of the test's predicted signals (dashed lines) line up on top of each other. The team then used the flitted line for each test (dot-dashed line) to calculate the the average signal (the dashed red line) which becomes the model signal used in the system. In order to determine the error of the system, each actual signal value was subtracted from its corresponding degree on the average fitted line. The average, standard deviation, and maximum error for each of these tests are compiled into the bar graph here:

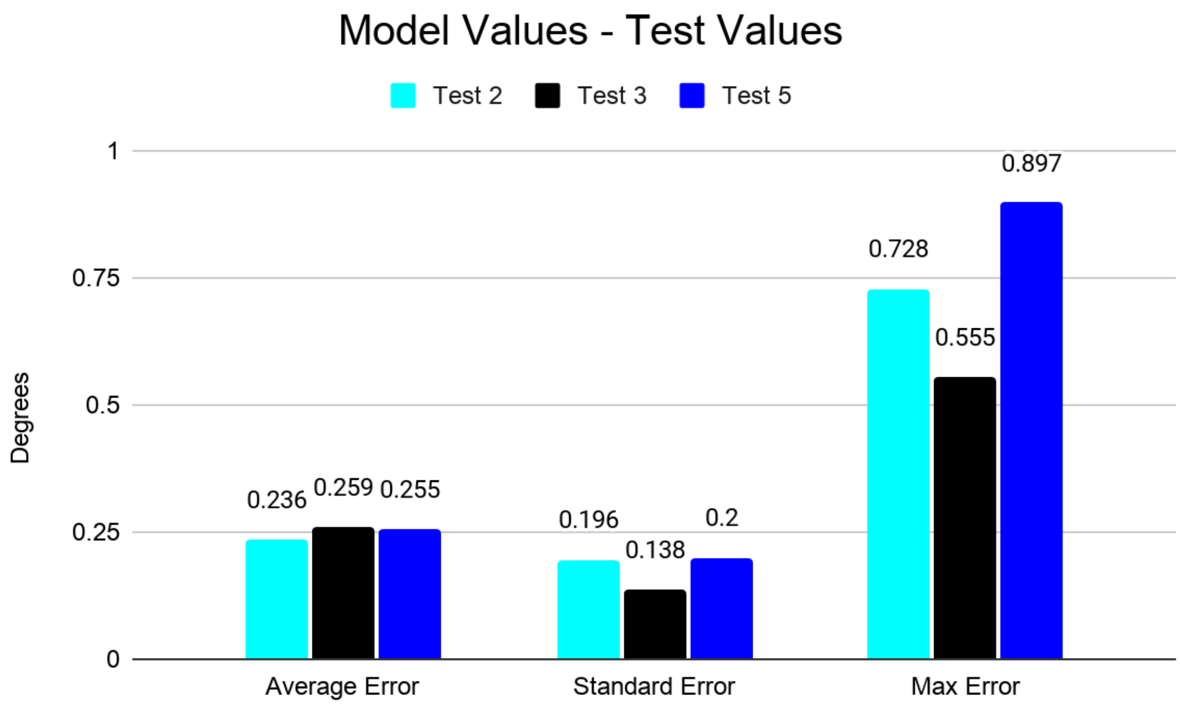


Fig. 23 Potentiometer test errors

From these results, the team was able to determine that the potentiometer can read a change in the systems angle with an accuracy on average of approximately 0.26°. With a stand rd deviation ranging from 0.14° to 0.2°, The team can expect to see errors ranging from 0.02° to 0.40°. Any max errors measured were measured outside two standard deviations as these wouldn't be values that the system would typically see. It is also important to note that the system is also is heavily skewed towards 0. This makes sense seeing that the difference values were never negative.

Through this analysis, the team found that this potentiometer currently does not meet even our first level of success of being able to measure snow depth within ±50cm. Under a degree error of 0.26° the system can read snow depth at approximately 90cm accuracy. However, the teams believes that this is due to the fact that the output power supply used during these tests was outputting noise signals creating an error 5 times larger than we expect. Therefore, we further testing using the newly purchased batteries, the team believes that we can get the accuracy error down to 0.05° giving an approximate snow depth error below 20cm.

14. Analog to Digital Converter Error Determination

A. Test Setup

The analog to digital converter (ADC) is responsible for measuring the reference voltage created by the PCB power supply and the potentiometers voltage. The ratio of these two values is how the system determines its pointing angle. Measurement error in the ADC will create noise in the pointing error which cascades down to increasing the error in the snow depth measurements. Therefore, quantifying the ADC error is important for understanding the performance of the entire system.

To determine the ADC error, the initial test plan was to use a bench top power supply to supply a steady voltage to the ADC. The averaged DC component of the ADC would then be compared against the power supply voltage to tell us the DC offset error of the ADC. Then, an oscilloscope would be used to measure the power supply voltage to determine the peak to peak noise (or AC noise) of the power supply. This AC noise will be compared against the ADC noise. The result is the AC white noise of the ADC could also be quantified. The issue is the power supplies int he electronics labs turned out to be less accurate then our ADC. The oscilloscope measured the power supply AC noise around 29.5 mV with occasional spikes to 70mV. This kind of AC noise would result in meters of snow depth error. Therefore, a better voltage supply had to be found. Figure 75 in the appendix shows an oscilloscope screen shot of the power supply.

Lithium polymer batteries are quoted to have voltage fluctuations of 2-3 uV. Therefore, by replacing the power supply with our batteries, significantly better results should be yielded.

B. Results

Using batteries instead of the power supply, the testing ran into a new instrument limitation: our oscilloscope. The oscilloscopes in the lab appeared to have a noise threshold around 3.75mV. This threshold was determined by connecting the oscilloscope probe to ground. Lengthening the probe wires would increase the white noises on the oscilloscope. Therefore, it was speculated that when we hook up our batteries to the oscilloscope, the noise floor would rise sum. The yellow line shown below in figure 24 is the oscilloscope noise floor with the shortest probe. Again, this error is around 3.75mV. The green line is the battery noise. In this screen shot the noise was 10.5mV however this noise value would change depending on how the batteries were hooked up to the oscilloscope and even which oscilloscope we where using. The lowest noise threshold the oscilloscope ever read on the batteries was 5.8mV. Only looking at the oscilloscope noise of 3.75mV, this error converts to 58cm of snow depth error which is 387% of the total system error budget. Therefore, better measurements are still needed.

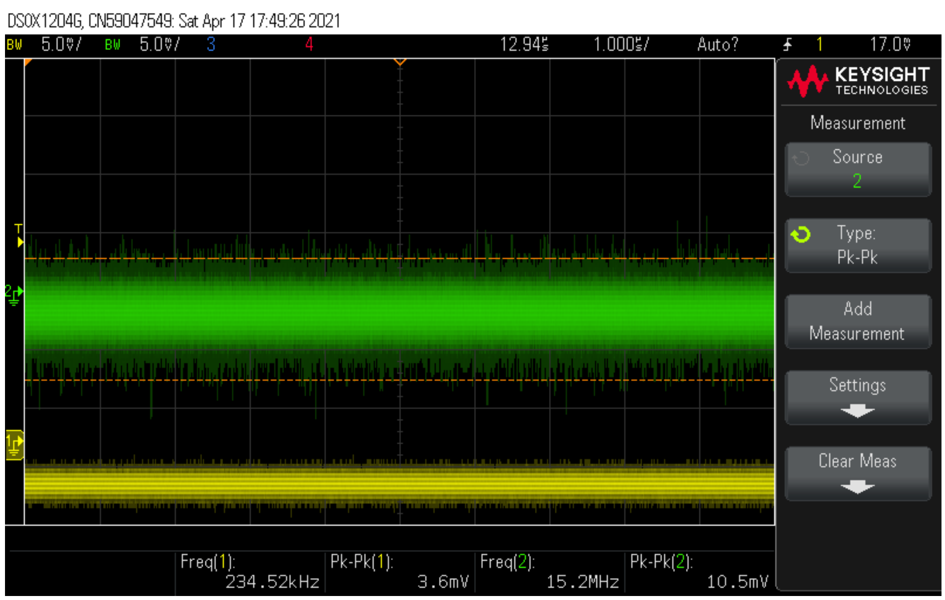
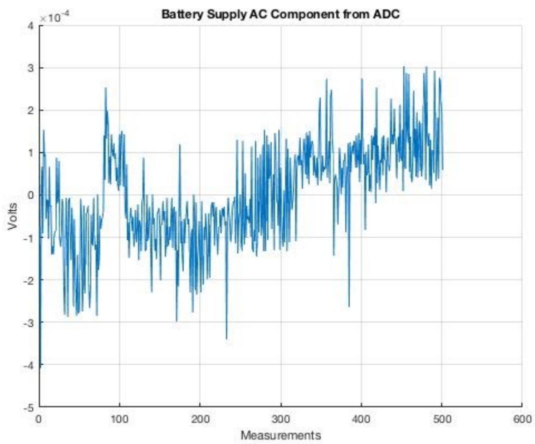
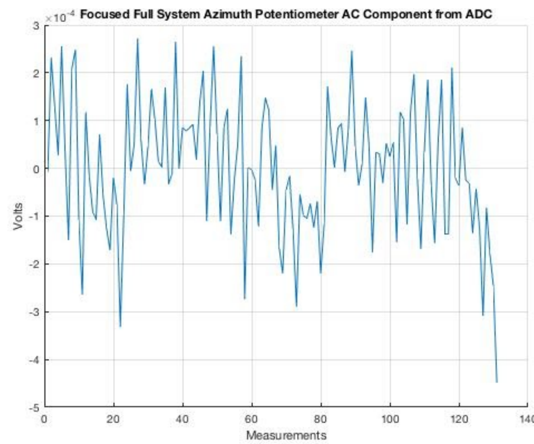


Fig. 24 Oscilloscope and measured battery noise

If the batteries are assumed to have an AC noise component significantly less then our ADC, then the ADC appeared to have a noise floor around 710uV. This error was highly replicable with multiple different batteries and test configurations yielding the same 710uV error. Even passing the signal through stationary potentiometers yield the error. Figure 28a and figure 28b below show the ADC results for the battery and potentiometer tests respectively. Therefore, while it can not be confirmed, it appears that the ADC noise floor is realistically 710uV. This results in a snow depth error of 9.24cm which is 61.6% of the total system error budget. While it exceeds the subsystem error allotted to the ADC and PCB, the error is approaching acceptable levels. There is a possible software fix to improve error which is discussed briefly at the end of the PCB section.



(a) ADC battery measurement



(b) ADC static potentiometer measurement

15. Printed Circuit Board Noise Determination

A. Test Setup

The printed circuit board (PCB) is responsible, among other things, to deliver a clean reference voltage to the ADC and clean voltage signal to the potentiometers. AC noise in the PCB power supply will result in snow depth error noise. Therefore, quantifying the PCB noise is important for understanding the whole system's performance.

The PCB was initially planned to be tested with the oscilloscope. The PCB would pull power from the batteries and the oscilloscope would measure both AC noise of both the batteries and the PCB. Comparing the two signals on the oscilloscope would delivered the noise introduced to the system by the PCB.

B. Results

The results however followed a similar pattern to the ADC testing. In this case the PCB appears to preform better then the noise threshold of the oscilloscope which is 3.75mV. The yellow line in figure 27 represent the battery line AC noise of 5.8mV and the green line represents the output of the 5V power regulation circuit. Interestingly, the 5V output appears to be cleaner then the battery. This implies that the on board voltage filtering components of the regulator circuit are working, cleaning up the oscilloscope noise before that point in the circuit. However, this is not a definitive conclusion since both the battery and 5V noise are very close to the threshold of the oscilloscopes noise floor.

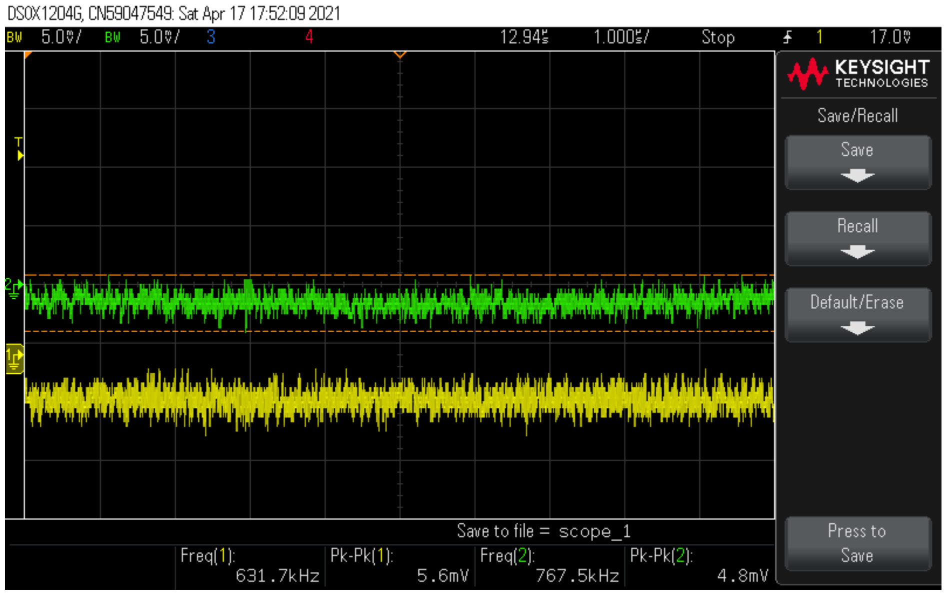


Fig. 26 Oscilloscope measuring battery and PCB

The oscilloscope results leave the PCB with a confirmed error on 58cm or less. This, like the ADC is not valuable data. If the ADC results from the previous section are to be trusted, then swapping the oscilloscope for the ADC would yield higher fidelity results. With the ADC measuring PCB output, the ADC noise floor of 710uV is reached. For all setups and configurations with the PCB, the recorded PCB noise covers a spread from 720uV to 750uV. This could mean that the PCB actually has a noise floor around 760uV. However, with these measurements very close to the noise floor of the ADC, it is safe to conclude the the actual PCB noise is probably less then 710uV. This means the snow depth error of the PCB is 9.24cm or less. In the final system setup, the PCB is directly connected to the ADC and battery just like in the test case here. Therefore, it appears that the PCB noise is contained within the ADC noise. Therefore, the PCB contributes no meaningful noise to the system since the ADC is the bottleneck. Therefore, it is concluded that the PCB and ADC subsystems together generate an AC noise of 710uV which translates to 9.24cm in snow depth error.

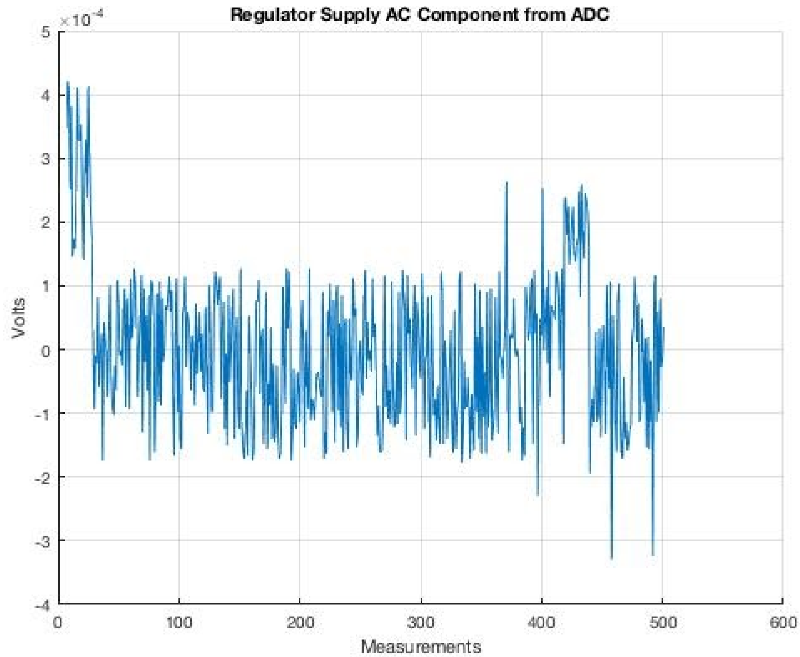
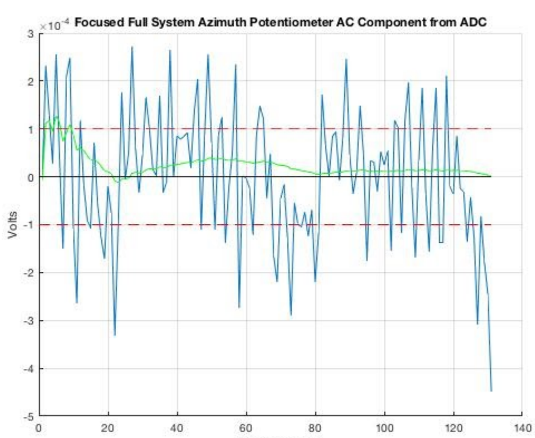


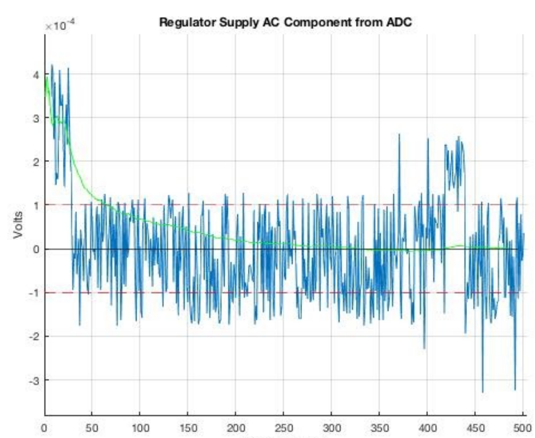
Fig. 27 Oscilloscope measuring battery and PCB

C. Possible Software Improvement

As hinted at in the ADC section however, there maybe a software solution that would improve the ADC/PCB sub system further. The ADC noise appears to be white noise. If this is true, then averaging the output of the ADC is a legitimate way to improve the ADC accuracy. The two figures below show the effect of a running average on actual data. The green line represents this running average and the black line represents the true voltage value. The two dashed red lines show the boundary where measured voltages in this region create a snow depth error of 2.5cm (subsystem error budget) assuming that 0V AC is the true value. If this assumption is true and we can average our values to the "real" value, then the subsystem is a success. Even if it is not, the PCB achieving a noise floor of 710uV or less is fantastic.



(a) ADC running average: static potentiometers



(b) ADC running average: power regulator

16. ArcGIS Capabilities Test

A. Test Setup

In order to test ArcGIS's capabilities, the team ran a dry scan test. The objective of this tests is to analyze the systems ability to convert physical system values into geographic values. In order to convert real system values to geographical locations, the user inputs the latitude and longitude that the system is reading from (retrieved from google) and the latitude and longitude of the first point that the system surveys into a text file. Another user defined component is the altitude difference between these two points. In regards to this test, the altitude was not calculated. However, the method used to calculate the altitude, the new longitude, and latitude will be detailed below for the whole system test will be detailed in this section.

Equations from the the Great circle are used to calculate the latitude and longitude of each point the system surveys.First, the bearings from the base point to the first scanned point is calculated. This equation is given as:

$$\Omega = atan2(sin(\Delta\lambda) * cos(\phi_2), cos(\phi_1) * sin(\phi_2) - sin(\phi_1) * cos(\phi_2) * cos(\Delta\lambda)) \tag{6}$$

Note that λ is the longitude and ϕ is the latitude. Once the initial system bearings are defined, the system is now tied to the actual geographic location. The next step is to output the new latitude and longitude given the distance read by the laser rangefinder and the change in azimuth added to the initial bearings:

$$\phi_2 = asin(sin(\phi_1) * cos(\delta_{dist}) + cos(\phi_1) * sin(\delta) * cos(\Omega + \Delta\theta_{pot})) \tag{7}$$

$$\lambda_2 = \lambda_1 + atan2(sin(\Omega + \Delta\theta_{pot}) * sin(\delta_{dist}) * cos(\phi_1), cos(\delta) - sin(\phi_1) * sin(\phi_2)) \tag{8}$$

Note that δ_{dist} is the angular distance d/R. However, it is important to note that the distance d is not the distance read by the laser range finder, but a combination of the laser rangefinder distance and the elevation angle. The distance needs to be the direct distance between two points on a sphere. Because the system will be reading data values from an elevated surface, the base value need to be projected to the same height as the value we are reading by multiplying the laser rangefinder distance by $cos(\epsilon_{pot})$. It is important to note that in using ϵ_{pot}, its 0 value is equal to when the system is flat with the earth. This was calibrated by rotating the elevation of our system until a bubble-level situated on top of the system was leveled. This is a major source of considering that the system needs to be incredibly accurate.

The results of this dry scan are the results of the base system on top of an apartment building scanning a parking lot across the street. However, because the ADC was not setup during this period, data points were record manually and for that reason, the sample size was a small 10x10.

B. Results

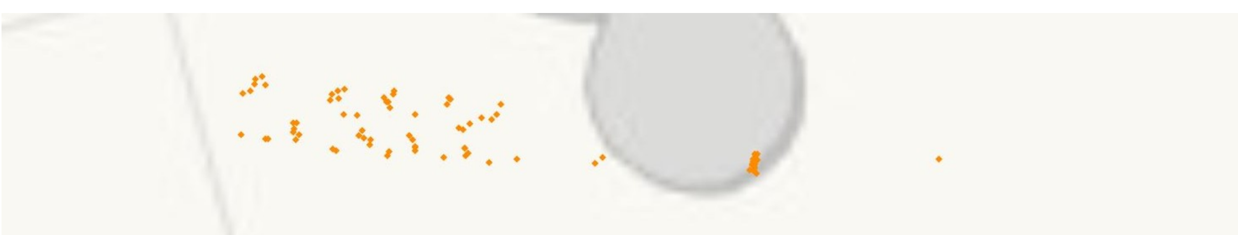


Fig. 29 Preliminary dry scan results

Through this test the team was able to verify that ArcGIS is capable of plotting this data and converting them to geographic coordinates. From this image, the team was also able to confirm that areas with large land features will cause a accumulation of points in a single area. Another important error found during this test was the error due to poor calibration of the elevation potentiometer. This can appear as an error in the data set when data points are not distant from the initial scan point. In figure 29, the furthest right point represents the initial scanned point. This error occurs because the initial point inputted into the grid of points is the user inputted latitude and longitude. Every corresponding value is based off that, so if the system's elevation is read with some error, data points will be some distance from the that initial point but not from each other. This can be corrected in the code by adding some value to the elevation point to account for this error. One way to quantify the absence of this error is to calculate the altitude difference between the base point and initial scan point using the initial laser rangefinder distance and the initial elevation angle with the added constant. By comparing this value to the vertical distance estimated by the laser rangefinder, the team can better calibrate the system in post analysis. However, it should be noted that the laser rangefinder vertical distance calculation functions with an error at a magnitude of approximately 1m. These results directly meet functional requirement 5. With a better understanding of the systems ability to integrate with ArcGIS, the team was better able to prepare for a final system test requiring two parts; a dry scan and a wet scan.

17. Full System Test

A. Test Setup

In order to test the whole system multiple scans were taken from elevated locations. The first full system test was conducted on the roof of a team members apartment. The full senor suite, a power supply, extension cords, a monitor, mouse, keyboard, and GPS device were all needed. From the roof of the the apartment a parking lot approximately 50 feet below and 300 feet away was scanned. The data points were recorded by hand. During the scan the GPS coordinates of the system and an easily identifiable location of the scan site were recorded using the maps app on an iPhone. Subsequent full system tests were conducted from the balcony of the aerospace building and required the same equipment minus the extension cords. The scans from the aerospace building balcony recorded the data directly to a file allowing capture of up to 900 data points. This marks the systems initial dry scan.

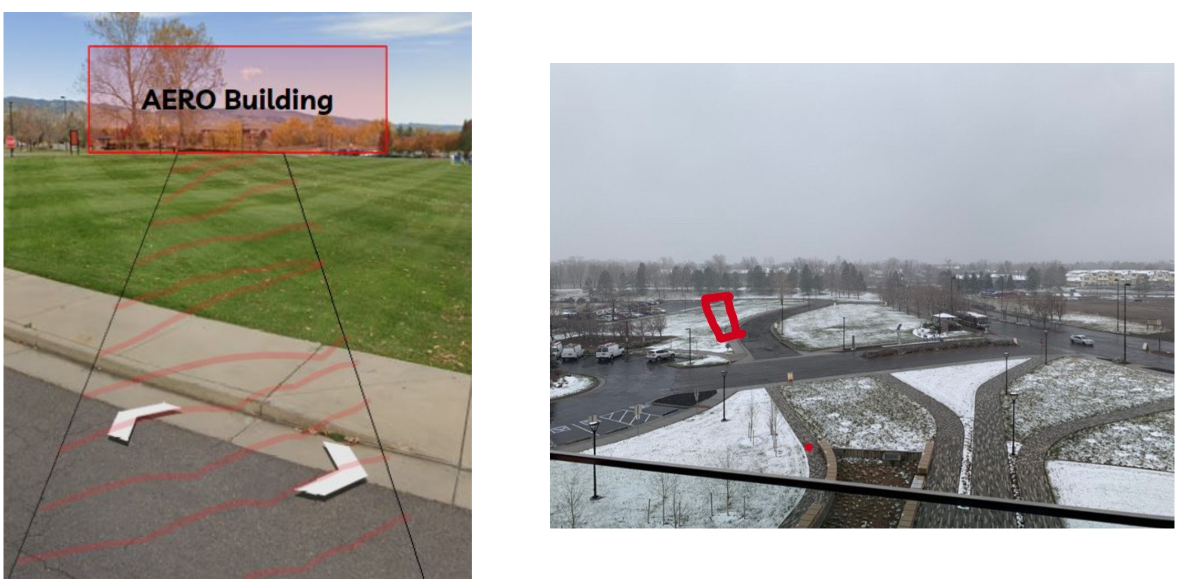


Fig. 30 Final test dry scan setup

One major difference between this test and the preliminary dry scan is that in the post analysis the altitude is calculated and applied to each point. Another difference is that the data is also compiled and uploaded to ArcGIS online for quick contouring. This part was not automated in order to assure that the contouring was plotted correctly without having to extract and develop feature layers through ArcGIS online. As mentioned in the previous section, the heights are calculated relative to the altitude difference between the base point and the first scanned point.

