CANARY: A TETHERED TOPOGRAPHIC MAP PRODUCING MOBILE ROBOT

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ABSTRACT

Tethered robotics has found its place in many fields of research, particularly for Simultaneous Localization and Mapping (SLAM) applications. Dominantly, the rise of tethered robotics in the applications of topography and archeology has been prevalent in recent times. The purpose of this report is to describe a non-invasive and mobile sensing platform (henceforth CANARY) that has been developed to aid the archaeological preservation of the area surrounding Fort Amsterdam in Ghana. Specifically, the system is a tethered robotic system capable of traversing across large areas to collect data that can be used to identify ground level topological maps. The team followed the track of using a Light Detection and Ranging (LiDAR) device as a means of collecting point-cloud data corresponding to a given external environment, merging wit with the aforementioned tethered robot to aerially conduct the data collection. The system was tested in both indoors and outdoors, and tests results revealed that the mechanical, as well as the scanning capabilities, were running as expected. Future work would aim to generate an altitude-sensing feature to make localization more accurate.

PROBLEM DEFINITION

The continued archeological research of Professor Christopher DeCorse and Professor Renato Perucchio consists of identifying valid digging grounds around ancient sites in order to analyze the structural integrity and design of said sites. The identification of the validity of these grounds comes at a cost, where man power is used to eliminate the vegetation and the area is cleared for inspection by physically removing vegetation. The aim of this project is to create a system that can be used to characterize the ground level on these digging sites non-intrusively, meaning it does not interfere with the surrounding vegetation. This design will equip a LiDAR in order to identify produce a topographical map of the surrounding terrain while traversing across a tether stretched across the target region.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

Specifications:

Description
scanner must have a minimum range of 12 meters
integrated system must be able to produce a model of a 100 m x 100 m area
raw scans must have resolution of 0.5m at 12m min. range
Must be able to complete 100 x 100m scan on a battery pack less than 100 W-hrs (TSA)
TSA protocols require that the sum of dimensions of system cannot exceed 62" (1.5748 m)
must weigh less than 50 lbs. (22.6796 kg)

Requirements:

Description
Non-invasively produce a topographic representation of terrain
Scanner must provide input data appropriate for foliage discrimination algorithm
Must meet Transportation Security Administration (TSA) flammability requirements

Deliverables:

Description
Integrated system that traverses a minimum of 100 meters of rope
Platform with sensing capabilities with a minimum range of 12 meters

CONCEPTS

The concepts generated to design this system are centered around using a Light Detection and Ranging (LiDAR) sensor as the primary means of collecting data. This decision was made after consultation with the customer and after research conducted on the advantage such a sensor has over other scanners used for similar purposes (i.e. RGB-D cameras). A LiDAR functions by emitting a light pulse and determining the distance of a certain object by measuring the time it takes for the pulse to be returned to the sensor. The selected LiDAR for the following concepts utilizes a planar rotation scanning method. This allows all the nearest points along the plane of the rotating LiDAR to be tracked.

The mechanical assembly of the system was designed to be as autonomous, stable, and non-invasive as possible, given the spatial constraints of the region in Ghana. Regardless, CANARY is designed to function in any terrain, given any two anchors points that allow adequate tensioning of CANARY's rope. The evolution of the driving mechanism is discussed in subsequent sections.

A governing factor in the designing of CANARY was the ease of localization. Localization is a key component of CANARY's map generation, as the data collection will be based off the position of the sensor. The map created from the collected data will hence rely heavily on where the sensor was when it retrieved specific data points, so an important evaluating factor for the validity of the design concepts is how accurate the localization of the sensor can be made. The methods in which the group plans to localize the sensor will be discussed in the description of the concepts.

The following concepts were made based on the factors that will be listed in the Pugh Selection Matrix.

CONCEPT #1:

Hand-held LiDAR Scan

- Hand held apparatus to carry around a planar LiDAR spinning perpendicular to the ground.
- In order to localize the sensor, an internal measuring unit with a barometric sensor and accelerometer will be mounted in order to obtain position and speed at different times of scan.
- This system will require human involvement in the scanning process as the person will have to physically carry the device and traverse the area.
- Drawing for concept is found in Appendix Section 1, figure 1.1

CONCEPT #2:

Drone mounted LiDAR

- Planar LiDAR mounted at the bottom of an aerial device such as a drone.
- Drone to be controlled through a remote controller and position feedback to be given through either physical observation by the user or the camera mounted on the drone.
- In order to localize the sensor, an internal measuring unit with a barometric sensor and accelerometer will be mounted in order to obtain position and speed at different times of scan.
- Drawing for concept is found in Appendix Section 1, figure 1.2

CONCEPT #3:

Spidercam-style tethered LiDAR

- A four-point anchor system consisting of two tethers, connected to the anchors diagonally.
- Allows planar motion that is capable of covering large areas at once.
- Varying slack exerted by the anchor points and motors mounted in the housing package of LiDAR allows for motion along the tethers.
- Motor encoder information from the motors in the package and on the anchor points used to localize the device across the tethers.
- Motion in all three axes can be obtained adjusting the slack of the two ropes.
- Drawing for concept is found in Appendix Section 1, figure 1.3

CONCEPT #4:

3D printed single-pass tethered LiDAR with non-adjustable mechanism

- A two-point anchor system with a single tether connected across it.
- The LiDAR mounted on a package that is 3D printed in order to traverse across the rope.
- Package will consist of motors to traverse between two anchor points.
- Motor encoder information from the motors in the package used to localize the device across the tethers along with an internal measuring unit.
- Altitude sensors embedded to account for slack on the rope and improve localization of the device.
- LiDAR mounted on the bottom of the housing package, with the scanner rotating perpendicular to the ground.
- Entire body 3D printed using ABS plastic.
- Drawing for concept is found in Appendix Section 1, figure 1.4

CONCEPT #5:

Machined single-pass tethered LiDAR with adjustable mechanism

- A two-point anchor system with a single tether connected across it.
- The LiDAR mounted on a package that is manufactured using traditional manufacturing methods in order to traverse across the rope.
- Package will consist of motors in order to traverse between two anchor points.
- Motor encoder information from the motors in the package used to localize the device across the tethers along with an internal measuring unit.
- Altitude sensors embedded to account for slack on the rope and improve localization of the device.
- LiDAR mounted on the bottom of the housing package, with the scanner rotating perpendicular to the ground.

- Body composed of Aluminum 6061
  - Reduced chance of degradation under extreme weather conditions
  - Added structural integrity
- Driving mechanism adjustable to change fit of rope through driving elements, to further account for slack.
- Drawing for concept is found in Appendix Section 1, figure 1.5

PUGH MATRIX OF CONCEPTS

Evaluation Criteria:

1. Ease of Use: How easy is it for the customer to use the mobile system?
2. Ease of Manufacturing: How much time and effort will the manufacturing of this system require?
3. Ease of Post-Processing: After data from LiDAR is collected, how easy would it be to generate the map from the collected data sets?
4. Accuracy: How accurate will the produced model be with respect to the actual environment?
5. Ease of Setup: How easy will it be for the customer to setup the mobile system on the site of use?
6. Cost: How expensive will it be to manufacture the mobile system?
7. Ease of Localization: How easy will it be to accurately localize the sensor?
8. Structural stability: How mechanically robust and sturdy is the assembly?

The criteria are assigned a number based on the list of criteria given above.

