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

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# Project ODDITY

## Optimal Descent Device for In-Situ Turbulence analYsis

Project Final Report

Monday, May 3rd, 2021

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## Acronyms

**CFD** Computational Fluid Dynamics.

**CONOPS** Concept of Operations.

**COTS** Commercial Off the Shelf.

**CP** Cost Plan.

**CPC** Communications, Power, and Control.

**CPE** Critical Project Element.

**FBD** Functional Block Diagram.

**FR** Functional Requirement.

**HYFLITS** Hypersonic Flight In the Turbulent Stratosphere.

**OC** Organizational Chart.

**ODDITY** Optimal Descent Device for In-Situ Turbulence AnalYsis.

**PAB** Projects Advisory Board.

**WBS** Work Breakdown Structure.

**WP** Work Plan.

# 1 Project Purpose

Authors: Alexander Larson, Anders Olsen

The Hypersonic Flight In the Turbulent Stratosphere (HYFLITS) program here at CU has been conducting high altitude turbulence data collection with the use of high altitude weather balloons. In order to collect this data, the sensor package (or as it will be called in this paper, the gondola) needs to collect data in air that is unperturbed by the large canopy of the balloon. As the gondola is suspended 10m below the balloon neck, the balloon must be descending in order to collect this turbulence data properly. In order to achieve this descent, helium must be removed from the balloon, which changes the buoyancy forces acting on the balloon, thus altering its trajectory. Currently, a legacy valve and servo system is being used to facilitate this helium withdrawal. However this method relies on the pressure forces exerted by the balloon canopy on the helium bubble that is naturally formed at the top of the balloon. These pressure forces become too weak to push helium out of the balloon once it undergoes plastic deformation due to the low pressures and large overall radius seen at the highest target altitude of 40km. In order to allow the balloon and gondola payload to reliably see the entire altitude range that the project targets (between 20 and 40 km) the project team will be developing a new venting system that will actively remove helium from the balloon. This will be done in such a way that the balloon will descend at a rate between 2 and 10 m/s at any altitude up to 40 KM, which enables proper data collection by the sensor payload on board the gondola. Successful data collection will be beneficial to the development of hypersonic aircraft, which would fly at the high altitudes that our project aims to investigate. Specifically this turbulence data could aid in wing shape and airfoil design, thermal design, and/or the design of the overall plane shape and the efficiency optimization for such hypersonic vehicles.

# 2 Project Objectives and Functional Requirements

Authors: Anders Olsen, Alexander Larson

## 2.1 Measures of Success

ODDITY is a project that may seem relatively small and simple from a high level overview, however the complexity of this project can be found in the design requirements imposed on the group by the customer and the extreme environment in which it must both survive and operate. For starters, the ODDITY system cannot exceed 300g, in order to sustain a proper force balance on the weather balloon throughout it's mission. Secondly the system is limited to a budget of $200 for each unit, as a new unit is needed before every test flight. This is due to the mission's end-of-life implementation; where both the balloon and ODDITY are are meant to be disposable (more on this later when the CONOPS are addressed). These mass and budget restrictions alone significantly limit the design space in which the group can work, and creates quite the challenge when trying to find a robust and efficient solution for the customer. The following table illustrates other thresholds of success that were developed by the team in conjunction with customer given requirements:

| | Descent Control | Balloon Attachment | Communications | Survivability |
|---|---|---|---|---|
| Level 1 | System is able to extract helium from balloon in conditions similar to those at 35km | ODDITY is able to attach to a 5cm neck diameter Kaymont balloon prior to being filled | ODDITY shares communication link with the Gondola via XBee radio | ODDITY is able to withstand pressures and temperatures similar to those seen at 35km |
| Level 2 | ODDITY and Gondola will match legacy system performance in flight testing (35km altitude) | ODDITY is able to be installed on 8cm neck diameter Hwoyee balloons prior to being filled | ODDITY is able to receive data and commands from the Gondola | ODDITY is able to survive the temperatures and pressures seen at 35km |
| Level 3 | ODDITY and Gondola are able to reach a target apogee of 40km | | ODDITY is able to transmit data to the Gondola | ODDITY is able to survive the temperatures and pressures seen at 40km |

Figure 1: Levels of Success for Project ODDITY

Upon inspecting Fig. 1, one can see that the group's measures of success have been divided into 4 areas which correspond to sub-systems and critical project elements (CPEs) that have been identified. The "Altitude Control", "Balloon Attachment", "Communications" and "Suvivability" categories correspond to the descent control, neck attachment hardware, control power and communications, and thermal control sub-systems respectively. These categories are further divided into different levels of success with which to measure the group's project success and final outcome. The Level 1, or base level of success, correspond to the minimum requirements that we must meet with an ODDITY prototype, these can also be tested and verified without requiring a test flight. This was an important level as it represents the minimum the ODDITY project must accomplish to prove successful, while also not requiring a flight test for validation; as a flight test could not be guaranteed at the outset of this project. Level 2 requirements speak to the more effective and ideal capabilities of an ODDITY unit, and some of the more significant features the customer would like to see in the final product. This level also requires that the ODDITY can survive conditions along the entire target trajectory, and prepares the unit for the third and final level of success. This third and final level includes the complex features and capabilities the customer would ideally like to see, and additionally implies/requires one or several flight tests to ensure an ODDITY can function in its intended mission.

| | Descent Control | Balloon Attachment | Communications | Survivability |
|---|---|---|---|---|
| Level 1 | System is able to extract helium from balloon in conditions similar to those at 35km | ODDITY is able to attach to a 5cm neck diameter Kaymont balloon prior to being filled | ODDITY shares communication link with the Gondola via XBee radio | ODDITY is able to withstand pressures and temperatures similar to those seen at 35km |
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| Level 3 | ODDITY and Gondola are able to reach a target apogee of 40km | | ODDITY is able to transmit data to the Gondola | ODDITY is able to survive the temperatures and pressures seen at 40km |

Figure 2: Achieved Levels of Success for Project ODDITY

After thorough testing and evaluation of ODDITY and its subsystems, the group was able to achieve the Levels of Success highlighted in Fig. 2. This figure shows that Project ODDITY met all Level 1 requirements meaning it achieved all of the minimum requirements set forward by the group and the customer. This was important because it did not require a test flight to happen to achieve these. Despite having achieved this, the group pressed on and tried to meet other levels of success as well. These other achieved levels of success were done through performing two flight tests with ODDITY to test its in flight performance. Through this testing, ODDITY was able to match and even exceed legacy Descent Control performance from 35km in altitude, achieving Level 2. This was measured by assessing the descent rate of the balloon versus its altitude as will be discussed more in the testing section of the report. The Level 2 level of success for Survivability was also met in the test flights because ODDITY showed that it was able to survive the extreme temperatures and pressures seen at high altitudes and remain functional.

The group was not able to perform a test flight that achieved 40km in altitude due to time constraints and budgetary constraints. This caused the group to not reach the Level 3 levels of success for Descent Control and Survivability. Despite this, the group is confident both are possible and will be able to be achieved by the HYFLITS team here at CU Boulder. The Level 2 level of success for balloon attachment is also within reach, however, as the project progressed, it was made clear to the group that this was not as important to the customer as the other success criteria.

In order to visualize the groups' project and overall purpose in the research mission, a Concept of Operations (CONOPS) has been developed which gives a high level overview of the various project elements. This CONOPS can be seen below as Fig. 3.

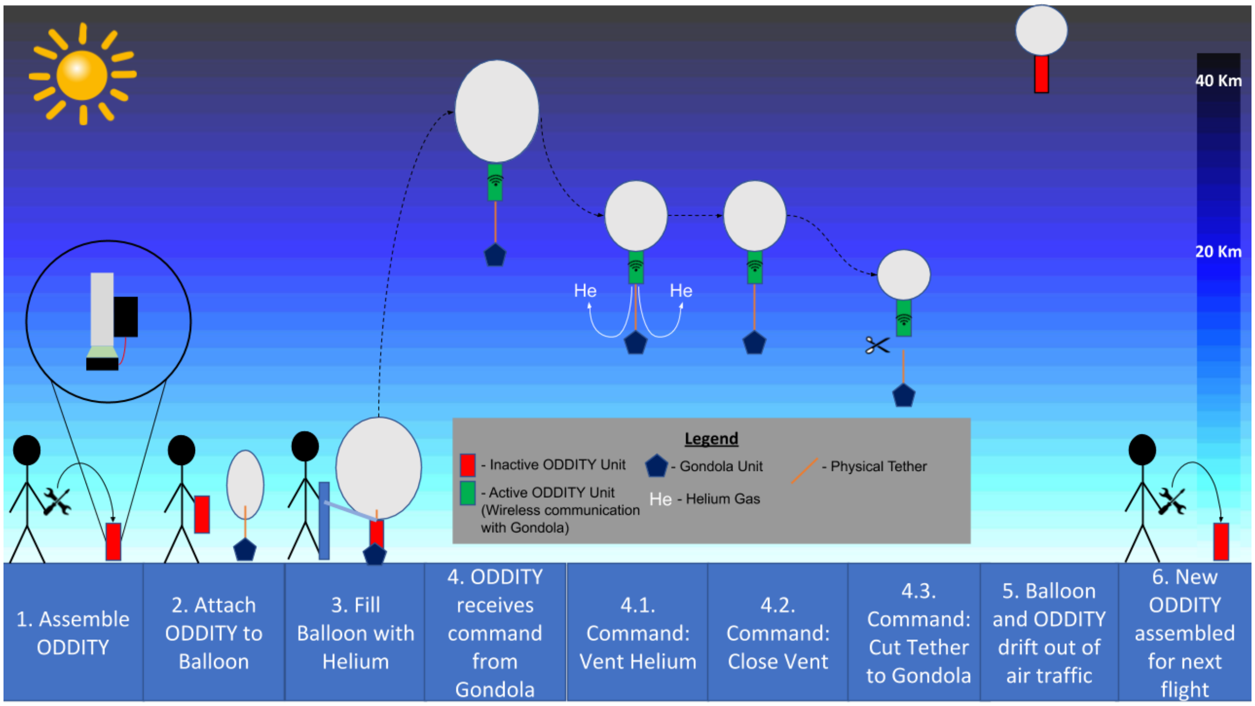


Figure 3: Concept of Operations (CONOPS) for project ODDITY

The overall operation of project ODDITY, shown in Figure 3 above, is fairly straight forward from a high level view. Once an ODDITY unit has been assembled for flight, a user will attach it to the balloon and fill the balloon up with the necessary helium. After this, the balloon, ODDITY, and gondola are launched, and the gondola will begin sending commands to the ODDITY based on GPS location and altitude. These commands will take the form of steps 4.1-4.3 on Figure 3. The close vent command in particular (4.2 in Figure 3) will also check against the desired vertical flight path during the ascent portion of the flight. If the balloon is estimated to fall short of the target apogee, the flow of helium will be sealed off by the valve in order to slow or cease upward deceleration. Once the balloon is descending the axial fan component of the descent control CPE will turn on and assist in active helium withdrawal from the balloon. The cut tether to gondola command (4.3 in Figure 3) will come when the balloon descends back down to around 20km, at which point all turbulence data will have been collected and the mission can come to an end. From here the gondola will float back down to Earth with the aid of a parachute while the balloon and ODDITY system drift up and away from any potential air traffic that it could be occupying. The last step is of course to begin repeating this process by building and assembling a new ODDITY unit for the next balloon flight.

## 2.2 Critical Project Elements

***CPE-1*** *RF Communications and Controls System*:

The system shall be capable of 2-way wireless communication with the gondola. The system will also read commands sent by the gondola and output those commands to the other on-board systems as necessary.

***CPE-2*** *Descent Control System*:

The system shall provide some means to control balloon descent, such that a descent rate between 2m/s and 10m/s can be maintained. This descent rate is to allow the sensor payload to be within its operating range of vertical velocities.

***CPE-3*** *Neck Attachment System*:

The system shall have a neck attachment such that it is capable of securely interfacing with multiple brands of high altitude balloon.

***CPE-4** Insulation and Heating System*:

The system shall include thermal control measures to ensure system reliability throughout the range of expected altitudes/conditions.

***CPE-5** Gondola Cut-Away System*:

The system shall be able to cut the balloon away from the gondola for safety at the end of the mission.

## 2.3 Functional Block Diagram

One can get a more detailed and in depth look into the design of ODDITY by inspecting the Functional Block Diagram (FBD) that has been produced by the team.

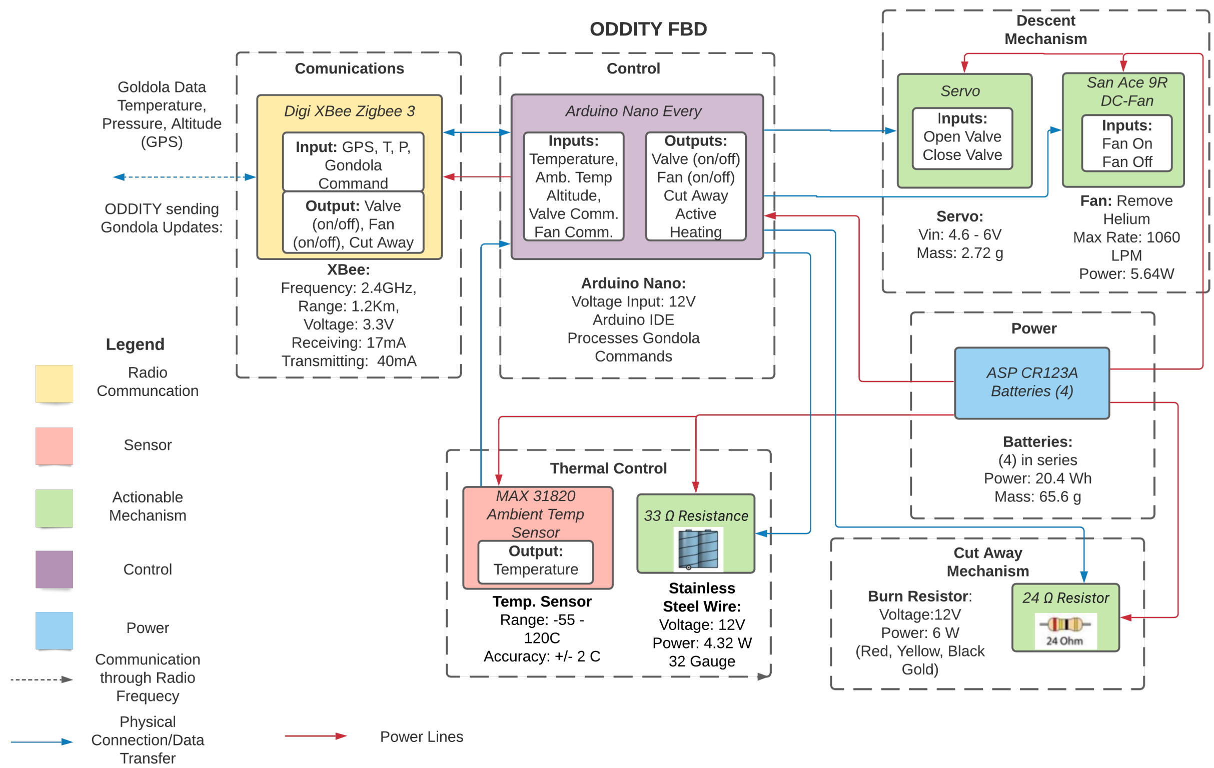


Figure 4: Functional Block Diagram for Project ODDITY

As can be observed above, Figure 4 offers a detailed look into the ODDITY design, in addition to the components that the group plans on using for manufacturing a prototype. This FBD divides ODDITY's subsystems and shows both the flow of power and communication between all components. Specific components are named at the top of each component block, and below that, one can find specifications and details of each of these components. There are some important things to note that Figure 4 does not state explicitly. The first of which being that the ASP CR123A batteries that will be used on ODDITY have a voltage output of 3V each. So in series, the ODDITY will have 12V total to use for all of its electronics on top of it's 20.4Wh equivalent capacity. The next thing to note is that the active thermal control (i.e. the stainless steel wire) will be switched on and off with the aid of an ambient temp sensor and a control law implemented on the Arduino Nano Every. The details of this active thermal control and thermal control law will be explained in more detail later in the Final Design section of this report. Finally, the resistors pictured in the block diagram are merely representative of the resistor color code the group will be using and are not pictured exactly in this figure.

### 2.4 Functional Requirements

The following is a list of Project ODDITY's Functional Requirements. Discussion on the sources and rational for each requirement will be presented, following the enumeration of all the requirements.

**FR 1.0:**

> The *descent control system (CPE-2)* shall achieve descent rates between 2m/s and 10m/s from the target altitude until the gondola is cut away.

Functional Requirement (FR) 1 is driven by the customer and is necessary for collecting proper turbulence data. The consideration stems from the resolution, measurement frequency, and calibration limitations of the turbulence probes utilized in the gondola sensor package.

**FR 2.0:**

> The *system (CPE-1,2,3,4,5)* shall survive until the gondola is cut away from the balloon.

FR 2 is driven by the extreme conditions that the balloon and ODDITY unit will see during the flight. The extreme cold in particular is a threat to the operable state of an ODDITY unit and therefore measures must be taken to ensure all temperature sensitive components will be operable during the flight.

**FR 3.0:**

> The *RF communications and control system (CPE-1)* shall have a communication link with the gondola and process gondola commands properly.

FR 3 ensures that the ODDITY system will be equipped with the proper hardware (i.e. radio chip and microcontroller) to be able to communicate with the gondola, as well as receive the various commands and process them correctly; by sending electrical signals to the corresponding sub-systems.

**FR 4.0:**

> The *system (CPE-1,2,3,4,5)* shall not interfere with the data gathering equipment.