B. Results

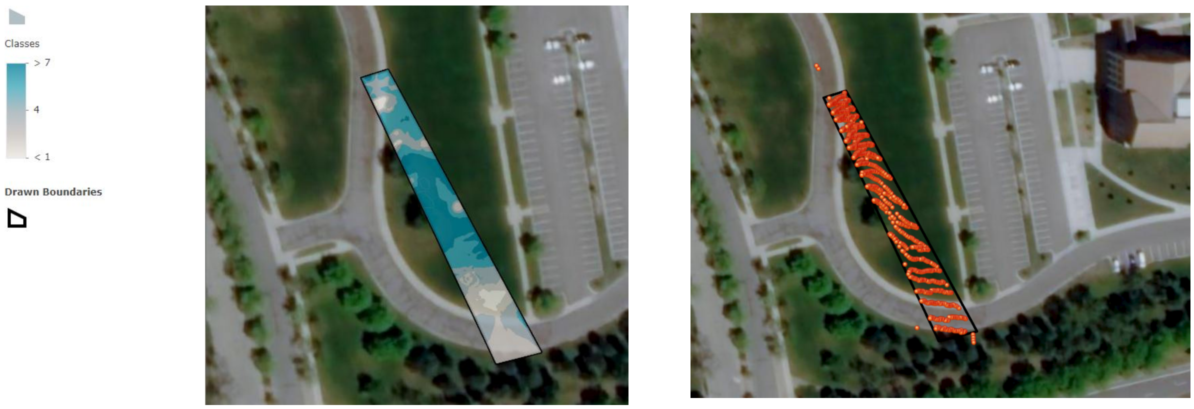


Fig. 31 Estimated altitude values given in meters

The above results show the plotted latitude and longitude points (right image) as well as an interpolated contour map (left image). An important result form the contour map is that physical features and terrain that is represented. For example, the contour map states that an area in the middle of the field is between 4 and 7 meters. The reason for this is due to the tree that was in the field. If the system reads a physical feature like this, it will appear as a closer value with a height that is very different from its surroundings. It will also leave a shadow behind it that is impacted mostly by the contouring rather than the lack of measurements. Although there is no way to quantify the success of the dry scan test, its ability to plot relative contours proves that system is able to read in system values and convert them to meaningful geographic and altitude values. This directly validates FRs 5 and 6.

Unfortunately, because the time window for the teams final tests fell between mid April and the end of April there were no good opportunities to capture snow data. The team had attempted one final test with a large box placed in the field in hopes of characterizing the boxes height, but unfortunately an error occurred and the azimuth pot did not read data values correctly. For this reason, the team was not able to validate the system's accuracy in determining snow depth or heights of physical features. More specifically the team was able to validate parts of FR1, but was not able to validate DR1, the most critical DR for the project.

Part VI.

Risk Assessment Mitigation

Authors: Saad Syed

To assess the risks of this project, a list was created of all of the possible risks. The most concerning risks were determined and will be discussed here. The risks were analyzed by assigning each risk a likelihood and a severity rating. The severity and likelihood rating was given to each risk on a 1 to 5 scale. The risks considered are also in the table below.

Severity Level	Severity of Risk
1: Negligible	No effect to project success
2: Minor	Not critical to project success
3: Moderate	Risk will impede project success
4: Significant	Failure to meet one element of project success
5: Severe	Failure to meet multiple elements of project success

Table 4 Severity level descriptions

Likelihood Level	Likelihood of Risk
1: Very Unlikely	We do not expect this problem to occur
2: Unlikely	
3: Possible	Risk is realistic and previously documented
4: Likely	
5: Very Likely	We expect this problem to occur

Table 5 Likelihood level descriptions

Risk ID	Risks Considered
R1	Thermal drift in potentiometer
R2	Water damage
R3	Fogging of sensor
R4	Raspberry Pi failure
R5	Tripod deflection
R6	Error in sensor due to snow reflectivity/ direct sunlight
R7	Potentiometer backlash

Table 6 Actual risks considered

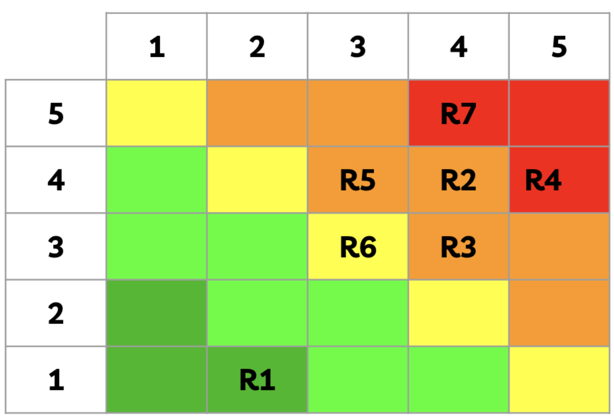


Fig. 32 Risk matrix prior to mitigation.

As shown in the risk matrix, there are 7 major risk concerns. The y axis represents the likelihood of the problem to occur while the x axis represents the severity. Risk 1 of thermal drift in the potentiometer is not likely to cause a significant change but has the potential to make the potentiometers less accurate and biased. This will lead to less accurate measurements for snow depth and could cause our accuracy to become worst than ±10cm. Risk 2 is the risk of water damage and is a major concern for the electrical components which leads to a rating of 4 for both likelihood and severity. The rangefinder has waterproofing which makes it less of a concern, but the Raspberry Pi, potentiometer, and other electrical components could short and stop working. This would cause failure of the system to meet any kind of measurements for snow depth. Fogging of the sensor is the 3rd risk and will cause extreme inaccuracy in snow depth measurements. Raspberry Pi failure will also cause total lack of ability to measure snow depth depending on how extreme the coding failure is. Risk 5 is tripod deflection and will cause an increase in accuracy to snow depth measurements. Risk 6 is error in the sensor due to sunlight entering the rangefinder directly or after reflecting off of the snows surface. This will cause inaccuracy in snow depth measurements. Potentiometer backlash is the final risk considered and would cause inaccurate orientation measurements that lead to major and unknown inaccuracies in snow depth measurements and the locations the sensor thinks it is measuring.

In plan has been created for each of the seven risks to mitigate their effects on the success of the project. For risk 1, an enclosure has been created and a self temperature regulating heating pad will be inserted into the enclosure to ensure the electronics stay at a steady and safe temperature. This enclosure will also help to mitigate risk 2 by keeping snow and moisture away from the electronics. Risk 3 will be mitigated by maintaining a consistent temperature of the system during transport and giving the system and glass within the system time to stabilize. This should decrease fogging. In order to mitigate risks of the code failing, we will extensively test for bugs and validate performance in different scenarios to make sure code works properly. Tripod deflection is risk 5 and will be mitigated using guide wires that are driven into the ground and connected to the top of the tripod to ensure minimal deflections. For risk 6, we will use the sensors TruTargeting flag that determines if the measurement quality is too poor to assume the accuracies provided for the sensor. Additionally, we will find the optimal times of day or night that allow measurements to be taken accurately without interference from reflections on the snow or sunlight shining into the sensor. Risk 7 is potentiometer backlash and this will be mitigated to have minimal effect by realigning the voltage every time a change in elevation occurs during a scan. The errors will still be present but will be minimal and will not propagate across multiple measurements.

After these mitigations, the risk matrix is updated to be shown as below. All of these risk are moved into green and yellow territory from orange and red territory. This means that risks have moved from being likely to cause multiple mission failures to being much less significant risks. This risks are not negligible and must still be considered and taken note of throughout the rest of testing and of the project, but it is unlikely that these risks will be any danger to project success.

During testing, the laser rangefinder was tested in a range of outdoor conditions. The rangefinder did not get fogged up when the system was given time to reach equilibrium temperature. The measured range was not sensitive to the surface measured when tested against dirt, snow, wood, concrete and the road surface. Similarly, once the tripod was acquired and set up, the team decided the planned mitigation would not be necessary. The Raspberry Pi 4 had a short-circuit during testing. After this, the Pi was unusable and a replacement was bought. This caused delays in testing. The problem was traced to the exposed aluminum structure, which is also conductive. More precautions were taken as part of the testing procedure, including increasing the length of the wires and placing the Pi on non-conductive surfaces. Further planned mitigation included a PLA insulating plate underneath the microprocessor but this was not completed.

The designed enclosure and heat management subsystem minimized the risk of water drift or thermal drift. However, testing under extreme conditions did not occur and the risks were not encountered. There were more significant factors contributing to error while the temperature is above freezing 0 °C.

Backlash in the potentiometer was not an issue as the initialization procedure included positioning and realigning the potentiometers to zero so the measurements are within known bounds. There was backlash encountered between the tripod mast and the platform. Using a 1/4" quick-release pin radially through a sleeve at the bottom of teh platform, this was addressed through manufacturing.

	1	2	3	4	5
5	R7				
4	R5				
3	R6	R2			
2				R4	
1	R1			R3	

Fig. 33 Risk matrix after mitigation.

Part VII.
Project Planning

Authors: Stephen Peng, Adam Gourmos, Sean Yoo

18. Organizational Chart

The organizational chart for Team SIMBA shows the structure of the team. The customer, Hagen Lyle, defines the needs and purpose of the project. The team's advisor, Zachary Sunberg, provides the team with technical expertise and constructive criticism involving the design process and class expectations.

The Project Manager, Stephen Peng, is responsible for keeping the team organized. The project manager is responsible for setting meetings, agendas, and tasks for the duration of the project to stay on track with the workflow plan and schedule. The PM keeps up with logistical issues and steers the direction of meetings to ensure the team is meeting course deadlines and internal deadlines. The systems engineer, Saad Syed, is responsible for moderating between all subteams and systems to ensure cohesion. The systems engineer ensures the integration needed to meet the objectives of the project and satisfy the needs of the customer and the class. The financial lead, Adam Gourmos, is responsible for delegating the $5,000 budget. The financial lead must ensure that each sub team and subsystem has adequate funding to accomplish the project objectives without overspending and leaving some budget for back ups and emergencies. The manufacturing lead, Sean Yoo, is responsible for the manufacture and testing of the system. The enclosure lead, Jordan Walters, the modeling lead, Aidan Sesnic, and the safety lead, Max Fidler, will also be very involved in this aspect of the project. The focus for manufacturing is the housing of the sensor, the payload mounting sleeve, and the motor actuating system. The safety lead will also be responsible for ensuring proper procedures are followed in all testing and integration to ensure the safety of everyone. The Software Systems Engineer, Brett Papenfuss, and the ADCS lead, Travis Griffin, will be mainly responsible for the functionality of the microcontroller stack and production of the visual snow depth map. The sensor lead, Luke Dickinson, will lead the testing and integration of the sensor to ensure that the laser is making accurate readings. The thermal lead, Kevin Yevak, will focus on ensuring that the system functions properly in the cold conditions of Copper Mountain. Finally, the Battery Lead, Devon Ricken, will focus on providing adequate power to support the 20 hour dry scan and the shorter 1-2 hour wet scans. The battery lead will also be responsible for the electrical connections of the system. Even with the defined roles in the organizational chart, the work and expertise in each subsystem will be divided by multiple team members to ensure quality of work.

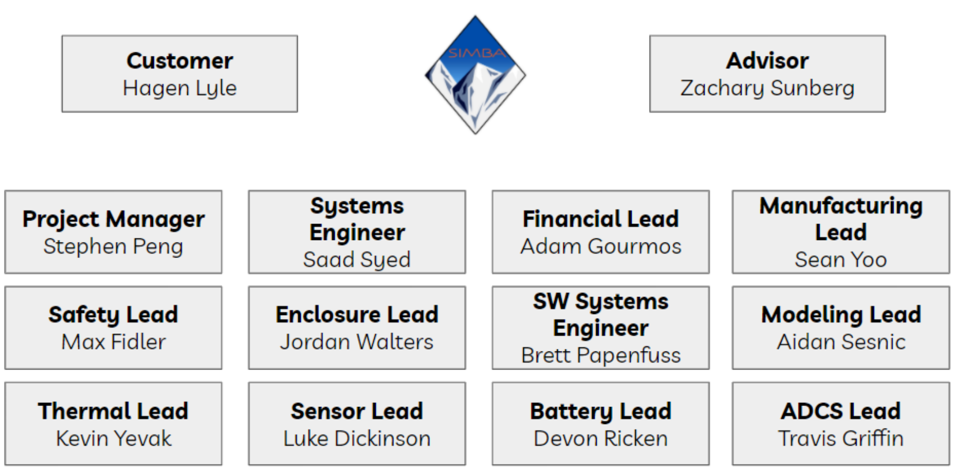


Fig. 34 Organizational Chart for SIMBA

19. Work Breakdown Structure

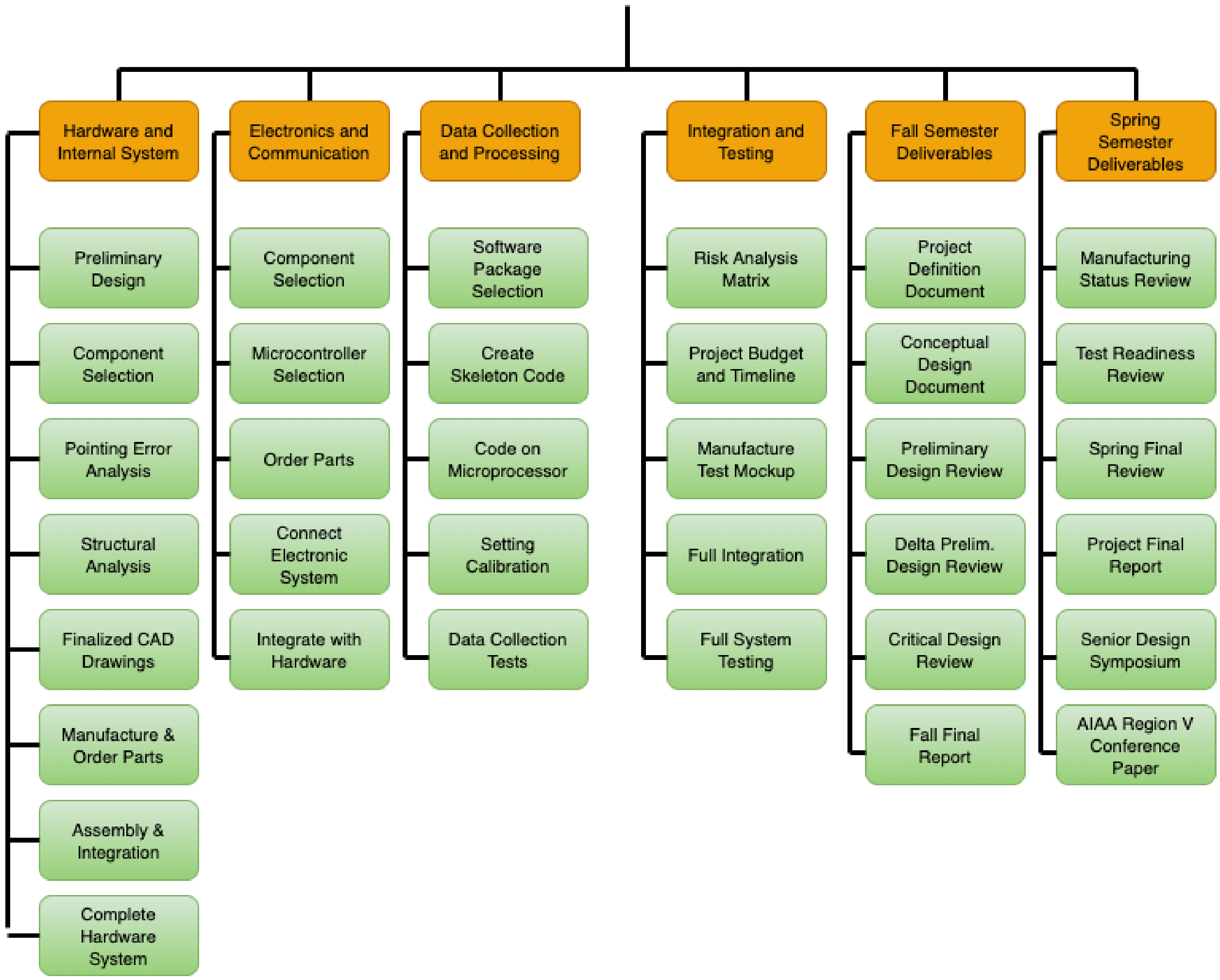


Fig. 35   Work Breakdown Structure for SIMBA

The Work Breakdown Structure outlines work packages that have been achieved by the team so far as well as work that was not complete. The work packages are organized by subsystems as well as class deliverables and are sequential.

The hardware and internal system was reviewed through trade studies to determine a preliminary design and select components to meet the functional requirements. Since accuracy and operation in cold conditions are the most critical aspects to project success, a detailed analysis was completed for pointing accuracy and the structure. The team finished the Fall semester by creating a detailed CAD drawing to prepare for manufacture early in the Spring semester. The CAD drawing was reviewed and discussed by Professor Rhode who signed off on the team's work and the team plans to order some parts to begin manufacturing before the start of the Spring semester. Manufacturing of the sensor assembly and housing was completed early Spring, with the assembly and integration completed in late February.

The electronics and communication subsystem required component selection for the microcontroller stack as well as the battery. All electronic parts were ordered once the Spring semester started excluding the battery. All tests were done using a power supply throughout the semester as talks with the battery manufacturer had halted, forcing the team to purchase batteries late into the semester. Once the electronic components arrived, they were integrated with the hardware system to ensure proper wiring and mechanical functions.

Data collection and processing also required a trade study to select a software package for this application. Once ArcGIS was selected, the team needed to familiarize with the software as experience was limited. The team worked on building a preliminary skeleton code that was fleshed out at the beginning of the Spring semester. The team ended the Spring semester with working code on ArcGIS that outputs the necessary information to visualize snow depth. In addition, code was uploaded onto the Raspberry Pi 4 in order to collect the necessary pointing data from the potentiometer and laser range finder. Once the code was made, data collection tests were performed to calibrate and account for errors since the required error tolerance of pointing is extremely small. It is important that these tests be performed and analyzed before moving onto the full system test.

Integration and testing was done locally. The team initially contacted Nancy Glaze about potentially doing preliminary testing in the yard behind the Smead Aerospace building to set up a test mockup. The team eventually settled on using the third floor balcony of the Aerospace building to do a full system test. Full integration was performed at a team members roof top balcony, where the team had a chance to setup the full system on top of the tripod to weed out any problems that may occur before performing the full system test.

All Fall deliverables were completed and submitted on time. The Spring Semester class deliverables are shown at the very right, in which all are completed with the exception of the Spring Final Report.

20. Work Plan

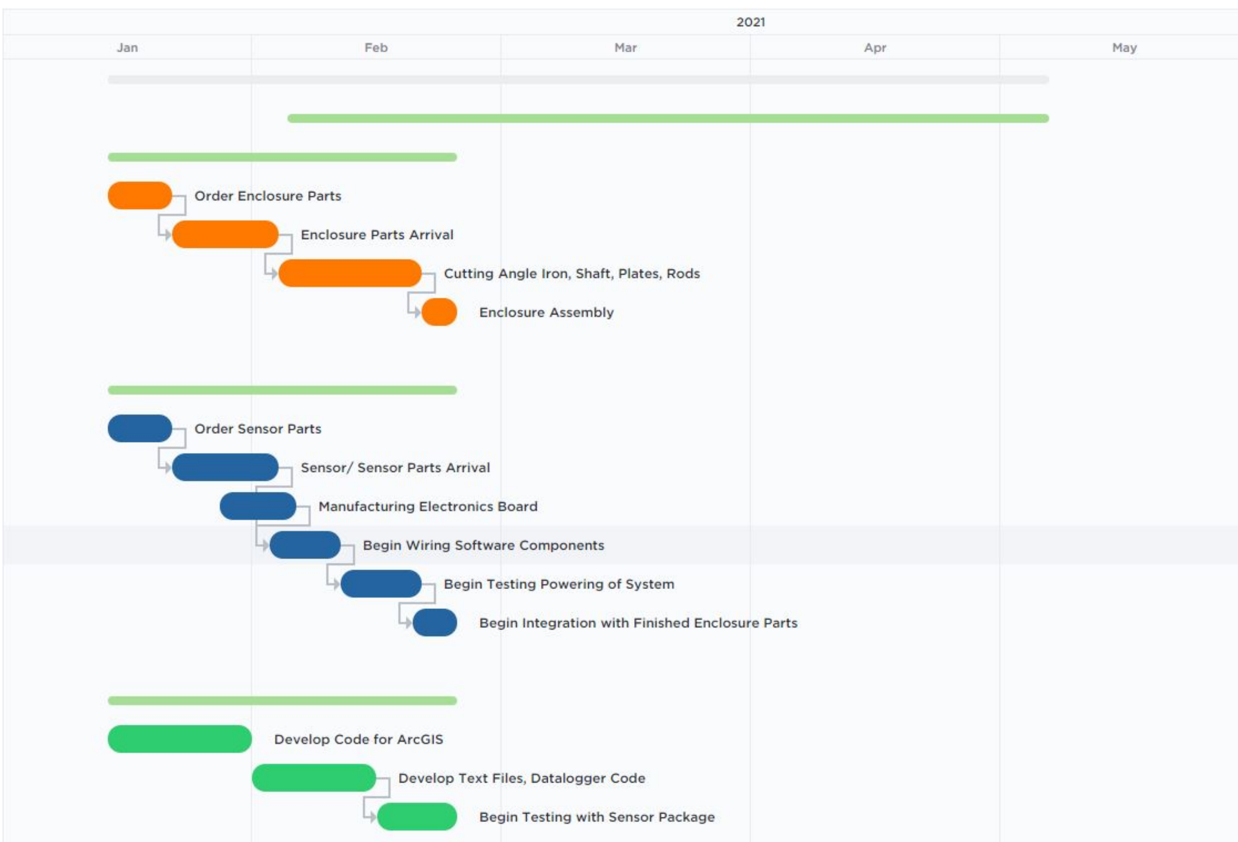


Fig. 36 Sub-Team Work Plan

Going from top to bottom from figure 36, the project consists of three sub-teams. The sensor housing team, in orange, is responsible for ordering, manufacturing, and assembling our systems enclosure and attitude control platform. The first month of the semester is spent ordering and waiting for the parts to arrive, although we do expect this to be shorter. The majority of the time is given to cutting our pieces to the necessary length as COVID has limited manufacturing opportunities. The sensor package team, represented in blue, is responsible with ordering our sensor package components and assembling the microcontroller. This team consists of the sensor package and actuator subsystems. We hope to start a preliminary test of powering the system before integrating it with the finished enclosure parts. The software team, represented in green, is tasked with developing code for ArcGIS that will get us our snow depth. This is followed by developing the software that will control our sensor package.