	Hand Held LiDAR Scan: (Baseline)	Drone Mounted LiDAR:	Spider-Cam Tethered LiDAR	3D printed Single Pass:	Machined single Pass:
1	**0**	-	+	+	+
2	**0**	-	- -	-	-
3	**0**	**0**	+	+	+
4	**0**	**0**	+	+	+
5	**0**	+	- -	-	-
6	**0**	-	-	-	-
7	**0**	+	++	+	+
8	**0**	-	**0**	**0**	+
TOTAL	**0**	**-2**	**0**	**1**	**2**

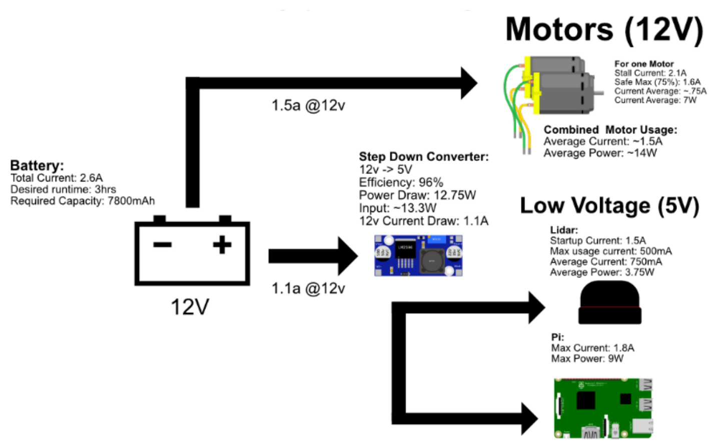
FINAL DESIGN CHOICE

Based on the Pugh Selection Matrix and mechanical analysis, which will be discussed further in following sections, it was decided to use the machined single pass design. Following that, team LiDAR's initial proposed solution was to employ a drone with a mounted LiDAR, to make a continuous sweep of the area, as per the user's input. However, this solution was not ideal, given the spatial and environmental constraints of the area, which would result in under-utilization of the drone's maximum capacity.

CANARY's current model was selected as the top contender, given its highest point value in the Pugh Matrix, as well as having the load support that the next best option, the 3D printed CANARY, did not offer. Compared to the material strength of PLA, which has a modulus of elasticity (E) of between 2.7 – 16 GPa, Al-6061 offered a more reliable strength under the weight load of the package and tension across the rope it would be traversing on. The choice to choose Al 6061 is evident from the finite element analysis conducted on the idler, which bears the brunt of the weight of the assembly (Appendix figure 2.3). With a max stress of 9.7 MPa, Al-6061 is a much safer choice than PLA, which has an modulus of elasticity of 2.7-16 GPa, whereas Al 6061 has a modulus of elasticity of 68.9 GPa. The aluminum will be much better at handling repeat loading as compared to a 3D printed alternative.

Furthermore, the machined elements of CANARY would reduce the need to replace parts more frequently, which reduces replacement costs and efforts.

ENERGY BUDGET



Moreover, the final design also satisfied CANARY's energy budget, which in turn was governed by factors such as weight, ease of transportation, and charging capacity. In cases where CANARY is to scan an expansive region to produce a topographic map, the power sources needs to sustain the energy demand for the entire duration of the scan, without producing the need to be recharged or replaced. To satisfy the energy demands stipulated in the energy budget (link to budget), the most economical solution to the energy supply is to employ the usage of Lithium Ion Batteries (LiPo), specifically two 3P, 12 V Lithium Ion batteries connected in series. Given the weight to charge ratio, recharging capability, and conservative size, the current version of CANARY can hold up to two LiPos during its flight. This is a rapid upgrade form the usage of heavy and spatially restrictive Lead Acid batteries or employing a portable generator, which is what would be needed for design 1 and 3, for example.

MECHANICAL ANALYSIS

The mechanical design of the package that would support the LiDAR and traverse the tether was designed under very clear restrictions. On top of the specifications that dictated the structure and mass of the system, the necessity to traverse the rope in a continuous manner required designs that would ensure no slipping between the motor and the rope. The initial designs consisted of pulley configurations seen in figure 2.1 and 2.2. For the first design, the angle for which the rope made contact with the pulley was calculated as:

$$\theta_1 = 180^0\ x\ 2\ +\ 60^0\ x\ 2\ =\ 480^0 = 8\pi/3\ radians$$

From the belt friction equation given in the following equation,

$$\frac{T_2}{T_1} = e^{\mu_s \theta} \tag{1}$$

Where T_2/T_1 is the ratio of the tension across the rope, μ_s is the static coefficient of friction and θ is the angle that is wrapped around the pulley. For the first configuration, seen in figure 2.1, the ratio of the tension amplification can be calculated as

$$(\frac{T_2}{T_1})_1 =\ e^{\mu_s \theta_1} =\ 4.349e + 03$$

Where the coefficient of static friction is assumed to be 1 for no slipping. For the second configuration, the angle for which the rope made contact with the pulleys could be approximated as

$$\theta_2 = 90 + 90 + 180 = 360 = 2\pi\ radians$$

Following the same calculation as equation 1,

$$(\frac{T_2}{T_1})_2 =\ e^{\mu_s \theta_2} =\ 535.49$$

Even though between the two configurations, there was a large decrease in the tension required to move the rope, $(\frac{T_2}{T_1})_2$ was still too large of a ratio to find a motor to supply the necessary torque for. In ensuing tests of the two configurations, the group saw that the friction between the ropes could not support continuous motion and lead to absolute slippage between the rope and pulley.

Inspired by systems that also consist of feeding ropes across a motorized pulley, the next design consisted of a simple idler-driver system. This design, shown in figure 1.4b, consisted of a driver capable grabbing onto the rope, which would ensure a lack of slippage, and an idler to press down the rope and guide the rope to the driver. Ensuing tests using a simple gearmotor proved the system to be viable, and motor and mass specifications were chosen around such a design that dictated the motor torque not to carry amplified tension, but simple loads dictated by pulley ratios and the mass of the system.

The following design steps included the packaging of all required hardware for the LiDAR to operate. The package was to compactly house the multiple PCBs used for the computing and controlling, the battery and the motors. For this, a multiple layer design was drawn, where the electronics, gears and batteries could be separated on separate plates. A rough sketch of this design can be seen in figure 1.5 a,b. A crucial step taken in this design was the use of bevel gears, eliminating the off-axis load on the motors and translating the rotational motion of the shaft from the y-axis to the x axis. This meant that the load torque (T_L) on the motor would simply be dictated by the tension across the rope and the diameter of the driving gear, as the 1:1 gear ratio of the bevel gears would eliminate the torque requirement of it:

$$\mathrm{T}_L =\ T * \left(\frac{D_3}{2}\right)$$

Where T is the tension across the rope and D_3 is the diameter of the driver. From a finite element analysis conducted on the rope under the distributed load of its mass and the 3 kg mass of the package (see figure 3.2 under Appendix) the maximum tension was found to be 487.58 N. Assuming the worst case and plugging in the value for D_3 = 40.2 mm, the load torque on the motor is given as 9.8 N-m.

$$\mathrm{T}_m = (\mathrm{T}_L + \mathrm{T}_a)\ x\ n \tag{2}$$

Equation 2 gives the torque required by a motor to operate in a certain system. As the load torque was calculated, the acceleration torque, T_a, was to be calculated. The calculation of the acceleration torque requires the acceleration time, which from tests and datasheets were not accessible for the motors in question. In order to compensate for the acceleration torque, which relative to the load torque is very minimal, a factor of safety, n, of 1.5 was given. Under these constraints, a motor that could transmit 14.7 N-m was required. The motors finally selected were two 99:1 gear ratio brushed DC gearmotor that transmit 8.83 N-m each and 17.66 N-m in total, comfortably meeting the requirement.

One issue that team LIDAR encountered was the difficulty in producing an accurate representation of the tethered rope, with the appropriate constraints and weight distribution. Initially, this problem was considered to be a standard statics problem (figure 2.5 in Appendix), given the simple load distribution and point loading on a rope. Though this simplistic modelling gave team LiDAR a good starting point, there were still difficulties in understanding the slack mechanism that would inevitably arise in the rope, which proved to be more than just a fundamental statics problem. This representation was crucial for determining the supports necessary for a rope of 100m to be lined across the two anchor points. A simple FEM was created for this purpose. Modeling the rope with its geometric properties, material being

Nylon with an 8 mm diameter, and assuming the material to be fully constrained at supports, a maximum displacement of 6.03 meters occurs. This FEM was constructed using a 3D mesh with a 100-mesh size. Figures from the finite element analysis can be seen in the Appendix, labeled figure 2.4.