FR 4 makes sure that the ODDITY is not designed in such a way that it would potentially interfere with data collection by the gondola sensor package. Accordingly, this functional requirement was considered throughout the design process and it will be shown that no components will pose any threat to the mission data.

**FR 5.0**

> The *system (CPE-1,2,3,4,5)* shall mount to the neck of a standard weather balloon.

FR 5 ensures that the design will include proper hardware that will allow the ODDITY unit to interface with the neck of the weather balloon. This is extremely important as if the ODDITY does not interface well with the balloon, then it is in danger of either detaching from the balloon mid flight or creating flow problems (for example, leakage) which could inhibit the helium withdrawal.

### 2.5 Project ODDITY Deliverable's

As the group nears the end of the project, numerous documentation presentations have been submitted and given to the Projects Advisory Board (PAB), including the Manufacturing Status Review (MSR), Test Readiness Review (TRR), Spring Final Review (SFR) and will be finishing off the project with the submission of this report, Project Final Report (PFR). With the conclusion of PFR, all deliverables for Spring of 2021 will have been completed and turned into the PAB for course grading. A separate deliverable will be handed over to the customer, Prof. Argrow and his HYFLITS team, as well. This will come in the form of an assembly guide clearly detailing how to manufacture and recreate an ODDITY unit for future test flights once the group is no longer involved with the project. The group will go over this document with the customer and make sure that everything is clear and repeatable for him and his team and then will leave the further use and development in their hands.

# 3 Final Design

Authors: Elliott McKee, Thania Ruiz, Marcus Bonilla, Steven Priddy, Corey LePine, Emily Riley

## 3.1 Descent Control

The descent control subsystem is the system what will handle any processes relating to the sealing/venting of the interior helium within the balloon canopy. This section will detail the requirements flowdown as it pertains to the Descent Control subsystem, followed by an overview of the final subsystem overall design.

The overarching requirement for this subsystem was **FR 1.0** given above, which specified that the system shall achieve balloon descent rates between 2m/s and 10m/s from the target altitude until the gondola is cut away. While there are other critical requirements that this subsystem must satisfy, the requirements flowdown for determining the detailed functional parameters of how to translate this descent rate into detailed design metrics was most complex for this requirement. As such, a significant portion of the following section will be dedicated to the requirements flowdown/determination for this descent rate requirement.

The additional requirements that this subsystem had to satisfy were; mass limitations, power draw limitations, and general mounting constraints. Total mass of the descent control team which consists of the servo, music wire, valve, diffuser, and fan, resulted in a total of 119g. The power draw from the descent control subgroup including the fan, servo and their respective resistors and MOSFET came out to be roughly 5.58 Wh.

The subsystem mass requirement for this subsystem was derived from the total subsystem mass requirement, as dictated by our customer. Specifically, the Descent control portion of the system was allocated an overall maximum mass allocation of 100g, or one third of the overall system mass. It was determined that, because the descent control subsystem was crucial in the removal of helium, that it should also have a relatively large portion of the overall mass budget.

It was also expected that the power requirements of the fan system would be one of the largest factors driving the overall design and sizing of the Communications, Power, and Control (CPC) subsystem; specifically with regard to battery sizing. The CPC subsystem had its own requirements with regard to mass, which dictated the maximum amount of batteries, and thus available power, for the fan system to use. From analysis of previous flight data, as well as additional balloon dynamics modelling, which is discussed in more detail in later sections, it was possible to determine the expected amount of time that the fan is expected to be on for. Knowing this, as well as the expected current draw of all the other necessary electronic components, it was then possible to put an overall current draw requirement for the entirety of the descent control subsystem.

Finally, from a functional standpoint, the system must be able to seal helium within in the balloon, in order to attain a nominal ascent trajectory. Furthermore, this system must also be able to actuated on and off throughout the flight, in order to help the balloon maintain a desired trajectory.

In the design portion of the ODDITY system design, many options were considered in terms of the primary helium removal device. Using the requirements above, a trade study was performed to select the axial fan, which is used in the final design, as the overall descent control actuator. More details on the descent control system trade study can be found in the ODDITY Fall Final Report [1].

### 3.1.1 Balloon Dynamics Modelling

Balloon Dynamics modelling was performed by the ODDITY team in order to help refine specific requirements for not just the descent control subsystem, but for many of ODDITY's subsystems. This allowed for a more holistic understanding of how long components are going to be powered for, the determination of flow rate requirements, and more.

To this end, a numerical simulation was developed to predict the balloon's trajectory and to explore different design options, and their overall effect on the flight path of the balloon. While this was a relatively straight forward simulation, a few notable assumptions were made. The first and arguably most important assumption was that there is no vertical wind. While previous experimental results provided by the HYFLITS team were affected by wind, critical locations in the trajectory were not meaningfully altered by varying wind effects.

Another major assumption is that all atmospheric values are taken from the standard atmosphere tables [2]. This is reasonably accurate because these balloons will only be sent up when the weather is fair, making standard atmosphere a reasonable assumption.

The last major assumption is that the drag on the balloon is approximated as a sphere. While this is a reasonably accurate assumption upon balloon ascent, it is not as accurate on the descent. Once the balloon has been fully stretched, and then returned to slack volume, the balloon will more resemble a plastic bag, with a helium bubble in the top, as opposed to a sphere.

To ensure that the assumptions in the model were accurate, a test trajectory was created to emulate the experimental balloon flight data that the group received from the HYFLITS team. Here the experimental Ascent Rate vs. Altitude plots are plotted on top of one another, alongside the results from ODDITY's balloon flight dynamics simulation.

We see relatively low discrepancy between the theoretical model and the experimental tests, especially with regard to high level performance trends, which shows that the assumptions are reasonably accurate for this scenario. Because of the ideal nature of the balloon, the simulation, shown in black, consistently outperforms the experimental data.

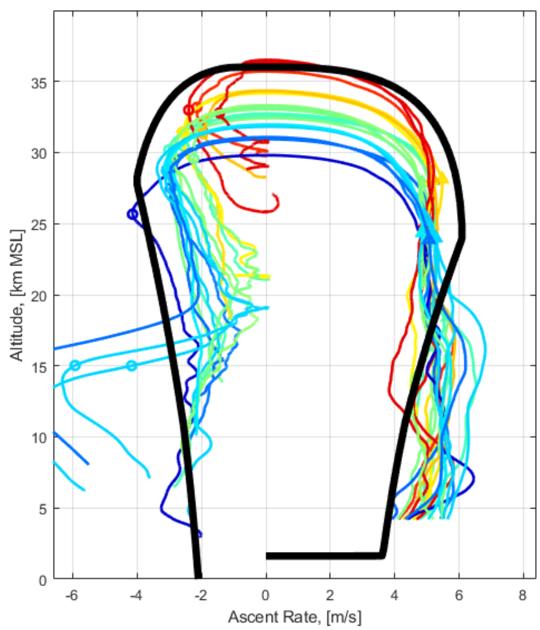


Figure 5: Experimental Altitude vs. Velocity Data with Simulation Result (Black)

### 3.1.2 Flowrate Requirements Flowdown

From the above modelling, it was found that the dynamics of the balloon in the vertical direction could be entirely controlled by the helium flow rate out of the balloon. Using this knowledge, a helium flow rate out of the balloon was computed in order to maintain a descent velocity of 2 m/s. Figure 6 below shows the required flow rate of helium needed to maintain a descent velocity of 2 m/s from 40km to 20km. It can be seen that the maximum volumetric flow rate our system needs to achieve is 100 LPM, which occurs at 40 km in altitude.

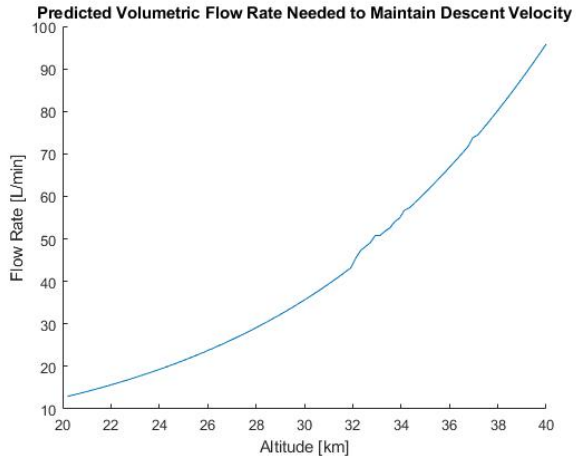


Figure 6: Required Volumetric Flow Rate to 2 m/s Maintain Descent Velocity

the results given in Fig. 6 were utilized in order to determine the high level flowrate requirements for the descent control subsystem. Because the system is able to be turned on and off at will, throughout the flight, the above plot in Fig. 6 simply shows the flowrate that the descent control subsystem must be able to exceed at any altitude.

It was expected, and confirmed through experimentation, that the fan flowrate performance was going to degrade with altitude; as the fan will be performing in off-design conditions.

Thus, we can simply enforce the requirement that **the fan flowrate must be in exceess of 100 LPM at 40KM in altitude,** in order to ensure at least a 2 m/s descent rate at any point throughout flight.

#### 3.1.3 Descent Control Final Design

The Descent Control system is the system that facilitates/controls the rate of Helium removed from the balloon canopy. A diagram highlighting the final design of the Descent Control components of ODDITY is given in Fig. 8 below. This subsystem includes a COTS 60mm axial cooling fan, attached to the bottom of the balloon neck attachment tube via a 3D printed diffuser, to provide an active means of removing helium in flight. Additionally, it also includes a valve, which forms a seal within the balloon attachment tube, along the collar of the 3D printed diffuser, in order to seal helium within the balloon, when desired. This valve can be actuated by means of a servo, attached to the side of the balloon neck attachment tube. This servo, when actuated, rotates the valve, which releases the seal between the interior of the balloon neck attachment tube and the surrounding atmosphere, allowing for helium to be vented.

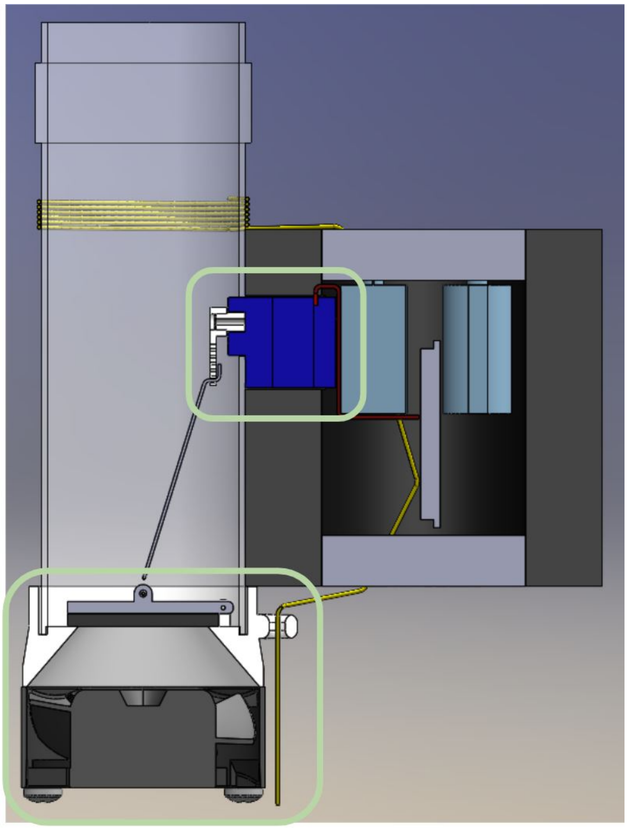

Figure 7: Descent Control Subsystem Elements

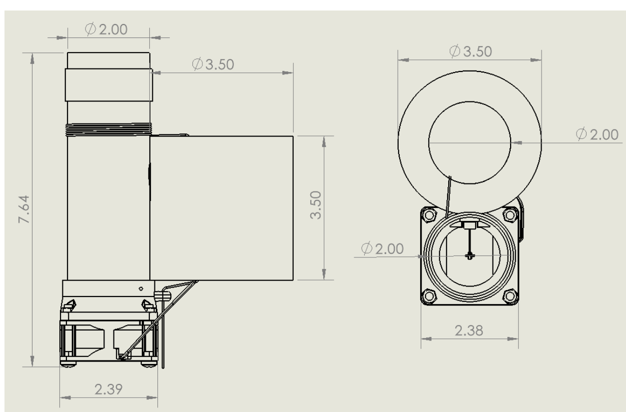


Figure 8: Dimensioned Drawing of Descent Control in Inches

## 3.2 Communications, Power, and Control

The CPC subsystem is driven by **FR 2.0** and **FR 3.0**, which relate to the survivability of ODDITY during flight as well having a communication link with the gondola, respectively. To ensure that the system survives and communicates with the gondola, the power budget and electrical layout were the most important part of the physical side of this subsystem. Below is the power budget for ODDITY.

| Component | Nominal Voltage [V] | Nominal Current [A] | Time ON [h] | Power [W] | Power Loss [W] | Power Consumption [Wh] |
|---|---|---|---|---|---|---|
| Descent Control | | | | | | |
| Fan | 12.0000 | 0.4700 | 0.6900 | 5.6400 | 1.4100 | 3.8916 |
| Fan Resistor | 3.3000 | 0.0132 | 0.6900 | 0.0436 | ~ | 0.0301 |
| Fan MOSFET | - | - | 0.6900 | 0.0169 | 0.0169 | 0.0117 |
| Servo | 3.3000 | 0.1000 | 5.0000 | 0.3300 | ~ | 1.6500 |
| BC Subtotal | | | | 6.0305 | 1.4269 | 5.5833 |
| Thermo Control | | | | | | |
| Active Thermal Wire | 12.0000 | 0.1250 | 4.0000 | 1.5000 | 1.5000 | 6.0000 |
| Thermal MOSFET | - | - | 4.0000 | 0.0045 | 0.0045 | 0.0180 |
| Temp Sensor | 3.3000 | 0.0040 | 5.0000 | 0.0132 | ~ | 0.0660 |
| Temp Sensor Resistor | 3.3000 | 0.0007 | 5.0000 | 0.0023 | ~ | 0.0116 |
| Thermo Subtotal | | | | 1.5177 | 1.5045 | 6.0956 |
| Cutaway Mechanism | | | | | | |
| Cutaway Resistor | 12.0000 | 0.2500 | 0.0028 | 3.0000 | 3.0000 | 0.0083 |
| Cutaway MOSFET | - | - | 0.0028 | 0.0090 | 0.0090 | 0.0000 |
| Cutaway Subtotal | | | | 3.0090 | 3.0090 | 0.0084 |
| Command, Control, and Communications | | | | | | |
| Arduino Nano Every | 12.0000 | 0.0200 | 5.0000 | 0.2400 | 0.3840 | 1.2000 |
| XBee 3: Transmit | 3.3000 | 0.0400 | 1.5000 | 0.1320 | 0.0130 | 0.1980 |
| XBee 3: Receive | 3.3000 | 0.0200 | 4.0000 | 0.0660 | 0.0070 | 0.2640 |
| Voltage Divider | 12.0000 | 0.0003 | 5.0000 | 0.0036 | ~ | 0.0180 |
| C3 Subtotal | | | | 0.4380 | 0.4040 | 1.6800 |
| | | | | | | |
| | | | Total: | 10.9952 | 6.3444 | 13.3673 |
| | | | | | Total with FoS: | 16.0407 |
| | | | FoS | 1.2000 | Under/Over | 7.0327 |
| | | | Total Wh | 20.4000 | Under/Over with FoS | 4.3593 |

Figure 9: ODDITY Power Budget for 5 Hour Flight

The four batteries that are used for ODDITY are put in series that gives the whole system approximately 12V (despite being advertised as 3.3V). This series of batteries also give a max power consumption capability of 20.4 Wh. A standard flight can last between 4 and 6 hours, and so the power budget above was done for a flight of 5 hours (average time). Referring to the above power budget, it can be seen that ODDITY is in the green with and without a factor of safety (standard aerospace FoS of 1.2 was used) which means that the ODDITY system will last during a nominal flight (assuming batteries stay warm and the flight is not too long). It should be noted that the two subsystems that take up the most power from the batteries are the Descent control and Thermo control subsystems. This makes sense, since the heating wire from the Thermo control subsystem must keep ODDITY warm and also because the fan draws the most active current.

The electrical layout of ODDITY is shown below.

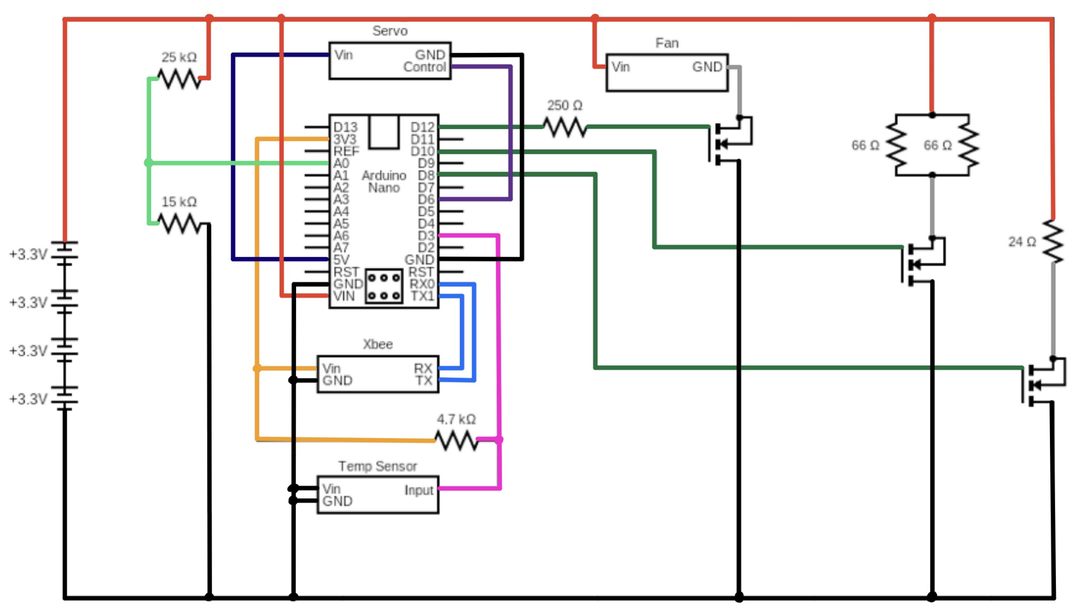


Figure 10: ODDITY Electrical Schematic

From the above schematic, it can be seen that ODDITY essential has 5 parallel branches that run off of the batteries. The first branch contains the voltage divider of ODDITY which tracks the battery voltage during flight. The second branch powers the Arduino Nano Every which in-turn powers the servo, Xbee, temp sensor, and temp resistor. The third branch contains the fan and fan MOSFET. The fourth branch has the heating wires and heating MOSFET. It will be explained in further sections as to why the heating wire is split into two of its own branches. The last branch of the ODDITY circuit holds the cutaway resistor and MOSFET. Since the Arduino Nano Every is the microcontroller for ODDITY, it must control and actuate all other components of ODDITY based on gondola command packets and a thermal control law.