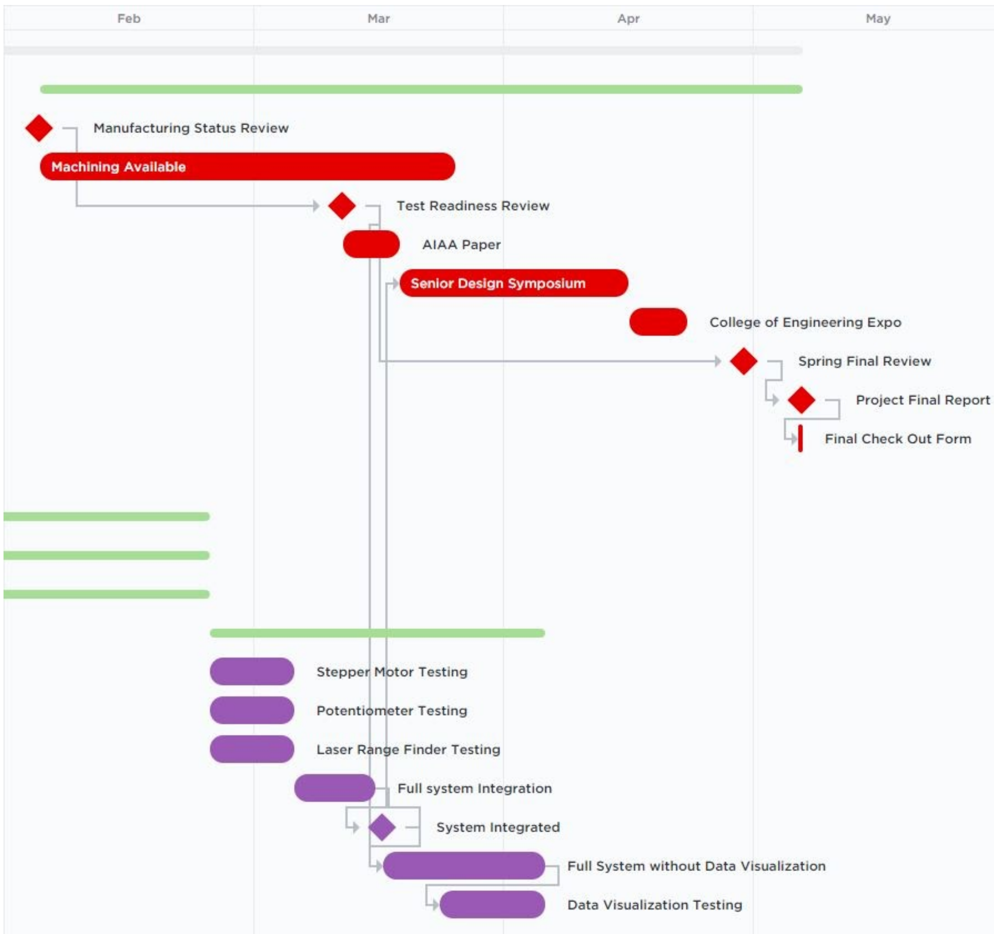


Fig. 37 Administrative and Testing Plan

Figure 37 shows a general administrative timeline (red) along with our testing plan (purple). All sub-teams are expected to have tested each of their components before the team's Test Readiness Review on March 11th. This includes stepper motor, potentiometer, and laser range finder testing. A week will be spent after Test Readiness Review for integrating the entire system, followed by system testing. All tests were expected to be completed before the College of Engineering Expo, however, an extra week was allotted after the expo to perform PCB testing.

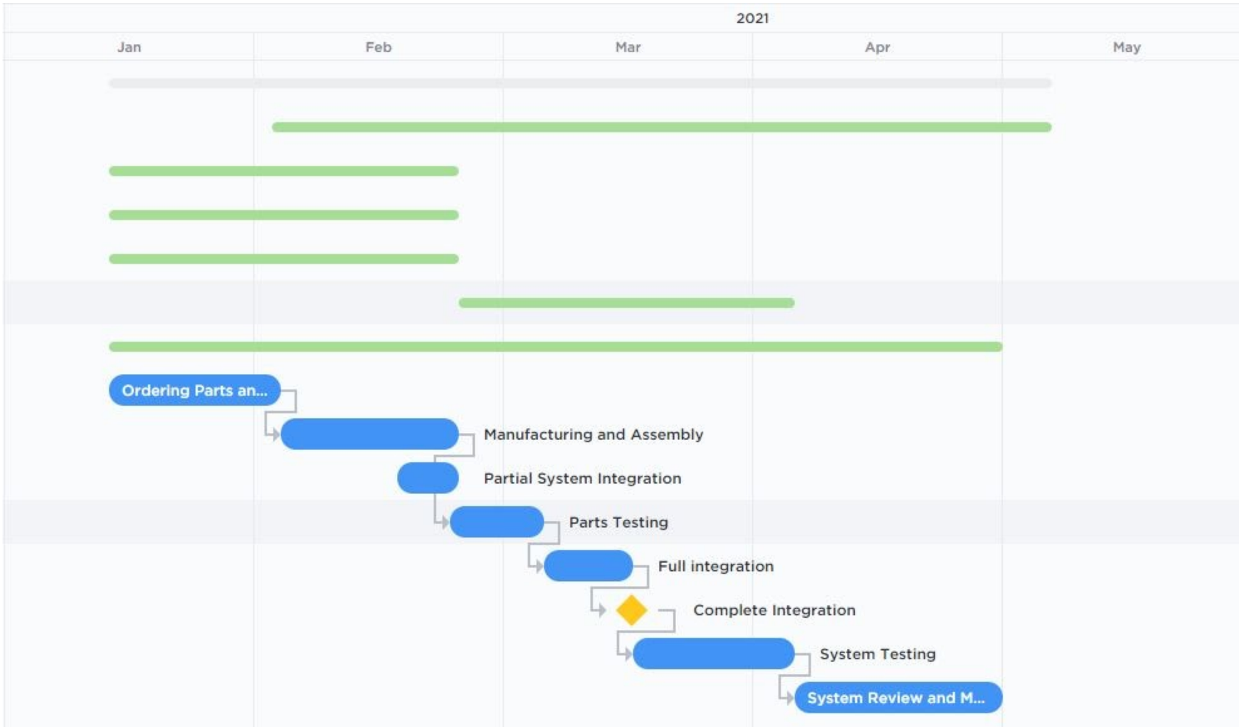
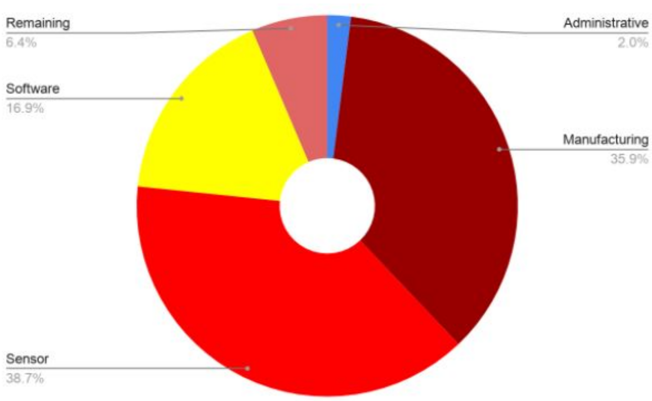


Fig. 38 Critical Path

In review, figure 38 shows the team's critical path moving forward. January and February are dedicated to ordering and manufacturing the components of each sub-team. The end of February marks the beginning of our individual component testing, followed by full system integration before Senior Design Symposium on March 19th. Fully integrated system tests will be performed including a system review and analysis before Spring Final Review. An extra 2-3 weeks of margin was added to the manufacturing of the sensor housing team to alleviate the workload on Professor Rhodes and Josh Mellin. Although the team had all the components ready to be ordered at the start of the Spring semester, an extra week was given to allow the team to discuss any changes needed on certain components.

21. Cost Plan



Manufacturing Package Total:	$1,795.56
Sensor Package Total:	$1,935.94
Software Package Total:	$846.72
Administrative	$99.87
Total w/ Margin:	$4,677.90
Remaining Budget:	$322.10

Fig. 39 Cost Plan

Figure 39 represents the final budget breakdown. A key feature to note is the remaining budget of $322.10 which is $200 less than what the team predicted the remaining budget would be at the beginning of the Spring semester. Below will be a breakdown of each of the different packages and the major components purchased within those packages as well as some of the uncertainties in major purchases

- **Manufacturing:** The manufacturing package consisted of the tripod, the enclosure and the batteries. Some uncertainty stemmed from the tripod and the batteries. Prior to testing, the team was unsure whether or not the a tripod from the ski resort would be available. When it was learned that the tripod was not available for testing, the team purchased a tripod from Campbell Scientific which required reallocating money form different packages. The batteries also posed some uncertainty as the power requirements of the system was not entirely understood and validated until the middle of the Spring semester. Even more so, the required battery capacity was also not known until later in the semester.
- **Sensor:** The sensor package consisted of the TruPulse laser rangefinder and the RS-232 cable that transfers communications between the Pi and the sensor. Originally there was not uncertainty in purchasing either of these, but the the RS-232 cable needed to communicate with the sensor was proprietary and required that we ordered two different cables before we received the correct one.
- **Software:** The software package consisted of the Raspberry Pi stack, potentiometer, motors, and power supply boards ordered from OshPark. The uncertainty in these purchases mostly stemmed from the multiple iterations of the power supply board. Originally this was not in the initial planned budget, but once the team learned that the voltage supply going into the system needs to be more regulated (because the accuracy of the system is dependent on the cleanliness of the power source running through the potentiometer), money was reallocated from other packages to account for this.
- **Administrative:** The only administrative fee consisted of ClickUp which is the scheduling application that the team used to communicate project tasks and deadlines.

One last important note in discussing the final budget is that there used to be a testing equipment package as well as a calibration package. These were reallocated to account for the tripod as well as the power supply board (unforeseen purchases).

22. Test Plan

A test plan is presented on figure 37 showing all major tests to be done after subsystem integration. Verification tests such as the stepper motor, potentiometer, and laser range finder tests were planned to start and finish before the Test Readiness Review. These tests were performed to ensure the components are working and that none are broken. For the laser range finder, the team purchased a 100 ft measuring tape and some plywood and recorded distance results at an outdoor track located at Manhatten Middle School in Boulder, Colorado. The stepper motor and potentiometers were performed in the projects room using a power supply borrowed from the aerospace building. After TRR, the team integrated said components onto the sensor assembly, in which more potentiometer tests were performed with the addition of the electronics to record voltage readings and to control the entire system for the purpose of analyzing system error tolerances. A power supply was used to power all of the components as well and tests were done in the Aero 140 lecture hall. At this point the team has integrated the full system and has performed a full system test without data visualization. An extra two weeks of margin was given to this portion of testing as the team expected potentiometer error testing to take the longest. After potentiometer error testing was completed, a full system test with functioning ArcGIS code was performed and completed before the expo.

Part VIII.

Lessons Learned

Authors: Stephen Peng

23. General Team Challenges

Some general challenges the team faced were the pace of scheduling, team project comprehension, team availability, and leadership structure.

It was somewhat of a challenge for the team to tackle scheduling in the beginning of the Fall semester in terms of pacing and expectations for the required reports and presentations. Specifically, the time between the Conceptual Design Document and the Preliminary Design Review was relatively short. The team felt that if more time was allotted between presentations, better research and explanation of our initial idea of using a UAV would result in an improved PDR. A better understanding of the presentation schedule would have resulted in an improved workflow across the team. Due to the circumstances, working on Zoom proved to be a challenge for team project comprehension. Specifically in terms of knowing how to operate Zoom in an efficient manner, such as creating breakout rooms, annotating, and sharing research and information. These issues were resolved by creating internal deadlines for assignments in order to revise and practice presentations ahead of their actual due date. Weekly agendas were made for the team, outlining the schedule and specific tasks to be accomplished in order to stay on track. In addition, the structure of team meetings became more rigid by starting with progress updates from team leads then moving onto the agenda followed by working on the tasks from the agenda and ending with any questions or concerns. Finally, encouraging different team members to participate in different system tests instead of having the same people to a particular test improved overall project understanding.

Team availability proved to be challenging particularly during testing. This was due to a combination of working online, as mentioned previously, as well as fluctuating personal schedules of team members. Some team members had job conflicts, job interviews, or unforeseen illnesses. Having each team member upload their general schedule on When2Meet helped alleviate these problems and allowed the PM and team leads to schedule times to test as well as times to meet for practice presentations. Surprisingly, having a limited number of people in the project space benefited the team as, at times, more people wanted to participate than allowed. This let those who had last minute obligations free to commit to said obligations and allowed others to join in testing, however, there were instances in which the team had less than expected. A recommendation to future teams would be to develop some sort of a backup roster for testing even if those restrictions are still in place or not. It is also recommended to round up every members schedule as early as possible.

Lastly, a lack of interaction between team members that is inherent in an online work environment, proving to be difficult for structuring team leadership and knowing teammates skills and weaknesses. The team does recognize this to be a particularly extraordinary year due to COVID-19, however, even if in-person labs are approved for next year, it is recommended that future teams discuss each team members' interests as well as existing skills and weaknesses in order to develop an efficient leadership structure. This should be done as soon as teams are created and can be done during lab meetings or through team bonding exercises outside of class.

24. Project Challenges

Some challenges the team faced with respect to the project came down to having to rescope the original project idea and having to quickly understand new ideas related to component operations.

As for needing to rescope the original project, the team did this relatively late into the fall semester. This resulted in canceling some existing subteams and creating new ones as needed, which set the team back in terms of effort and schedule. If given a second chance, the team would have consulted more with the customer, projects advisor, and PAB members before critical project deadlines to discuss and explain project feasibility and needs. Luckily, the team revisited past trade studies to discuss a new solution, allowing some leeway in terms of scheduling. It is recommended for future teams to be heavily involved with their projects advisor and other PAB members in order to catch concerns earlier and to raise these concerns to their customer to conclude on a feasible solution. This would prevent a scramble to rescope if needed.

Finally, the team had issues with understanding how certain components operate. Components such as potentiometers and ArcGIS were especially difficult as no one on the team had experience in using these before. Understanding how linearity tolerances work for the potentiometers was particularly challenging so the team found it essential to consult with Professors Bobby Hodgkinson and Trudy Schwartz to gain more knowledge. It was suggested to use an analog encoder instead of a digital potentiometer, however, the team felt that it was too late to switch given the effort and timing of upcoming presentations and having to rescope. If the team were to redo this selection, consulting professors earlier would have been the ideal path. As such, again, it is highly recommended that future teams reach out to professors as early as possible when snags such as this present themselves to prevent unneeded complexity and confusion to the project solution.

Part IX.

Individual Report Contributions

Team Members	Section names	Detailed Contributions
Dickinson, Lucas	VV, PP, FD	VV: Laser finder testing and results. FD: sensor package, rangefinder, and resulting error discussion.
Fidler, Max	FD, DD	Reviewed both sections. CD: reviewed sensors DD: rangefinder. Edited project purpose, specific objectives, CONOPS sections.
Gourmos, Adam	Formatting, FD, VV, PP	Wrote requirements flow down, potentiometer accuracy determination, ArcGIS testing, final system testing verification and validation, and wrote the final cost plan
Griffin, Travis	FD, PP	Wrote about potentiometer and laser range finder functionality in final design. Edited final design section. Made the work breakdown diagram in the project planning section
Papenfuss, Brett	Manufacturing, FD, VV, Formatting	Wrote about software and microcontroller design, helped with formatting and editing, microcontroller and software design, trade studies
Peng, Stephen	Formatting, LL, PP, Project Planning, FD	Overall Paper Formatting, Wrote lessons learned, test plans, organizational chart, updated work plan, updated work breakdown structure
Ricken, Devon	FD, PP	Conceptual Design options, mostly on the RC aircraft and its sub-components along with the power system subsection in detailed design.
Sesnic, Aidan	DD, FD, Manufacturing	Enclosure thermal modelling, preparing CAD files for archive, responsible for generating some of old RC aircraft material, almost all CAD modeling, manufacturing
Syed, Saad	FD, RD, RAM	Detailed requirements development, risk assessment, mitigation and consequences
Walters, Jordan	Manufacturing, VV	PCB manufacturing and testing. ADC testing and verification. Potential software improvement
Yevak, Kevin	FD, RD, VV	Trade Study, Requirement Development, and contributed to Whole System testing. Document setup and organization
Yoo, Sean	PO, FR, FD, VV, PP	CONOPS and FBD and rationale for FRs. Requirements Flow down and part of Final Design and Verification and Validation. Organizational chart and WBS discussion. Sensor key design options considered and trade studies.

Table 7 Individual contributions

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Part X.
Appendix

25. Key Design Options Considered

A. Data Processing Software

To make the data that will be gathered by the system have worth, it needs to be processed and presented in a useful and understandable manner. To do this, software with terrain mapping capabilities are required. Raw, unfiltered and unprocessed data does not mean anything to the Ski Patrol; they need to know where and when the data was taken. Beyond that, they also need to compare the data to previously collected sets of data (i.e. a dry mountainside in the summer to a snow-covered one in the winter) to determine how the snow depth has changed over time. Finally, the data is much more useful and quicker for a person to process if it is presented in a visual manner (in this case some kind of map). Software post-processing of the data needs to be able to fulfil all of these requirements in a reasonable amount of time.

1. Python 3

One option for software data processing is Python 3. Python has many libraries that could be used to complete the required data processing and visualization requirements (**FR 5**), like the matplotlib, mplot3d, and basemap libraries.

The main advantages of using Python are its flexibility and availability. Python is a free and open-source programming language, meaning it is usable for free even by commercial entities. It is also used widely, so there are many free support forums and open-source libraries for all sorts of different problems (including terrain mapping). Python downloads are also available for most computer devices and operating systems, so the Ski Patrol's devices should not have any issue using a program developed in Python (**DR 5.4**). Another advantage is that the design team has some experience using Python in the past, so the learning curve would be small.

A major disadvantage is that 3D rendering tends to be very slow in Python, and the 3D mapping/graphing libraries are less refined than some other programming languages. Another disadvantage is that most (if not all) members of the ski patrol will not have familiarity with the software (**DR 5.4.1**). This disadvantage could be minimized by developing a GUI to interact with, but this an additional load on the team. Finally, Python is not a programming language that is focused on 3D terrain mapping, so while there are many libraries for Python, the design team would likely have to create some of the terrain mapping elements from scratch. [18]

Advantages	**Disadvantages**
Free and open-source	3D Rendering slow and not well-optimized
Widely available and plenty of support	Unfamiliar to Ski Patrol
Some members have proficiency in Python	Python not focused on terrain mapping

Table 8 Advantages and disadvantages of Python 3

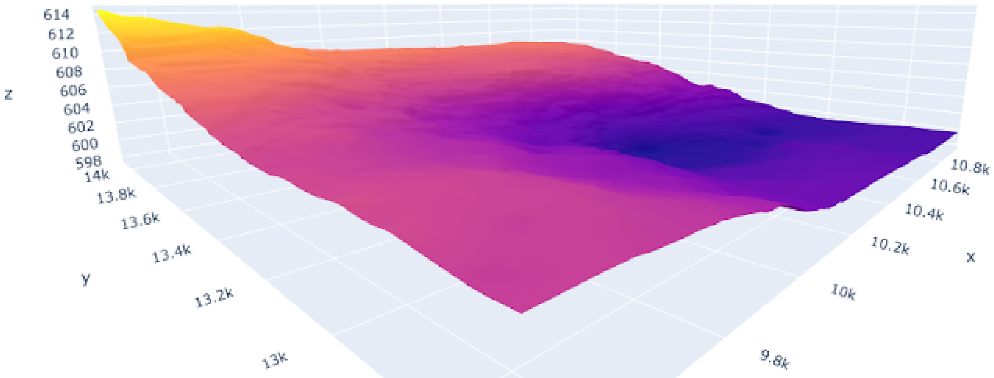

Fig. 40 An example of Python's 3D data visualization capabilities

2. Matlab

Matlab is a computer programmed used in the University of Colorado School of Engineering and is a capable data processing tool. Matlab is capable of fulfilling the data visualization required by this system (**FR 5**), but is not commonly used for our data visualization needs.

The main advantage of Matlab is that all members of the team are proficient in it. This is not true with the customer. Some training would be required to operate Matlab even if a fairly robust GUI was made.

The main disadvantages are the limited and somewhat clunky data visualization capabilites of Matlab, the training required in order for the Copper Ski Patrol to operate it, and the cost. Matlab is not a program that Copper Mountain currently owns and licensing costs $860 annually or $2,150 for a perpetual license. [26]

Advantages	Disadvantages
Familiar to the design team	Training required for Copper Mountain
Large-scale data analysis	Data visualization
	Cost

Table 9 Advantages and disadvantages of Matlab

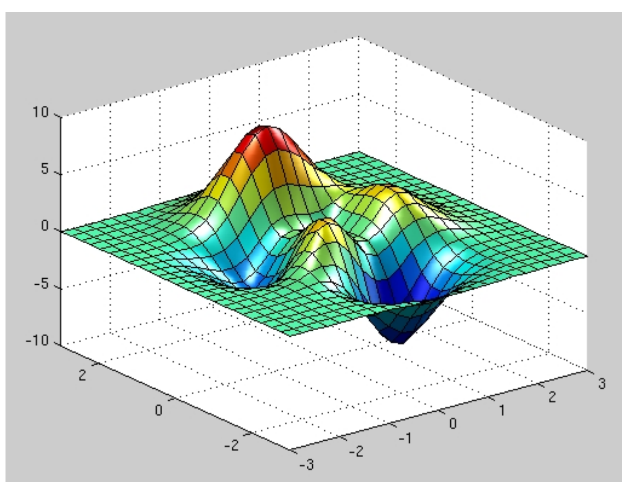

Fig. 41 An example of Matlab's 3D data visualization capabilites

3. ArcGIS

ArcGIS is a desktop application that overlays physical data on top of geophysical features. One major appeal of this application is the fact that it accepts a large variety of data types which means that there would be a good chance that its robust ability in file intake would not hamper other design choices. So this would satisfy the requirement for the application to be able to read in datalogger data (**DR 5.1**) and process it (**DR 5.2**). In terms of data visualization, ArcGIS has a a large amount of mapping interface options and geophysical maps, satisfying our previous design requirements as well. It also has a large amount of 3D mapping options which directly satisfies **DR 5.3.1**. One con is our team is unfamiliar with ArcGIS's libraries so we are unfamiliar of the quality of geophysical data. If there is no library containing quality grid data in ArcGIS then it would hamper the quality of our data and put our team at risk of not meeting resolution requirements specified by the instrument package. Another con is that the training and tutorials for the program cost money. However, it is available to CU students for free, and is currently used by Copper Mountain's ski patrol, establishing familiarity. Any extra training necessary can be done by the design team.

In discussing the team's ability to build a program for the user so that post-processing is easy enough for a non-technical employee use (**DR 5.4.1**) and a program that outputs an easy to read graphic (**DR 5.4.2**), ArcGIS allows multiple methods to complete this requirement. To further explain, ArcGIS has multiple application programming interfaces (API) available to use. This allows our team a variety of languages they are comfortable coding in to create a program for our end user. However, if our team finds that building a program for the end user is too timely, there are user-friendly interface programs readily available so we could provide instructions on how to use these programs. However, this might require some training from the staff at Copper Mountain which could fit into the 40 hour training period that customer has allotted for their employees. [3]

Advantages	**Disadvantages**
No experience in coding is necessary if we build a program	Not an intuitive program without an interface
Training is available for user-friendly APIs	Training directly from ArcGIS costs money outside of CU.
A large variety of interactive mapping options	Experience is necessary to make quality maps
There are multiple APIs including Java and Python	The APIs will take some learning
Large suite of applications for user interface	This interface would take some training
Overall good quality package options and customization	Not sure if there are libraries with geophysical data
Has a large variety in 3D mapping options	
Large variety of data types ares supported	

Table 10 Advantages and disadvantages of ArcGIS

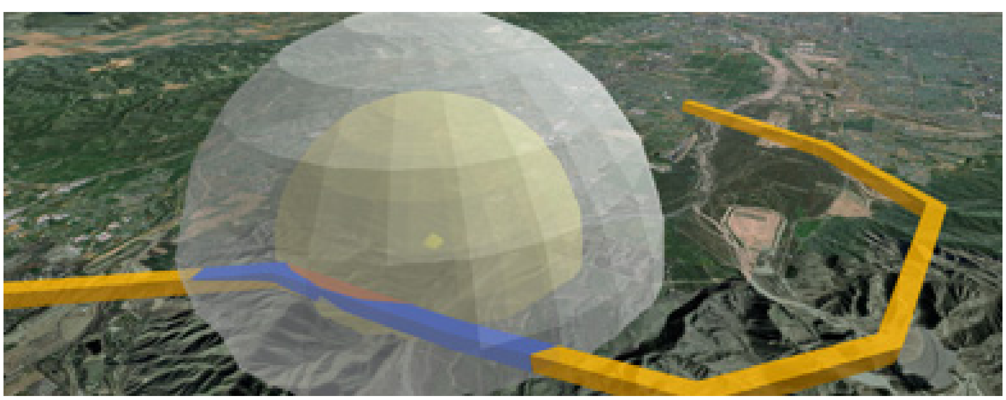

Fig. 42 Image showing an example of a 3D model of LiDAR data taken over a mountainous terrain which was processed by ArcGIS

4. Google Earth Engine

Google Earth is a software suite that focuses on providing high-resolution images and maps of the Earth's surface. Google Earth Engine is the component of the software suite that focuses on data processing and customizing 3D images.

The main advantage is that Google Earth has a huge volume of preexisting data about the Earth's surface. Also, the graphics developed in Google Earth are the best looking out of all of the options considered (**DR 5.4.2**).

The main disadvantage is that Google Earth Engine is not free for commercial groups. Also, the data input types in Google Earth Engine are extremely limited. The design team currently has no experience with Google Earth Engine, so there will be some learning curve. Finally, the programs developed in Google Earth Engine are not very user friendly (**DR 5.4.1**). [27]

Advantages	Disadvantages
Allows data input to be overlayed	Input file types are limited
Geophysical has good quality that would meet resolution standards	Google Earth Engine is expensive outside of CU
Allows developers to make user-friendly interface	Making user friendly interface is time-consuming

Table 11 Advantages and disadvantages of Google Earth Engine

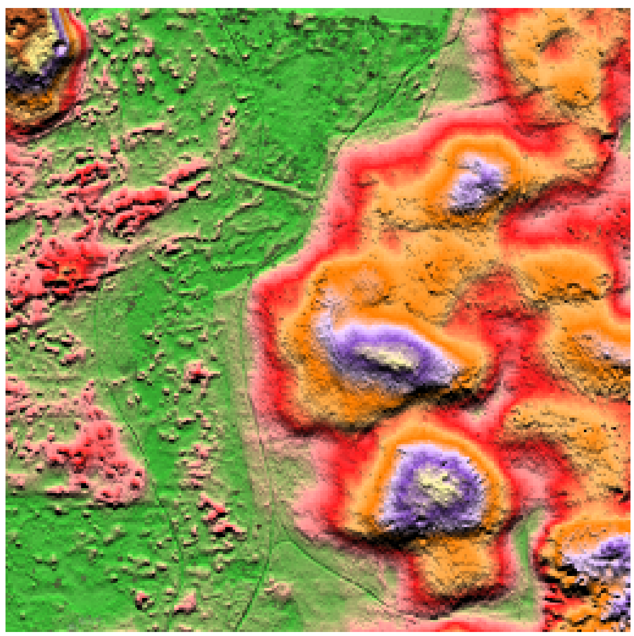

Fig. 43 Image created from LiDAR data from the Netherlands between 2007 and 2012. Contains ground level samples with all items above the ground removed.