The dimensioning of CANARY was crucial in order to develop a compact and lightweight packaging system. As seen in the exploded view of the final design, there are many parts, most of which have critical dimensions for the operation CANARY. One of the most important dimensions was the placement of the entire driving mechanism on the top plate. This mechanism, which consists of two L-plates, the idler, the driving gear and ball bearings, not only dictates the center of mass of the entire system but is crucial to allow the rope to traverse through the package. An issue that arose while making the designs was that there were too many critical dimensions that dictated the placement of the mechanism. The hole placement of the L-bracket connecting the driver-idler mechanism to the top plate was important for the positioning, but the standoffs connecting the two L-brackets also dictated this placement as well. The presence of two critical dimensions would contribute to major manufacturing issues and high tolerance values. In order to deal with this, a simple slot was made on the L-bracket instead of a single hole, which allowed the placement of the mechanism to adjust, while the critical dimension that was the distance between the two plates remained constant throughout from the standoffs in between.

MANUFACTURING

As discussed in earlier sections, CANARY can be 3D printed, and still perform competitively with the aluminum model. However, given the most immediate application of this system in Ghana, where temperatures reach up to 40^0C, the use of plastic would introduce issues with rapid degradation, which would only be addressed by replacing the parts frequently. As an alternative, the assembly was made from standard Aluminum 6061, which was machined in the Rettner Machine shop.

The primary material used in the manufacturing of the CANARY was Aluminum 6061, given its great strength to weight ratio, ease of manufacturing, and ease of purchasing. 15 out of 20 parts were manufactured by the members of Team LiDAR using traditional manufacturing methods, because of the simplistic design of the assembly. Moreover, this method was also the most economical, as no extra costs associated with outsourcing were incurred to the team.

CANARY was developed over the course of nearly four months, or approximately 90 working days. Approximately 75 of these working days were dedicated to design and concepting of the system, including both the design of the physical mechanism, as well as software and electronics development. The total system can be estimated to cost around $774, given the cost of the raw material, electronics, and LiDAR. Regarding the cost of the manpower, the total cost of hiring team LiDAR would amount to $26,770, based of a collective 2677 working hours used by team LiDAR to design and produce CANARY. A more detailed breakdown of the additional purchasing costs can be seen in the Appendix, labelled figure 5.1.

In order to improve scalability, the primary change that can be made is a customized PCB for the purpose of CANARY. This PCB, including the computing, motor driving and the various other sensor setups, could significantly shorten the wiring process and the size restrictions that come with wiring large numbers of components together. This will significantly cut down on manufacturing time.

TEST PLAN AND RESULTS

Each of the specifications are required to go through their individual test. These tests were set up in an outdoors environment, at the Eastman Quad. Two trees were used as anchors for the tether and a length of 10 meters was available to be traversed across. Images from the test can be see in Section 5 of the Appendix and the scan results can be seen as well.

1. *Scanner must have a minimum range of 12 meters:*
   The testing for this specification is primarily dictated by the sensor which will complete the scans. The sensor for the scanning, rp-LIDAR A2M6, has a listed range of 18 m. In order to pass this test, a simple scan in an area where known objects were beyond 12 meters was made. The test was completed during the outdoor testing where objects at above 12 meters were read.

2. *Integrated system must be able to produce a model of a 100 m x 100 m area:*
   This test primarily required the mechanical components of CANARY to produce results over a 10000 m^2 area. For this, the test requirement was met by proving scalability and fatigue of CANARY to last over such an area. This was done by making multiple passes over a 10 m rope and observing performance and material deterioration. From the 10 passes made over a 10 m rope, there were no material or electronic deterioration. This yielded this specification to be met with.

3. *Raw scans must have resolution of 0.5m at 12m min. range:*
   This test, similar to the first, was again heavily dependent on the sensor being used. From the specifications supplied about the rp-LIDAR A2M6, resolution can go down to an angular measurement of 0.9^o and a linear measurement of 0.5 mm. This was again tested from the scans. The distance between the two different points was the best indicator for the scans resolution. With the measurements at x mm, this test had satisfied the specification.

4. *Must be able to complete 100 x 100m scan on a battery pack less than 100 W-hrs (TSA):*

For this purpose, team LiDAR was unable to derive a feasible testing plan to test this specification, as testing CANARY over a 100m x 100m was logistically and physically challenging given the limited testing time frame and scope of spatial needs for such a test. Initially, the testing plan was to identify the discharge of the batter after 10 m of run and scale it. However, battery charging and discharging are not linear activities; scaling would therefore produce inaccurate results.

5. *TSA protocols require that the sum of dimensions of system cannot exceed 62" (1.5748 m):*
   In order to satisfy this requirement, a simple measurement of the dimensions of the package was completed. A dimension of 0.192 m x 0.185 m x 0.120 m measurements yielded a success for this specification.

6. *Must weigh less than 50 lbs. (22.6796 kg):*
   A simple measurement of the weight on a scale yielded the package weight to be 2.4 kg – satisfying the specification.

Description	Method of Evaluation	Status
scanner must have a minimum range of 12 meters	perform initial test with a static model and analyze data.	PASSED
integrated system must be able to produce a model of a 100 x 100 m area	test mechanism prototype on a test area of 100 x 100 m	PASSED
raw scans must have resolution of 0.5m at 12m min. range	compare dimensions of a mapped feature to known features	PASSED
Must be able to complete 100 x 100m scan on a battery pack less than 100 W-hrs (TSA)	voltage*amp-hrs	UNDETERMINED
TSA protocols require that the sum of dimensions of system cannot exceed 62" (1.5748 m)	measure dimensions	PASSED
must weigh less than 50 lbs. (22.6796 kg)	measure weight	PASSED

SOFTWARE AND ELECTRONICS

CANARY has multiple components that collect or transmit data that are crucial for the functionality of the system. Each of these components are called the "nodes" of the software architecture. In order to communicate the data between the nodes, a communication protocol was implemented. Although generally Robotic Operating Software (ROS) is used for such applications, this OS was too heavy for the Raspberry Pi. Instead, the internodal communication was completed through a protocol called Lightweight Communication Protocol (LCM). Through this protocol, information such as the LiDAR data could be used in the viewer for the user to observe the scans in live time.

The tethered system was primarily supported by a static climbing rope. This separated CANARY from typical tethered robots, which through the use of the tether typically can connect to a constant power supply and transmit data. On top of the internodal communication, it was necessary to transmit data over the air, through wireless communication protocols. For this purpose, a 433Mhz radio telemetry module was used. The ground module of the telemetry system is connected to the controlling laptop via USB and the air module is connected to the UART interface on the Pi. The controller software allows the user is to send high level commands such as "start or stop scan" over the radio bridge to the robot which will interpret them appropriately. In addition, some of the data will be transmitted back to the controller laptop to verify that the scan is working; however, not all data will be sent given the volume of data and high scanning frequency. Instead, the majority of the data will be logged to the Pi.

The computational core of the CANARY is a Raspberry Pi 3 B+ running Ubuntu Mate 18.04. Ubuntu was used instead of the more traditional Raspbian OS to satisfy the requirements for some of the software dependencies. ROS Melodic was installed and used to install Point Cloud Library (PCL) which is used as the backbone for both data storage and post-processing. The data is stored by the robot as a '.pcd' file which is the PCL proprietary file format for storing point cloud data. The data from each scan can be combined using the PCL Registration API for feature-based registration. This system uses a SIFT (Scale Invariant Feature Transform) based method which determines the appropriate transformation between two clouds by detecting keypoints and matching them based on local feature descriptors. SIFT is obviously scale invariant and very robust to affine transformations between images and datasets making it a very powerful tool for registration. After all the scans have been merged, the combined point cloud can be filtered into ground returns and object returns use the PCL Progressive Morphological Filter base on "A Progressive Morphological Filter for Removing Nonground Measurements from Airborn LIDAR Data" published by Zhang et al. in 2003. After tuning a few hyperparameters for the algorithm such as ground slope and initial distance, the post processor will output two clouds, one for ground returns and one for objects such as trees, buildings and whatever else might get between the lidar and the ground.