Using the above schematic and the PCB software maker Eagle, a PCB was designed for ODDITY. The designed PCB is shown below as an Eagle design and before and after integrating some electrical components. The integration procedure as well as a list of the components integrated onto the PCB can be found in section 4.2 of this report.

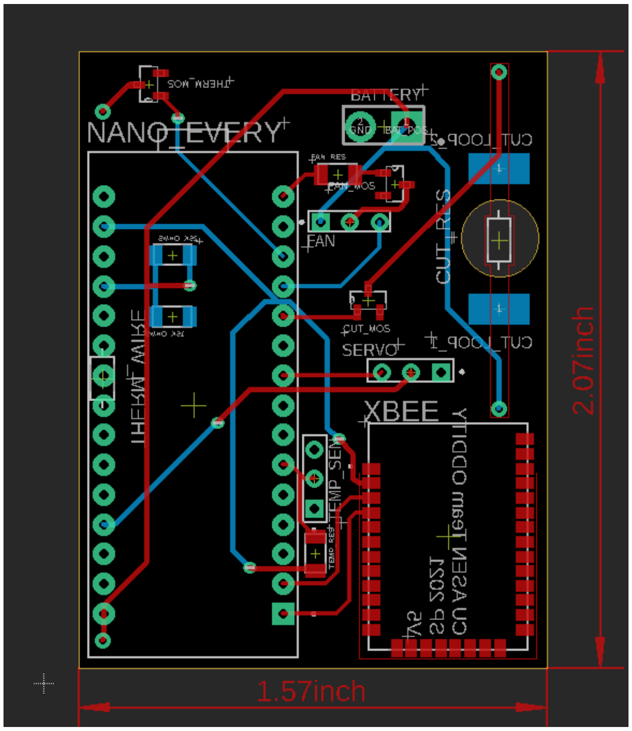


Figure 11: ODDITY PCB Design

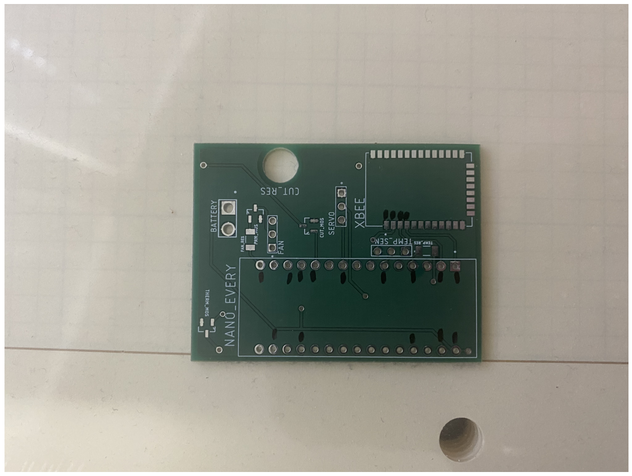


Figure 12: ODDITY PCB Before Integration

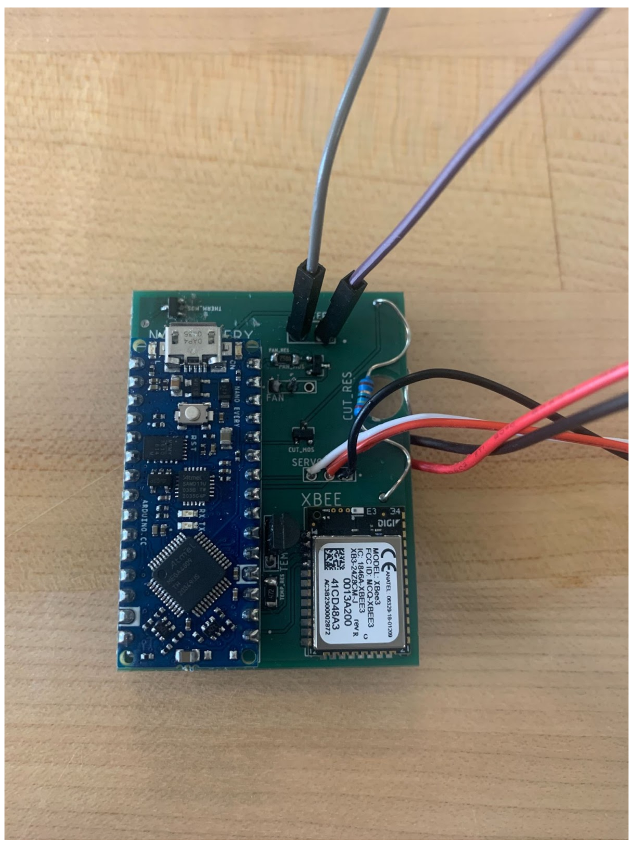


Figure 13: Integrated ODDITY PCB

## 3.3 Thermal Control

The thermal control subsystem is driven by **FR 2.0**, this requirement as stated above specifies that the system must survive until the gondola is cut away from the balloon. To ensure the survival of the system the main risk is the change in temperature as the system increases altitude. According to the U.S. Standard Atmosphere Air Properties Table[2], as altitude increases the air temperature decreases then increases with the lowest temperature at $-56.5°C$. In the design of the system it was noted that all components of ODDITY must survive these temperatures or design a system that allow the components to remain within nominal functional temperatures. Narrowing down the requirements for this subsystem, further research was done on each electronics component to determine the temperature range for survival and function. The most critical electronic components are the batteries, servo, and fan, which have a survival temperature range of -20°C to 60°C. In order to maintain a high voltage and long duration discharge rate from the batteries, it was determined that they should maintained at around 20°C. Temperatures below 10°C cause the discharge rate of the battery to drop off significantly as shown by the data-sheet[3] of the batteries chosen for ODDITY. The following sections outline the detailed design of the thermal control system and its ability to meet the requirements of system.

#### 3.3.1 Thermal Insulation

The insulation package that houses most of the electronic components will be constructed from polyethylene insulation, which is different than the one determined from the trade study as seen in Figure 50. The change in insulation was due to procurement issues and recommendations from Dr. Lawrence. This cylinder will have a height of 3.5 inches, inner diameter of 2 inches, and a wall thickness of $\frac{3}{4}$ inch. To maintain the temperature required by the battery, a combination of a stainless steel wire and temperature sensor will be employed, in order to maintain the internal temperature of the insulation at approximately 20°C.

#### 3.3.2 Thermal Active Heating

The heating system that will focus on maintaining the temperature of the batteries around 20°C consists of a ambient temperature sensor, heating wire, and thermally conductive tape. A 3 feet of 32 gauge stainless steel wire will be wrapped around each battery cell with a total of 10 loops as shown in Figures 14 and 15. This wire has a resistance of approximately 33 Ω and dissipates approximately 4.32 W of power. One layer of thermal tape is placed between the batteries and the wire and another layer is placed on top of the wire. Foam tape is stuck onto the face of each battery cell that rests against the PCB in order to prevent shorting. Finally, the leads of heating wire are wrapped in electrical tape. The heating wire is programmed to maintain temperatures between 18°C and 22°C.

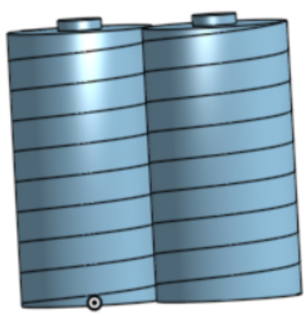

Figure 14: Stainless Steel Wire CAD

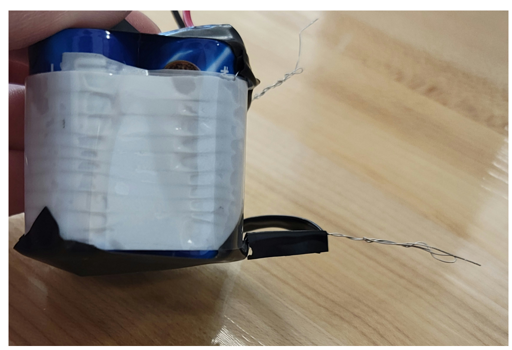

Figure 15: Stainless Steel Wire

### 3.4 Neck Attachment

The Neck attachment was a key part of the ODDITY system that interfaces all of the components together. It is attached to the balloon neck, holds the diffuser at the other end and on its side it has all of the insulation with the electronics. The final design of the Neck attachment was using a plastic CAB tube. This tube has a cross section of an outer diameter of 2in with a wall thickness of 1/32in. The length of this tube was reduced to 6in in height.

### 3.5 Cutaway Mechanism

The cutaway mechanism design was driven by **CPE-5** which specifies that the system shall be able to cut the balloon away from the gondola at the end of the mission. As mentioned previously, the target range of data collection is between 20 km and 40 km. Therefore, after the balloon descends below 20 km, there is no use in collecting any more data. At this time, the valve is closed and the tether connecting the gondola to the balloon is to be cut. This process results in the balloon rising until it bursts and the gondola package descending to ground with aid of a parachute. Having the balloon rise until burst is desired to ensure the balloon does not descend into restricted air space.

The cutaway mechanism utilizes a 24 Ω metal film resistor with a power rating of 1/4 Watts to enable the cut process. In order to cut the tether, 12 Volts is drawn across the resistor to exceed the power rating by around 6 Watts. When the resistor is over-powered, it acts as a heat source and burns through the tether.

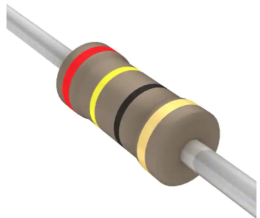

Figure 16: Cutaway Resistor

The cutaway mechanism consists of the 24 Ω resistor and a MOSFET transistor which is connected to ODDITY's microcontroller (Arduino Nano Every) and to the 12 Volt power source supplied by the on-board batteries. Once ODDITY receives the cut command from the gondola, ODDITY's microcontroller sends current to the MOSFET to open its gate, completing the cutaway circuit and supplying 12 volts across the resistor.

It is critical for the tether to remain in contact with the cutaway resistor throughout flight to ensure that cutaway will occur. Thus, ODDITY's PCB has a hole through it and a metal wire attached around the hole. This configuration can be seen in Figure 18 (tether is yellow).

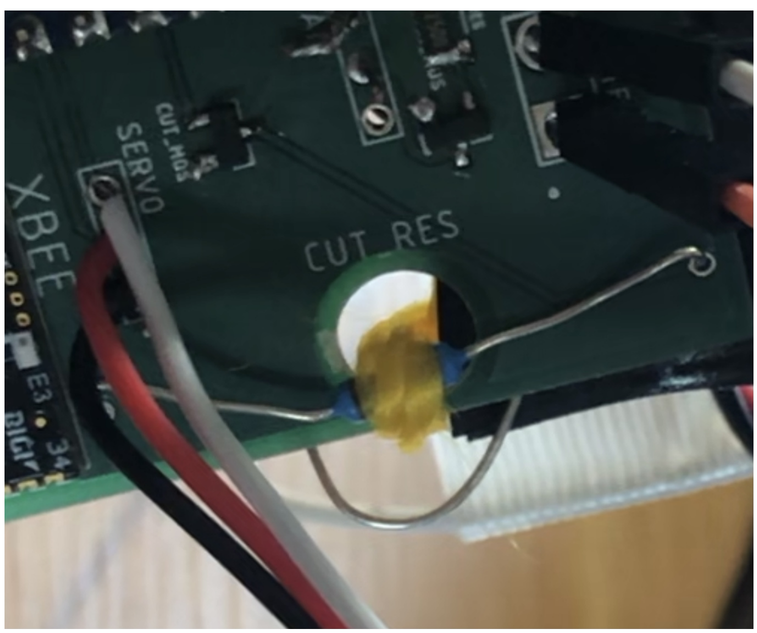


Figure 17: Cutaway Configuration to Ensure Tether Contact with Resistor

This configuration secures the tether around the resistor throughout flight by creating tension in the tether so it is less likely to slip off of the resistor.

# 4 Manufacturing

Authors: Marcus Bonilla, Steven Priddy, Corey LePine, Anders Olsen, Stephen Chamot, Emily Riley, Thania Ruiz

## 4.1 Descent Control

### 4.1.1 COTS Components

The Descent Control subsystem utilized an assortment of COTS components to save time and cost for this project. Some of the COTS that were used in this subsystem were a DigiKey 5V Micro Servo, 0.02in diameter music wire, 1/8in R-1 Foam Insulation Tape, a Sanyo Denki 12V DC axial fan, and M5 nylon nuts and bolts. These COTS components utilized in one ODDITY unit can be seen below in Table 1.

| COTS Component | Quantity |
|---|---|
| Sanyo Denki 12V DC Axial Fan | 1 |
| DigiKey 5V Micro Servo | 1 |
| 0.02in Diameter Steel Music Wire | 5.9 cm |
| 1/8in R-1 Foam Insulation Tape | 1.48 in diameter circle |
| M5 x 0.8 x 35 Nylon Bolts | 4 |
| M5 x 0.8 Nylon Nuts | 4 |

Table 1: COTS components for the Descent Control subsystem

### 4.1.2 Custom Components

The Custom components that were manufactured for this critical project element were the diffuser and the the valve. The diffuser section was designed to both reduce complexity, number of parts and cost for the project. It is easily manufactured with a 3D printer requiring minimal support material and can be printed in under 2 hours. This one part interfaces with the tube, fan, tether and seats the valve. The valve is manufactured in a similar way. The valve top is 3D printed and a circular piece of foam insulation tape is cut to size and glued to the valve top. Lastly the valve actuating wire is bent into the correct shape with the aid of a template to ensure consistency and an additional 1" section of music wire is cut for use as the valve hinge. The main challenges that were faced when designing this component were ensuring that everything fit correctly and that everything was strong enough while reducing weight and size.

The components used in the low pressure testing (Fig. 26) were manufactured custom for this purpose as well. The Inlet nozzle and fan attachment/diffuser were printed using the ITLL's 3D printing capabilities. The Venturi tube section was made out of brass tubing. This brass tubing was cut to length using a bandsaw and then had a hole drilled in it for a pressure port using a drillpress. This proved to be durable enough and useful for our testing that is discussed later.

## 4.2 Communications, Power, and Control

### 4.2.1 COTS Components

The main components of the CPC system for ODDITY are easily found at electronic stores or can be ordered online. The following table lists all the electronic COTS Components used for ODDITY as well as the subsystem they belong to. Although, the following components are off the shelf products, the components were integrated onto ODDITY in a custom fashion. These COTS components can be seen below in Table 2.

| COTS Component | Quantity | Subsystem |
|---|---|---|
| SMD XBee Zigbee 3.0 | 1 | Communications |
| 15k Ohm SMD Resistor (1/4 W) | 1 | Power |
| 25k Ohm SMD Resistor (1/4 W) | 1 | Power |
| ASP CR123A Lithium Button Top Batteries (3.3V) | 4 | Power |
| Arduino Nano Every | 1 | Control |
| SMD MOSFET N-Ch 20V 6.5A | 3 | Control |
| 4.7k Ohm SMD Resistor (1/4 W) | 1 | Thermal Control |
| Sparkfun One-Wire Ambient Temperature Sensor (Through Hole) | 1 | Thermal Control |
| Sanyo Denki 12V DC Axial Fan | 1 | Descent Control |
| 250 Ohm SMD Resistor (1/4 W) | 1 | Descent Control |
| Digi Key Servo Moto RC 5V 360 Deg Micro | 1 | Descent Control |
| 24 Ohm Through-Hole Resistor (1/4 W) | 1 | Cutaway Mechanism |

Table 2: COTS components for the Communications, Power, and Control subsystem

#### 4.2.2 Custom Components

The only custom CPC component used for ODDITY was the custom PCB that was described and shown in Section 3.2 of this report. The custom PCB was manufactured through Advanced Circuits in Aurora, Colorado and were manufactured in batches of 3-5.

The assembly of the electrical components onto the custom PCB can be split into two categories: assembly using a reflow oven and assembly by hand solder. For using the reflow oven, all SMD components (XBee, MOSFETs, and most resistors) were soldered on using the reflow oven at the ITLL or the Aerospace Electronics Lab. The PCB was wiped clean using an electronics safe alcohol solution. Then liquid solder paste was applied to the SMD pads of the PCB; enough was put down to hold the components in place. After putting the solder paste down, each SMD component was placed on marked locations on the PCB. After making sure the components are on good, the PCB was placed in the reflow oven at 160°C for 3 minutes. After cooking and being cooled, a connectivity test was done to verify that all the components were soldered on correctly and are correctly connected. All other electronic components were hand soldered onto the PCB using a normal soldering iron and solder wire. Note, the fan and servo had wires that got soldered to the PCB. Another connectivity test was performed after soldering on the remaining components to verify each connection was solid and going to the correct port.