B. Platform Design

1. Fixed wing UAV

The following parameters are considered:

- Stall speed. While there are no explicit stall speed requirements for the aircraft to meet, a stall speed of 8 m/s is chosen to ensure that the aircraft is not flying unduly fast during landing which would make manual flight difficult.

- Landing distance. While the design requirements do specify the required landing distance, it is suspected that, due to uneven terrain and the expected low friction coefficient between the aircraft's landing gear and the snow, the aircraft will need to be landed on an uphill slope, which does not lend itself easily to being modeled by takeoff distance equations.
- Takeoff distance.
- Climb.
- Maneuvering.
- Speed. The assumed cruise speed of 10 m/s and the dash speed of 30 m/s are used to ensure that speed requirements are met.

See the appendix for the corresponding constraint curves that apply to each of these criteria.

Using all constraint curves, the performance sizing plot is generated:

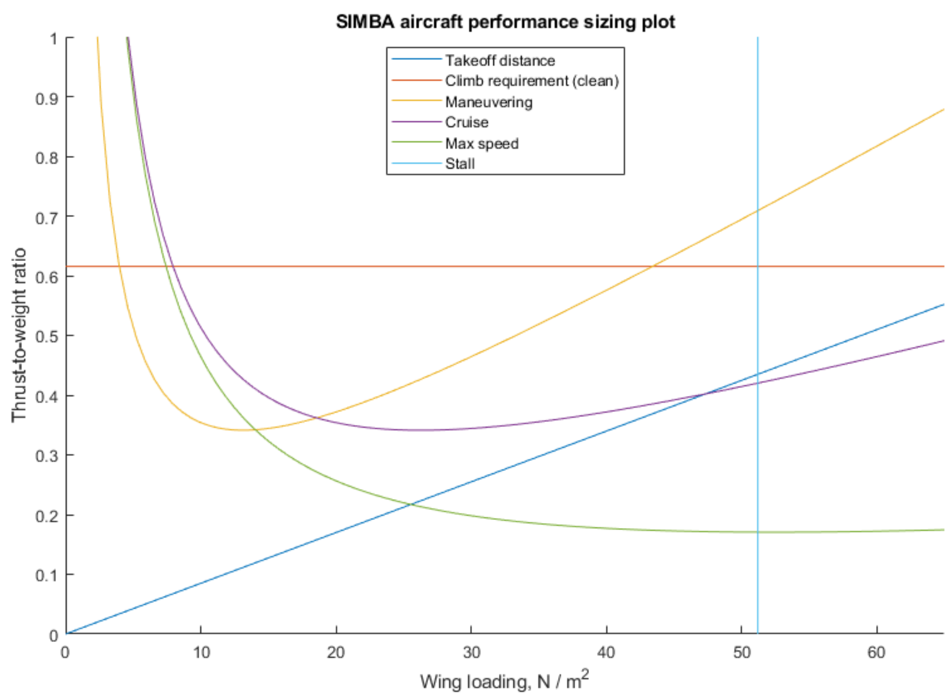

Fig. 44 SIMBA performance sizing plot. The acceptable design area is the area above the climb requirement line and bounded by the cruise, maneuvering, and stall speed curves.

While the wing area does not need to be immediately determined, the climb requirements generally set the required thrust-to-weight ratio; a value of approximately 0.62 is required. This isn't surprising: a UAV this small climbing 305 m/min (1,000 ft/min) is significant. For the sake of determining an estimate of the wetted area, the wing loading is chosen as the wing area associated with the intersection of the climb and maneuvering lines, which calls for a wing area of 44 N m^{-2}. This results in a wing area of 1.93 m^2. The wetted area is estimated as $S_w = 4S = 7.71$ m^2. In turn, the parameter m/S_w takes a value of ≈ 1.12 kg m^{-2}.

This analysis provides the data required to assess weighting matrix points to the airplane solution.

Advantages	Disadvantages
Significant endurance advantage over multirotors	More pilot training required
Better payload weight fraction than multirotors	Novel methods needed to slow aircraft on landing
Can design for very fast airspeeds to escape strong winds	
Can be flown to safe landing in event of propulsion system failure	

Table 12 Advantages and disadvantages of a fixed wing UAV

2. Multi-rotor UAV

Multi-rotor UAVs are widely used for surveying and geo-mapping in many different situations. There are whole technology companies such as Action Drone USA that develop custom drones for the users specific needs. The custom drone needed to fit the requirements of this project however would be quite expensive and beyond the scope of this project's budget. Multi-rotor UAVs offer their advantages when it comes to safety, still being able to fly or allow the user to make a controlled emergency landing if one or more motors fail. If one fails the other motors can increase speed and therefore thrust output so the UAV can remain airborne. However, this does hinder the rover's performance with stability with the loss of a rotor making it more difficult for angular momentum to be conserved. This would require the rotor with the same rotational motion as the fail rotor, to increase its speed to conserve angular momentum. If the UAV is a hexa or octocopter then even more motors could fail and the rover will still work and make effective emergency landings.

The UAV does not preform well with endurance especially in extreme conditions. On average most UAVs that would be within the cost range of this project's budget could last for about 35 mins. This flight time is also under ideal conditions and not under the cold and wind that would be experienced flying at such altitudes. A sensor could be designed to where the sensor can collect all the data in this flight window. Although, this would limit the possible sensors that could be used and places a hindrance on accuracy. It is also possible to have the ski patrol bring extra batteries that can replace the dead ones when needed, however this adds complexity to the drone and the drone systems.

Advantages	Disadvantages
UAVs are already in use for this purpose	Expensive and most are out of range of budget
Increased stability and safety even with motor failure	Inefficient in power sources and short time of flight

Table 13 Advantages and disadvantages of a multi-rotor UAV

3. Lighter than Air

Blimps, zeppelins, balloons, and plimps (plane blimp combination) have all been used for aerial surveillance and data sensing. Lighter than air vehicles offer a stable platform and long endurance's. Balloons offer very high endurance and the least amount of complexity at the sacrifice of mobility and wind resistance. Most envelopes for lighter than air vehicles are made of 3-10 mm polyester. These envelopes can be easily pierced and are worn out by UV rays. Blimps, zeppelins, and plimps are mobile while balloons are not. Zeppelins have an internal frame while blimps do not.

Dry air has a density of 1.29 g/L at STP and an average molecular mass of 28.97 g/mol. Helium has a density of 0.179 g/L at STP and an average molecular mass 4.003 g/mol. The buoyant force is equal to the weight of the displaced air. To lift a payload mass of 2 kg 10 m^3 of helium is required. The total mass of a blimp system that can lift 2 kg of payload would be approximately 5 kg. The payload, motors, and batteries account for 96 percent of the mass. A commercial remote controlled blimp that is 6 meters long and holds 10 m^3 of helium has a max speed of 5-6 m/s. The front profile area of a 6 meter long blimp is 1.666 m^2 and the side profile is 3.43 m^2. The large cross sections and low mass of lighter than air vehicles make them vulnerable to wind.

Advantages	Disadvantages
Potential to significantly increase endurance	Cost prohibitive (Helium)
Very stable platform	Largest vehicle option
Lift is not effected by temperature and altitude	Cannot fly in mild winds

Table 14 Advantages and disadvantages of a lighter than air vehicle

4. Stationary ground based platform

An alternative to an aerial approach is a ground mounted sensor/camera. The sensor/s would be mounted on poles or fixtures. A ground-based sensor would eliminate the need for a UAV, cutting costs and complexity. The ground based sensors could be riskier if positioned in the path of avalanches or skiers. The sensor/s would need to be weather proofed due to long duration and stationary exposure to environmental conditions. The depth measurements would need to be avalanche-proof. Multiple measurements from one location can be compiled for changing depth throughout the season. To cover the large avalanche-prone area multiple sensors or a rotating system may be needed, increasing complexity. The team initially chose to go with a custom built fixed wing aircraft, however, after much deliberation with PAB members the team has decided to go with a stationary platform. This was because the trade study did not take into account the added error in pointing accuracy when dealing with a moving platform.

Advantages	Disadvantages
Lowest unit cost	Limited range
Stable platform	Avalanche/weather risk
Better Accuracy	

Table 15 Advantages and disadvantages of a stationary ground based platform

C. Sensor Package

The sensor package is critical to mission success and will be selected based on its ability to perform in cold weather conditions, meet our accuracy requirements, and optimal endurance. Five different options will be considered. We will look for sensors that are available for purchase as developing our own would require complex fabrication and testing techniques not possible given our resources and time.

1. LiDAR

Light Detection and Ranging, or LiDAR, initially started in 1970's for applications in terrain mapping. The system calculates distance by measuring the time it takes for an emitted laser pulse to travel from its origin to a surface and back as shown in figure 45.

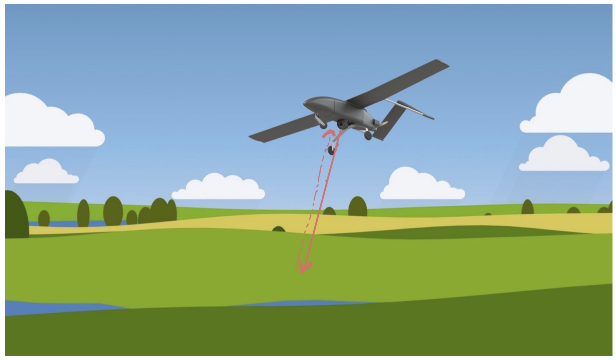

Fig. 45 Solid line is the emitted pulse the dotted line is the return signal. Both are equal are equal in length.

The time of travel of the laser beam is then multiplied by the constant speed of light and divided by two to get the distance between the sensor and the surface. Concurrently, the position and orientation of the sensor is taken by some Global Navigation System(GNS) and Inertial Navigation System(INS) respectively to calculate the X,Y,Z coordinates of a surface for input in terrain generation modeling.

The main advantages for a LiDAR include higher point densities and its large max range. A higher pointing density allows the sensor to pick up finer details for improved resolution while also flying at higher altitudes. LiDAR can also function at night allowing for low light operating conditions. Furthermore, LiDAR has the capability of penetrating vegetation for accurate snow depth measurements in vegetated areas.

The main disadvantage is the cost of a survey grade LiDAR sensor, often quadrupling the cost of other sensor packages and easily exceeding our budget. In addition, precise calibration between the laser and GNS/INS is required to minimize positional error.

Advantages	**Disadvantages**
High point density for finer detail/resolution	Exorbitant Cost
High maximum operating ranges	Requires Precision Calibration
Operations in any lighting	
Canopy Penetration	

Table 16 Advantages and disadvantages of LiDAR

2. Photogrammetry

Structure from Motion (SfM) is a photogrammetric technique for high-resolution topographic surveying. Digital single-lens reflex (DSLR) cameras capture two dimensional still-images of the visible environment. Photogrammetry is the use of photography in surveying and mapping. For snow-depth measurement, careful photogrammetry yields digital models accurate to within centimeters[32].

Accurate photogrammetry requires many photos, and camera sensors are not as fast as other sensors considered. This leads to longer flight times and introduces concerns about endurance. Recent technological advances make photogrammetry possible. The image quality of relatively cheap digital cameras has increased the popularity of photogrammetry. As a result, there are many free and commercially available software programs available for photogrammetry. The post-processing software compiles the photos to output digital surface models and elevation models. Photogrammetry is easier when using a UAV platform compared to a ground based platform, as a UAV can cover a large area of remote and variable environments from an aerial perspective.

Using a DSLR camera is cost-effective and reliable as it has been used in similar conditions and os proven to work. Because DSLRs are commercially available, equipment and solutions for most problems of camera operation can be diagnosed and fixed. Low-voltage differential signaling (LVDS) based cameras are also considered. LVDS cameras are small and consume minimal power [39]. However, the small sensor reduces quality and information within an image signifcantly. A complete sensor package by SenseFly also satisfies our objectives. The S.O.D.A. Photogrammetry Camera is optimized for UAV use that produces digital elevation model with a precision of up to 3 cm. It has additional sensors including thermal imagery and collects GPS data within the sensor package [38]. The proprietary nature of the camera and software included may introduce difficulties when attempt to optimize, adjust, or troubleshoot this camera system. This is likely as the S.O.D.A has not been tested on surfaces covered by snow. The cost of the system, close to half our budget, further discourages this method.

Advantages	**Disadvantages**
Low cost & high heritage use	Larger processing resources & time needs
Hardware available and easy to use	Longer scan times
Open-source & COTS software available	Susceptible to changing weather

Table 17 Advantages and disadvantages of photogrammetry

3. Radar

Radar is a technique for remote sensing that has the main advantage of being ground penetrating. The sensing not only measures distance to the surface of the ground, but can display what is underneath the surface. For our purposes, radar could be used to measures the distance to ground level as well as the distance to the top layer of snow. This would provide accurate snow depth measurements without relying on knowing the location of the platform to extreme accuracy. The range of complexity of radars varies greatly. Some more advanced systems can identify layers or objects in the ground and classify them based on how the radar waves reflect or are absorbed [34]. Simple systems, like altimeters, also exist that simply give a distance measurement. This can be useful, but does not overcome the need for a very accurate position location measurement.

Radar has been utilized for surveying over many application before, including proving accurate in determining depth of snow. However, in most applications the radar sensors are fixed to a stationary object or are ground based systems that are on the surface of the ground and measure what is below it. This is especially the case for accurate ground penetrating radar systems, which unfortunately is not feasible within the budget of this project. From a COTS stand point, most options are intended for construction or measuring snow on roadways. Many are heavy, are only accurate when stationary, or are intended to be used on the surface but there are limits to its range and accuracy.

Advantages	**Disadvantages**
Potential to ease UAV position accuracy requirements	High weight
Gives instantaneous depth (no need to compare to previous data)	COTS intended for specific platform use
Sensing can differentiate between ground and snow	

Table 18 Advantages and disadvantages of a radar

4. Ultrasonic

Ultrasonic sensing is a method used to measure distances by measuring propagation times of ultrasonic waves. The sensor will emit a wave towards an object and it converts the reflected wave into an electronic signal.

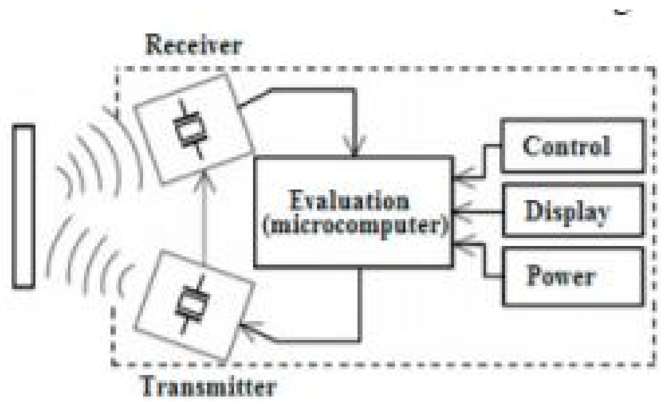

Fig. 46 Ultrasonic Sensor Diagram

This diagram shows a separate transmitter and receiver, but in many cases the two are combined into one sensor component. The same equation is used to measure distance as in LiDAR, however, in this case, C, is the speed of sound. The advantages of using ultrasonic sensors are they are inexpensive, have low power consumption, and most can operate in low temperature environments. Ultrasonic sensors have been utilized to measure snow depth on the ground by attaching the sensor to a beam and pointing the sensor straight down. Another application for ultrasonic sensors is object detection for aircraft. The use of ultrasonic sensors on an aircraft for surveying is limited mainly due to inaccuracy of measurements.

There is dramatic fall off to reading accuracy as distance increases, and past applications have found that 10 meters is the maximum range for these sensors. When designing for a UAV system, the ultrasonic sensor had major disadvantages. The limited range would require a longer flight time by having to fly so close to the ground, which also posed a safety risk. The ultrasonic sensor also requires the aircraft to remain still until the transmitted signal is received which would eliminate the possibility of a fixed wing UAV. Other sources that can also impact the performance of these sensors are high wind speeds that can attenuate ultrasound and vibration of the aircraft while recording data. There is very little heritage of ultrasonic sensors being attached to a moving aircraft for accurate distance measuring, mostly due to these sources of error.

When the team transitioned from a fixed wing UAV solution to a ground based solution, the major disadvantage of range remained. In order to provide a visual snow depth map, the sensor requires a range much higher than that of 10 meters that the ultrasonic sensing can accurately provide.

Advantages	**Disadvantages**
Low power and lightweight system	Maximum range of 10 meters
Works well in cold conditions	COTS intended specific paltform use
Low cost	Precision accuracy affected by flight

Table 19 Advantages and disadvantages of ultrasonic sensor

D. Georeferencing System

1. Pressure Altimeter

Pressure altimeters (also known as barometric altimeters) use a reference pressure at ground level to calculate the current altitude given the current pressure. Pressure altimeters also account for the current weather conditions to create a more accurate reading of its current altitude. The equation used to calculate the altitude z is

Advantages	Disadvantages
Low cost	Incredibly fragile
Accurate at lower altitudes	Inaccurate at higher altitudes
Very low energy costs	Inaccuracy is typically on a scale of over 100cm

Table 20 Advantages and disadvantages of a pressure altimeter

$$z = cTlog(\frac{P_o}{P}) \tag{9}$$

where c is a constant that depends on at the acceleration of gravity as well as the molar mass, T is the absolute pressure, P is the pressure at altitude z, and P_o the pressure at sea level or a reference pressure. Pressure altimeters tend to work better at lower heights (heights lower than approximately 70m to 80m) with an error of about 2%. However this error is far too large to provide an accurate reading of snow depth. Barometric altimeters tend to be cheaper and typically come in a form of a chip so integration with this kind of georeferencing equipment should lack in complexity. Because they are so cheap, this option allows us the flexibility to purchase multiple barometric altimeters in order to find the most accurate one.

2. Traditional GPS

The Global Positioning System uses four or more satellite signals in order to determine geolocation and time information for a satellite receiver. GPS is used by a multitude of systems including smartphones in order to locate the device in space. GPS can typically provide location data that is accurate to within 2 or 3 meters, but accuracy can be increased through ground control points. Ground control points are known way points used to calibrate the GPS receiver and improve accuracy. Although, even with the use of ground control points GPS data will not be accurate to within 10cm.

One big advantage of traditional GPS is cost. GPS receivers can be bought off of the shelf for cheap, under 100 dollars. These GPS units are fairly simply and have been used extensively. This means that implementation of a traditional GPS unit in our project should not be difficult. The accuracy means that it could not be used as a reference for our sensor to get snow depth measurements, but it could be used to collect latitude and longitude data for use in snow depth mapping.

Advantages	Disadvantages
Low Cost	Low Accuracy
Widely used/Easy implementation	Accuracy can be affected by surroundings

Table 21 Advantages and disadvantages of using traditional GPS

3. PPK GNSS

PPK GNSS, or Post-Processed Kinematic Global Navigation Satellite System, is a technique which gathers raw GNSS positional logs from a rover and a base station and applies correctional algorithms to account for satellite signal errors. The rover in this case would be our designed aircraft and would require the purchase of an on-board PPK GNSS receiver. The base station, also known as a reference station, is used as a baseline for the data collected from the rover and is a required component to this technique. Cost can be reduced with the use of existing, publicly available reference stations such as CORS (Continuously Operating Reference Station) offered by NOAA. It is recommended the base station be located, at most, 15 km away from the rover to reduce signal attenuation that may occur due to differing atmospheric conditions between the rover and base. Figure 47 shows the nearest available CORS, stationed between

8.7-13 km away from Copper Mountain in nearby Breckenridge.

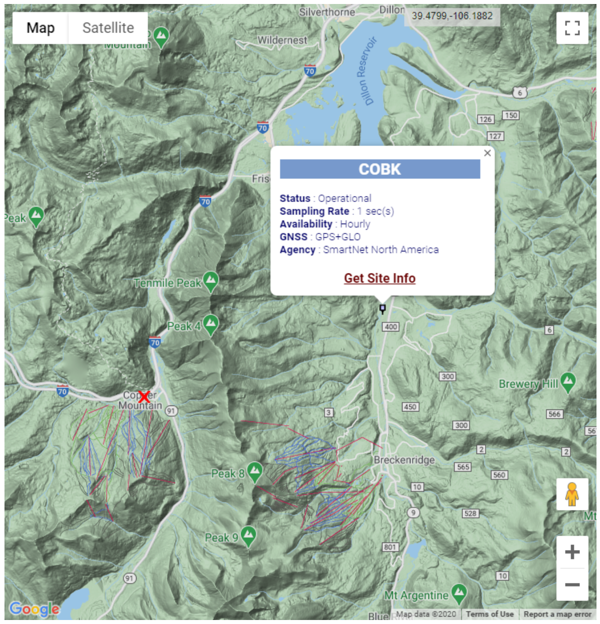

Fig. 47 Closest Available Base Station (Copper Mountain marked in red)

The main advantage to using PPK GNSS is the centimeter level accuracy it is able to achieve, allowing the system to meet the vertical error budget of 10 cm. In addition, the availability of a nearby ground station makes PPK GNSS a cost effective solution for georeferencing sensor data. The biggest detractors for PPK GNSS is the additional post-processing time needed to perform correction algorithms and purchasing software to perform these algorithms. Fortunately, access to software is often included when purchasing PPK GNSS receivers and open source software is a possibility.

Advantages	Disadvantages
Positional Accuracy to within Centimeters	Requires additional software
Existing Base Station Available	Increased post-processing times
Easy to setup and maintain	

Table 22 Advantages and disadvantages of using PPK GNSS

4. Ground Control Points

Ground Control Points (GCP) are physical markers that are placed on the area to be surveyed. The exact locations of these markers is measured and is used as tie points to increase the accuracy of a GPS system. These only improve surveying with other GPS systems and are not a stand alone geo-referencing system. GCP are only applicable to image based surveying such a photogrammetry and LiDAR and they help with the stitching process of the images in post processing. The locations of the GCP must be measured with real time kinematic (RTK) or PPK GPS systems to ensure the measurement is precise which requires additional equipment. Using around four or more GCP can increase the accuracy of the maps measurements from a few meters to a few centimeters [13]. The main issues for using GCP for this project is that the markers would need to be placed and measured in the snowfield. If using permanent GCP, there must be a way to keep the points clean and clear of snow. If using temporary GCP, personnel would have to go into the snowfield to place and measure them which reduces the purpose of the project to improve ski patrol safety and autonomy.

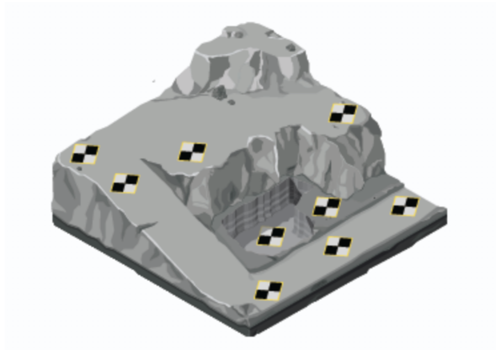

Fig. 48 A terrain map with GCP distributed throughout [2]

Advantages	**Disadvantages**
Increases positional accuracy of GPS to within centimeters	Only applies with photogrammetry and LiDAR
Can improve measurements on hilly terrain	Points placed must remain visible
	Points must be measured very accurately

Table 23 Advantages and disadvantages of using ground control points

26. Trade Study Process and Results

A. Software

1. Software Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Perpetual or Permanent Cost	**PAB REQ.**	0.3	The project has many different aspects to it, all requiring a portion of the allocated $5,000 budget. It is likely that both the vehicle and sensor systems will be costly, and the more money that can be spent on those systems, the more effective they will be. Therefore, it is of great importance to save money on the software system, so that already places cost as an important metric in the software trade study. Next, with costs varying so much for different software packages that provide similar utility, (free for Python, more than $2,000 for Matlab) the cost becomes the main distinguishing factor. Thus, the cost is one of the most important factors for the trade study and is assigned a weight of 30%, equal in importance to the ability to integrate with the sensor package.
Data Visualization Quality	**DR 5.3**, **DR 5.4**	0.1	The data collected from the sensor needs to be conveyed to the Copper Mountain Ski Patrol in a useful way. The quality of the data visualization produced will directly relate to how well they understand the data and, in turn, how useful the data is to them. While poor data visualization does not make the data useless to ski patrol, better data visualization will make the data accessible to more people. The 10% weight assigned to data visualization quality reflects the fact that poor data visualization will still work for our purposes but is not desired.
Integration with Sensor Package	**FR 1**	0.3	The software's ability to integrate with the sensor selected to collect data is critical to the function of our system. If the two are unable to interface, then each becomes useless and our system is not able to complete the minimum requirements of our project. The easier it is to integrate our sensor and software, the more time we can spend dialing in our sensor to collect accurate readings and tweaking our vehicle to provide a better platform for our sensor. The weight of 30% was decided because of how necessary software integration is to our project.