As discussed in the mechanical analysis section of this paper, CANARY is driven by two brushed DC gearmotors. In order to control the direction and speed of these motors, a dual H-bridge L298 motor controller was used. A step-down converter was also connected from the 3S LiPo to the Pi to regulate the voltage and sustain the energy budget that was discussed before. In order to keep track of the battery level of the LiPo, a MCP3002 Analog to Digital Converter (ADC) was used. This allowed for simple regulations of the battery throughout the scan.

Due to the large number of electric components and the overwhelming number of windings and wirings, a custom-made printed circuit board (PCB) was made. The schematics of this shield can be seen in figure 6.1. Through clear labeling and short connections, this PCB served as a shield to the Pi. The many PCBs that were used in the operation and their wiring can be seen in section 6.

The software required to set up the CANARY and to present the data to the customers was too extensive to include in a single file. As improvements and debugging are always present in these types of projects, the link the GitHub will include all the software that is necessary for this project to run. All software written for this project can be viewed from these links:

- Code for user to run on their PC. This code is used for viewing the data collected by the LIDAR. Reading run instructions will allow user to start the scans and view them on a custom built frame:
  - https://github.com/agutier4/canary-console.git
- Code for the hardware. This repository includes software for starting communications between various sensors and actuators. Read build instructions:
  - https://github.com/agutier4/canary-SDK.git

INTELLECTUAL PROPERTY

CANARY does not make use of any novel or unique components that could make it eligible for a patent. The concept of using a LiDAR to produce topographic maps is not in any capacity an exclusive use of a LiDAR; organizations such as United States Interagency Elevation Inventory, National Ecology Observatory Network, and Unites State Geological Survey all employ LiDAR technology to produce a plethora of maps, many of which are open source and available to the consumer public [2].

The mechanical, and subsequent electronic components, might be eligible for filing a patent, given the unique assembly that constitutes the driving mechanism of CANARY. The use of off axis motors, knurled drivers, and an idler has not been observed in substantial industry and academia literature review, which is why CANARY has the potential to be a patented product.

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

The motivations for this project are to improve the current understanding of the history of Fort Amsterdam. The topographic map of the region will allow the archeological dig team to accurately unearth the ruins surrounding the fort. This will allow the researchers to study, and thus preserve, the heritage of these sites during these investigations.

CANARY was commissioned to produce the topographic map of a region non-invasively, that is, without the need to physically Heat or alter the region. The region surrounding fort Amsterdam, for example, support considerable foliage. CANARY enables researchers to produce the map of the region without having to clear excess foliage to produce an accurate map. This drastically reduces the impact of an archeological dig plan on the local environment and plant life, this producing an eco-friendly solution for the any future archeological expeditions.

RECCOMENDATIONS FOR FUTURE WORK

The next phase of design for CANARY will address independent mobility of the LiDAR, to allow it to move and rotate about its central axis, in order to scan a more expansive area. Not only will this allow for larger scans, it will improve the localization phase that is implemented in the post processing, as a virtue of possible repeat scans which enhances the ability of the team to utilizes SLAM localization. This, in turn, allows for more accurate estimation of CANARY's position. In addition, the implementation of a more sensitive altitude sensor will also prove helpful for post processing of data, as positioning of CANARY will be much more accurate in case of unexpected slack or slippage. Another solution for this issue can be to employ a gyroscope to allow the LiDAR to self-level/ orient itself to maintain any given position.

CANARY's ability to traverse across ropes with compromised tensioning can be enhanced by implementing a more reactive driving mechanism, which can accommodate a significant level of slack within the rope without slipping on the rope. This can be implemented by using a spring latched assembly.