For the battery packs, 4 batteries and 5 varying length solid core wires were used. The following section (4.3) describes the heating aspect of the battery packs. The wires used were: two 3.75" wire leads for connecting the battery pack to the PCB (hand soldered on), two 0.94" wires used to connect batteries within the battery cell (2 batteries), and one 1.88" wire used to connect the battery cells with each other. To solder on the wires to the batteries, a file was taken to rough up the negative terminal of each battery so that the solder would stick. A picture below shows what the battery pack looks like when soldered together (no heating element added yet).

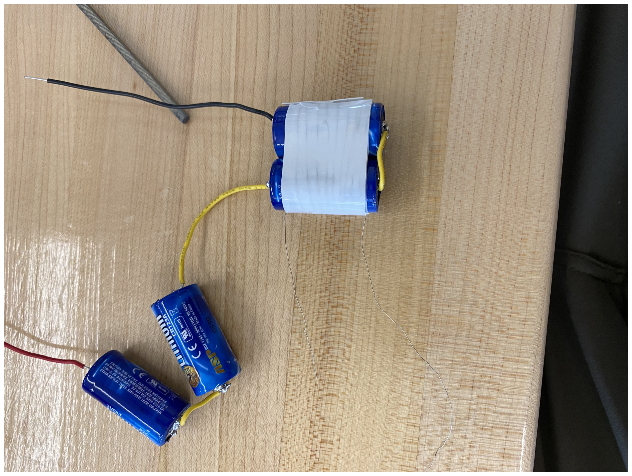

Figure 18: Battery Pack Pre-Heating Wire

There were three major challenges that occurred while assembling the PCB with the electrical components. The first issue came when making battery packs and soldering on the connective wires to the batteries. It was found that a coating was on the negative terminals that repelled solder and which would cause a short for the battery pack. This was prevented by using metal files to rough up the negative terminals so the solder can stick to the battery button top. The second issue came with hand soldering the stainless steel wire to the PCB since the stainless steel wire also repelled solder. This was rectified by pushing the wire through the port on the PCB and then soldering but sides of the port so the solder sticks with the hole on each side of the PCB. The final challenge was the leads from all the through hole components on the PCB. These leads would bump with the metal heating wire on the battery pack and cause shorts that would damage the Arduino Nano Every. This challenge was quite devastating since the Arduino Nano Every would get fried and an entire new PCB had to be assembled. This was fixed by clipping all leads down to be flush with the PCB and then tapped over with electrical tape.

## 4.3 Thermal Control

### 4.3.1 COTS Components

The main components of the thermal control of ODDITY are easily found at stores or can be ordered online. These components include the polyethylene insulation, 32 gauge stainless steel wire, temperature sensor and the thermally conductive tape. However, all these components were assembled in a custom manner that would suit the purposes of this project.

### 4.3.2 Custom Manufacturing

As mentioned before, all the components are off the shelf although the stainless steel wire is set up in a very custom way. The main purpose of the active heating is to warm the electronics to a comfortable 20°C. At very high altitudes it is difficult to transfer heat through convection thus heat must be transferred through conduction which leads to the set up of the stainless steel wire. Again, to maintain the voltage of the batteries it is essential they remain at 20°C thus follows the stainless steel is wrapped around the batteries for nominal heat conduction. First, a 3 inch in length of the thermally conductive tape is wrapped around one battery cell. From there the stainless steel wire is wrapped around the same cell approximately 10 times with enough space that each loop does not touch which could cause a short. Once the wire is wrapped around a second layer of thermally conductive tape is wrapped around the battery cell. An inch of wire is left out on each end of the battery cell to allow it to be soldered onto the PCB. The exposed wire is wrapped around with electrical tape to avoid any shorts in the system. A small piece of foam tape is placed between the battery cells and the PCB, again to avoid any possible shorts in the system.

The housing for the electronics is comprised of an insulation tube and a set of foam plugs. First, a polyethylene foam tube with an inner diameter of 2 inches and wall thickness of 0.75 inch was cut to a length of 3.5 inches. Opposite of the manufactured slit in the insulation, .8 inches is measured from one edge of the tube and a cut is made parallel to the end of the tube. A servo is aligned against the mark and it's shape is traced out and cut in a rectangle to fit the servo with dimensions of 3.2 x 1.2 x 2.9 cm. On either side of the hole, about 1/8 inch is measured and cut at an angle into the hole to cut out two wedges. This is to match the shape of the servo with the tape used to secure it to the hole. Use these wedges, or if needed, cut new wedges from another piece of foam, to fill the gap between the servo and the tape when it is attached to the neck tube.

Next to begin constructing the insulation plugs, 2 circles with the a 2 inch diameter are traced using the hole from the insulation tube on a piece of cardboard. Then, the insulation tube with the 1/2 inch thickness and 1 3/8 inch inner diameter is flattened and the cardboard is glued to the foam. Once dry and secure, the foam is cut around the cardboard and trimmed until the plugs fit snugly inside the insulation tube on either end. In order to easily allow the tether to slip out of the housing after it is cut, a small slit is cut into the side of the insulation plug that will be used on the bottom of the housing. A slightly bigger slit is cut from the cardboard so the ether doesn't get caught in the cardboard.

Some challenges that occurred while manufacturing the thermal include ensuring that the insulation plugs would stay in the housing and the wire and manufacturing of the heating system. During the thermal chamber testing, one of the insulation plugs became dislodged and created a gap in the housing. This was partially due to the the curved nature of the foam that was used to construct the plugs. In order to prevent this, the foam was glued to a piece of cardboard to flatten the foam and to provide a stronger surface to fit into the insulation hole. Finally a piece of tape was used to secure each plug to the end of the housing. Another challenge that was that when placing the electronics and batteries in the insulation housing, shorts would occur, especially when the heating wires were exposed to the PCB or other heating wires. In order to mitigate this, a piece of foam tape was attached to the face of the batteries that would come into contact with the PCB and electrical tape was wrapped around the leads of the heating wires.

## 4.4 Neck Attachment

### 4.4.1 COTS Components

The only COTS that was used in this project element is the CAB tubes and the end caps. These tubes can be ordered in bulk from Petro Packaging and they come in 6ft lengths. The end caps are also from Petro Packaging and can be ordered in bulk to fit he ave mentioned tubes.

### 4.4.2 Custom Components

As far as the actual manufacturing of this tube, since the tubes come in 6ft bulk sections, it is needed to cut them to length. This would mean cutting them to 6in length and cutting out a servo hole. The servo hole is placed about 5cm from the bottom of the tube. This servo hole is cut with the aid of a template as to ensure consistency across every device. Lastly a spare piece of tube is cut to 1/2" in length and slipped over the top of the tube to create a barb for the balloon to hold on to. This piece is glued in place with diluted Shoe Goo.

## 4.5 Cutaway Mechanism

### 4.5.1 COTS Components

The cutaway resistor is the main component of the cutaway mechanism and can be purchased from many online electronics stores. Any 24 Ω metal film resistor with a power rating of 1/4 W will suffice for cutaway purposes. ODDITY's PCB has contact points for soldering the resistor on the PCB. The MOSFET for the cutaway circuit was also purchased off the shelf.

### 4.5.2 Custom Components

As discussed previously, the ODDITY's custom PCB will have a hole through it to pass the tether through and around the cutaway resistor. Also, the metal wire around the hole was custom made. The wire is a lead from an extra cutaway resistor and is snipped from the resistor and is used as the metal guide wire. The metal wire is soldered on contact pads around the hole on the back of the PCB.

## 4.6 Full ODDITY Assembly

Once all of the components were manufactured, the group assembled the completed ODDITY unit. This process first starts with the diffuser and valve section. Shown below is the completed valve and the valve in place on the diffuser.

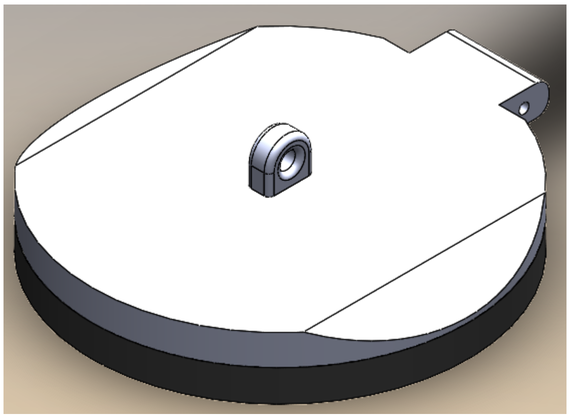
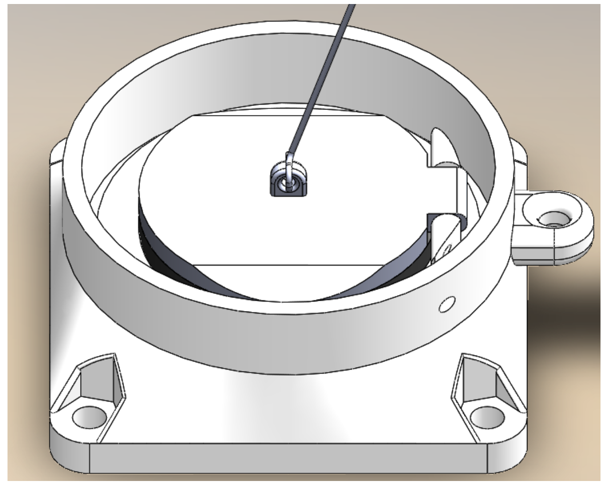

Figure 19: Valve and Assembled Valve/Diffuser section

The valve is put into position and the hinge pin is inserted through the access hole on the side of the diffuser. Once in place, the actuating wire is looped through the top of the valve and the neck attachment tube is added, sliding over the valve. The tube slides into a grove in the diffuser section and is glued in place with Shoe Goo. The orientation of the tube is very important. The hole that was cut for the servo needs to be in line with the ring on the diffuser. In the picture, the overlap of components is to account for 3D printing inaccuracies and is to ensure a tight fit.

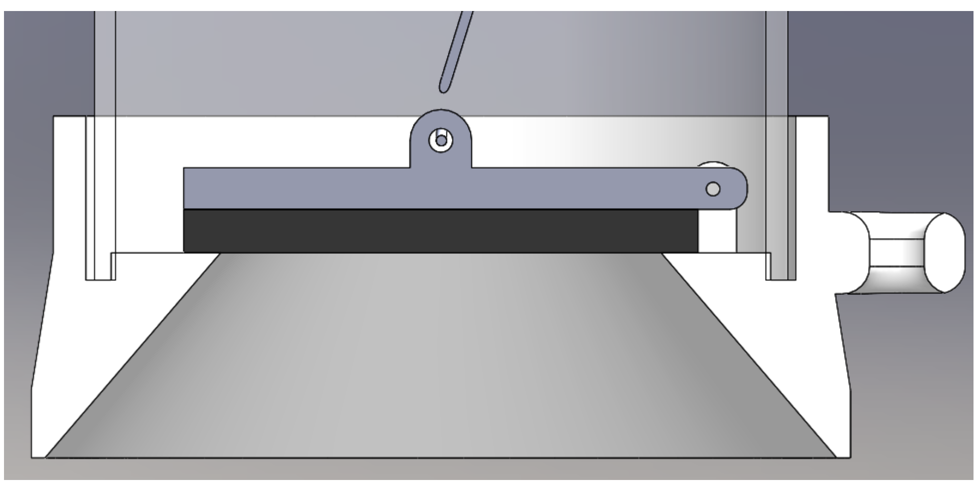

Figure 20: Diffuser Cross Section

Once the glue has set, the servo can then be added as shown in the picture below. The key aspect to this assembly is ensuring that the actuating wire is hooked in the servo arm. The user may need to use pliers or rotate the servo to hook the wire. Once hooked securely the servo can be fully mounted by inserting it in the tube all the way and taping it in place with ample fiber tape. The fiber tape should wrap around the entire tube and servo combination to ensure a strong attachment.

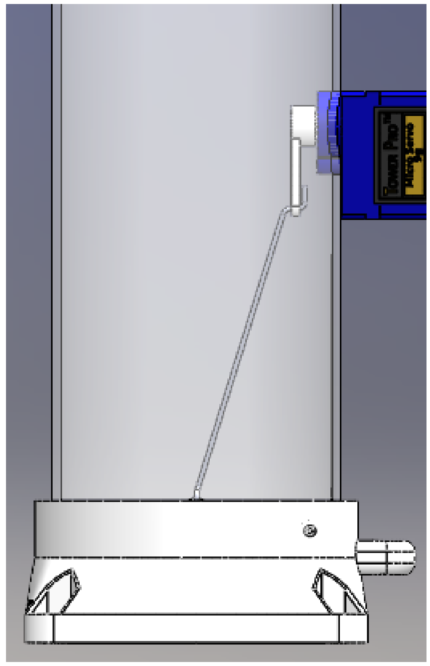

Figure 21: Assembly with Servo Added

Next the foam insulation tube is added to the side of the neck attachment tube, and is fitted around the servo using the pre-cut hole as described before. It is important that the servo wires are routed inside the foam insulation. Then everything can be soldered to the main PCB (described in section 4.2 of this report). This includes the batteries, the servo and the fan. After everything has been soldered and tested the tether can be tied and taped around the tube and routed through the cutaway attachment as previously shown before exiting the foam insulation and being threaded through the retaining ring on the diffuser section. Once these components are all in place, all the electronics can be put inside the insulation and the end caps can be added. It is important to ensure that all wires are secure inside the insulation tube with the exception of a single board wire lead and battery wire lead so that they can be plugged in to complete the circuit and power on ODDITY right before the flight. The insulation is then taped to the the tube with fiber tape and the end caps are added and secured with more tape. The completed positions of all the components are shown below with the exception of the fan.

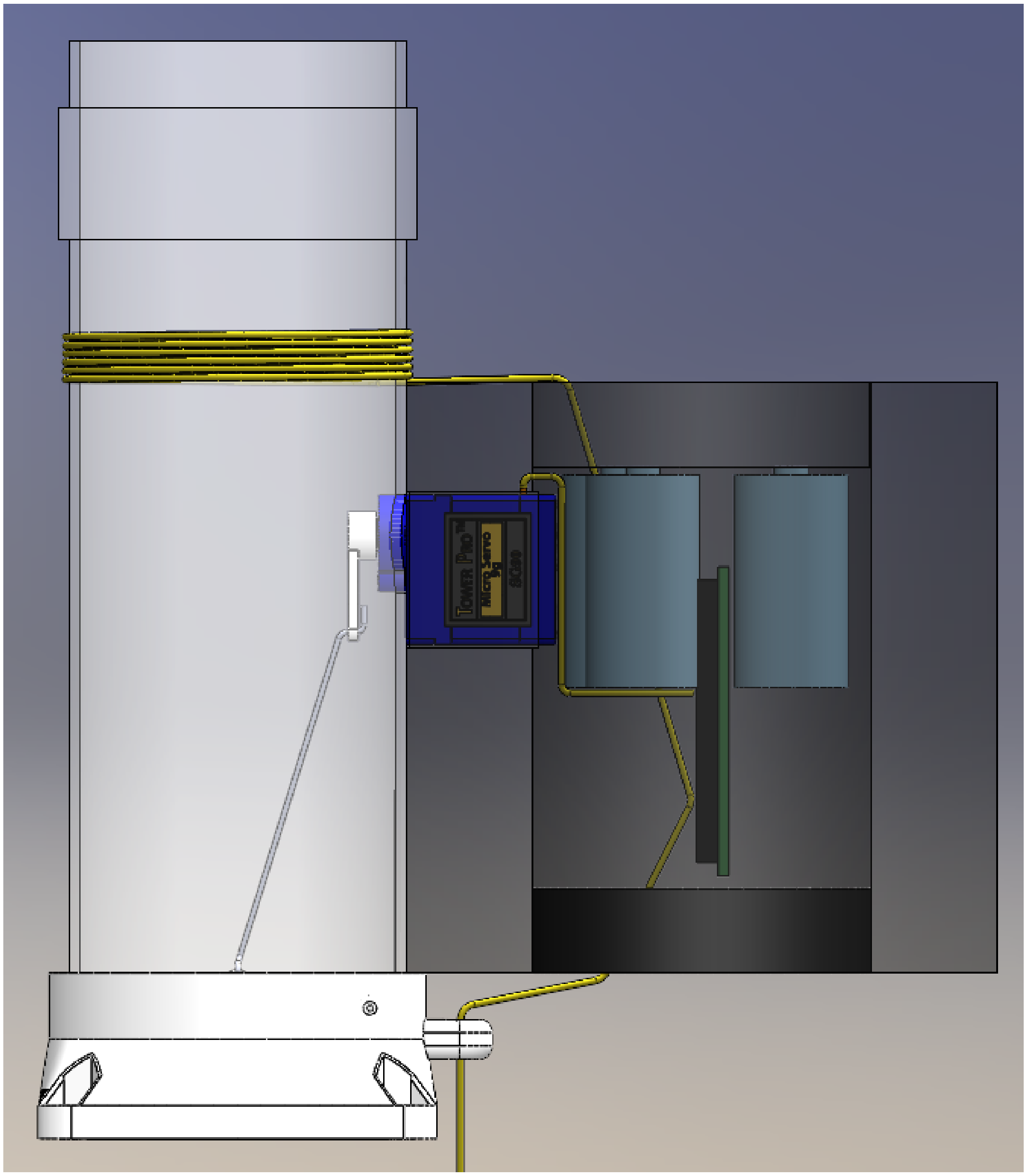

Figure 22: Full Assembly Without Fan

For the most part the exact positions of the electronic components are unimportant. However, It is important for the batteries to be high in the insulation while the PCB is oriented so the radio module is at the bottom. This is to reduce possible radio interference. At this point, the balloon neck is slipped over the top of the tube and taped in place. It is important that the neck of the balloon at least overlaps the tube but 3 cm or more to ensure a firm connection. Then the fill adapter is bolted on to the bottom of the diffuser section, the valve is actuated to the open position and the balloon is filled with the desired amount of helium. For our project this fill adapter interfaces with the HYFLITS teams helium filling tube, but for other iterations the adapter can be redesigned to fit other fill options.