Ease of Use by Predicted Training Time	**DR 5.5**	0.2	This metric highlights the interfacing capability of our system. This is important to our customer because they do not want their team spending too much time dealing with a complicated system. Ideally a staff member should little interaction with the software in order to get the information they need to assess avalanche factors. However, this does not have a direct impact on the functionality of the software and therefore is not a critical of the software.
Data Processing Speed	**DR 5.5.3**	0.1	This has a low weight because it is not critical to the functionality of the software nor was it requested. This just provides quality user experience and a baseline for the time of the processing process.

Table 24 Weight and criteria for data processing software trade study

2. Software Trade Study Scoring

Criteria	1	2	3	4	5
Perpetual or Permanent Cost	$2,000+	$1,500-$1,999	$1,000-$1,499	$500-$999	$0-$499
Data Visualization Quality	unusable	low	readable	high	pristine
Integration with Sensor Package	incompatible	requires extreme effort	requires moderate effort	requires low effort	integration is seamless
Ease of Use by Predicted Training Time 80 Hours+	40-80 Hours	40 Hours	20-40 Hours	10-20 Hours	10 Hours or less
Data Processing Speed	1-hour+	30-60 minutes	10-20 minutes	1-10 minutes	1 minute

Table 25 Trade study scoring for the data processing software

3. Software Trade Study

Criteria	Weight	Python 3	Matlab	**ArcGIS**	Google Earth Engine
Perpetual or Permanent Cost	30%	5	1	5	3
Data Visualization Quality	10%	4	2	5	5
Integration with Sensor Package	30%	3	4	3	3
Ease of Use by Predicted Training Time 80 Hours+	20%	4	3	5	4
Data Processing Speed	10%	4	5	5	5
Total:	100%	4	3	**4.4**	4

Table 26 Trade study for data processing software

<u>*Python 3*</u>

Perpetual or Permanent Cost: Python 3 is a free program and running its software is also free.

Data Visualization Quality: Python 3 has a few geophysical libraries with good quality imagery with high resolution. Python also has multiple options for displaying 3D data. However, Python requires that we create our own user interface.

Integration with Sensor Package: Depending on the sensor, there may be some programs that are built in Python that come with the sensor which would make integration seamless. However, if there is no built code, then we will have to design the code requiring at minimum a moderate amount of integration. Python also allows for a large variety of file inputs to read so there is practically no limit on which files the sensor package can output in.

Ease of Use by Predicted Training Time: The interface that is created will take some training in order to use it. There would also be some training require in order to customize and personalize the output data to the users preference.

Data Processing Time: Because Python is a base language, processing time should take no longer than a minute. However, with large data sets and especially when printing 3D images, Python can take more than a minute to output its figures. [18]

<u>*Matlab*</u>

Perpetual or Permanent Cost: Matlab's perpetual license costs $2,150, which could prove to be prohibitive. For our project, this cost would take up close to half of our budget leaving a small amount of money to purchase a sensor and vehicle.

Data Visualization Quality: Matlab is designed to handle large data sets organized into matrices. It is very good at performing computations on these large data sets but it's data visualization capabilities are limited. It will not be able to display the data required in this project in a way that will be easy to interpret for the Copper Mountain Ski Patrol.

Integration with Sensor Package: Matlab will integrate with the sensor package well. It is capable of inputting many standard file formats including common file formats for scientific data. Matlab is also capable of interfacing with other coding languages such as C/C++ which could help with sensor integration.

Ease of Use by Predicted Training Time: Matlab will not be a program that is familiar to the Copper Mountain Ski Patrol. It also lacks a user friendly interface or a way to build an all encompassing GUI. Even if a GUI is built, knowledge about the structure of the code will need to be conveyed in case errors are encountered down the road. This

will require a moderate amount of training.
Data Processing Time: Matlab should not have an issue processing the amount of data we will collect in a timely manor. An optimized program should be able to return a visualization of the data well within the time required. [26]

ArcGIS

Perpetual or Permanent Cost: The actual program itself will cost $700 and the training can cost over $500. However, the staff at Copper Mountain already have access to ArcGIS, so for the purposes of this project, the software is free.
Data Visualization Quality: ArcGIS specializes in outputting data overlayed onto geophysical maps and is packed with geophysical libraries that can provide high resolution imagery and grids. It also has multiple options for user interface; either already built interfaces or we can design one ourselves. It even has different coding APIs such as Python and Java.
Integration with Sensor Package: Similar to Python 3, this would take some coding and preparation to integrate with the output data of our software. However, even worse than Python, it only accepts a limited number of file types which heavily impacts the options of the sensor package.
Ease of Use by Predicted Training Time: There are already available training to use this application and also has multiple user interface options so we can choose from the best!
Data Processing Time: ArcGIS has shown to have processing speeds for large projects as quick as 5 seconds showing me that it would be capable of producing an image of estimated snow height on a mountain in under a minute. [3]

Google Earth Engine

Perpetual or Permanent Cost: Google Earth Engine is free to use for research, academia, or personal uses. There is a cost for commercial use but it is not disclosed on their website. We have requested a quote but have not heard back from Google.
Data Visualization Quality: Google Earth Engine allows access to images taken from space of the Earth. You can overlay data on to these images leading to great data visualization. A heat map could be created indicating snow depth overlayed on an actual image of Copper Mountain Ski Resort.
Integration with Sensor Package: Google Earth Engine is somewhat limited in the file types that can be used. The engine can input CSV, Shapfile, GeoTIFF, and TFRecord file types. While the options are limited, these file types should not be prohibitive for our projects purposes. Regardless of what file type our sensor outputs data in, conversion to a CSV file should not be difficult.
Ease of Use by Predicted Training Time: Training would be required in order for an program to be created for use by the Copper Mountain Ski Patrol using the Google Earth Engine. The code editor uses JavaScript. which is not a language anyone on our team is proficient in. There is some experience with JavaScript on the team but not extensive use. The Google Earth Engine does have a user interface API, meaning the final product delivered to Copper Mountain should be easy to use.
Data Processing Time: Data Processing time should not be an issue. Google Earth Engine was built to display data on top of images of the earth, so it is well optimized for our use case. [27]

B. Platform Design

1. Platform Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Complexity in Design and Integration	**DR 1.1**	0.4	The platform must be simple enough for easy operation by the Copper Mountain staff and easily attachable to the sensor in order to be efficient and accurate.
Ability to Scan Large Areas	**DR 1.2, 1.4, 2.1**	0.05	A large scan area reduces the amount of locations a scan needs to be performed and produces a larger and more useful visual representation for the customer.
Susceptibility to Errors Due to Terrain and Meteorological Conditions	**DR 3.1, 3.2, 3.3**	0.05	The platform must be able to overcome terrain conditions, the snowfall, and wind present at Copper Mountain that may impact the stability of the platform.
Stability in Providing Accurate Measurements	**DR 1.1**	0.4	Measuring snow depth within 10 cm accuracy is the main requirement of the system which depends on the stability of the platform itself.
Easy to Power	**DR 2.2, 2.3, 2.4**	0.1	Scan times can take upwards of 1 hour and the platform must be easily integrated with a power source for the duration of the scan.

Table 28 Weight and criteria for platform design trade study

2. Platform Design Trade Study Scoring

Criteria	1	2	3	4	5
Complexity in Design and Integration	Considerable amount of time or complexity		Either difficult to design or integrate		Simple to integrate and design
Ability to Scan Large Areas	$< 0.1 km^2$	$0.1 - 0.25 km^2$	$0.25 - 0.5 km^2$	$0.50 - 1 km^2$	$1 km^2 <$
Susceptibility to Errors Due to Terrain and Meteorological Conditions	No stability in mountain conditions	Some stability in mountain conditions	good stability in mountain conditions	Can operate on/over mountain terrain, struggles with mountain meteorological conditions	Unimpaired by mountain conditions or terrain
Stability in Providing Accurate Measurements	no stability (without control system)		Good stability (without control system)		No source of instability
Easy to Power	Can maintain power for <1 hour	Can maintain power for over 1-5 hours	Can maintain power for over 5-10 hours	Can maintain power for over 10 hours	Can be connected to infinite power supply

Table 29 Trade study scoring for platform design

3. Platform Design Trade Study

	Weight	Fixed-wing	Multirotor	Airship	Ground effect vehicle	Ground Stations
Complexity in Design and Integration	40%	1	2	1	2	5
Ability to Scan Large Areas	5%	4	4	5	1	3
Susceptibility to Errors Due to Terrain and Meteorological	5%	4	3	4	2	3
Stability in Providing Accurate Measurements	40%	1	2	1	3	3
Easy to Power	10%	2	1	4	2	4
Total:	100%	1.4	1.8	1.65	2.35	3.9

Table 30 Trade study for platform design

Fixed wing

Complexity: Designing and building an aircraft would take up a large portion of our budget as well as time where most of our concern should be focused on accuracy of our sensor package. However, buying one of the shelf would be easy, but integration would still be difficult.

Scan area: Can scan large areas typically. Mostly based on power supply it can carry.

Errors due to meteorological conditions and terrain: Fixed-wing drones can typically operate in difficult weather and over mountainous terrain.

Structure stability: Without a feedback system for stability, the drone can maintain steady level flight. Especially in strong wind conditions.

Power required: Operates is limited by power of rechargeable batteries.

Multirotor

Complexity: The multirotor would have substantial complexity just as all airborn platforms would due to multiple sources of error. Multirotors would be impacted severely by wind, temperatures, and weight restrictions. Multirotors do not perform well in extreme conditions and the failure of one rotor could lead to instability and safety that would add complexity to the project.

Scan area: The multirotor as with all airborn platform has a large scan area. The scan area would not be restricted by the platform, but by the sensor's operating range.

Errors due to meteorological conditions and terrain: Multirotors do not perform well in extreme conditions but do not face any challenges from terrain conditions.

Structure stability: Multirotors under ideal conditions can maintain steady level flight needed to make accurate readings, but even the smallest winds can impact flight stability. In expected conditions at Copper Mountain, this instability will likely be unavoidable.

Power required: On average most UAVs that would be within the cost range of this project's budget could last for about 35 minutes. This flight time is also under ideal conditions and not under the cold and wind that would be experienced flying at such altitudes.

Airship

Complexity: The airship has substantial complexity because of its lack of mobility and susceptibility to wind resistance which would greatly impact measurement accuracy.

Scan area: The airship as with all airborne platform has a large scan area. The scan area would not be restricted by the platform, but by the sensor's operating range.

Errors due to meteorological conditions and terrain: Lighter than air platforms can perform well in snowy conditions but have limited mobility and can be affected by the presence of winds.

Structure stability: Lighter than air platforms have limited mobility and the need for a starting calibration point for the sensor severely limits the ability to produce accurate measurements.

Power required: The total mass of a blimp system that can lift 2 kg of payload would be approximately 5 kg. The payload, motors, and batteries account for 96 percent of the mass.

Ground Effect Vehicle

Complexity: Difficult to design a ground vehicle that can maneuver over mountain slopes and foliage. Integration and design would also be too difficult.

Scan area: Limited by ability to climb slopes as well as move over a large area in certain time frame.

Errors due to meteorological conditions and terrain: This would be tough to operate in snowy conditions.

Structure stability: Would provide good sensor stability, but structural stability would be difficult to maintain over such a steep terrain

Power required: Can only carry a small power supply

Ground Stations

Complexity: Simplest of solution to build and integrate with other systems.

Scan area: On top of a ridge, it can scan a large portion of a bowl. Can also be moved to scan more areas.

Errors due to meteorological conditions and terrain: Won't operate during storms, but can operate any other time on a mountain.

Structure stability: Can be built into the ground assuring there is instability. However, weather conditions local to the mountain can create some affect on the data.

Power required: Can have large power source, but no method to insert permanent power source.

C. Sensor Package

We will be looking into 4 types of sensor options represented as 4 different matrices in the trade study. Each matrix will compare 3 commercially available sensors for a combined total of 12 sensors.

1. Sensor Package Criteria and Weighting

Previously, when the team selected a UAV solution, the weighting selection for the sensor was heavily influenced by this decision. The power budget was given a weight of 0.1 out of 1 because a more efficient sensor would require a smaller battery that would reduce aircraft payload weight and increase flight time.In turn, the precision/ accuracy weighting was increased to 0.3 and the cost weighting was increased to 0.1.

2. Sensor Package Trade Study Scoring

3. Sensor Package Trade Study

LiDAR

Temperature Sensitivity: Both the Puck and Scout-16 have a minimum operating temperature of -10°C which can severely limit operational availability in cold climate environments such Copper Mountain. The TruPulse 200X has operational ability at -20°C which is significantly better, however, more leeway is preferred.

Maximum Range for Measurements: Maximum range measurements were used when the surface is assumed to be 80% reflective, which is a reasonable estimate for snow. All sensor have a maximum range of at least 75m. The TruPulse 200X has the best range, with a max range of 2,500 meters to reflective targets as listed on the specification sheet. The range to meet accuracy requirements is still around 400 meters which is still useful for this project.

Precision/Accuracy: All sensors can achieve accuracy of ±3cm. Note these are estimates are based on terrestrial surveys. There may be additional error added due to backlash in the gears and error in potentiometer readings in the system.

Power Budget: All sensors scored low in terms of power consumption, with the TruPulse consuming the lowest with 4.4W. The M8 and Scout-16 consume 16W and 40W respectively. The high power consumption was a concern with

Criteria	Driving Requirements	Weight	Reasoning
Temperature Sensitivity	**DR 3.1**	0.25	System will most likely operate in below freezing temperatures where electronics are susceptible to performance degradation.
Maximum Range for Measurements	**DR 2.1**	0.25	A higher range for the sensor reduces the amount of locations a scan needs to be performed and produces a larger visual representation of the terrain for better understanding of avalanche mitigation.
Precision/Accuracy	**DR 1.1**,**DR 6.1**,**DR 6.2**	0.3	Measuring snow depth within ±10cm is the main requirement of the system and depends on the sensor itself as well as any GNS systems to track sensor location and attitude.
Power Budget	**DR 2.3**,**DR 2.4**	0.05	Battery performance degradation can occur in cold conditions, and a more power efficient sensor package will reduce power requirements.
Weight	**DR 3.2**	0.05	The weight of the combined system must be able to be supported by the ground station platform.
Cost	**PAB REQ.**	0.1	The project must remain $5000 as a whole. The cheaper the sensor, the more budget remaining for other subsystems of the project.

Table 31 Weight and criteria for sensor package trade study

Criteria	1	2	3	4	5
Temperature Sensitivity	15°C	0°C	-10°C	-25°C	-40°C
Maximum Range for Measurements	10m	15m	25m	50m	75m
Precision/Accuracy	25cm	20cm	15cm	10cm	5cm
Power Budget	10W	5W	3W	2W	1W
Weight	< 2,000g	<1,000g	<600g	<400g	<200g
Cost	$4,000	$3,000	$2,000	$1,000	$500

Table 32 Trade study scoring for sensor package

LIDAR	Weight	**TruPulse 200X**	Velodyne Puck	Pheonix Scout-16
Temperature Sensitivity	25%	4	3	3
Maximum Range for Measurements	25%	5	5	5
Precision/Accuracy	30%	5	5	5
Power Budget	5%	2	1	1
Weight	5%	4	2	1
Cost	10%	3	1	1
Total	100%	**4.35**	3.75	3.7

Table 33 Trade study for LiDAR

RADAR	Weight	LUFFT Snow Depth Sensor SHM31	**US-D1 Radar Altimeter**	SDMS40
Temperature Sensitivity	25%	5	5	5
Maximum Range for Measurements	25%	2	4	1
Precision/Accuracy	25%	4	5	5
Power Budget	10%	3	4	1
Weight	10%	3	5	2
Cost	5%	2	4	5
Total	100%	3.45	**4.6**	3.65

Table 34 Trade study for RADAR

ULTRASONIC	Weight	NovaLynx 260-700	USH-9 Snow Depth Sensor	**MB1340 XL-MaxSonar-AE4**
Temperature Sensitivity	25%	5	5	2
Maximum Range for Measurements	25%	1	1	1
Precision/Accuracy	30%	4	4	4
Power Budget	5%	3	4	5
Weight	10%	3	1	5
Cost	10%	2	2	5
Total	100%	**3.2**	3.15	2.95

Table 35 Trade study for ultrasonic sensors

Photogrammetry	Weight	**DSLR** Camera	LVDS Camera	eBee SODA
Temperature Sensitivity	25%	4	5	5
Maximum Range for Measurements	25%	5	2	5
Precision/Accuracy	30%	4	1	4
Power Budget	5%	4	3	2
Weight	5%	3	5	2
Cost	10%	4	5	2
Total	100%	**4.2**	2.95	4.1

Table 36 Trade study for photogrammetry

flight time when desigining for a UAV system, but will not be as much of a concern with the ground based system being implemented with no substantial weight restriction for the battery.
Weight: The sensors scored relatively low on weight given the aircraft requirements, however the weight is not as much of a concern on the ground based platform.
Cost: It is important to note that cost varies by how the system is sold. For example, the Scout-16 includes an integrated GNS and INS and is sold with proprietary data handling software. Although very appealing, the starting price comes out to $35,000. Cheaper LiDARs like the Puck start at $4,000, leaving little room for other sub-teams. The TruPulse 200X has a price just under $1,800 which is well within budget.

Radar
Temperature Sensitivity: All radar options operate down to -40°C which is colder than conditions typically found on Copper Mountain.
Maximum Range for Measurements: The LUFFT SHM31 [35] has a maximum range of 15m and the SDMS40 [37] has a maximum range of 5m. The 15m is a reasonable distance but doesn't allow for much coverage of the terrain. The 5m is a very small distance and would not serve to be much more useful than digging a snow pit. The US-D1 radar altimeter[36] can operate at a range of 50m which is much better than the other two options.
Precision/Accuracy: The LUFFT SHM31 has a accuracy of about 8 cm which gives little leeway on the snow depth accuracy requirement for the project. This sensor is more precise when flying closer to the ground as well. The US-D1 is accurate to 5cm and is intended for UAV use. The SDMS40 is accurate to 3mm. Accuracy could degrade once again with the introduction of backlash and potentiometer error.

Power Budget: The LUFFT SHM31 requires 3.4W. The US-D1 uses 2W. The SDMS40 uses over 24W. The first two valus are acceptable while the SDMS40 likely requires too much power to be used on this project.
Weight: The LUFFT SHM31 and SDMS40 are intened to be mounted to a pole and are rather heavy at 2.3 and 1.8 kg respectively. The US-D1 is only 110g.
Cost: The LUFFT SHM31 sensor is about $ 2500, the US-D1 is about $600, and the SDMS40 has an unknown price currently as the manufacturer has yet to respond with a quote. For analysis purposes, it was assumed to score a 5.

Ultrasonic
Temperature Sensitivity: The NovaLynx 260-700 and USH-9 Snow Depth Sensor are capable of operating to -40°C which gives significant leeway. However, the MB1340 is serviceable to 0°C which severely limits operational use.
Maximum Range for Measurements: Almost all ultrasonic sensors will have a max range of about 10 meters, making a 3d visual map difficult to produce.
Precision/Accuracy: All three ultrasonic sensors have precision below 1 cm. There are many factors explained in key design options considered that reduce accuracy. As a result, the scores were reduced by 1.
Power Budget: The NovaLynx has the highest power budget of 3.3W and the USH-9 uses 1.08W. The MB1340 has the lowest power output at .02W but once again will require integration that may increase the power budget.
Weight: The NovaLynx 260-700 has a weight of .6kg, the USH-9 has a weight of 1.2kg and the MB1340 is very lightweight, but it would require some integration that may increase the weight.
Cost: The quote for the USH-9 is $2,278 and the quote for the NovaLynx 260-700 is $2,682. The MaxSonar sensor itself is only $150 but would once again require integration that will factor into cost.

Photogrammetry
Temperature Sensitivity: The operational limit of both the SODA Camera and the LVDS sensor is -40°C. DSLRs are operational to -25°C but solutions exist for improving cold weather performance of the DSLR cameras.
Maximum Range for Measurements: Previous studies that used DSLRs for snow depth imaging were on average conducted at 50 m. This is standard for DSLR imagery as using a short focal length forces the camera to be close to the terrain while capturing larger areas. The SenseFly SODA's recommended altitude is 43 m above ground level. The size of sensor on the LVDS camera means it has to be closer to gather useful information in an image.
Precision/Accuracy: The SODA photogrammetry camera has produced digital elevation maps with 3 cm precision. Using DSLRs, the models were between 3 and 10 cm, but quantified information is limited. The LVDS camera is not viable due to its small sensor size, 1280 by 800 pixels.
Power Budget: The low-voltage differential signaling camera is operational nearly 3 W. The SODA and the DSLR have removable batteries. While the S.O.D.A's battery cannot be modified, it may be possible to connect the DSLR camera to the system's central power.
Weight: The LVDS sensor and its wires are less than 10g. The DSLR is 575g with a lens. The SODA unit with mounting hardware is 750g.
Cost: The LVDS camera sensor is $275. The advanced DSLR in question with a lens is approximately $750. The SODA camera with integrated GPS and thermal capabilities is upwards of $2,000.

D. Georeferencing

The importance of a georeferencing trade study is critical in meeting our allowed vertical error budget. Positional data is taken in tandem with the sensor package to provide accurate X,Y,Z coordinate data for post processing. In this trade study we will be comparing three systems, each with a respective trade matrix with three commercially available options for each matrix. Note, matrices are filled out based on available manufacturer data sheets either found online or requested via email.

1. Georeferencing Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Vertical Accuracy	**DR 1.1**,**DR 6.1**,**DR 6.2**	0.20	Vertical Accuracy is required because in order to obtain the snow depth, you need the vertical position of the aircraft as well as the distance to the ground. With this information you can get data on the ground level, which can be compared to the ground level when there is no snow in order to obtain snow depth. If the vertical position of the vehicle is not known with extreme accuracy, then the depth of the snow will not be able to be obtained to within 10cm as is required. The crucial role that vertical accuracy plays in our project justified the 20% weight.
Cost	**PAB REQ.**	0.20	Cost is important because we are constrained by a hard budget of $5,000. This money needs to be split between the vehicle, the sensor package, and the software so only a portion can be used to get a georeferencing system. The weight of 20% was decided because it is crucial that we get a system that is within our budget.
Weight	**DR 3.2**	0.20	The weight of the georeferencing system is critical for the function of our system as a whole. The vehicle selected must be able to carry this sensor as well as other components in order to operate. Weight is critical to platform operation so it was weighted 20%.
Lowest Operating Temperature	**DR 3.1**	0.15	Temperature is a large concern when operating any device at the top of Copper Mountain. Extremely cold temperatures are somewhat normal so any device used in this project will need to be able to sustain cold temperatures. This criteria was only given 15% weight because a separate thermal solution could be used to heat the sensor if necessary.
Power Budget	**DR 2.3** ,**DR 2.4**	0.15	The device needs to draw a reasonable amount of power in order for it to be usable for this project. The power required by this device needs to be small enough to allow all other devices to operate without requiring a prohibitively large power source. The weight of 15% was given because this is important but can be a tradeoff between all devices needing power.

Complexity	**DR 5.5.1**,**DR 5.5.2**, **Time Constraints**	0.1	Since the georeferencing system is only one part of this project, it must be sufficiently simple in order to implement it in our system. A large portion of time cannot be spent figuring out the georeferencing system if it prohibits us from completing other portions of the project. It was given a weight of 10% because more time could always be dedicated to the project by the group.