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APPENDIX

Section 1: Concept Drawings

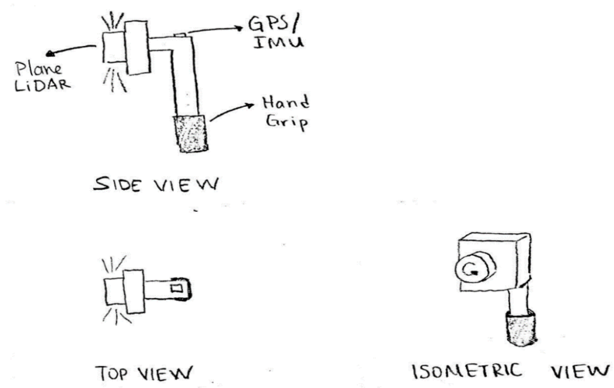


Figure 1.1: Handheld Scanner Isometric Drawing

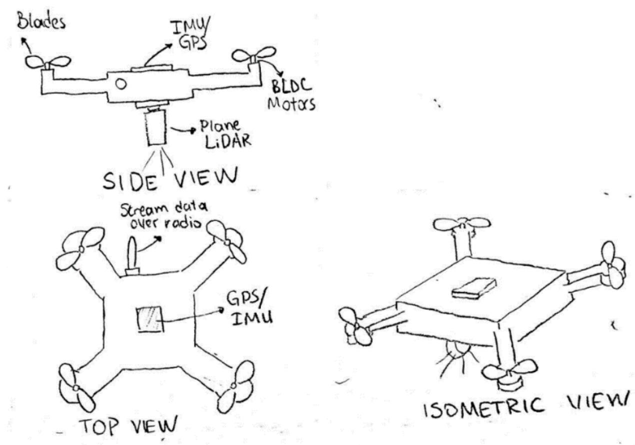


Figure 1.2: Drone Mounted LIDAR Isometric Drawing

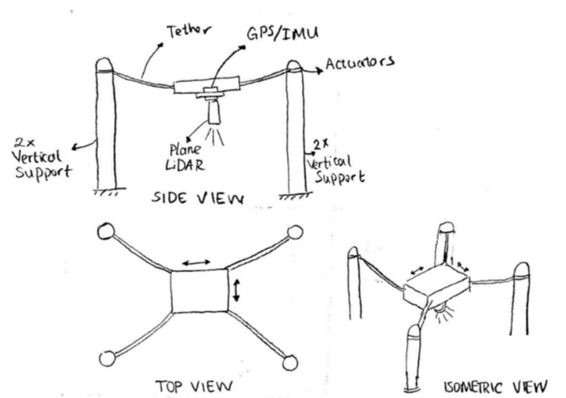


Figure 1.3: SpirderCam Style LIDAR Isometric Drawing

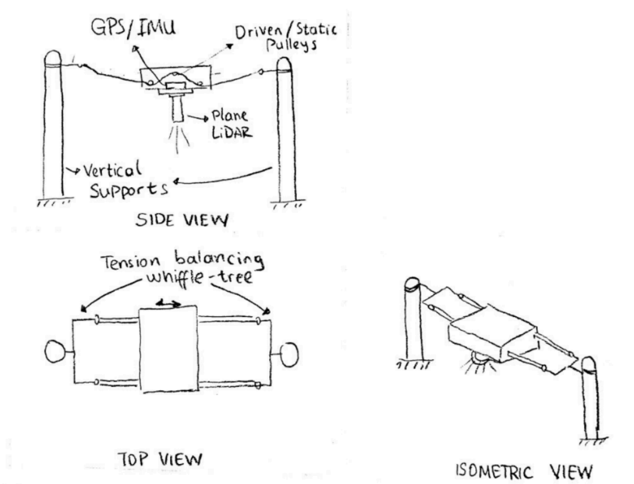


Figure 1.4 a: Single Tether LIDAR Isometric Drawing

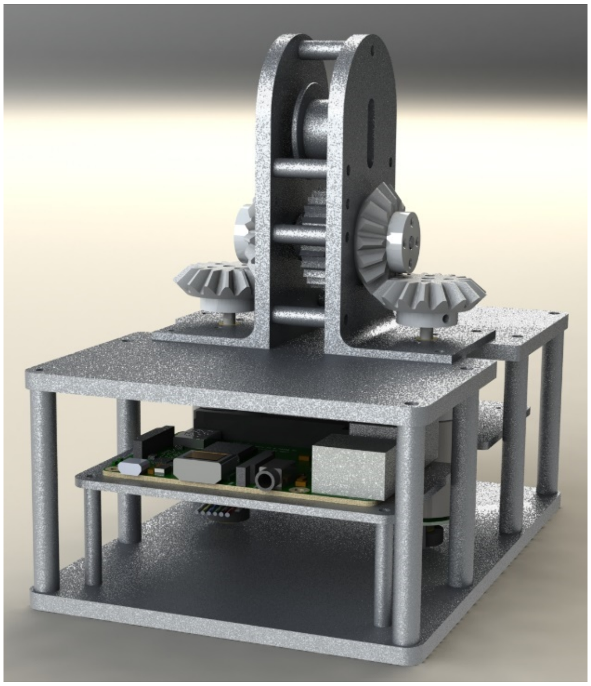


Figure 1.4 b: Single Tether LIDAR rendering

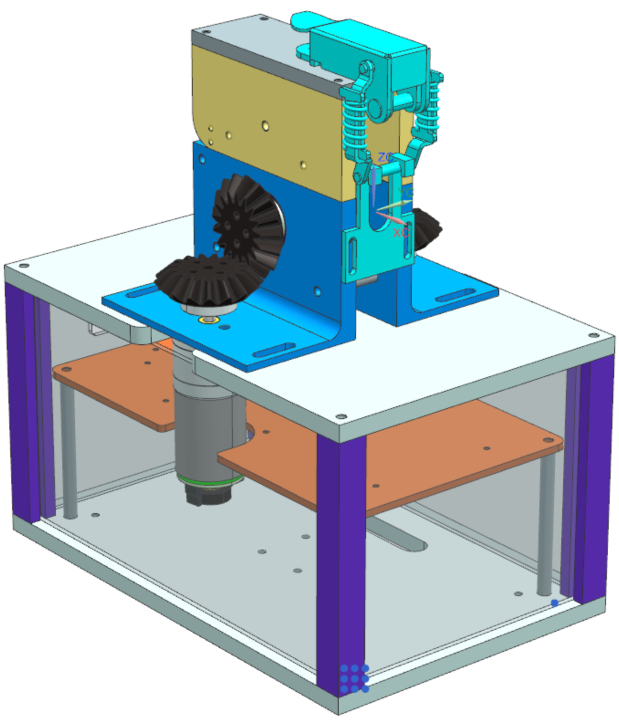


Figure 1.5 a: Single Tether LIDAR w/ reactive mechanism isometric rendering

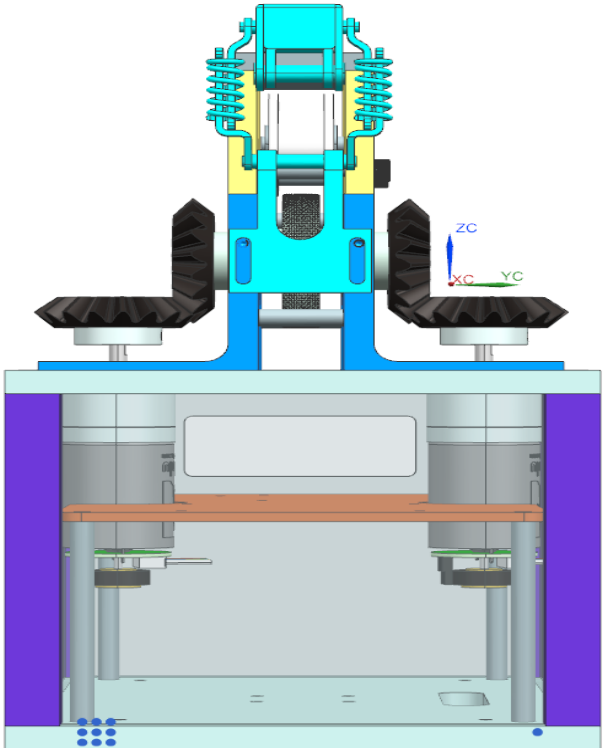


Figure 1.5 b: Single Tether LIDAR w/ reactive mechanism front view

Section 2: Mechanical Design Analysis

Figure 2.1: Pulley configuration for driving package

Figure 2.2: Pulley configuration

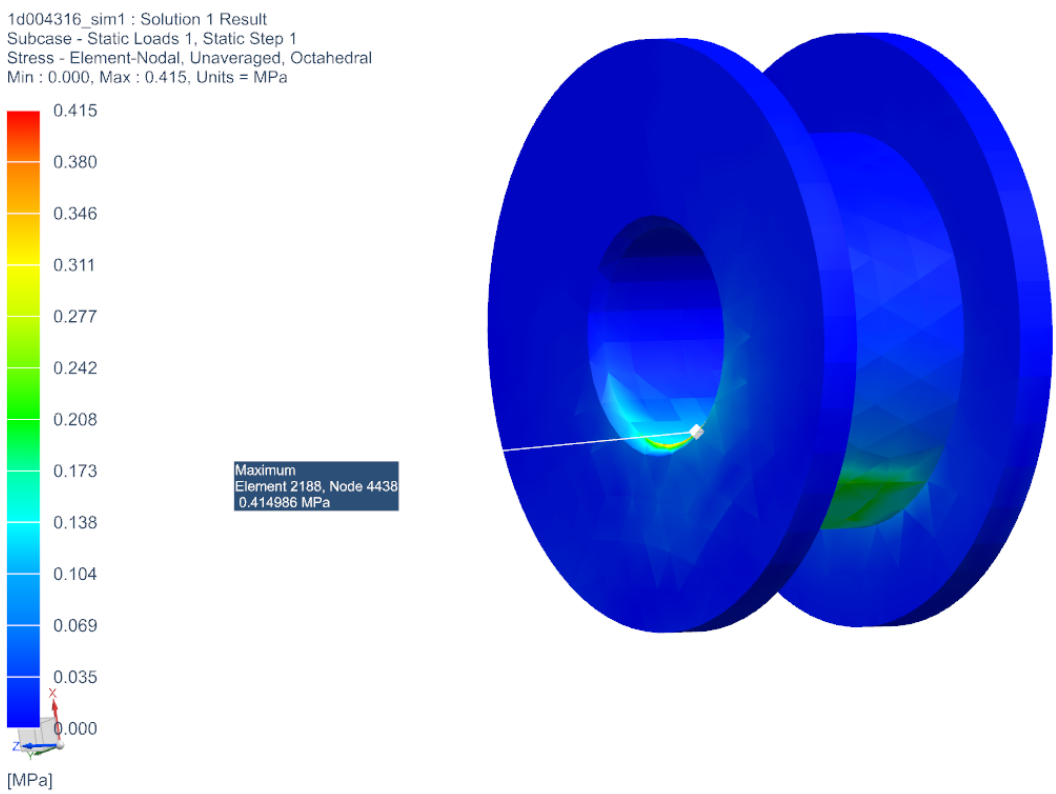


Figure 2.3 Finite Element Analysis of Idler

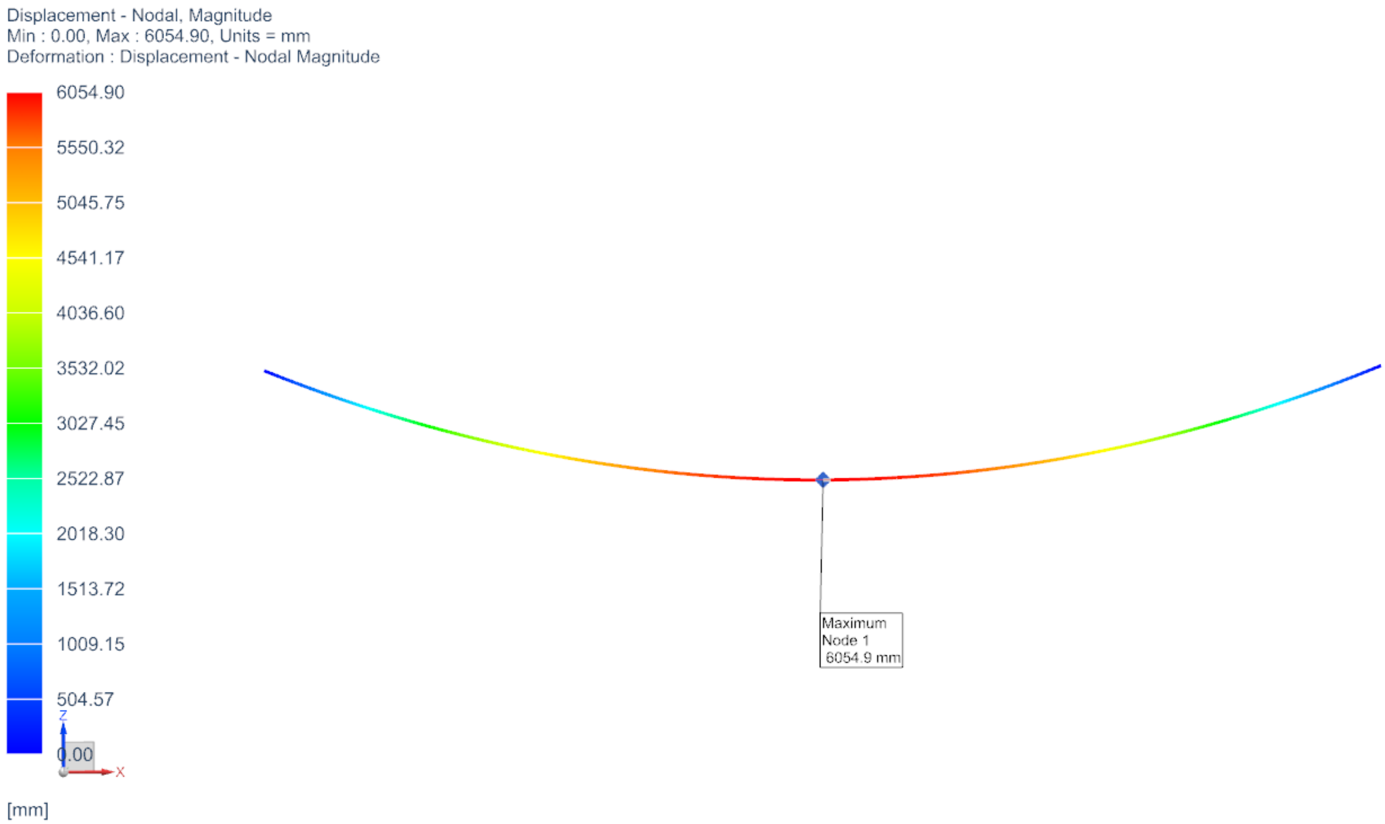


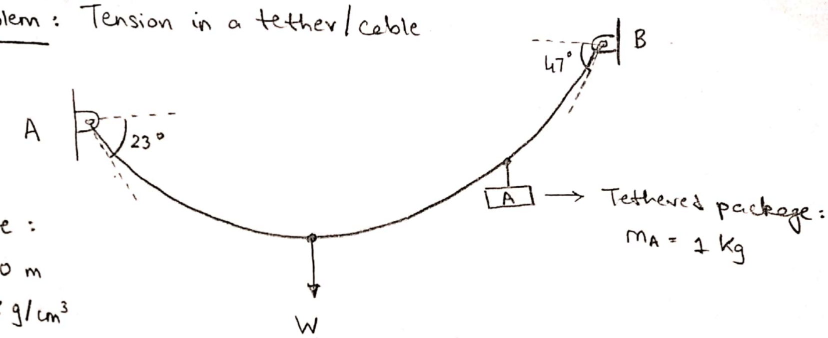
Figure 2.4 Finite Element Analysis of 100m of rope

STATICS PROBLEM

Our design consists of a rope that will be fixed between two anchor points, one elevated and one fixed to the ground. A small robot will be attached to the rope with a set of gears that generate friction allowing the robot to actuate across the rope. The system will be controlled by two dc motors controlled by a PI (proportional