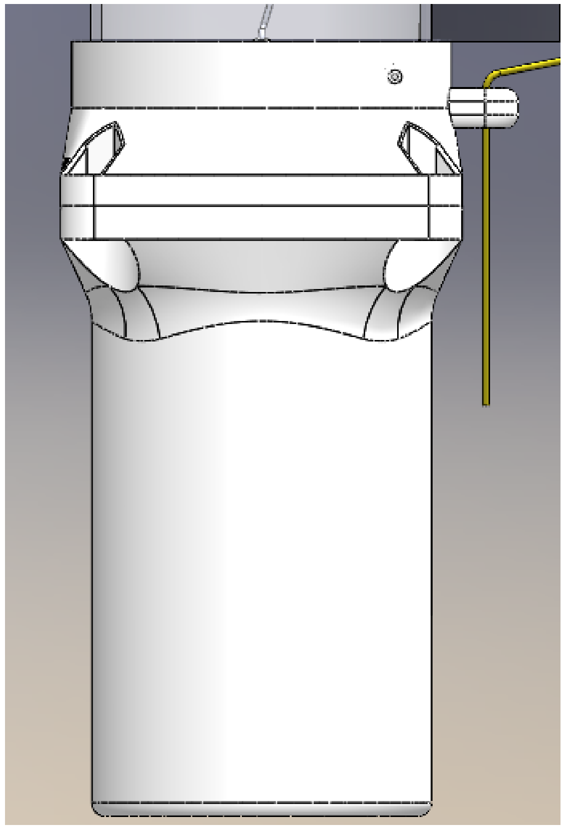

Figure 23: Fill System

Once filled, the valve is closed and the fill adapter can be removed and replaced with the fan as shown below. It is important that the fan is oriented such that the flow is going out of the balloon. At this point the ODDITY system is complete and ready to fly.

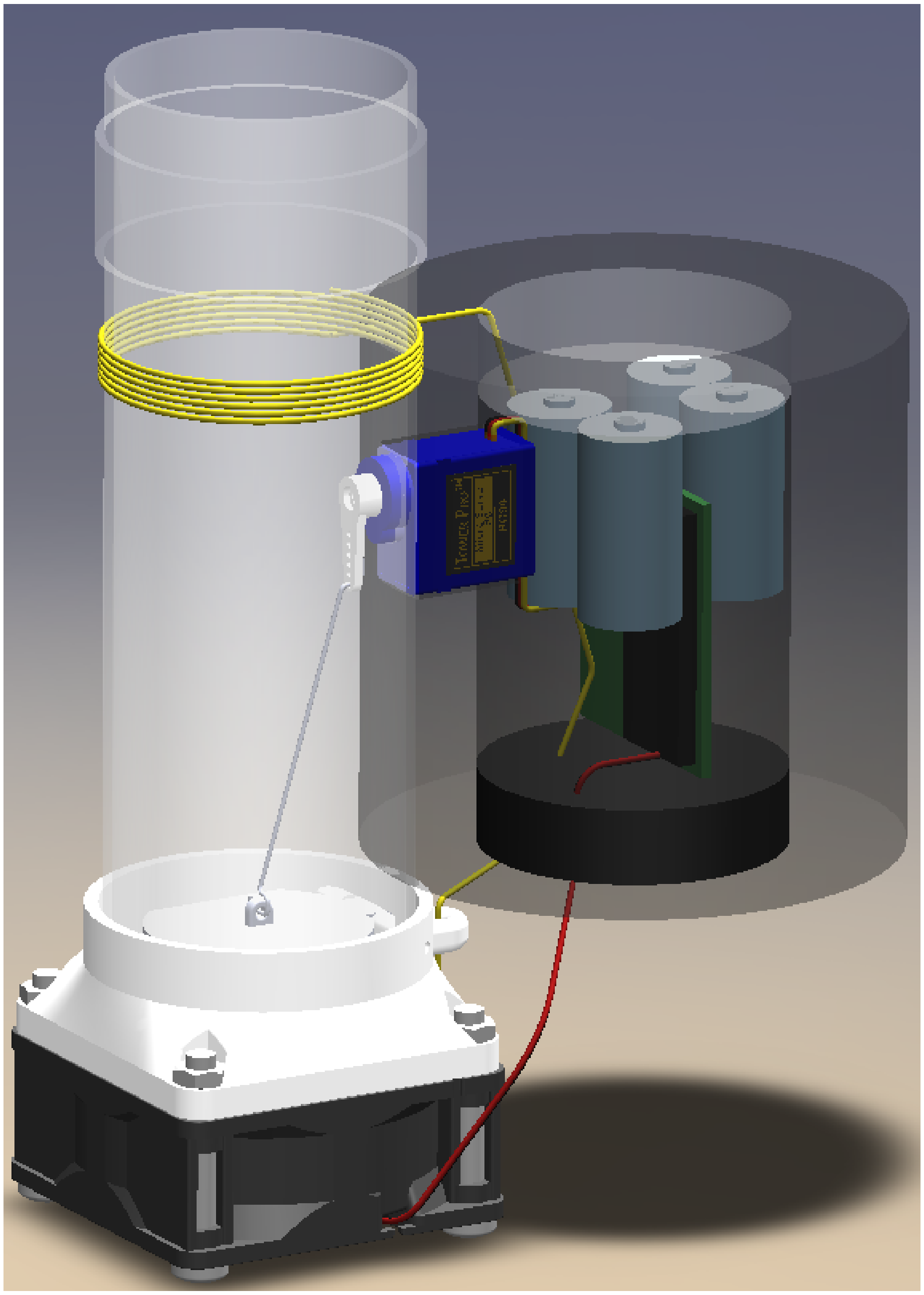

Figure 24: Full Assembly

# 5 Verification and Validation

Authors: Elliott McKee, Michael McCuen, Emily Riley, Marcus Bonilla, Steven Priddy

## 5.1 Descent Control Levels of Success

In this section, the Descent Control characterization testing that was performed will be described in detail. The relevant performance results of these tests will then be presented, and discussion on how the results found relate back to the levels of success outlined in Fig. 1, will be discussed.

#### 5.1.1 CFD Flowrate Modelling

A significant challenge for this project was the quantification of fan performance at the extreme altitudes expected in flight. Because we were using a COTS axial cooling fan for this task, combined with the extremely off-design operational environment, fan performance estimates at altitude were non-trivial.

Extensive research into the topic yielded little to no usable analysis or performance correction factors that are applicable to ODDITY's particular use case.

As such, much of the predictive flowrate modelling, performed in the Design Synthesis portion of the design, was conducted using Computational Fluid Dynamics modelling (CFD).

Using a 3D file provided by the fan manufacturer, a relatively high-fidelity mesh (given available computational power) could be created that corresponds to the fan we will actually be using in flight.

Once the mesh for a specific ODDITY configuration was created, it was the possible to simulate a wide variety of operating conditions for the ODDITY system. Of particular importance, was the simulation of the fan and its performance at extreme altitudes. This was completed by defining simulation boundary conditions that corresponded to those at certain flight altitudes, as determined from the US Standard Atmosphere [2]. Additionally, it was expected, and confirmed through testing, that the fan RPM increases at altitude, due to the thinner at low pressure. These simulations also allowed us to correct for this effect within our simulations.

This CFD modelling was the primary model that was to be validated with our following tests.

The CFD modelling process was a very in-depth, extensive process that has carried on throughout the majority of this project and design. For a more in-depth discussion of the overall CFD methodology, including assumptions, models, setup, assumptions, etc., see the Project ODDITY Fall Final Report [1].

#### 5.1.2 Characterization Testing Overview

While CFD modelling has the capability of being quite accurate, if modelled and tuned correctly, it still needs to be verified before relying on the results of such a simulation in a final design. At the end of the previous semester, we had flowrate data corresponding to Boulder altitude. However, additional data was desired, specifically to validate the fan flowrate performance at flight altitudes.

To this end, a low-pressure chamber was utilized in order to simulate these high-altitude flight conditions. Such a chamber is available for use through the CU Aerospace department, where equipment access was provided by Matt Rhode. Images of this vacuum chamber are shown in Fig. 25. This chamber allowed for the fan to be tested at air pressures and densities similar to those within our 20-40 km range, as it is capable of pumping down to about $70Pa$. It should be noted that the temperatures at a given altitude will not be simulated in the vacuum chamber in question. This was predominantly due to limitations of the Pressure Chamber provided. However, the effect of temperature was expected to have a much less significant effect on the flowrate efficiency and performance, relative to the order-of-magnitude changes in density and pressure experienced at in-flight altitudes. Additional fan survivability testing was performed in order to ensure that the fan has the capability of functioning in these low temperatures, and will be detailed more in following sections.

Figure 25: Pictures of Vacuum Chamber

The primary goal of this testing was to validate the CFD modelling that was being utilized. However, the critical performance characteristic with respect to the Descent Control Levels of success was the relationship between fluid flowrate that is created by the fan, and altitude. As such, a test was designed in order to provide an estimate of fan flowrate, at the simulated flight altitudes, as replicated in the pressure chamber.

#### 5.1.3 Characterization Testing Detailed Design

**Equations Utilized** This test was designed in order to provide an estimate of fan flowrate at simulated flight altitudes, within a low pressure chamber.

The primary calculation utilized in order to determine the volumetric flowrate through the fan, was:

$$Q = V \cdot A \tag{1}$$

where $Q$ is the volumetric flow rate, $V$ is the flow velocity measured at a specific point, and A is the flow cross sectional area, at the same along-stream point at which the velocity is measured. It should be noted that this calculation incorporates the significant assumption in that it assumes a constant cross-sectional velocity profile at the point at which the flow velocity is being measured. We will discuss the implications of this assumption in more detail in later sections, but this assumption likely causes our measurements to over-predict flowrate, relative to the physical values. This is likely due to effects of boundary layers, and flow constriction; both of which can be thought of as effectively reducing the effective cross sectional area of the flow at the point being measured.

From Equation 1 above, we can see that we need an estimate for the flow velocity, at a location with a known cross sectional area.

In order to determine flow velocity at a given point, an idealized, Bernoulli-Equation analysis was utilized. Specifically, if we assume;

Pressure measured far from the fan apparatus can be assumed to be the total pressure

No pressure losses in the flow

Incompressible flow

Irrotational flow

No Body Forces acting on the fluid

Gravity effects negligible

we can then write the simplified version of the Bernouilli equation as follows;

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \tag{2}$$

Where $P_1$ and $P_2$ are static pressures at two respective points in a flow, and $v_1$ and $Pv_2$ are flow velocities at two respective points in a flow.

If we assume that the point 1 is at a nearly ambient (zero flow velocity) point in the test chamber, we can assume that $v_1$ is zero;

$$P_1 = P_2 + \frac{1}{2}\rho v_2^2 \tag{3}$$

Which we can then re-arrange into an equation to determine the flow velocity, under the assumptions stated above;

$$v_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho}} = \sqrt{\frac{2\Delta P}{\rho}} \tag{4}$$

where $\Delta P$ is the differential pressure between an ambient point in the chamber (total pressure), and the point at which the velocity is being estimated. Additionally, $\rho$ is the flow density measured at any point in the flow, as we are assuming incompressible in our analysis. This assumption was seen to be valid, upon analysis of the relatively low flow velocities expected, determined from expected volumetric flowrates from our CFD analyses.

Equation 4 requires only two measurements to determine the velocity of the flow at a given point. The first of which is a differential pressure reading from between an ambient point in the chamber (total pressure), and the point at which the velocity is being estimated. The second is a measurement of the density of the flow at any point in the chamber. This was accomplished in the following tests by measuring the temperature and pressure at an ambient point in the chamber, and solving for air density through the Ideal Gas Law.

**Challenges/Hardware Limitations** Ideally, we would like to test a nominal, flight configuration of our ODDITY unit in order to get a representative idea of the in-flight flowrate performance of the descent control subsystem. However, it was determined that that was not possible, due to pressure sensor resolution limitations.

More specifically, in Equation 4, we must measure the differential static pressure between an ambient point in the chamber, and the point at which we wish to know the flow velocity. If we re-arrange Equation 3, we can see that what we are effectively measuring in this analysis, is the dynamic pressure of the flow, with this differential pressure reading;

$$P_1 - P_2 = \frac{1}{2}\rho v_2^2 \tag{5}$$

In the above Equation 5, we can see that the magnitude of the differential pressure we expect to measure is dependant on the flow density, and the flow velocity. We can estimate the flow velocity at a given altitude from our previous CFD simulations, and we can calculate the flow density at a desired testing pressure, via the Ideal Gas Law.

The flow velocities, in our case, are not especially large. In addition, the air density decreases by several orders of magnitude as we increase in altitude from Sea-Level-Standard, all the way up to 30+ KM. As such, this differential pressure measurement we desired to make, was expected to be incredibly small in magnitude, if we were to perform testing of our flight configuration, at most in-flight altitudes. Basically, this differential pressure was expected to be much smaller than the resolution of all available pressure sensors available to us, for any simulated test altitude that would net any additional, useful data.

To allow for the collection of flowrate data at the altitudes desired, the velocity of the flow being measured had to be increased, in order to make this differential pressure measurement attainable with available pressure sensor resolutions.

This was accomplished by attaching a Converging-Diverging Duct, similar to a Venturi Tube, to the inlet of the fan, where the balloon attachment tube would normally occupy. Testing diagrams, and pictures of this inlet can be found in Figures 26 and 27 below. By restricting the flow area, we increase the velocity of the flow in this reduced-area region. This allows for the differential pressure measurement to be attainable, given available sensor resolutions, which then allows us to back out the volumetric flowrate through the inlet, using the equations described in the previous section.

However, this inlet also severely constricts the flow, and as such, reduces the overall performance of the fan, relative to the less restrictive, balloon neck attachment tube that will serve as the inlet to the fan in a flight configuration inlet. This means that this testing will no longer be representative of the system performance in flight, from a fan flowrate perspective. However, it can still be used in order to verify our CFD modelling. Specifically, this configuration, with the modified inlet, was modelled identically to the flight configuration inlet, which allows a representative comparison/verification of physical flowrate parameters between our CFD methodology, and experimental data. Again, this trade-off was required, as otherwise, it would be impossible to collect flowrate data at simulated flight altitudes, given pressure sensor resolution limitations.

With the designed Venturi Tube area ratio and pressure sensor selected in the final testing design, it was possible to get data up to nearly 30KM in altitude for fan flowrate, before approaching the resolution of the sensor, and causing measurement error to become too large to be usable.

**Characterization Test Diagram and Pictures** A diagram of the test setup utilized, is shown below, in Fig. 26

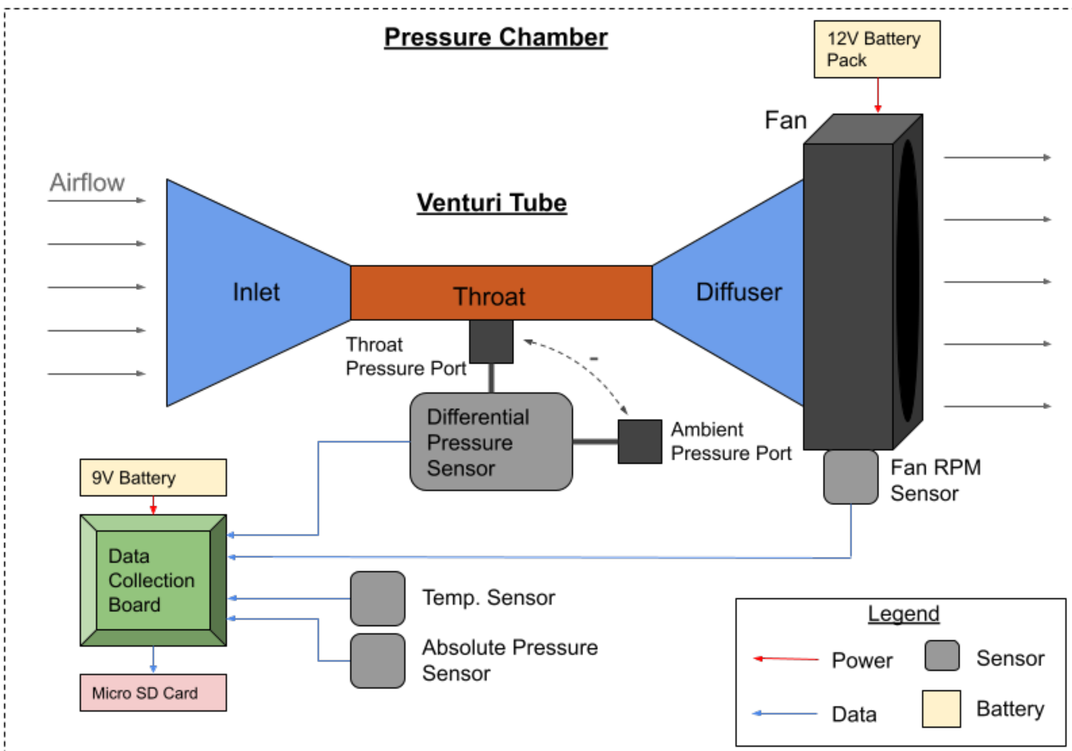


Figure 26: Diagram of Vacuum Chamber Test Setup for Flowrate Testing

In the above Fig. 26, we can see the Venturi Tube apparatus discussed previously, picture in blue and orange to correspond to the test hardware photos shown in later sections. We see that this Venturi Tube is attached to the fan inlet, and the fan serves to pull air through this apparatus.