Table 37 Weight and criteria for referencing system

2. Georeferencing Trade Study Scoring

Criteria	1	2	3	4	5
Vertical Accuracy	25cm	20cm	15cm	10cm	5cm
Cost	$2,500	$2,000	$1,500	$1,000	$500
Weight	<1000g	<800g	<600g	<400g	<200g
Lowest Operating Temperature	15°C	0°C	-10°C	-25°C	-40°C
Power Budget	10W	5W	3W	2W	1W
Complexity	extremely complex	very complex	moderately complex	somewhat complex	low complexity

Table 38 Trade study scoring for georeferncing system

3. Georeferencing Trade Study

PPK GNSS	Weight	Tersus UAV PPK Solution	RTKITE Receiver	**Seagull GPK2**
Vertical Accuracy	20%	5	5	5
Cost	20%	3(Estimate)	4	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	3	3	3
Complexity	10%	4	4	3
Total	100%	4.2	4.4	**4.5**

Table 39 Trade study for PPK GNSS

GPS	Weight	Hornet ORG1410 [28]	**Adafruit Ultimate GPS** [29]	Copernicus II [30]
Vertical Accuracy	20%	1	1	1
Cost	20%	5	5	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	4	3	3
Complexity	10%	3	5	4
Total	100%	3.83	**4**	3.83

Table 40 Trade study for GPS

Pressure Altimeter	Weight	BMP388	SEN-11084	**29124-ND**
Vertical Accuracy	20%	1	1	2
Cost	20%	5	5	5
Weight	20%	5	5	5
Lowest Operating Temperature	15%	5	5	5
Power Budget	15%	5	5	5
Complexity	10%	3	3	5
Total	100%	4	4	**4.4**

Table 41 Trade study for a pressure altimeter

PPK GNSS

Vertical Accuracy: It is evident that the achieved accuracy (to within ± 1.5 cm) of PPK GNSS is significantly higher than those of other techniques. Furthermore, all three sensors scored a 5 in this category.
Cost: The Seagull GPK2 is the most cost effective solution of the three coming in at $600. The RTKITE Receiver comes in around $1,200 with the Tersus being an estimate of around $1,500 until they respond to our inquiry. The cost disparity being the addition of proprietary software used to perform algorithms with the RTKITE whereas the Seagull comes with the receiver only.
Weight: All receivers with antennas weigh less than 200g. This is true for all georeferencing equipment compared in the trade study.
Lowest Operating Temperature: All receivers can operate in as low as -40°C, which exceeds our operational temperature requirements.
Power Budget: All receivers operated around the same wattage with a typical power consumption of 2.8W
Complexity: All receivers are relatively easy to operate as all three can connect to the same dual band GPS and GLONASS satellite constellation tracking used by the nearest base station. None were given above a score of 4 as integration between base station, receiver, and the sensor is still needed. Seagull was given a 3 as the cost does not include PPK correction software.

Adafruit Ultimate GPS

Vertical Accuracy: The positional accuracy listed on the Adafruit provided data sheet is 1.8m. This will not allow us to collect accurate snow depth measurements and is not viable for vertical geolocation. This could be viable for location data in the other two directions because our accuracy constraints are much less strict.
Cost: The Adafruit Ultimate GPS costs just under $40. This easily fits within our budget for the project.
Weight: This GPS unit weighs 8.5g. This amount of weight should pose no problems and be light enough to cause no issues.
Lowest Operating Temperature: The working temperature range listed in the data sheet is -40°to 85°C. Temperature should not cause problems for this GPS unit for our use case.
Power Budget: The wattage required by this device to operate is 3-5.5W. While this is not ideal, it does not prohibit its use in our project
Complexity: The complexity of this device is not an issue as it has a fairly extensive user manual. The manual includes all relevant information including common wiring setups and example code for parsing and data logging. [29]

29124-ND

Vertical Accuracy: This chip has a vertical accuracy of ±20cm.
Cost: This chip is fairly cheap at $30 with options to buy in bulk (which doesn't seem necessary for this project, but

could come in handy).
Weight: This chip is very light weighing about 2g
Lowest Operating Temperature: This chip can operate well in temperatures as low as -40°C.
Power Budget: One reason why this chip is so good is combined with its accuracy, it also does not need a lot of power to function. This chip needs less than a watt to function.
Complexity: This chip is not very complex to integrate because it comes with pins already attached and a pretty large user manual. However, it will take some wiring in combination with the on-board sensor package.

27. Airplane sizing and performance estimation analysis

Note that the following data is used in analyzing the performance of a fixed-wing UAV:
Summary of data used in airplane performance analysis:

- m_{PL} = 1.5 kg. Mass of payload. This is subject to change based on the chosen sensor package and its mass.
- ηc = 200000 J kg^{-1}. Product of propulsion system efficiency and LiPo capacity in cold conditions. More data is needed to determine what a reasonable value for this parameter is.
- $\frac{L}{D}\Big|_{max}$ = 10. Maximum lift-to-drag ratio. This information can be found more precisely during more detailed design, but this value is fairly conservative for the purpose of initial analysis.
- t = 3600 s. Required endurance. This value may change depending on the sensor package.
- $\frac{W_e}{W_{TO}}$ = 0.65. Empty weight fraction. Estimated based on experience with UAVs. Subject to change depending on aircraft construction techniques; i.e. use of composites could lower this value.
- v_{crs} = 10 m s^{-1}. Cruise velocity. Subject to change depending on sensor requirements.
- v_{max} = 30 m s^{-1}. Maximum velocity. Value chosen to escape strong headwinds.
- ρ = 0.8 kg m^{-3}. Air density. Based on standard atmosphere for 14000 feet.
- S_{to} = 12 m. Takeoff ground roll length. From design requirements.
- g = 9.81 m s^{-2}. Gravitational acceleration.
- $C_{L_{max_{to}}}$ = 1.8. Conservative estimate for maximum lift coefficient with flaps in takeoff configuration. Subject to change based on wing design.
- V_{climb} = 5 m s^{-1}. Required climb rate from design requirements.
- n_{man} = 2. Load factor for maneuvering. Value is chosen to avoid extreme bank angles.
- C_{D_0} = 0.028. Parasite drag coefficient. Estimated based on $\frac{S_{wet}}{S}$ = 4 and C_{fe} = 0.007 which is a high value for drag typical of single engine airplanes. Subject to change depending on aircraft drag properties.
- AR = 7. Aspect ratio of wing. Reflects estimated/desired aspect ratio.

- $e = 0.7$. Oswald efficiency factor. Conservative estimate for Oswald efficiency.
- $\frac{T_{TO}}{T_{man}} = 2$. Ratio of takeoff thrust to maneuvering thrust. Very rough estimate.
- $\frac{T_{TO}}{T_{crs}} = 4$. Ratio of takeoff thrust to cruise thrust. Very rough estimate.
- $\frac{T_{TO}}{T_{max}} = 1$. Ratio of takeoff thrust to thrust required for maximum speed. Assume that full thrust is used for maximum speed.
- $r = 10$ m. Turning radius. From design requirements.
- $V_{S0} = 8$ m s^{-1}. Stall speed in landing configuration. Value is chosen to not create undue pilot difficulty.
- $C_{L_{max_{ldg}}} = 2$. Conservative estimate for maximum lift coefficient in landing configuration. Subject to change based on wing design.

The takeoff weight is to be estimated first to guide further analysis into the performance of the airplane. Takeoff weight is the sum of empty weight, battery weight, and payload weight: $W_{TO} = W_E + W_{BATT} + W_{PL}$ [9]. The weight of the payload is specified as 1.5 kg for the sake of this trade study, and the empty weight can be estimated as a fraction of the takeoff weight based on typical values for fixed-wing UAS. So $W_E = 0.65W_{TO}$.
Estimating the weight of the batteries requires a determination of the thrust used by the aircraft: based on a free body diagram, the trust of the aircraft must counteract drag and in turn must take a value of $T = \frac{m_{TO}g}{(L/D)}$. The power required is simply the thrust T times velocity v. The energy required is the power times the required endurance t: $E = \frac{vm_{TO}gt}{(L/D)}$. Now the energy content of typical RC aircraft batteries, such as Lithium Ion Polymer (LiPo) batteries, needs to be considered. Typical LiPo batteries have an energy density of 125 Wh kg^{-1}. In order to account for performance degradation due to cold temperatures and inefficiencies in the propulsion system, this value will be taken as a little bit under half of the typical value, or 200000 J kg^{-1}. It is assumed that this value accounts for the inefficiencies in the propulsion system since the estimate for LiPo capacity is very rough anyway. This value is named ηc. The mass of the battery then can be expressed as $m_{batt} = E/c = \frac{vm_{TO}gt}{(L/D)}\frac{1}{\eta c} + m_{PL}$. Having formulated expressions for each contribution to the aircraft's takeoff mass, the following expression can be written:

$$m_{TO} = 0.65m_{TO} + \frac{vm_{TO}gt}{(L/D)}\frac{1}{\eta c} + m_{PL} \tag{10}$$

In order to solve for m_{TO}, the following values are used:
- $M_{PL} = 1.5$ kg
- $\eta c = 200000$ J kg^{-1}
- $L/D = 10$
- $t = 3600$ s
- $\frac{W_e}{W_{TO}} = 0.65$
- $v = 10$ m s^{-1}

Solving for the corresponding takeoff mass of the aircraft and mass of batteries, the aircraft would weigh approximately 9kg and require approximately 1.5kg of batteries. In turn, both the payload and the batteries would make up approximately 17% of the aircraft's takeoff weight.
In order to determine the appropriate ranges of wing loading and thrust-to-weight ratio, the aircraft performance sizing plot must be generated. All data is taken at a standard atmosphere altitude of 14000 feet which results in an air density of 0.8 kg m^{-3}.
Stall speed. While there are no explicit stall speed requirements for the aircraft to meet, a stall speed of 8 m/s is chosen

to ensure that the aircraft is not flying unduly fast during landing which would make manual flight difficult. The stall speed constraint curve is defined by the following equation [10]:

$$\left(\frac{W}{S}\right)_{TO} = \frac{1}{2}\rho v_{S_L}^2 C_{L_{max_L}} \tag{11}$$

Landing distance. While the design requirements do specify the required landing distance, it is suspected that, due to uneven terrain and the expected low friction coefficient between the aircraft's landing gear and the snow, a supplemental system will be needed to stop the aircraft upon landing. One such concept is a sort of deployable anchor which drops down from the aircraft upon landing, digs into the snow, and stops the aircraft. The aircraft can also be landed uphill. Later design work and modeling will be needed to ensure that landing distance requirements are met, but there are feasible options to ensure that an airplane can meet these requirements.

Takeoff distance. Assuming that thrust forces are significantly greater than drag and friction forces, the following equation holds for takeoff distance [11]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{1.44}{(S_{FL}/1.66)\rho g C_{L_{max_{TO}}}}\left(\frac{W}{S}\right)_{TO} \tag{12}$$

Climb. It is desired that the aircraft can escape a 1000 ft/min (5 m/s) downdraft. Note that CGR is the climb gradient: $CGR = \frac{V_{climb}}{V_\infty}$. The constraint curve for this requirement is [11]:

$$\left(\frac{T}{W}\right)_{TO} = CGR + \frac{1}{L/D} \tag{13}$$

Maneuvering. A 10-meter turn radius is desired. A maximum load factor for the maneuver of 2 is set. In order to verify that the turn radius requirements can be met at normal cruise speed, the required airspeed to meet the 10-meter turn radius requirements is calculated: $V_{\infty,turn} = \sqrt{rg\sqrt{n^2-1}}$. The required airspeed is greater than the specified 10 m s^{-1} cruise speed, so these maneuvering requirements are met. Having established that these requirements can be met, the performance sizing curve for maneuvering is defined by[11]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{qC_{D_0}(T_{TO}/T_{man})}{(W/S)_{TO}} + \frac{n^2}{q\pi ARe}\frac{T_{TO}}{T_{cr}}\left(\frac{W}{S}\right)_{TO} \tag{14}$$

Speed. There are two constraint curves related to speed: one for normal cruise speed and one for a faster dash speed of 30 m s^{-1}. The governing equation for performance sizing is the same in each case [11]:

$$\left(\frac{T}{W}\right)_{TO} = \frac{qC_{D_0}(T_{TO}/T_{cr})}{(W/S)_{TO}} + \frac{1}{q\pi ARe}\frac{T_{TO}}{T_{cr}}\left(\frac{W}{S}\right)_{TO} \tag{15}$$

The final performance sizing plot is shown:

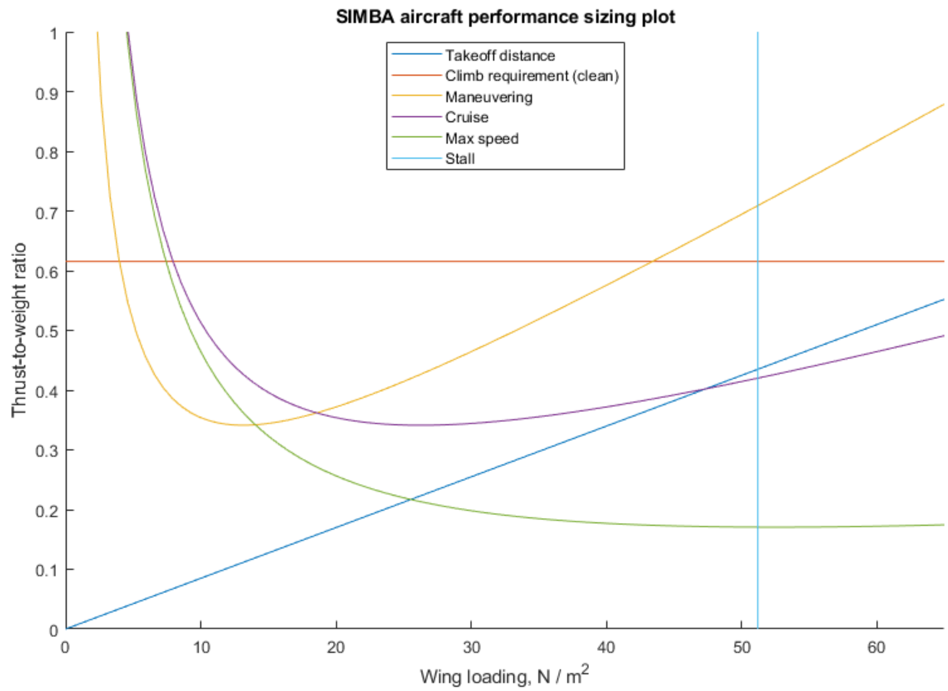

Fig. 49 SIMBA performance sizing plot. The acceptable design area is the area above the climb requirement line and bounded by the cruise, maneuvering, and stall speed curves.

28. UAV Trade Study and Results

A. UAV Criteria and Weighting

Criteria	Driving Requirements	Weight	Reasoning
Payload mass fraction: $\frac{M_p}{M_{TO}}$	**DR 3.6.1 3.6.2, 2.1.1**	0.1	A vehicles with a larger payload faction is able to carry more payload of less vehicle weight. Low payload fraction will result in heavy vehicles. Aircraft weight and size will impact both project cost, maintenance and usability by the user resulting in an intermediate weighting.
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	**DR 3.6.1 3.6.2, 2.1.1**	0.1	For the same payload mass, a vehicle with a smaller fuel/battery weight fraction is able to either have a smaller power plant or longer flight time. This then would cascade in overall aircraft weight and dimensions. Since the aircraft is operating at high altitudes in cold conditions, meeting the required endurance without a large vehicle is a critical design point. Aircraft weight and size will impact both project cost, maintenance and usability by the user resulting in an intermediate weighting.

Total takeoff weight	**DR 3.6.1 3.6.2, 2.1.1**	0.05	Heavy vehicles tend to have large dimensions. A large, heavy vehicle will create logistical challenges for Copper Ski patrol moving the vehicle to the area of interests. The customer has expressed the wish that the vehicle be transported preferably by human skier, then snow mobile and lastly by snow cat. Since this parameter overlaps with payload weight mass fraction, the weighting is reduced. Since aircraft takeoff weight has been represented in both payload mass fraction and fuel/battery mass fraction, the final aircraft weight is weighted less.
Expected maximum air-speed	**DR 3.3**	0.05	The aircraft is desired to be able to operate in 18 m/s wind speeds. If the aircraft is unable to fly above 18 m/s air speed, the vehicle will be unable to overcome the wind conditions and could be lost. The larger the vehicle air speed is compared to wind speed the better the vehicle will be able to overcome steady wind conditions. Also, high vehicle air speeds will be able to better fly the require flight path for the sensor package in high wind speeds. While the customer would prefer a high wind capable aircraft, it is more important to have a smaller and functional aircraft, hence the lower weighting.
Safety due to loss of thrust	**DR 3.11**	0.16	If the vehicle experiences some failure to the power plant system during flight, the ability of the aircraft to still be controlled and landed safely will vary between vehicle type. An uncontrollable vehicle is a major safety hazard. Since safety is a largest design concern, this is the most weighted section.
Safely due to ground im-pediment	**DR 3.11**	0.15	Ground based vehicles/stations could create imped-iment to freedom of motion on the ground. Since the vehicle will be used in a ski resort, it is ex-pected that people will occasionally be occupying the same space as the vehicle. Since skiers and snowboarders move quickly, especially on steep slopes, collision and crashing at these speeds can be extremely dangerous. Therefore, if the vehicle is on the ground, ground impediment is a serious concern. Since safety is a largest design concern, this is the next most weighted section.

Effect of gust: $\frac{M_{TO}}{A_{wet}}$	**DR 3.3, 3.4**	0.12	For the vehicle to operate it must be able to be controlled in gusting winds. Even if the vehicle is unable to provide the sensor with the required stability in gusting winds, the vehicle must still be controllable and landable else the vehicle will become a safety hazard. Therefore, $\frac{M_{TO}}{A_{wet}}$ is decided to be a good measure for a vehicle's ability to resist gusting winds. If the vehicle has a large enough $\frac{M_{TO}}{A_{wet}}$, the vehicle will be able to provide the sensor package with the needed stability to collect accurate data. Providing a stable platform such that accurate sensor measurements can be collected is a vital to the mission, hence the higher weighting.
Thrust-to-weight ratio: $\frac{T}{W}$	**DR 3.1.2, 3.5, 3.8**	0.12	Since the vehicle is operating in mountainous conditions, high climb rate is essential for avoiding collision with the ground. This can take the form of rapidly rising ground or significant downdrafts formed from the high mountain ridges and winter conditions. A high thrust-to-wait ratio is expected in order to meet these requirements. Reducing vibration is an important goal, and thrust-to-weight ratio is a proxy for vibration. So the aircraft which requires the lowest thrust-to-weight ratio (and consequently less vibration) is desired. Since the aircraft is operating in mountainous terrain, it is vital to keep the vehicle from crashing, hence the higher weighting.
Turing radius requirement met	**DR 3.7**	0.05	With the coarsest measurement grid set to 20m x 20m, if the vehicle is flying laps of the area of interest, a turning radius of 10m is a minimum requirement. If the payload package is able to create a finer measurement grid, it is deemed acceptable if the vehicle must perform dog legs. Since this is a binary parameter, either it is met or not, scoring is 1 or 5. Since turning radius is not critical to mission, the criteria is weighted less.

Density altitude requirement me	**DR 3.1**	0.05	For the vehicle to be usable most days, a density altitude of 4,267 m (14,000 ft) has been set. If the vehicle is unable to operate below this density altitude, the total number of usable flight days drops. While poor density altitude flight is acceptable since mission could still be occasional flown, to meet the customer's expectation of being able to take measurements most days, a vehicle capable of getting good density altitude is important. Since this is a binary parameter, either it is met or not, scoring is 1 or 5. Since high density altitude is not as common in cold winter conditions it is considered not critical to mission, hence the criteria is weighted less.
Navigate over uneven terrain	**DR 2.1**	1	Since the vehicle must operate in mountainous, snowy terrain, if the vehicle is unable to operate over, or maneuver around rough terrain, the vehicle will be both unable to operate without significant risk of crashing and a significant safety hazard. Therefore, the vehicle being unable to operate in rough, snowy terrain is a mission failure case.
Cost	**PAB req.**	1	Since there other project expenses like the sensor package, data processing, etc, the vehicle can only use a fraction to budget. Some vehicle configurations inherently have significant expenses. For example, large volumes of helium can quickly run into many thousands of dollars, exceeding project budget and being too expensive to operate for the costumer. Neither the vehicle, power plant consumables, (electricity, fuel, etc) or other operations expenses can be prohibitively expensive for constructing or continued operation. Exceeding reasonable building/operational costs results in a mission failure case.
Takeoff/landing distance	**DR 3.5 3.1.2**	1	If the vehicle type is unable to safely become air born on the maximum takeoff area of 20m x 20m, the vehicle could either crash or put people in danger. This is a mission failure case.

Table 42 UAV trade study criteria

B. Aircraft Design Trade Study Scoring

Criteria	1	2	3	4	5
Payload weight mass fraction: $\frac{M_p}{M_{TO}}$	<0.075	0.075-0.15	0.15-0.225	0.225-0.3	0.3<
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	0.3<	0.225-0.3	0.15-0.225	0.075-0.15	<0.075
Expected maximum airspeed	<8 m/s	8-16 m/s	16-24 m/s	24-30 m/s	<30 m/s
Total takeoff weight >15kg	15-12.5kg	12.5-10kg	10-7.5kg	7.5-5kg	5kg<
Safety due to loss of thrust	Losses thrust, can't maintain flight	Loss of thrust means aircraft is uncontrollable or cannot be effectively navigated	Losses thrust, can be maneuvered to avoid obstacles	Losses thrust, can be maneuvered to avoid obstacles and can glide to a specified location	Can't loose thrust (stationary)
Safety due to ground impediment	Area being measured is impassible safely	Multiple ground impediments	One ground ground impediment	Ground vehicle is able to avoid collisions	No ground impediment
Effect of wind: $\frac{M_{TO}}{S_{wet}}$	<0.75 kg m^{-2}	0.75-1.5 kg m^{-2}	1.5-2.25 kg m^{-2}	2.25-3 kg m^{-2}	3< kg m^{-2}
Thrust-to-weight ratio: $\frac{T}{W}$	>1.5	1.03-1.5	0.56-1.03	0.1-0.56	<0.1
Turing radius requirement met	Requirement not met	N/A	N/A	N/A	Requirement met
Density altitude requirement me	Requirement not met	N/A	N/A	N/A	Requirement met

Table 43 UAV scoring criteria

Criteria	0	1
Operate over uneven terrain	Requirement met	Requirement not met
Cost	Requirement met	Requirement not met
Takeoff/landing distance	Requirement met	Requirement not met

Table 44 Critical scoring criteria for UAV

C. Aircraft Trade Study

Since it was not possible to find an commercial vehicles that could meet the required flight profile for the given budget, it is expected that a custom vehicle will be designed and built either from scratch or possibly modifying an existing platform. Therefore five vehicle types were explored to see which type would most inherently be able to meet the mission requirements.

	Weight	**Fixed-wing**	Multirotor	Airship	Ground effect vehicle	Ground Stations
Payload weight mass fraction $\frac{M_P}{M_{TO}}$	10%	3	3	**5**	4	**5**
Fuel/battery weight mass fraction: $\frac{M_b}{M_{TO}}$	10%	3	2	1	4	**5**
Takeoff weight, total	5%	4	3	1	4	**5**
Expected maximum airspeed	10%	**5**	4	1	3	5
Safety due to loss of thrust	16%	4	4	2	3	**5**
Safety due to ground impediment	15%	**5**	5	5	4	2
Effect of gusts: $\frac{M_{TO}}{S_{wet}}$	12%	2	3	1	2	**5**
Thrust-to-weight ratio: $\frac{T}{W}$	12%	4	2	**5**	3	5
Turing radius requirement met	5%	5	4	5	5	5
Density altitude requirement met	5%	5	5	5	5	5
Sub Total	100%	**3.91**	3.54	3.04	3.43	4.55

Table 45 Aircraft trade study results

	Fixed-wing	Multirotor	Airship	Ground effect vehicle	Ground Stations
Able to navigate over uneven terrain	1	1	1	0	1
Prohibitive Cost	1	1	0	1	0
Takeoff/landing distance	1	1	1	1	1
Resulting Product	1	1	0	0	0

Table 46 Aircraft comprehensive trade study

	Fix-wing	Multirotor	Airship	Ground effect vehicle	Ground Stations
Composite Score	**3.91**	3.54	0	0	0

Table 47 Aircraft combined trade study results

D. UAV stability and Force

The equation for vertical thrust is simply $F_t = ma_y + mg$. Where a_y can be split into a $1x4$ matrix in order to solve for the thrust per motor.