integral) control loop on a Raspberry Pi. A RPLiDAR laser rangefinder will be attached to the base of the housing which will take planar sweeps as the robot actuates across the rope. Point data will be stored on-board and transmitted to a laptop.

One issue we came across in our design was finding a way to generate enough friction on the rope to drive the robot without generating extremely high forces in our system. We originally wanted to keep the rope extremely tight and use that tension generate friction on a set of pulleys. After doing some fundamental statics analysis we realized that these forces would be unmanageable, so we settled on a much simpler strategy with lower working loads.

Statics Problem : Tension in a tether / cable



For the cable :

$l = 100$ m

$\rho = 1.38\ g/cm^3$

$d = 8$ mm

(circular cross section)

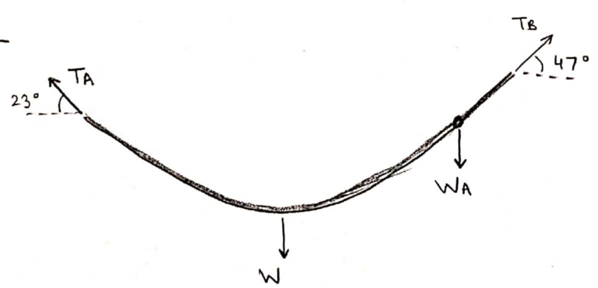
(a) Draw Free Body Diagram of the cable.

(b) Determine tension at A & B

(c) What is the tension in the cable at its lowest point ?

Answers

(a)



(b) $\Sigma F_x = 0 \Rightarrow -T_A \cos 23° + T_B \cos 47° = 0$

$\Sigma F_y = 0 \Rightarrow T_A \sin 23° + T_B \sin 47° - W - W_A = 0$

Here, $W = mg = \rho A l g = \rho (0.25\pi d^2)(l)(9.81)$

$= 1.38\ g/cm^3 \times 10^3 \frac{kg/g}{m^3/cm^3} \times 0.25\pi (8 \times 10^{-3})^2 \times 100 \times 9.81$

$= 68.05$ N

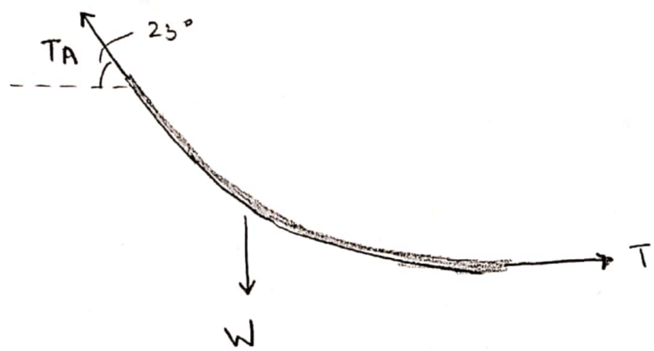
$W_A = 1 \times g = 9.81$ N

Solving,

$$T_A = 56.51 \text{ N}$$

$$T_B = 76.27 \text{ N}$$

(c)