Our primary sensor is the differential pressure sensor, pictured in grey in the above figure. This sensor measures the differential pressure between a static pressure port in the Venturi Tube throat, and the chamber ambient or total pressure. This is what allows us to estimate the flow velocity in the throat of the Venturi Tube. With the velocity and cross sectional flow area of this region known, we can then utilize equation 1 in order to estimate the volumetric flowrate.

Additional sensors include an ambient temperature and absolute pressure sensor, which are used to determine the density of the air within the pressure chamber; as well as a fan RPM sensor, which allows us to quantify the increase in fan RPM expected at higher altitudes, due to the thinner air. This RPM sensor was a digital tachometer, which, once reflective tape was placed on one of the fan blades, could measure the fan RPM. This RPM data was utilized in order to update the CFD simulations with a physically correct fan speed, in order to provide a more representative comparison between model and experiment.

All the sensor data is saved to an SD card, onboard an Arduino board within the test chamber. This was required, as there were no wire pass-throughs on the pressure chamber being utilized. As such, the entirety of the data collection system needed to be within the pressure chamber as well. This data collection board was provided by Matt Rhode of the CU Aerospace department, where it was originally intended for use on balloon payloads, to make similar temperature and pressure measurements.

Both the fan, and data collection board are powered on simple 12V and 9V battery packs, respectively; again, because the pressure chamber did not have any cable pass-throughs. It is likely that a regulated power supply would lead to lower uncertainties in the results of the test performed, due to the ratiometric pressure sensor used, as well as the Fan RPM dependance on voltage. Again, however, this was not possible due to limitations of the pressure chamber utilized.

Pictures of the Venturi Tube, and actual testing hardware/setup can be seen in Figures 27 and 28, below.

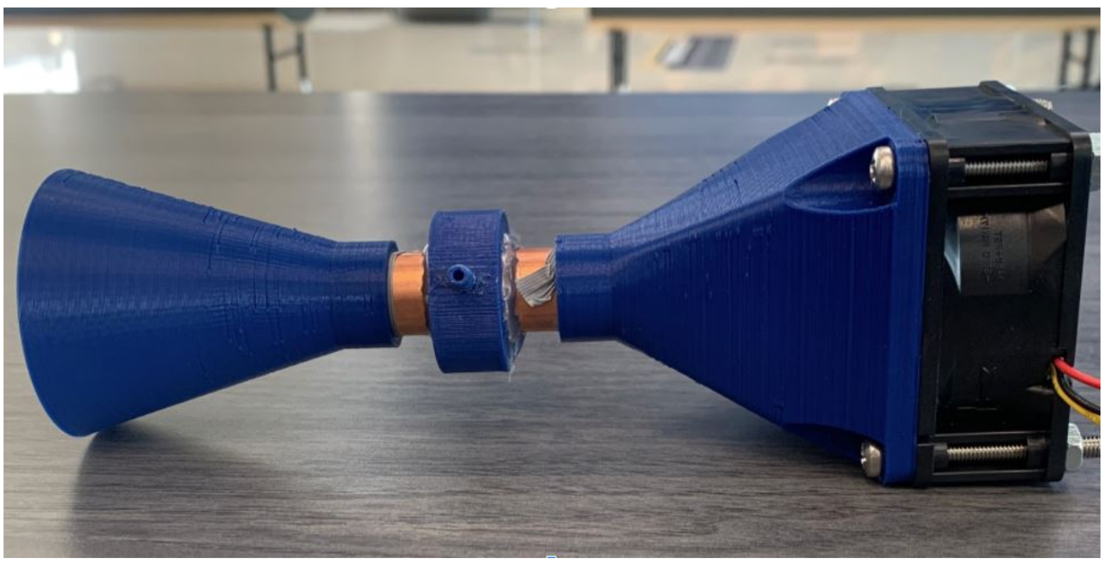

Figure 27: Venturi Tube Testing Hardware

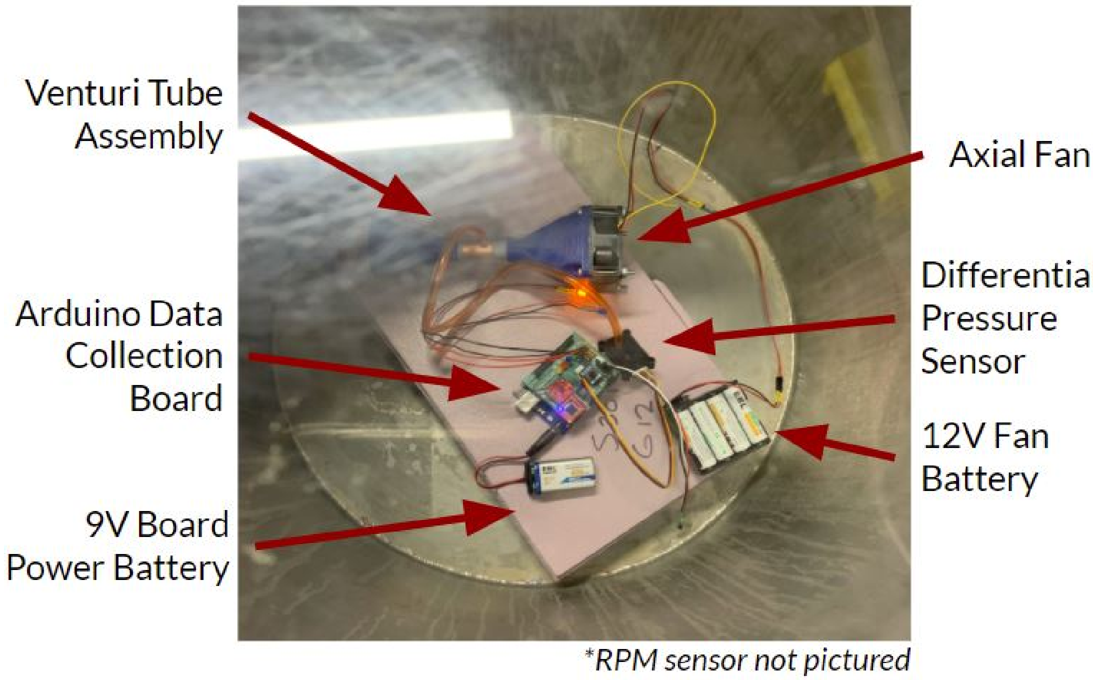


Figure 28: Picture of Vacuum Chamber Experimental Setup

#### 5.1.4 Characterization Testing Results

**Flowrate Results** Using the testing setup and methodology outlined in the previous section, we can then measure fan flowrate across a range of expected flight altitudes.

A plot of the experimental, CFD, and "modified" CFD flowrate results is given below:

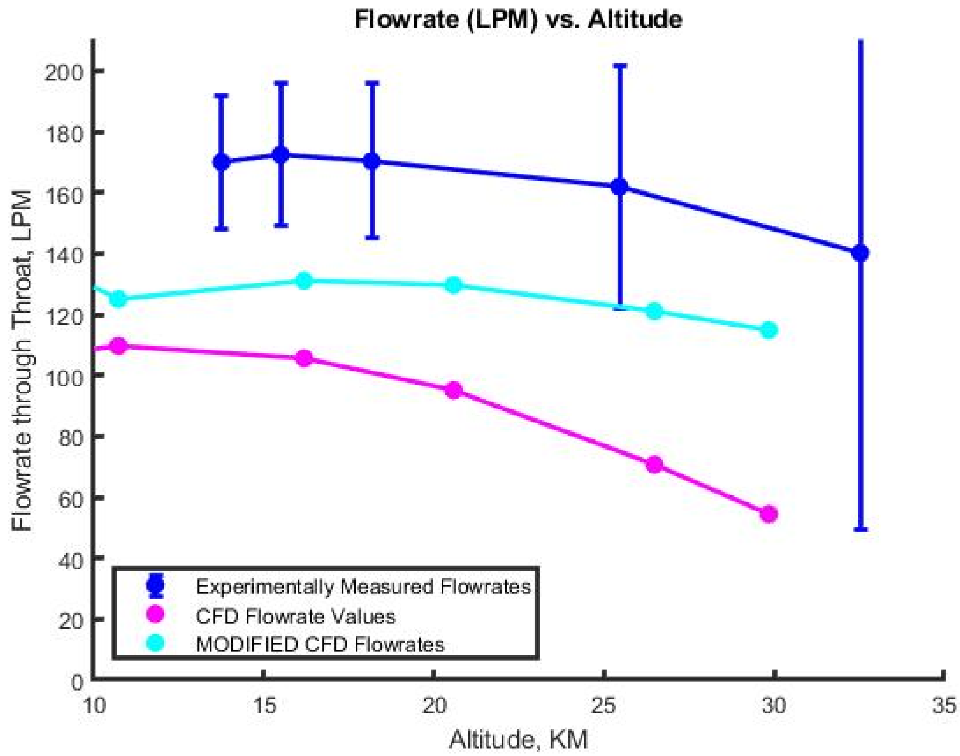


Figure 29: Descent Control Characterization Testing: Fan Flowrate Results

In Figure 29 above, we see very similar trends between the experimentally measured, and CFD simulated flowrate results. However, we see that the CFD results significantly under-predict the corresponding experimental values.

One significant area of discrepancy has to do with the assumptions made in the above sections with regard to the experimental calculations. Specifically, the assumption of constant cross sectional velocity within the Venturi Tube throat.

We can do a preliminary investigation of how significant of effect this assumption has on the overall results, by checking how much our CFD measured flowrates change when using the same calculations to determine flowrate as used in the experiment.

To give a little more detail, in the magenta plots above, we determine the flowrate in CFD by integrating the axial (relative to the fan impeller) velocity, across a cross section of the Venturi Tube throat, in order to determine the volumetric flowrate.

However, the CFD simulations performed also allow for the determination of the static pressure in the Venturi tube throat, which allows us to perform the set of calculations described in the **Equations Used** section above, that were used to determine the flowrate in the experimental case. This was performed in hopes of rectifying some of the discrepancy between the CFD and experimental results.

The result of utilizing the same experimental equations on the CFD data is labelled "MODIFIED" CFD data, and given in Cyan in Fig. 29.

We see that this helped rectify a significant amount of discrepancy between the CFD and experimental values, but does not resolve it all. Specifically, we see relative error values between the experimentally measured and CFD simulated values of approximately 20%, across the range of altitudes simulated.

This, however, does indicate that the assumption of constant cross sectional flow velocity is likely invalid, as it was seen to change the results of the CFD simulated flowrate values by anywhere from approximately 20% to over 100% relatively, with the discrepancy seen increasing with altitude; likely due the significant decrease in Reynolds number as altitude increases. As will be discussed in the following paragraph, the boundary layer status as the measurement point was unknown. The CFD simulations that were conducted suppressed turbulence in the inlet/throat sections of the Venturi tube; as a laminar boundary layer was expected, mainly due to the low Reynolds numbers in flight. However, this is not confirmed, and as such, could lead to inaccuracy in the above CFD results and correction methodolgy.

It is possible that some of the error associated with this assumption could have been accounted for by performing analytical boundary layer analysis; however, details about the boundary layer were unknown for the tests conducted. It was expected that the boundary layers experienced within the Venturi tube throat are likely laminar at high altitude, due to the extremely low Reynolds numbers, but it is unknown how the effect of surface roughness of the 3D printed material, or the sharp angle between the inlet and throat section were going to affect the flow. This, in addition to the small throat diameter not allowing significant measurement devices to be used, meant that we could not investigate the boundary layer behavior any further.

Additional areas of discrepancy that were noted include; slightly different throat diameters between experiment and CFD, different RPM's utilized in CFD compared to a specific experimental dataset, limitations of the rotating reference frame approach utilized in CFD, total pressure losses, and manufacturing inconsistencies/imperfections from the 3D printed geometry, burrs, etc.

**Differential Pressure Results** As was seen in the previous section, there were significant discrepancies seen, that were likely due to incorrect assumptions in the experimental equations utilized to determine flowrate.

As such, comparison of the raw differential pressure measurements were made (see Fig. 26), in order to try and provide the most rudimentary comparison between what was simulated, and what was measured, while still relating to physical flow parameters. Specifically, the differential pressure measurements from the experimental results were compared to corresponding differential pressures as found in our CFD simulations. This, again, provides a much more rudimentary comparison that requires none of the previous assumptions associated with the experimental flowrate calculation; while still providing a point of comparison with respect to physical flow parameters.

The experimental and CFD simulated values for the differential pressure measurement made, are given below;

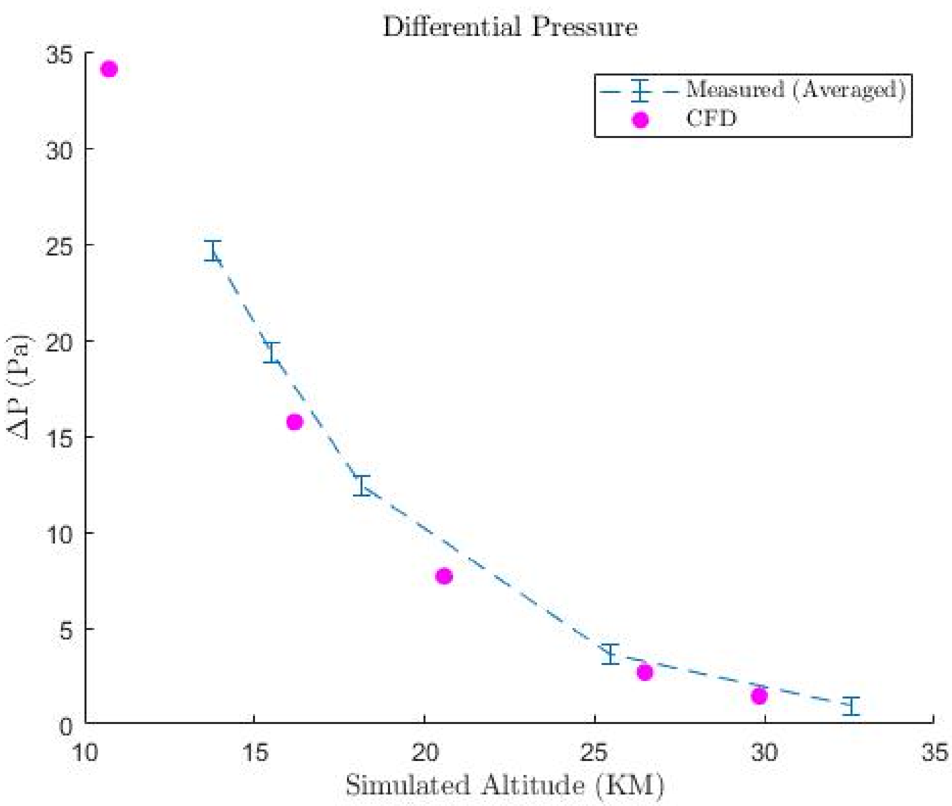


Figure 30: Descent Control Characterization Testing: Fan Differential Pressure Measurement Results

We can see that the results in the above plot show relatively close agreement between the experimental differential pressure and CFD simulated differential pressure results. We see very similar trends between each, with the CFD data slightly under-predicting the differential pressure measures relative to experiment.

Speaking more quantitatively, when comparing the error between the CFD simulated $\Delta P$ measures, we see a maximum of 11.3 % relative error from the experimentally determined values. It should be noted that the CFD data points are being compared with linearly interpolated data at the respective altitude, as both datasets were not taken at a matching set of altitudes. This could possibly be contributing to the error seen. Additionally, the maximum relative error calculated, was seen at the CFD datapoint corresponding to the highest altitude. This also is the point at which the air density, and flowrate, are the lowest; meaning the that the $\Delta P$ being measured is very small at this point. Because of this, there is much more relative error in our experimentally measured $\Delta P$ measurement at this point, as we are approaching the resolution of the sensor used.

To summarize the results of the previous two sections, the experimental verification of our models showed agreement with our predictive CFD modelling. It was seen that the comparison of expected flowrate was similar between the two, with similar trends being displayed, but with discrepancies being displayed due to assumptions in our experimental calculations. When removing these assumptions and simply comparing the differential pressure measurement readings, we saw better agreement, with a maximum of 11.3% relative error between the predicted and experimental values, at the maximum altitude tested. It was also seen that, in both cases, the CFD predictive data under-predicted the experimental values at a given altitude, and thus appears to be providing conservative flowrate estimates.

This section provides validation of the previously developed CFD predictive models with respect to physical flow parameters of a COTS fan at high altitude. While this was by no means an exhaustive verification of our predictive models, this afforded additional confidence in the use of these models, and the results derived from them, for use in the overall system design; and for the determination of the descent control levels of success. If there were more time, and resources, it would likely be beneficial to seek additional verification for the CFD flowrate models being utilized. However, given the nature of this project, there is no way to perfectly match the conditions expected in flight, and as such, the only additional verification explored was in the form a flight test.

**CFD- Flight Configuration Results** The sections above outlined the verification of our predictive modelling that was being used for the descent control subsystem of ODDITY. This afforded more confidence in the high-level flowrate results determined using our CFD predictive modelling.

In this section, the results of the predictive modelling of a flight-configuration ODDITY system are presented, and the implications of the results are then discussed.

The simulated fan flowrates for a fligh-configuration ODDITY, predicted from our CFD predictive modelling, are given below in Fig. 31.