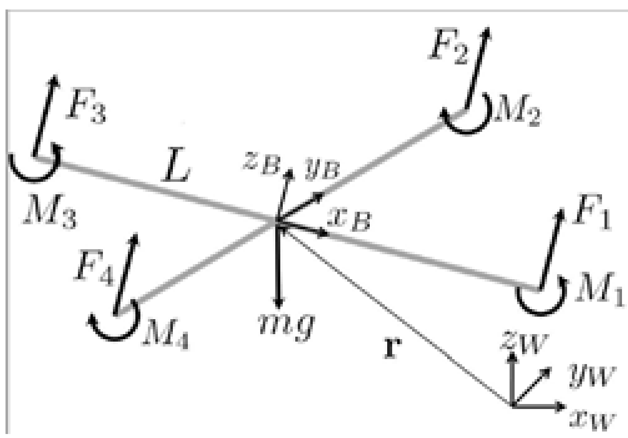

Fig. 50 Free Body Diagram of basic Quad-copter with Forces and Moments from internal and external factors

29. Actuator System Structure

A. Azimuth Plate

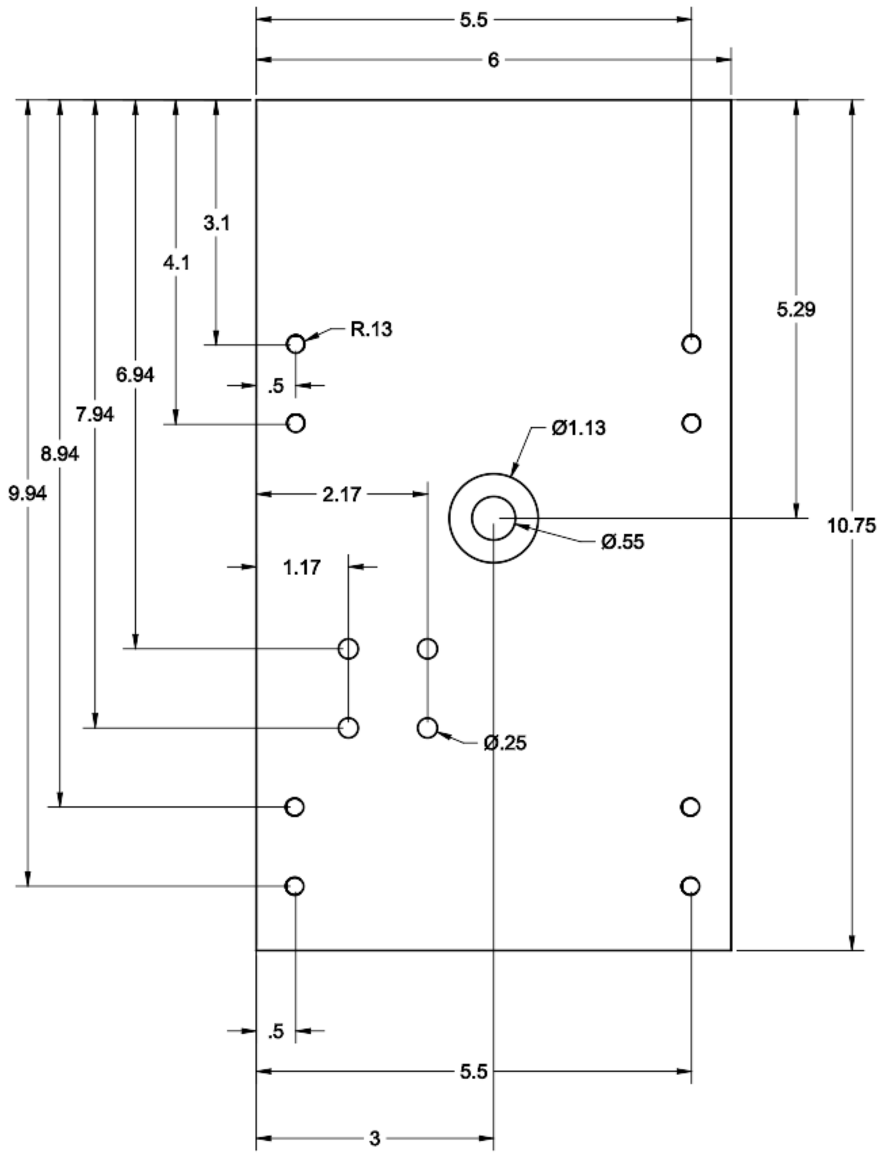

Fig. 51 P4: Drill Pattern for the Azimuth Plate

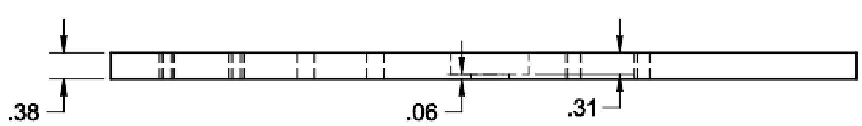

Fig. 52 P4: Hole depth for the Azimuth axle

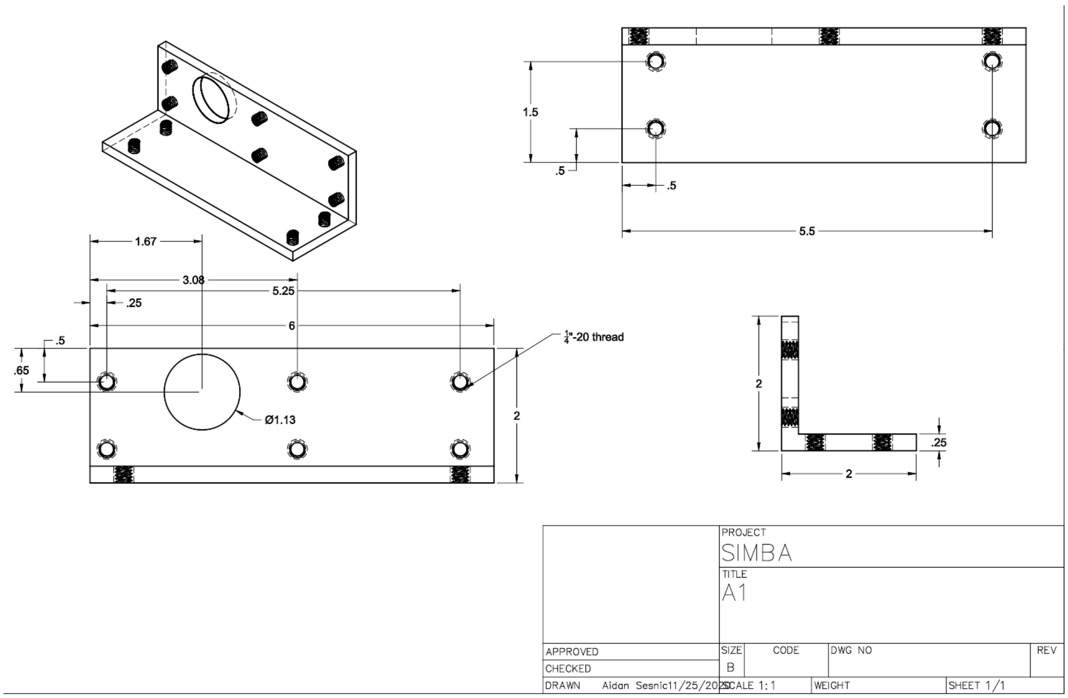

Fig. 53 A1: Angle iron piece 1 connecting the vertical plate to the azimuth plate

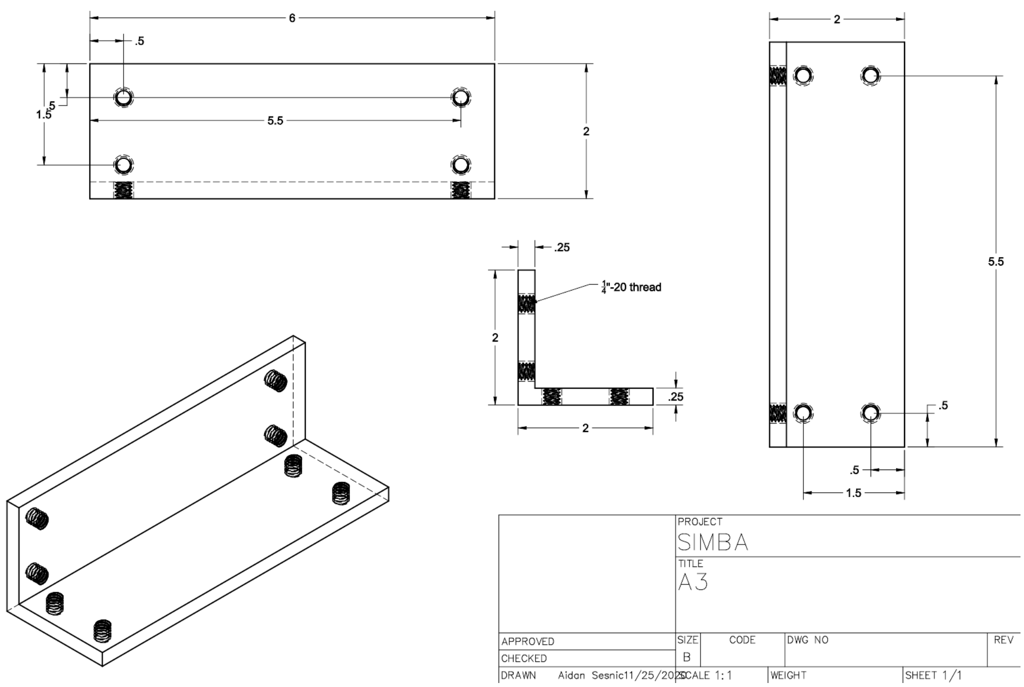

Fig. 54 A3: Angle iron piece 2 connecting the vertical plate to the azimuth plate