At lowest point, $\Sigma F_x = 0$

$$-T_A \cos 23^\circ + T = 0$$

$$T = T_A \cos 23^\circ$$

$$= 52.02 \text{ N}$$

Figure 2.5 statics problem

Section 3: Manufacturing

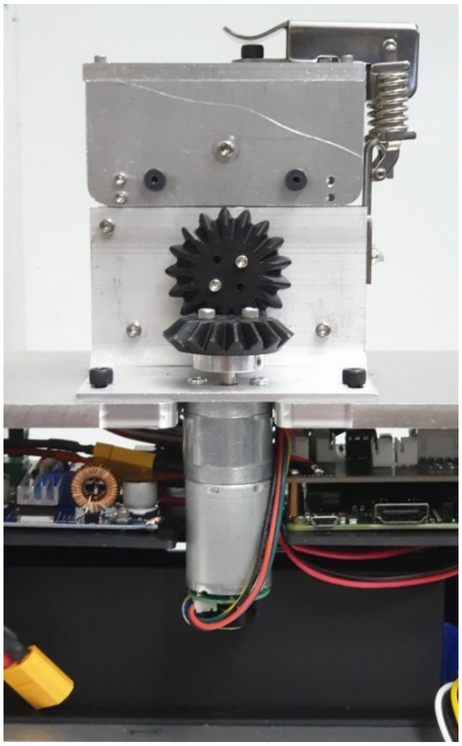


Figure 3.1: Side view of final assembly

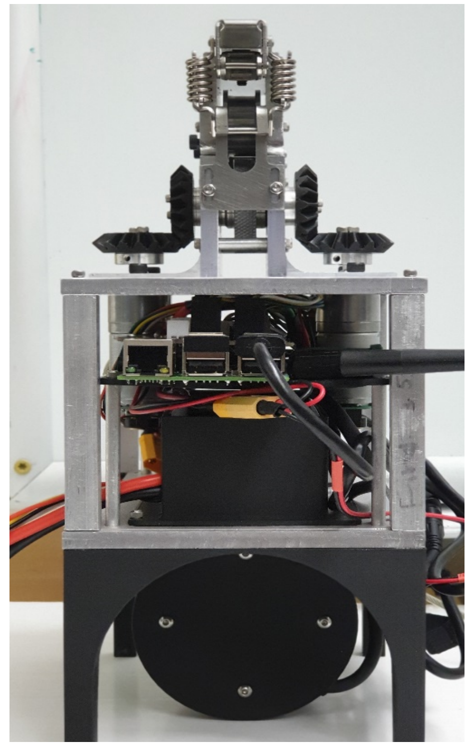


Figure 3.2: Front view of final assembly

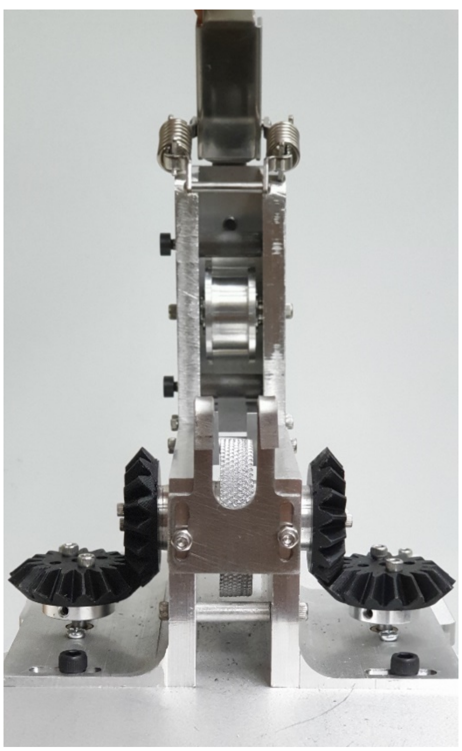


Figure 3.3: Open view of final assembly

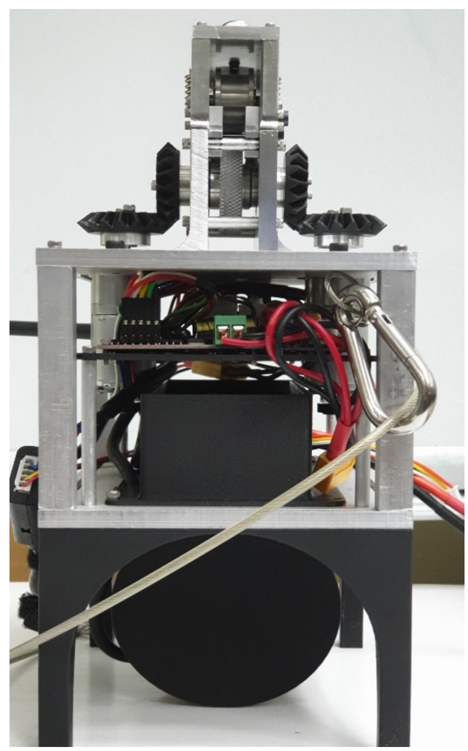


Figure 3.4: Back view of final assembly

Section 4: Testing

Figure 4.1: Testing area

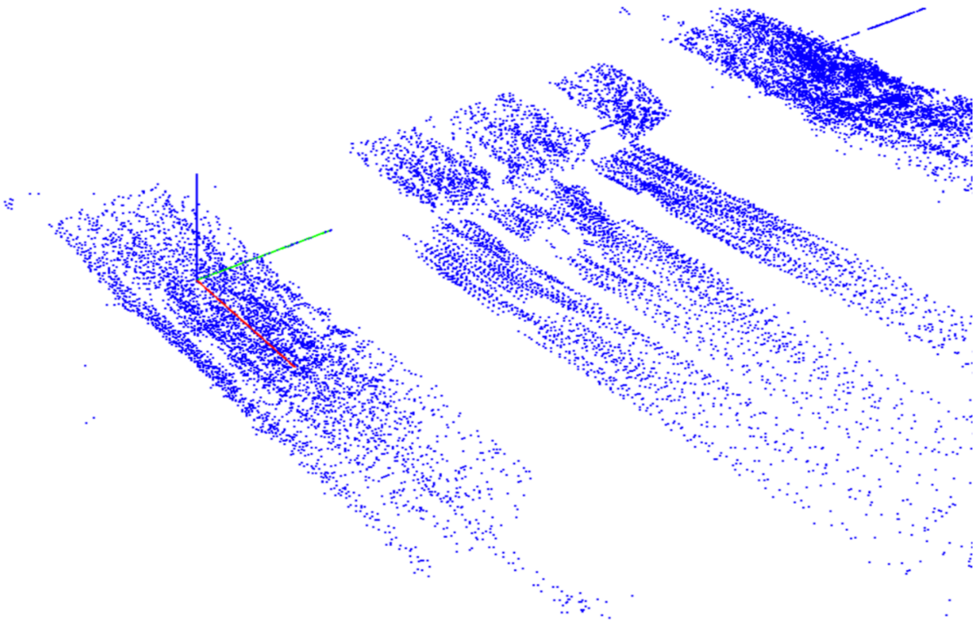


Figure 4.2: LiDAR scan of the Bausch and Lomb testing location

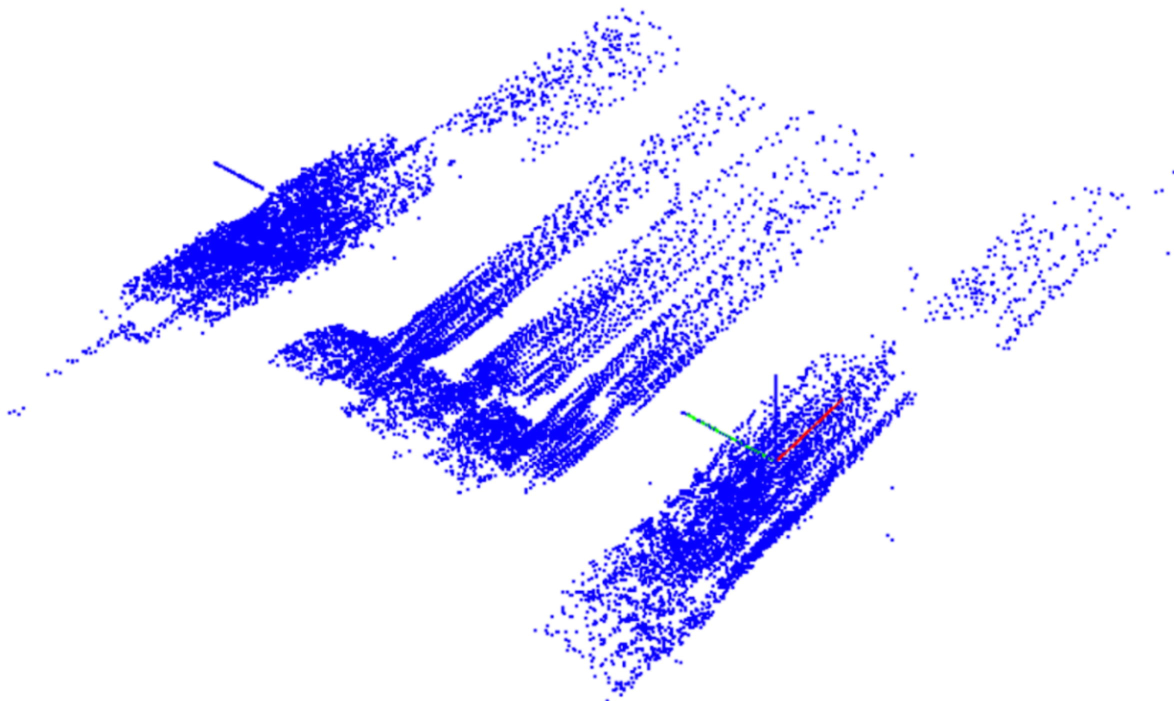


Figure 4.2b: LiDAR scan of test area

Section 5: Cost

Part/stock	Quantity	total
A2M6 360 LiDAR	1	$455.99
Pololu 99:1 metal gear motor	2	$69.90
Aluminum mounting hub	2	$6.95
17 mm ball bearings	2	$24.86
5mm ball bearing	2	$16.62
Corner latch	1	$22.50
Al 6061 stock	-	$25.34
Delrin stock	-	$4.10
bearings	2	$19
Lithium Ion batteries	3	$77.49
limit switch	20	$7.99
Radio wireless kit	1	$26.99
Dual H bridge	1	$16.99
Total		$774.58