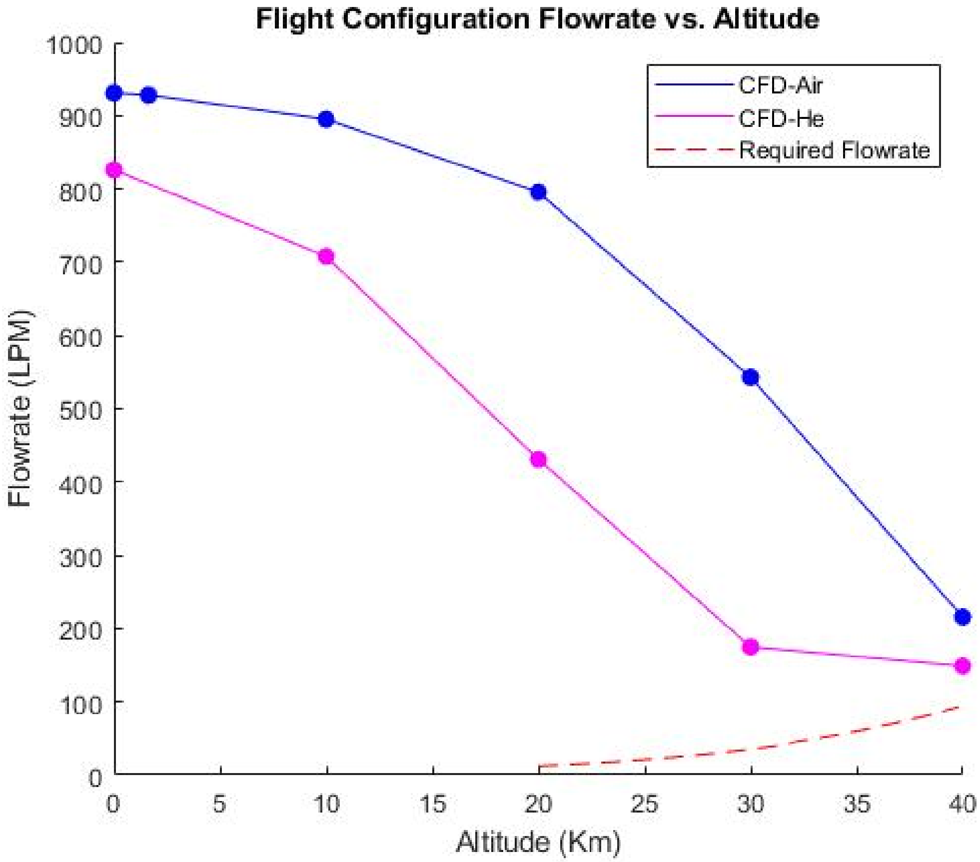


Figure 31: Predicted Flight Configuration Flowrate Results

We can see, in Fig. 31, the CFD predicted flowrate values for both Air and Helium as the working fluid, in relation to the expected required flowrate required from our balloon dynamics modelling discussed previously, throughout the range of flight altitudes expected.

As the balloon is filled with pure helium, it is more likely that the helium plots give a more representative view of what the ODDITY system will see in flight, as it will be extracting helium from the balloon envelope.

However, the important takeaways from this plot are that the system is predicted to have significantly more flowrate than as is required to maintain a descent rate of 2 m/s, throughout the range of flight altitudes expected.

More specifically, we see a positive flowrate margin all the way up to 40 KM in altitude, which is the absolute maximum altitude in which this system will be operating. At this point, we also see the smallest flowrate margin of approximately 60% relative to the expected required flowrate at that altitude, with Helium as the working fluid. At all other flight altitudes, we expect even large flowrate margins, as the predicted flowrate will increase, and required flowrate decreases at lower altitudes.

**Flight Test Results** The original flight test of the system experienced a failure, which ultimately caused the system to not initiate the descent portion of the flight. As such, no data about the descent control system was furnished from this initial test flight.

However, the second test flight of the ODDITY system was successful in achieving the performance and flight profile desired. With regard to the descent control system performance, we can analyze the balloon ascent/descent rates in order to assess the performance of the descent control subsystem in flight.

A plot of the test flight balloon ascent rate, versus altitude, is given in Fig. 32 below. Similar data is plotted for the HYFLITS balloon trajectory that did not incorporate the ODDITY system. The ODDITY test flight data is given in purple in the figure below, to stand out alongside the balloon ascent rate data using the legacy hardware.

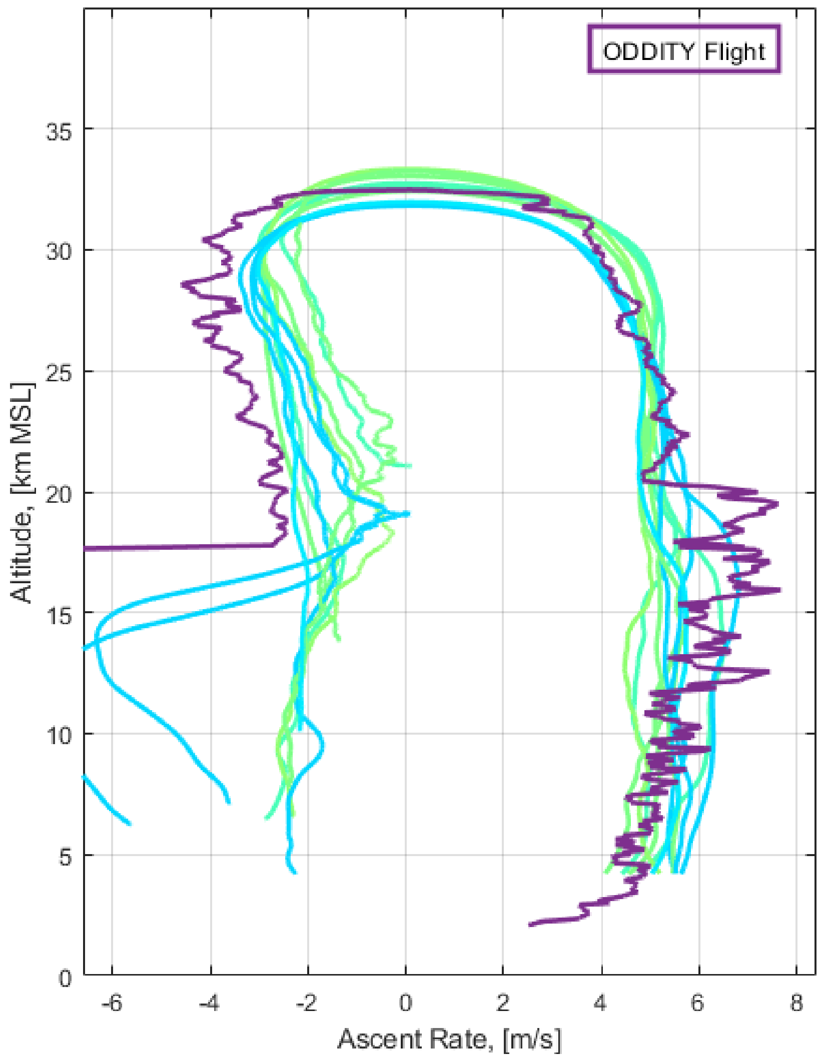


Figure 32: Flight Test Ascent Rate Results

In the above plot, the ODDITY test data, given in purple, is plotted alongside test data from previous balloon flights which did not include the ODDITY system. Looking at the right hand portion of the above plot, corresponding to the balloon ascent phase; we can see that the ODDITY system saw similar ascent rates for the ascent portion of flight below 20KM. Above this altitude, we see that our system was able to dynamically actuate the valve system, in order to get the balloon to follow a pre-determined ascent reference curve. We see that the ODDITY test flight data matches the previous legacy data, very well in this region.

This test flight saw an apogee that was very similar to the previous test flights (32-33KM MSL), which was desired. This indicated that our system did not hinder the ability of overall balloon system to reach a desired target altitude, accurately.

After the balloon reached apogee, the fan was turned on, in order to determine the increase in descent rate that the ODDITY system afforded. Looking at the left hand portion of Fig. 32 above, there are a few significant takeaways. It can be seen that the system descent rate, which is the negative of the ascent rate, never fell below the requisite 2 m/s descent rate requirement; all the way from apogee, until the system cutaway, at approximately 17 KM MSL. This was a requirement enumerated in Functional Requirement 1.0.

Additionally, we can see that the system saw increased descent rates, relative to the previous flight data that reached similar apogee altitudes. This can be seen in the left hand portion of Fig. 32 above, where the ODDITY system ascent rate, shown in purple, is more negative than that of the other flight data curves pictured, throughout the range of altitudes experienced during descent. There are a lot of external factors that could influence the comparison of our flight test to the previous data that we are comparing to; as well as unknowns about how the previous flight data was parsed (it is much less noisy than the ODDITY flight data). Additionally, this is also only a single flight test, so the conclusions that can be drawn are somewhat limited. If possible, it would be beneficial to perform many tests of this system in order to more rigorously investigate the descent rate performance of the ODDITY system, relative to the legacy hardware. However, due to financial and scope limitations of the ODDITY project, any further system characterization will fall on the HYFLITS team going forward.

#### 5.1.5 Level 1

From Fig. 1, the first Descent Control subsystem level of success is that the system will be able to extract helium in conditions similar to those experienced at 35 KM in altitude.

The achievement of this level of success was verified in two main ways, which are both discussed in the previous section.

Firstly, the low pressure fan flowrate testing showed that the physical system developed had the capability of providing significant Air flowrates at altitudes similar to that of 35 KM; even with the additional flow restriction that the Venturi Tube inlet provided.

Secondly, the predictive CFD modelling, which was validated in the above sections, showed that the system had a very significant flowrate margin when using Helium as the working fluid, at simulated altitudes of 35KM. Specifically, at 35KM, we see a 167% flowrate margin from the CFD predicted values, relative to the expected required flowrate at this altitude.

It is because of these reasons, that we have determined that the level 1 level of success for the Descent Control subsystem has been satisfied by our proposed design.

#### 5.1.6 Level 2

The level 2 level of success with regard to the Descent Control subsystem (see Fig. 1), stated that the system must be able to match the legacy system performance in flight testing. As such, validation of this Level 2 descent control level of success was dependant on the execution of a successful test flight. In the **Flight Test Results** section above, the results from the ODDITY system test flight were outlined.

It was seen in the test flight results above, that the system was able to achieve the desired ascent profile, and apogee altitude, similar to the legacy system performance.

It was also seen that the ODDITY flight test showed descent rates that were greater than that of the legacy hardware. This was only a single flight test, so more testing would be required in order to ensure that this result is repeatable; but this flight test exhibited system performance that both matched, and exceeded the descent rate performance relative to the legacy system.

Because the system was able to provide system performance that either matched, or exceeded the performance of the legacy hardware in the flight testing conducted; it was determined that our system satisfied the Descent Control Level 2 level of success, in addition to the Level 1.

### 5.2 Neck Attachment Levels of Success

The Neck attachments levels of success are based weather the ODDITY system is able to attach to the bottom of two different weather balloons. ODDITY being able to attach to the 5cm Kaymont balloon is the first level and the second is ODDITY fitting on to a 8cm Hwoyee balloon.

#### 5.2.1 Level 1

Team ODDITY was able to attach an ODDITY unit to a Kaymont balloon during out flight test. This was done prior to the balloon filling. The balloon neck section was put over the plastic neck tube and then secured with tight with multiple wraps of fiber tape. As an extra precaution a tube cap with a hole is place to provide a lip to the tube to prevent the ODDITY system from falling from the balloon neck.

## 5.3 Communications Levels of Success

The communications aspect of ODDITY is centered around the Xbee Zigbee 3 radio chip. Before the Xbee was soldered onto the ODDITY's custom PCB, the chip was configured to have the same RF parameters as the gondola's Xbee chip; the radios share a 2400 baud rate link. This was done using a configuration file provided by HYFLITS. Once the Xbee was configured, communications testing could being.

During flight, the gondola sends commands based on its GPS altitude and additional flight logic. Based on GPS altitude, the gondola will send commands to open/close the valve as well as turn the fan on/off.

When a command is sent, ODDITY is expected to be able to receive the command by establishing a communication link (level 1 success), interpret the command and turn on/off various ODDITY components (level 2 success), update the status of those components, and send status updates back to the gondola (level 3 success). After this process, the gondola downlinks the status of ODDITY, such as valve status, fan status, heater status, internal temperature of ODDITY, and ODDITY battery voltage to visualize ODDITY performance in real-time.

A full systems test was conducted to simulate flight and achieve all three levels of success for the communication component of ODDITY. The test consisted of three main components: ODDITY, the HYFLITS gondola sensor package, and a PC with a MATLAB GUI to visualize data packet collection. Instead of the gondola using GPS data to determine when to send commands, the gondola used preset ascent/descent ratios to simulate the flight. The data packets from the gondola were utilized to analyze the status of ODDITY throughout the test. Figure 33 shows the results of the test.

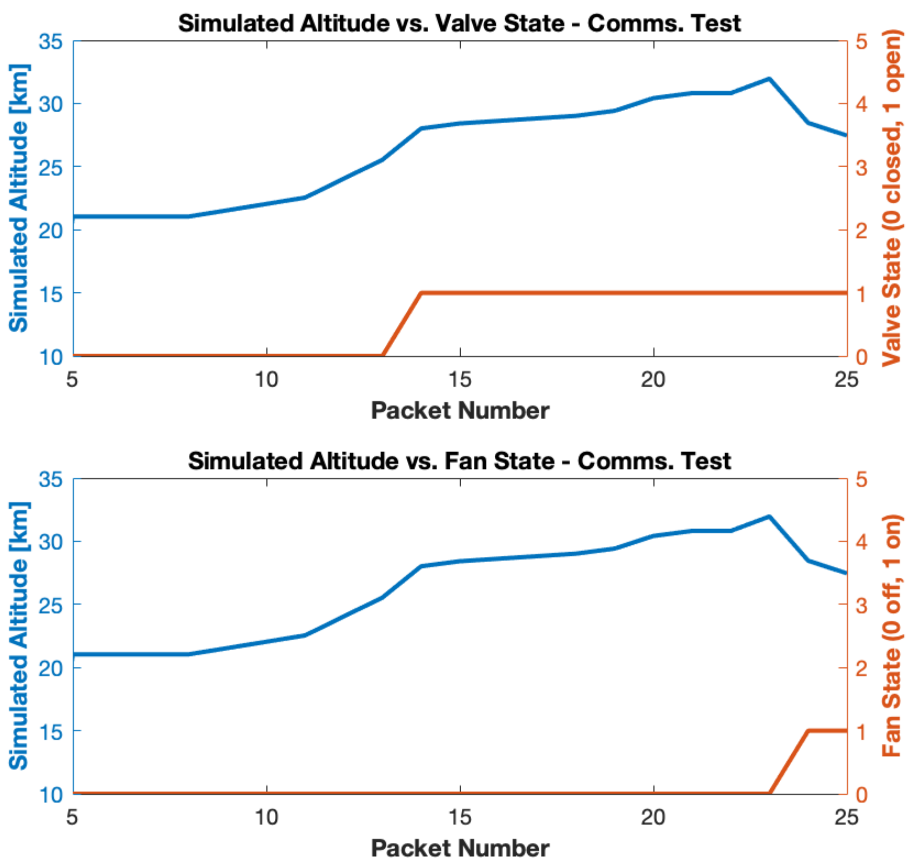


Figure 33: Simulated Altitude Full System Test Results

As seen above, the valve is initially closed and the fan is initially off. At the preset simulated altitude of 25 km, the gondola sends an 'open valve' command to ODDITY. The valve status of ODDITY was updated to 'open' and the updated status was then sent back to the gondola (seen at Packet Number 14); the group was able to visually verify the valve opened at this time and remained open. Then, the gondola sends a 'fan on' command 1 km below apogee. The fan status of ODDITY was updated to 'on' and the updated status was again sent back to the gondola (seen at Packet Number 24).

#### 5.3.1 Level 1

The first level of success for the communications of ODDITY was met once the communication link between the gondola and ODDITY was established. This was verified by analyzing that ODDITY was receiving data packets from the gondola; ODDITY's microcontroller was connected to a serial monitor and the collected packets were displayed.

#### 5.3.2 Level 2

During the full system communication test, the valve opened and the fan turned on after the gondola sent their respective commands; the components turning on were verified visually. This indicates that ODDITY was able to receive and interpret the specified commands from the gondola. Thus, the second communications level of success was met.

#### 5.3.3 Level 3

As seen in Figure 33, ODDITY component status was updated during the flight. Since the plotted data was received from the gondola, this indicates that ODDITY received commands from the gondola, updated the component status, and sent the updated status of ODDITY back to the gondola. Thus, the third communications level of success was met.

### 5.4 Survivability

#### 5.4.1 Level 1

The first level of success for the survivability of ODDITY states that the system should be able to survive in temperatures and pressures similar to those expected to be seen at altitudes up to 35 km. To verify this level of success, two tests were performed, both in a thermal chamber provided by Professor Palo, and a cooler filled with dry ice.