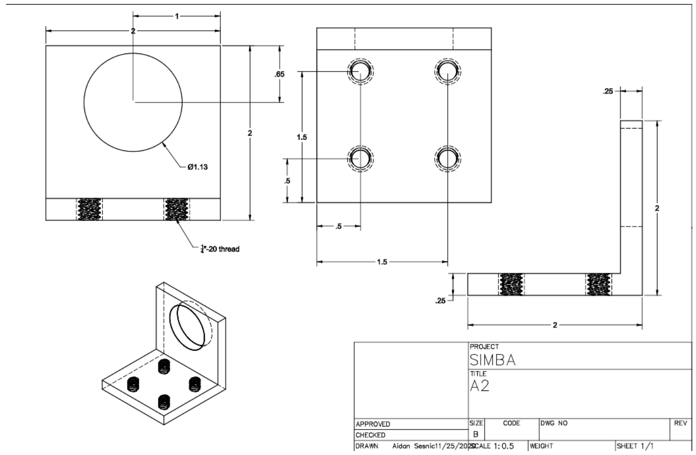

Fig. 55 A2: Angle iron piece 3 holding the azimuth driving axle

B. Vertical Plates

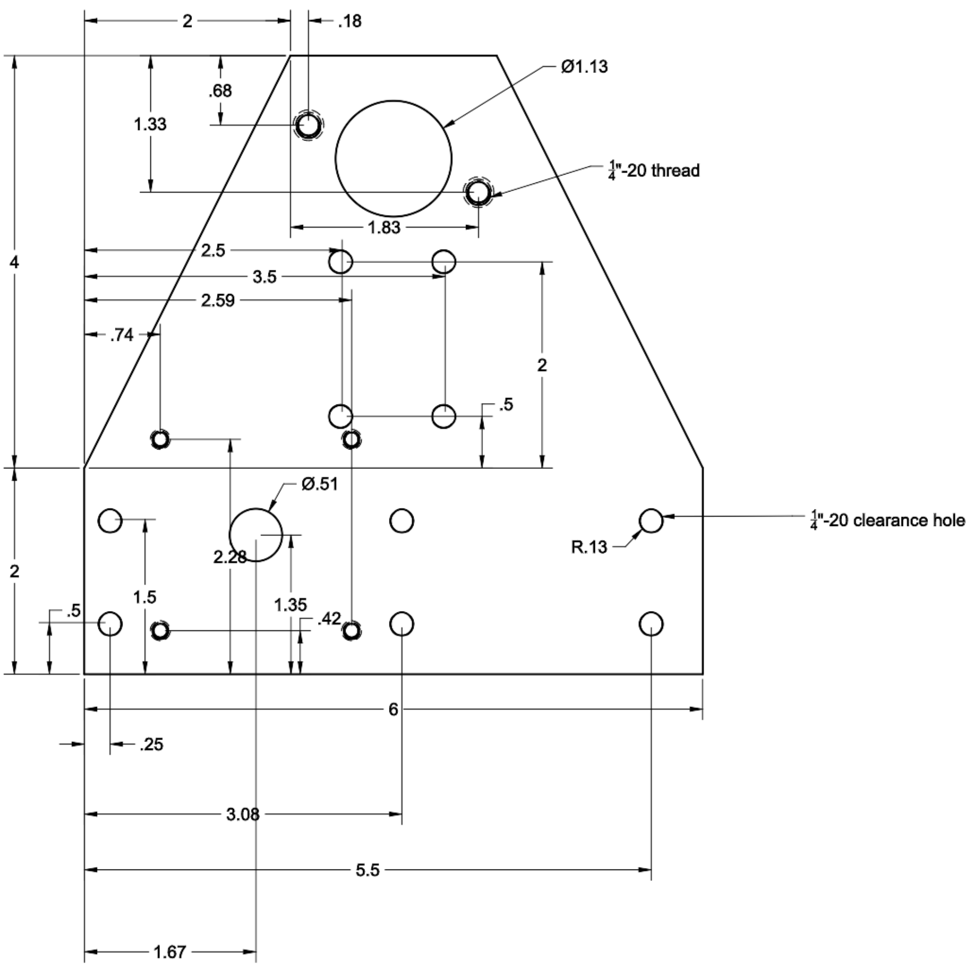

Fig. 56 P2: Vertical Plate 1 Drill Pattern

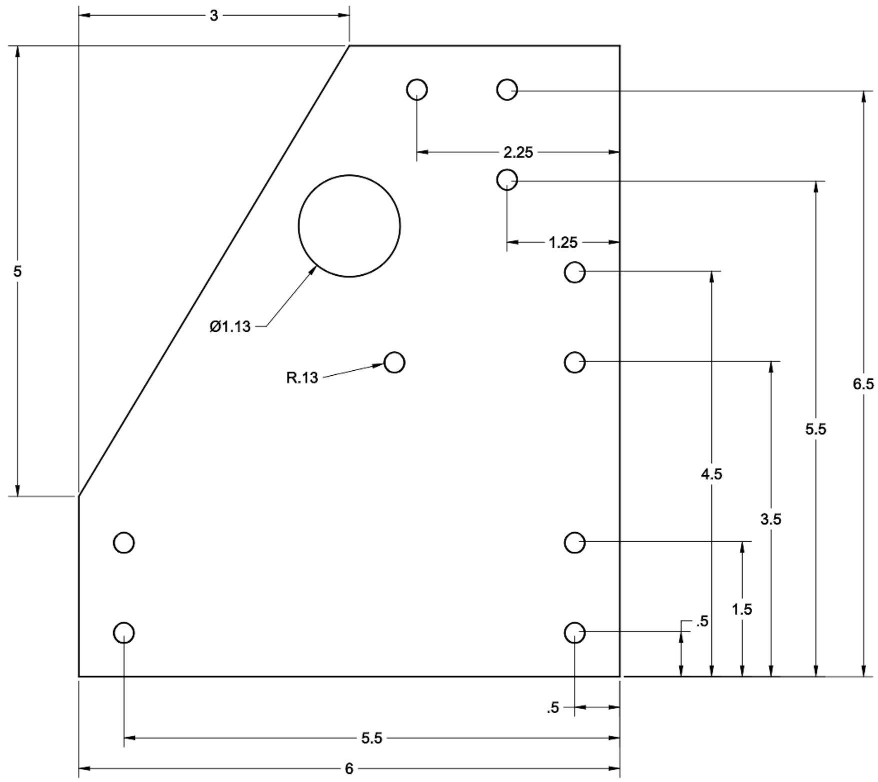

Fig. 57 P3: Vertical Plate 2 Drill Pattern

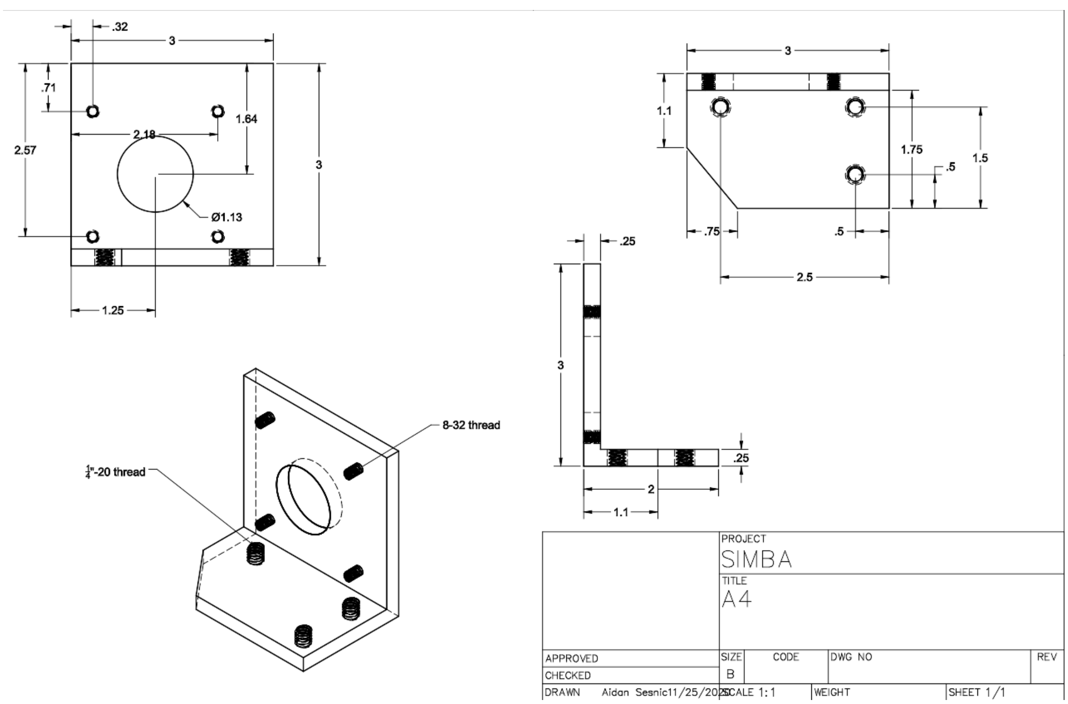

Fig. 58 A4: Lower angle iron holding the top of the pitching driving axle

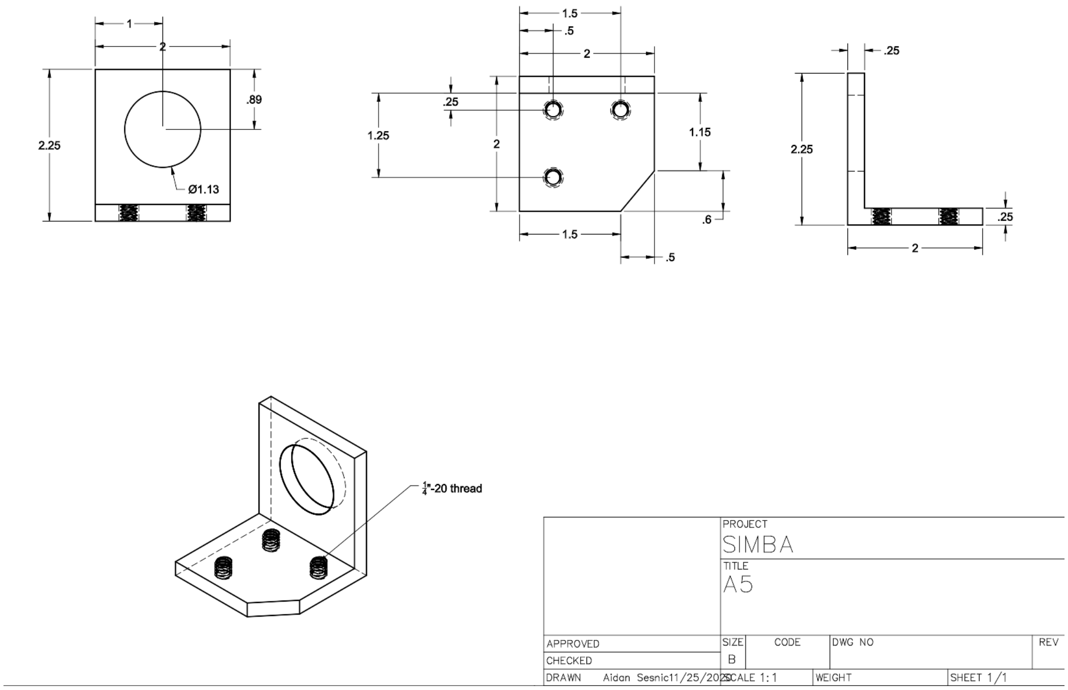

Fig. 59 A5: Upper angle iron holding the top of the pitching driving axle

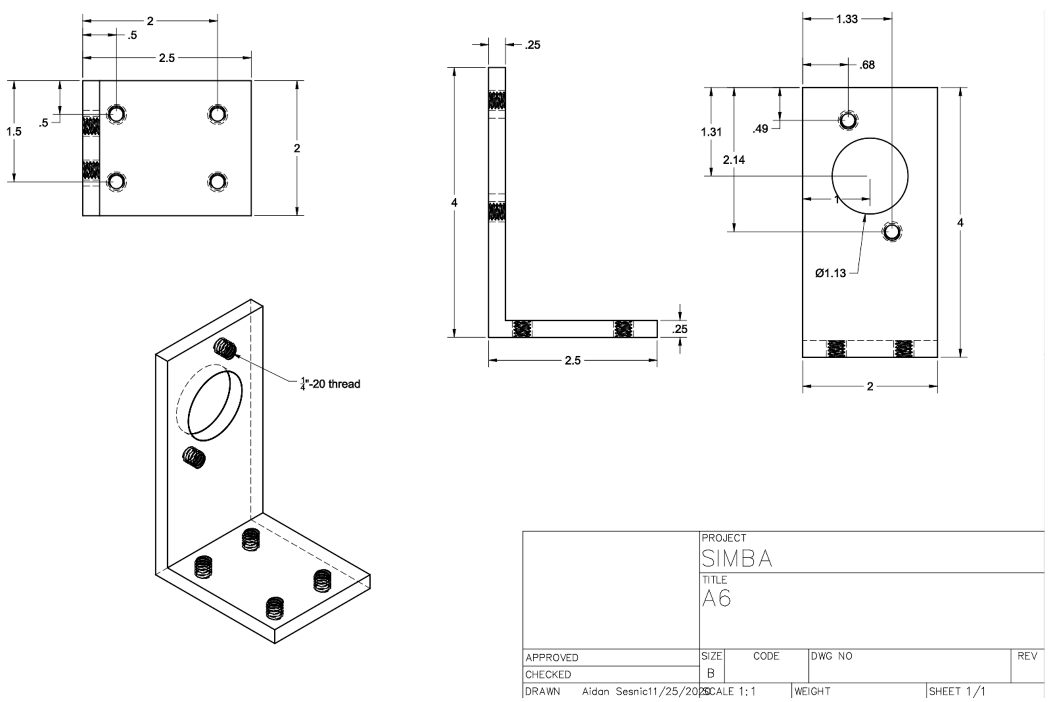

Fig. 60 A6: Angle Iron attached to P2

C. Pitching Plate

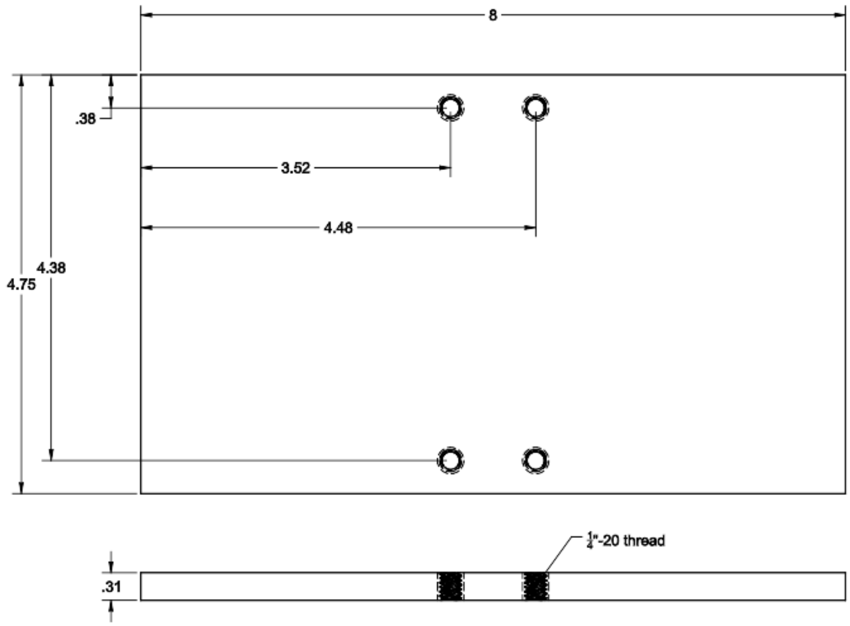

Fig. 61 P1: Pitching Plate Drill Pattern

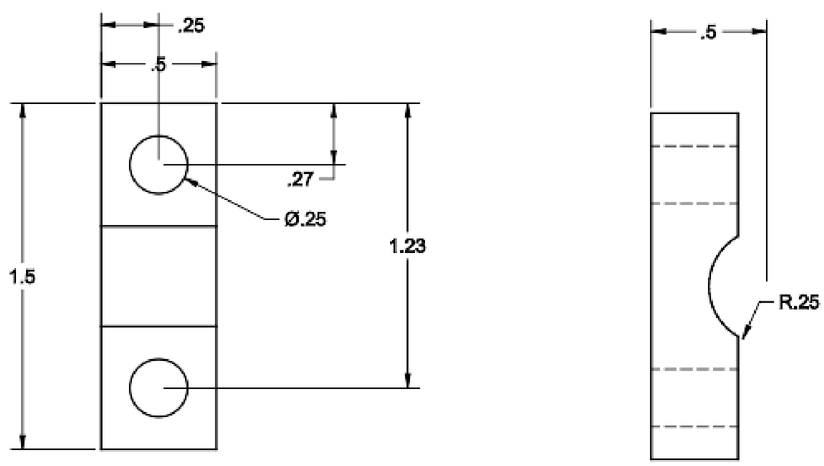

Fig. 62 C1: Pitching Plate Clamp for Connecting to Pitching axle

D. Axles

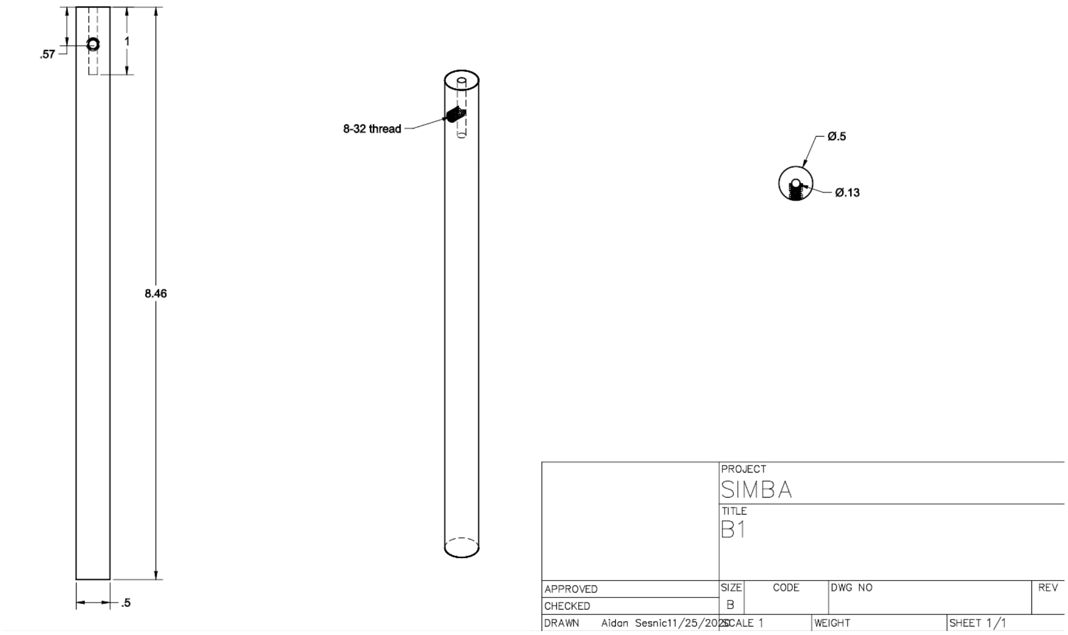

Fig. 63 B1: Pitching axle

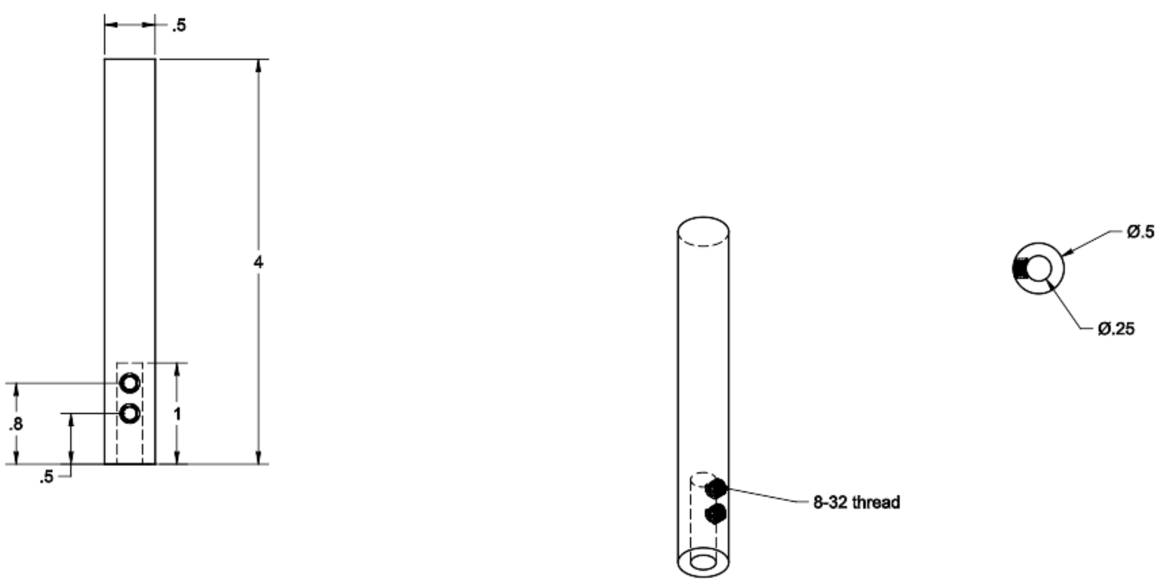

Fig. 64 B2: Pitching drive axle

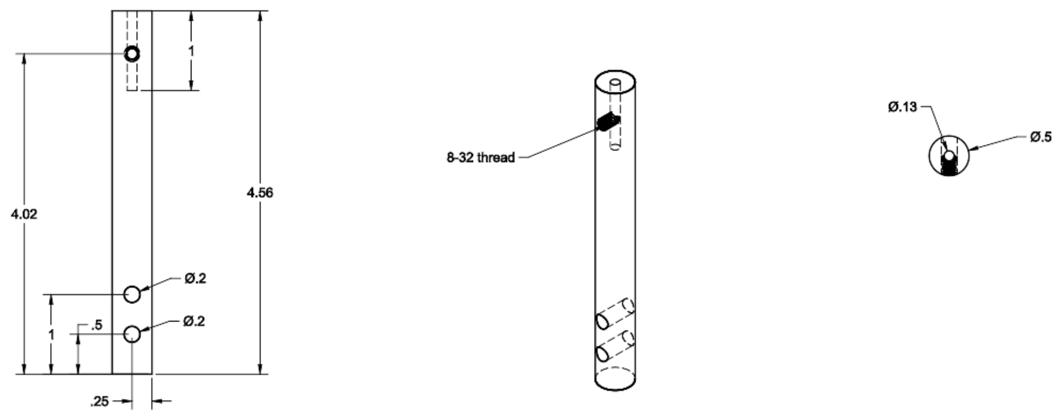

Fig. 65 B3: Azimuth axle

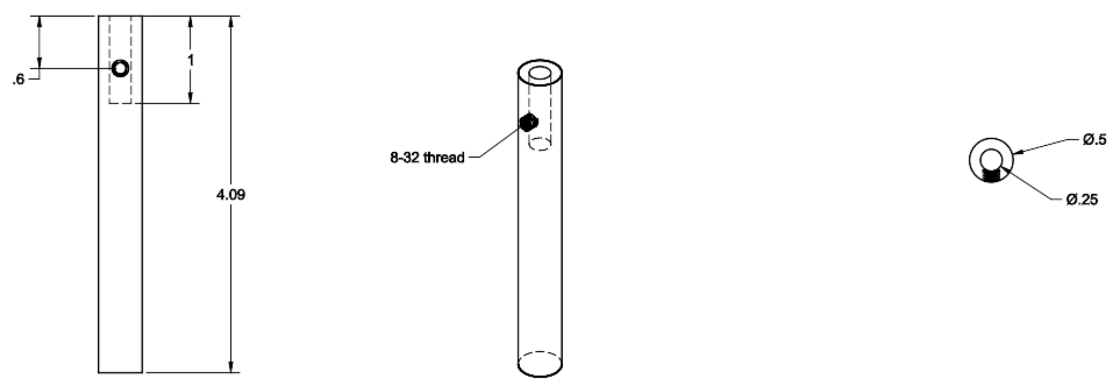

Fig. 66 B4: azimuth drive axel

E. Potentiometer Mounts

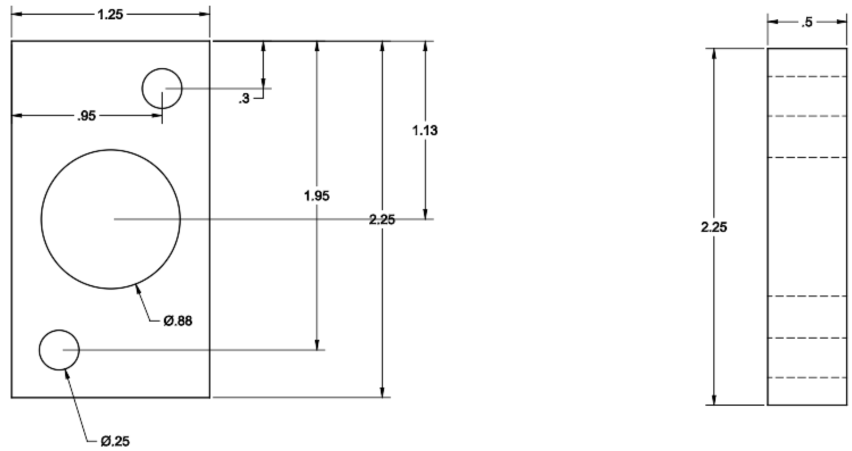

Fig. 67 C2: Potentiometer Mount

F. Actuator Structure Bill of Materials

Part ID	Quantity	Price per Unit	Total	Part Description
8982K36	2	13.19	26.38	6061 angle iron 2 inch, 1/4 inch thick, 1ft
4668K15	7	24.32	170.24	1/2 Ball bearing
57545K527	2	34.8	69.6	Worm
57545K513	2	73.66	147.32	Gear
8974K28	2	2.5	5	6061 1/2 inch shaft, 1 ft
9246K423	1	7.53	7.53	1/4 inch plate, 6x6
9246K466	3	20.64	61.92	5/16 plate, 8x8
8975K154	1	25.45	25.45	3/8 plate, 12x6
8975K11	1	4.59	4.59	1/2x1x12 bar
5909K31	1	3.33	3.33	Thrust Bearing, 1/2 inch
92185A195	1	6.77	6.77	Motor mounting screws, 25 pack
8982K5	1	14.81	14.81	6061 angle iron, 2x3,1/2ft
92627A330	1	7.65	7.65	Quick release pin
92196A274	1	11.48	11.48	18-8 bolts, pack of 100
8974K82	1	30.11	30.11	3 in rod diameter
92949A834	1	8	8	1/4-20, 7/16 length, round head, hex
92949A836	1	7.15	7.15	1/4-20, 1 3/8 length, round head, hex
98370A013	1	5.57	5.57	Washers for stand off
8619K441	1	4.44	4.44	1/8" HDPE Sheet: 12x12
8619K442	3	7.75	23.25	1/8" HDPE Sheet: 12x24
8619K444	1	13.32	13.32	1/8" HDPE Sheet: 24x24
8671K16	6	3.08	18.48	1" x 1" HDPE bar ($/ft)
91185A811	1	12.38	12.38	1/4" - 20 thread Thumb Screws (pack of 10)
		Total:	684.77	

Fig. 68 Actuator structure bill of materials

30. Microcontroller Subsystem

1. Software Overview

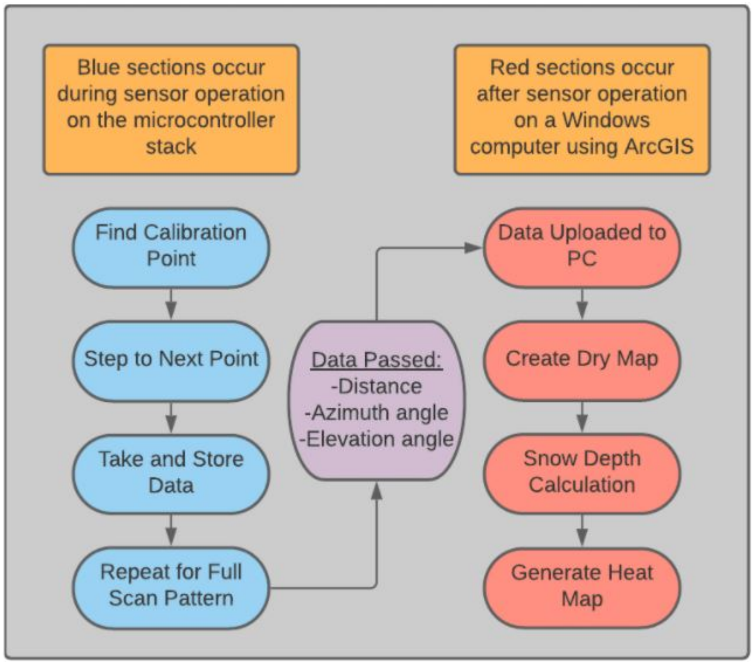

Fig. 69 Quick Software Overview

A. Raspberry Pi Pinout

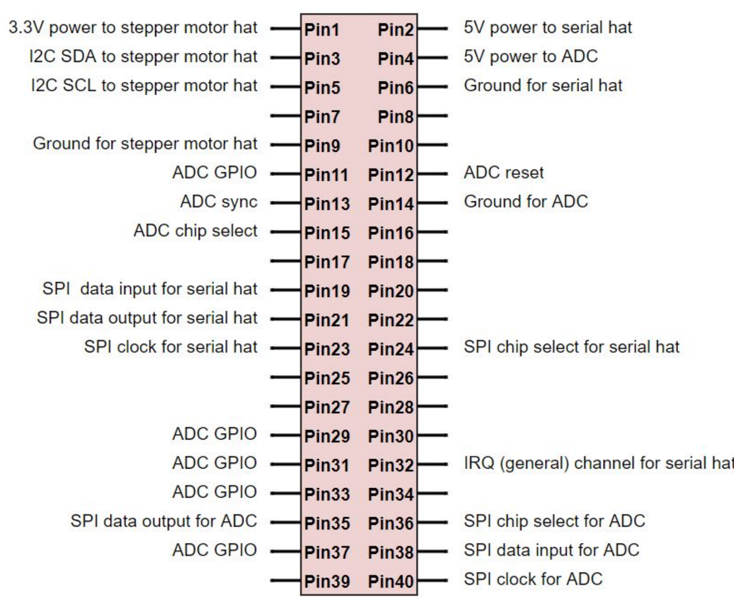

Fig. 70 Raspberry Pi 40 pin GPIO Pinout

B. Serial Hat Schematic

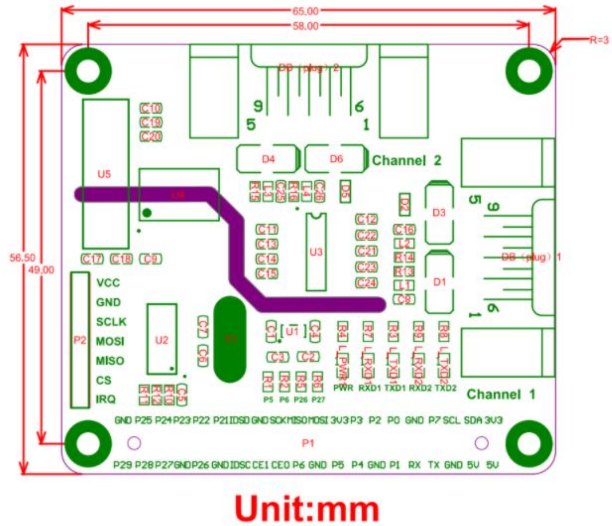

Fig. 71 Waveshare Serial Hat Schematic

C. ADC Schematic

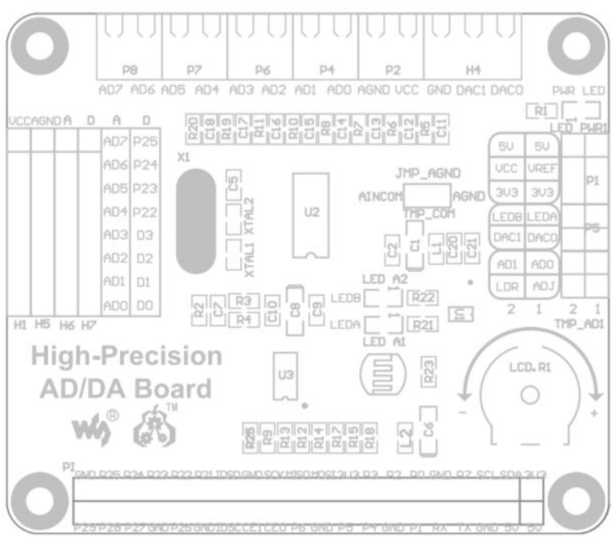

Fig. 72 Seeed Tech. ADC Schematic

D. Stepper Motor Hat Schematic

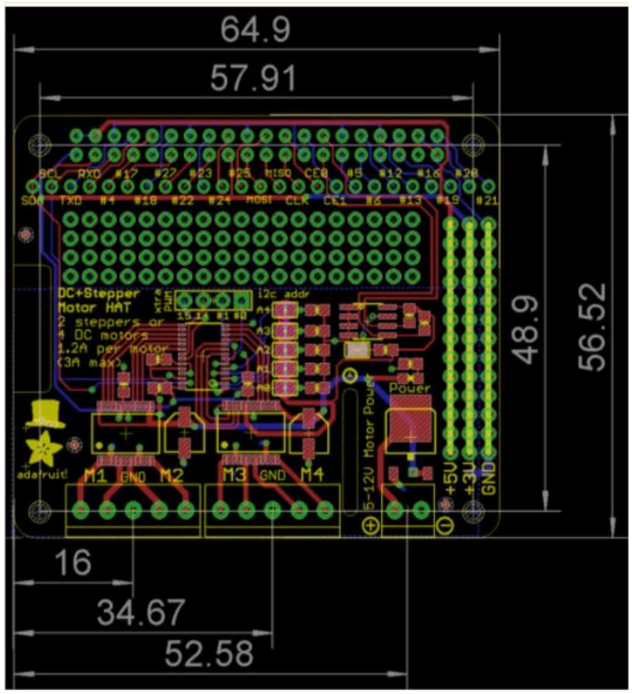

Fig. 73 Adafruit Stepper Motor Hat Schematic

31. Finances

Item	Company, Model	Design Choice (Yes/Maybe/Probably/No)	Sub-system	Single Price ($)	Quantity	Est. Shipping ($)	Item Total ($)
			Software (Datalogger, ArcGIS)				
Micorcontroller	Raspberry Pi 4 Model B (2 GB)	Yes	Microcontroller	$35.00	1	$7.09	$42.09
Serial Hat	Waveshare	Yes	Microcontroller	$21.15	1	$5.99	$27.14
Spools of Wire	Striveday 30 AWG Flexible Silicone	Yes	Microcontroller	$12.99	1	$5.99	$18.98
Resistor Set	BOJACK	Yes	Microcontroller	$13.99	1	$5.99	$19.98
ADC	1597-1425-ND	Yes	Microcontroller	$30.59	1	$7.99	$38.58
Stepper Motor Hat	Adafruit	Yes	Microcontroller	$22.50	1	$5.99	$28.49
Manufacturing (power conversion board)	Build locally	Yes	Microcontroller	$5.00	5	$5.00	$30.00
			Instrument Enviorment				
6061 angle iron 2 inch, 1/4 inch thick, 1ft	McMaster	Yes	Enviroment	$13.19	2	$3.99	$30.37
1/2 Ball bearing	BearingDirect	Yes	Enviroment	$24.32	7	$3.99	$174.23
Worm	McMaster	Yes	Enviroment	$34.80	2	$3.99	$73.59
Gear	McMaster	Yes	Enviroment	$73.66	2	$3.99	$151.31
6061 1/2 inch shaft, 1 ft	McMaster	Yes	Enviroment	$2.50	2	$3.99	$8.99
1/4 inch plate, 6x6	McMaster	Yes	Enviroment	$7.53	1	$3.99	$11.52
5/16 plate, 8x8	McMaster	Yes	Enviroment	$20.64	3	$3.99	$65.91
3/8 plate, 12x6	McMaster	Yes	Enviroment	$25.45	1	$3.99	$29.44
1/2x1x12 bar	McMaster	Yes	Enviroment	$4.59	1	$3.99	$8.58
Thrust Bearing, 1/2 inch	McMaster	Yes	Enviroment	$3.33	1	$3.99	$7.32
Motor mounting screws, 25 pack	McMaster	Yes	Enviroment	$6.77	1	$3.99	$10.76
6061 angle iron, 2x3,1/2ft	McMaster	Yes	Enviroment	$14.81	1	$3.99	$18.80
Quick release pin	McMaster	Yes	Enviroment	$7.65	1	$3.99	$11.64
18-8 bolts, pack of 100	McMaster	Yes	Enviroment	$11.48	1	$3.99	$15.47
3 in rod diameter	McMaster	Yes	Enviroment	$30.11	1	$3.99	$34.10
Tripod	Campbell Scienctific	Yes	Enviroment	$480.00	1	$16.40	$496.40
1/8" HDPE Sheet, 12x12	McMaster	Yes	Enviroment	$1.00	4.44	$3.99	$8.43
1/8" HDPE Sheet, 12x24	McMaster	Yes	Enviroment	$3.00	7.75	$3.99	$27.24
1/8" HDPE Sheet, 24x24	McMaster	Yes	Enviroment	$1.00	13.32	$3.99	$17.31
1" x 1" HDPE bar ($/ft)	McMaster	Yes	Enviroment	$6.00	3.08	$3.99	$22.47
1/4" - 20 thread Thumb Screws (pack of 10)	McMaster	Yes	Enviroment	$1.00	12.38	$3.99	$16.37
Manufacturing	* Through the school	Yes	Enviroment	$0.00	1		$0.00
			Sensor Package (Lidar, Potentiometer, Gearbox, etc.)				
Battery, Dry Use	27DC105 27	Yes	Sensor	$139.51	1	$20	$159.51
Battery, wet run	GRP9563159-25C-22.2V	Yes	Sensor	$150.00	1	$20.00	$170.00
Lidar	Tru-Pulse 200x	Yes	Sensor	$1,800.00	1	$40.00	$1,840.00
RS-232 Cable	Custom Cable Connection	Yes	Sensor	$8.99	2	$5.99	$23.97
Potentiometer	6187R10KL1.0LF	Yes	Sensor	$40.47	2	$7.99	$88.93
Stepper Motor	QSH5718-56-28-126	Yes	Sensor	$60.04	2	$7.99	$128.07
			Calibration Materials				
Reflectors	RangePal	Yes	Calibration	$70.50	1	$10.00	$80.50
Calibration Sign	Portrait OSHA	Yes	Calibration	$8.00	2	$3.99	$19.99
			Testing/ Verificaton Equipment				
BCA Stealth 300 Avalanche Probe	Evo	Yes	Testing	$56.99	1	$0.00	$56.99
Single Measuring Wheel	Uline	Yes	Testing	$49.00	1	$13.88	$62.88
Ultra Bright Green Laser Pointer	Edmund Optics	Yes	Testing	$169.00	1	$8.99	$177.99
			Administrative				
ClickUp			Admin	$60	1	$0.00	$60
			Totals				
						Total:	$4,314.34

Fig. 74 Comprehensive Financial Plan

32. ADC and PCB Figures

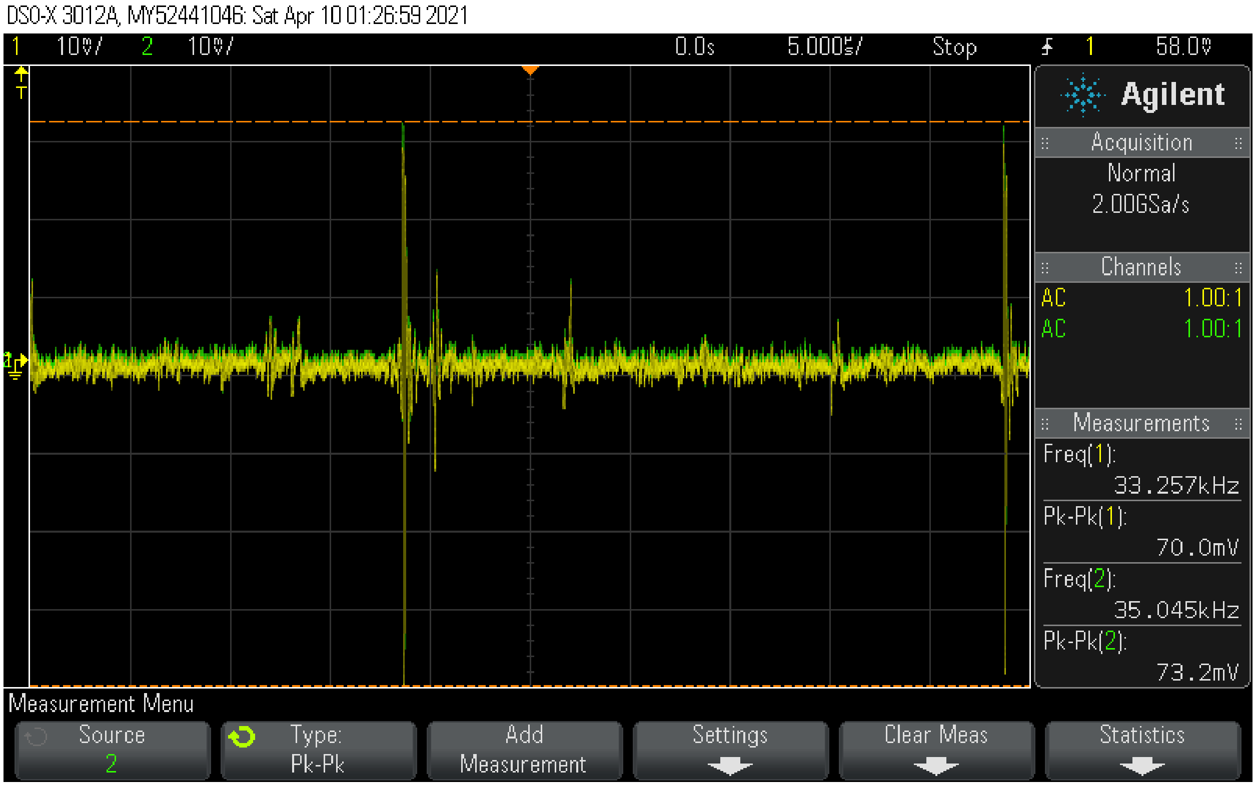

Fig. 75 Power supply noise