Figure 5.1: List of equipment/material purchased, and subsequent cost

Section 6: Software and electronics

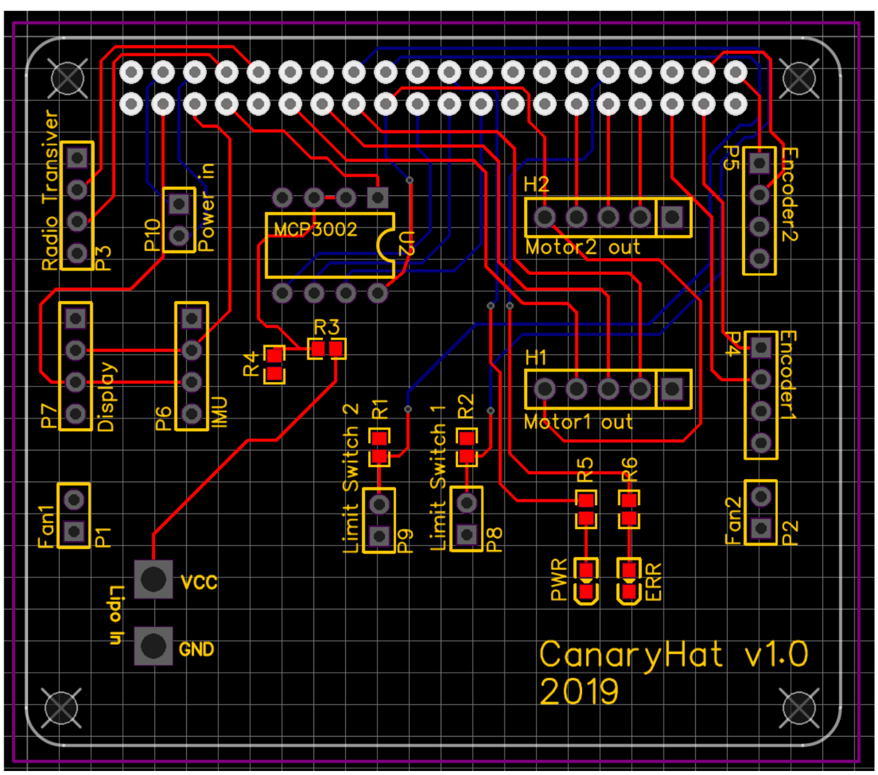


Figure 6.1: Shield for the Raspberry Pi

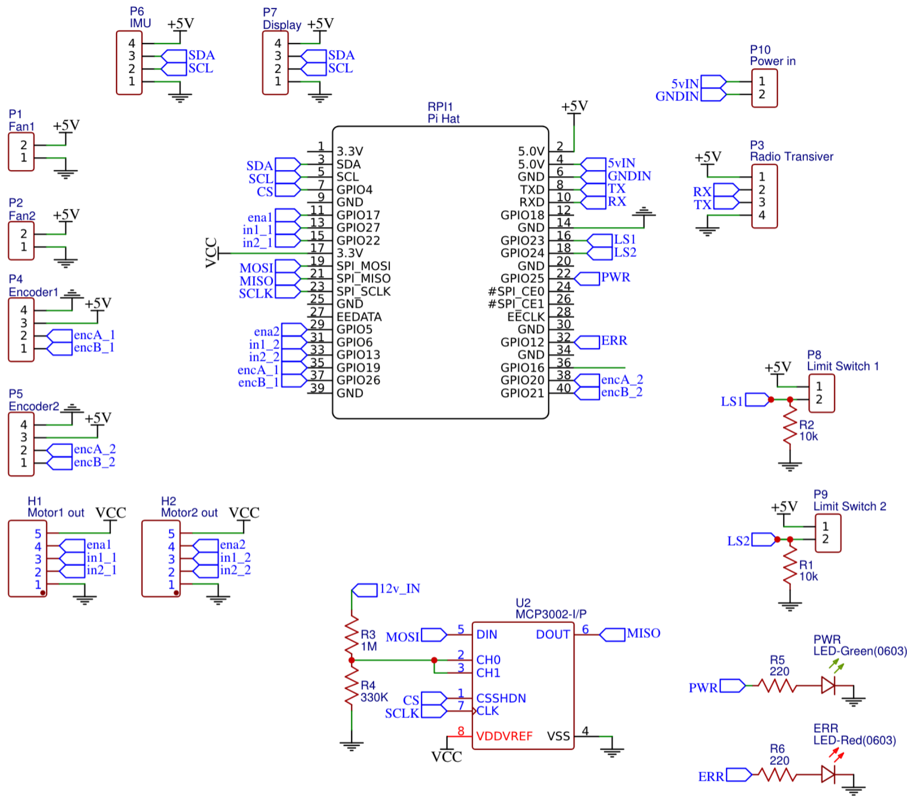


Figure 6.2: Schematics for all connections

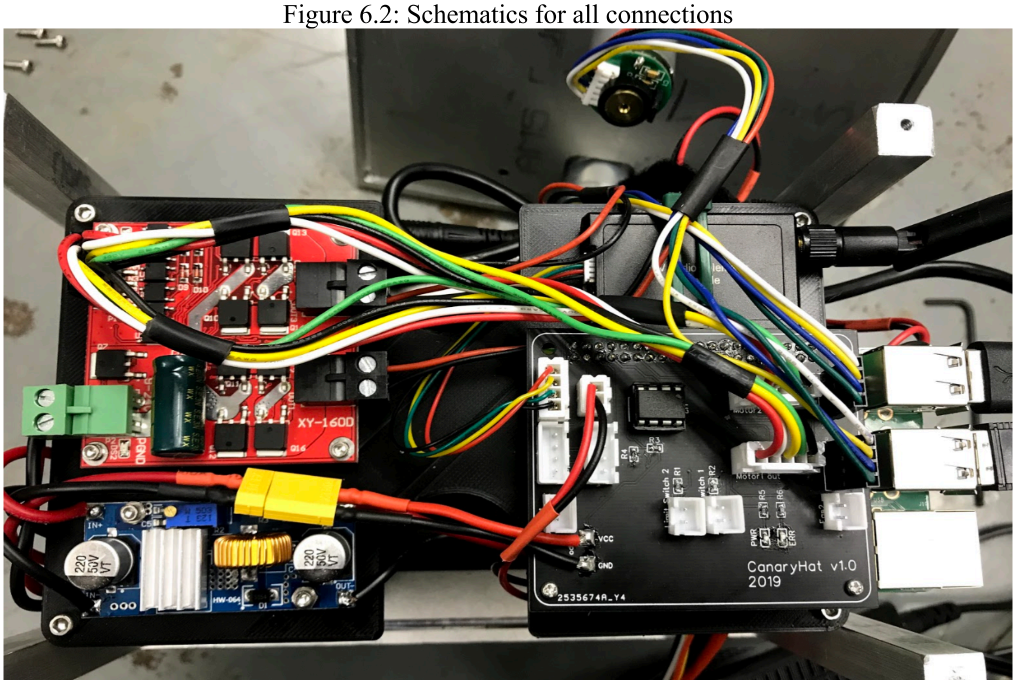


Figure 6.3: Connections on the electronics platform of CANARY