The first test that was performed was in the low temperature chamber provided by Professor Palo. For this test, the full ODDITY system was placed in the cold temperature chamber and it was programmed to simulate tasks throughout the duration of the flight. This included the servo being turned on to open and close the valve, the fan being turned on and off, the executing of the heating law, and the cutaway resistor being turned on. These commands were sent through RX/TX wires because the XBee radio was unable to communicate through the walls of the thermal chamber. The voltage output of the batteries and temperature of the chamber were also manually measured and recorded every 5 minutes. The ambient temperature provided by the temperature chamber was periodically stepped down from room temperature to -60 °C. The heating loop was set to turn on the heater when the internal temperature of the insulation housing fell below 15 °C and then continue to heat it until the temperature reached 25 °C. The test setup is shown in Fig.34

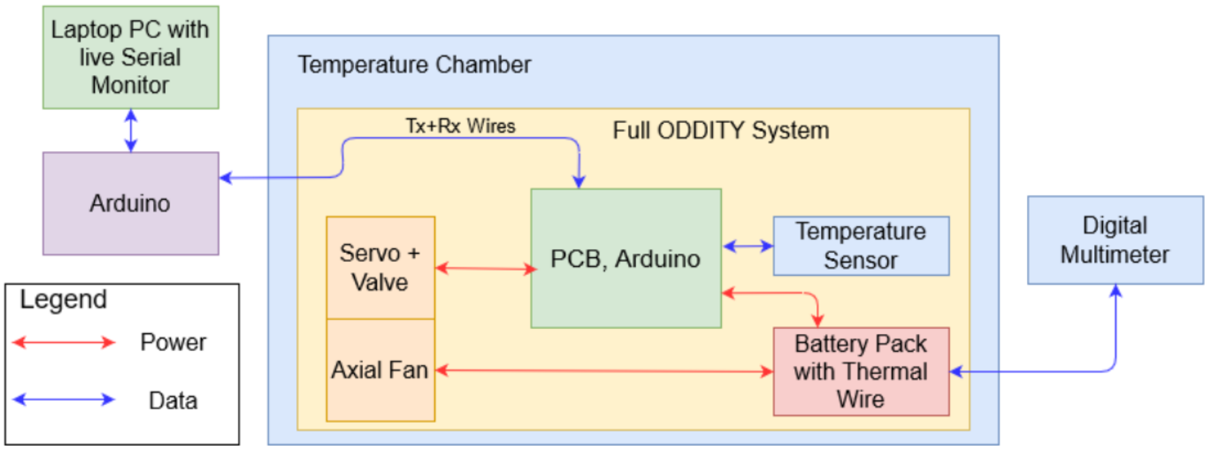


Figure 34: Thermal Chamber Test Setup

The results of this test are shown in Fig. 35.

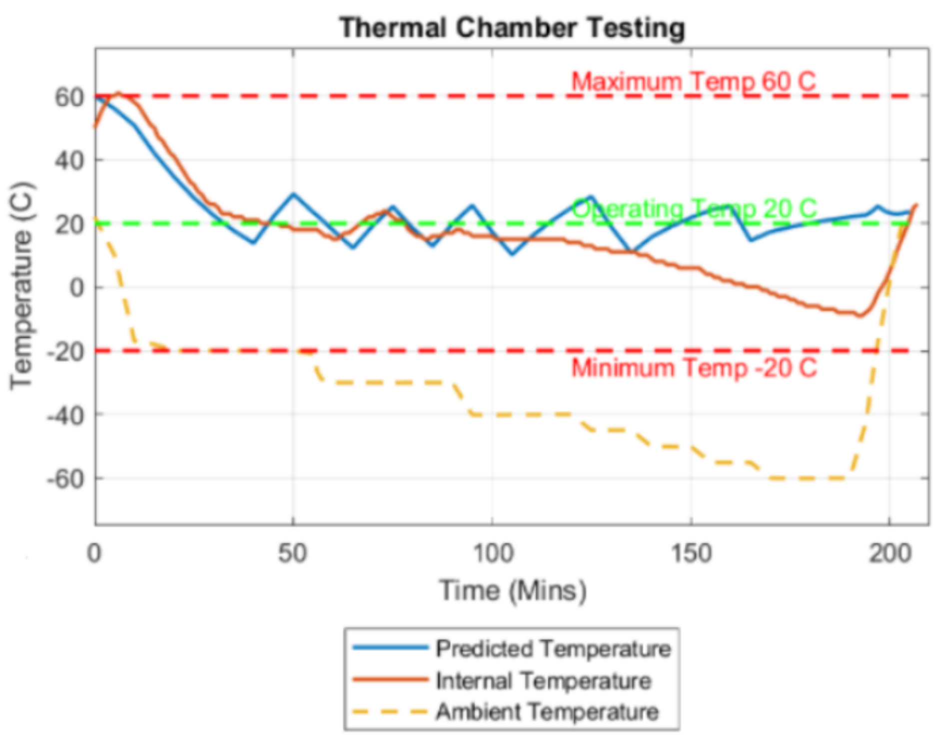


Figure 35: Thermal Chamber Test Results

This plot shows the ambient temperature of the thermal chamber in yellow, the temperature measured by the temperature sensor inside the insulation housing in orange, and the internal temperature predicted by the thermal model in blue. Unfortunately, the thermal chamber testing experienced a few issues which are seen in the plot. First, while placing the ODDITY system in the thermal chamber, there was a short within the insulation housing which visibly smoked and caused the temperature within the insulation housing to rise to about 60 °C, which is seen at the beginning of this plot. After fixing the short and placing the system back in the chamber, the insulation plug loosened and was ajar for the remainder of the test. Because of this, there was a gap in the insulation which caused air to escape the housing, therefore discounting the results of this test. A picture of this is shown in Fig. 36. The plug protrudes from the top of the insulation cylinder and is not flush with the edge.

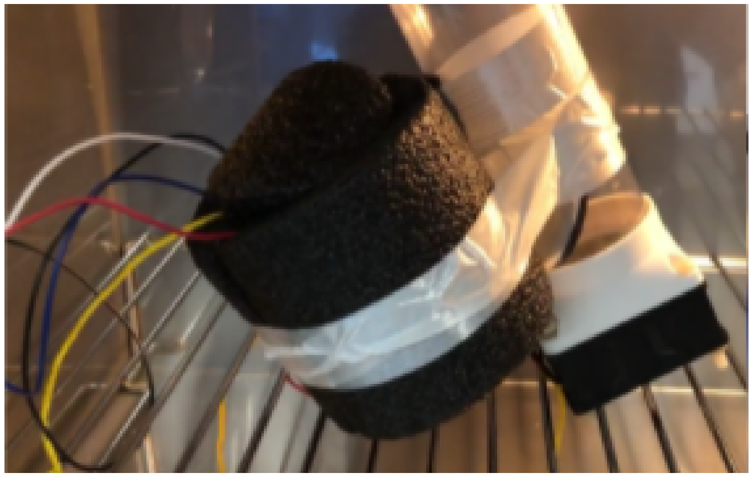

Figure 36: Insulation Cap Ajar During Thermal Chamber Testing

The thermal model predicts that with 1.5 W of power, the heater should be able to maintain the temperature within the insulation around the desired temperature of 20 °C, however the plot shows a divergence towards the end of the test. This is most likely due to the gap in the insulation housing. The lowest temperature within the insulation was recorded to be 9 °C at which point the voltage output of the batteries was measured to be about 5.86 V, which was far below the desired output of 12 V. Overall, the results from this test were inconclusive because the insulation was not sealed as it was intended to and the heater was not able to heat the chamber as desired. However, after this test, it was determined that the gauge of the heating wire should be increased to make it easier to solder to the PCB and to increase the number of loops around the battery packs to 10 loops in order to increase the amount of surface area that is heated which would provide more contact heating in cases with low convection which is expected at higher altitudes. This also increased the power dissipation of the heating system to about 4.32 W which ensures that the heater would be able to keep up with the ambient temperature.

The second test was performed in a Yeti cooler filled with dry ice. In this test, the full ODDITY system was placed in the cooler and surrounding by a "box" of dry ice blocks, including one elevated by a rack, which allowed the cool air to fall onto the system. Thermocouples were placed in three places around the cooler to quantify the ambient temperature gradient within the cooler. Three other thermocouples were placed on the fan motor, within the insulation close to the batteries, and within the insulation next to the servo in order to quantify the temperature close to and within the ODDITY system. Commands and statuses were sent between the ODDITY system and an Arduino through XBee radio communication. The commands were executed at the times that simulated a 4 hour flight including the servo and fan turning on and off, the heater turning on based on it's control law, and the cuataway system being activated. The system was placed in the cooler when the cooler was at room temperature, and then slowly lowered to temperatures between -60 °C and -70 °C by adding dry ice in order to simulate cold-day scenarios during a flight. The test setup and thermocouple placement is shown in Fig. 37. The thermocouples are represented by the blue dots.

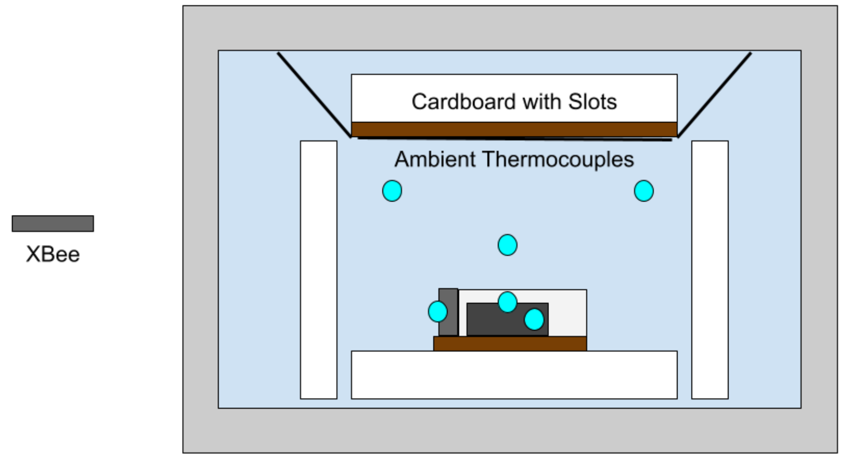


Figure 37: Dry Ice in Cooler Test Setup

The results from this test are shown in Fig. 38

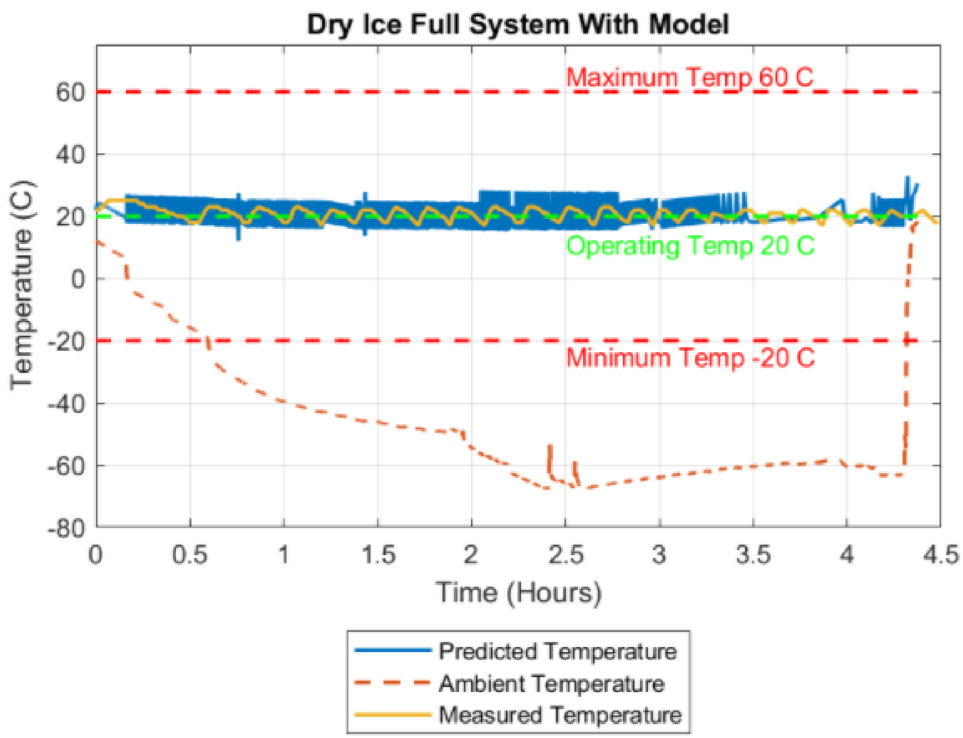


Figure 38: Dry Ice in Cooler Results

This plot shows the lowest recorded ambient temperature of the cooler in red, the temperature recorded within the insulation by ODDITY's temperature sensor in yellow, and the internal temperature predicted by the model in blue. This plot shows that the test was successful and the results were promising. First, the plot shows that the ambient temperature very close to the system was able to reach temperatures of -70 °C. The temperature within the insulation was also maintained within the 18°C to 22°C bounds that were specified by the thermal control law for the duration of the flight. The voltage output of the batteries was also measured to be around 11 V for most of the flight, only dipping to 9V while the ambient temperature was around -70°C on and both the heater and fan were on. The voltage measurement was truncated and rounded down, so though it recorded 9V, it could have been much closer to 10V. Additionally, all the electronic components of the system actuated at the desired times and for the desired duration except for the cutaway resistor. The data packages sent by the ODDITY system reported that the cutaway system was activated, however the resistor did not cut through the tether. This is believed to be due to the fact that the test code was designed to only turn the cutaway resistor on for 5 seconds. After the thermal test, the cutaway resistor was turned on with the same battery pack and it was determined that the tether was cut after 10 seconds which shows that the battery pack was still capable of cutting through the tether after the simulated duration of the flight. It is also important to note that in a real flight, the cutaway resistor would be left on in order to drain the batteries, so this gave the team confidence that the cutaway would be capable of cutting the tether after the duration of the flight.

The model also predicts that the heater should be able to maintain the system between 12°C and 32°C. The results show that the thermal system performed better than the model predicted which makes sense because the model is a fairly simple heat transfer model based on 2-D equations instead of 3-D heat transfer. The model also applies the full 4.32 W of heat to the system when the heater is meant to turn on. In the actual case, the wire would warm up slowly after being turned on. This is why the heater appears to turn on and off more frequently in the model than the experimental results. Overall, the results of this test show that ODDITY is able to survive conditions that simulate the temperatures seen at 35 km and that it satisfies the 1st level of success for survivability.

### 5.4.2 Level 2

To achieve the second survivability level of success, the team needed to verify that ODDITY can survive the pressures and temperatures seen up to 35 kilometers in altitude. The only true seal on the ODDITY is the valve which means that the low pressures at altitude were less of a concern than the low temperatures. Although the dry ice testing did show that ODDITY's heating system would likely be sufficient, the team still hoped to verify that flight conditions would not reduce the effectiveness of the active heating. One concern was that the thinner air would not allow for as much convective heat transfer within the insulation. The heating wire was chosen to help mitigate this risk, but actual flight results were needed to verify the heater's performance.

Since the first flight test only returned reliable data up to nine kilometers, the 2nd level of success was not fully verified. As shown in Fig. 39, the active thermal control system was performing well up until the GPS issues occurred. The ODDITY internal temperature, the heater status, and the battery voltage are all plotted together. The goal was to keep the internal temperature near $20^oC$. To do this in flight a simple control law was implemented. Using the reading from the on-board temperature sensor, the ODDITY was programmed to turn on the heater if the temperature drops to $18^oC$, and turn off the heater once the temperature reaches $22^oC$. The temperature sensor used to measure the internal temperature has an accuracy of $\pm 2^oC$. As shown in the plot, the temperature of ODDITY starts off warm and begins to decrease slowly as the balloon ascends. Then, the heater status changes to on and ODDITY heats up until it makes it up to $22^oC$. This process repeats several times with ODDITY cooling back down more quickly as the altitude increases. This was expected due to the decreasing temperature as the balloon ascends. Overall, ODDITY was able to heat itself up from $17^oC$ to $23^oC$ quickly each time, indicating that the heating system was performing nominally until the GPS issues occurred.

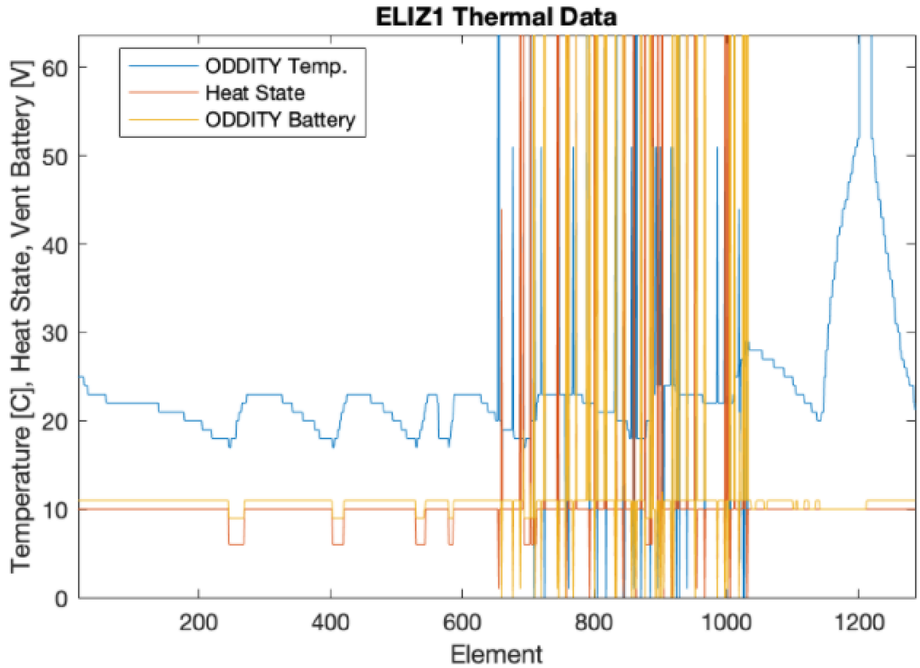


Figure 39: Thermal Control System Performance During Flight Test 1

The second flight test returned much better results seen in Fig. 40. The temperature recorded by the temperature sensor inside the insulation is shown in blue and the ambient temperature recorded by the gondola is shown in red. This time there were no GPS issues and the data packages returned reliable data. All the electronic components activated as planned and ODDITY achieved altitudes of 32 km. The active heater was set to turn on with the same temperature bounds as the first flight. Between launch, and an apogee of 32 km, the lowest temperature seen was around 20 km and according to the standard atmosphere, the coldest temperatures occur between 14 and 20 km. This means that though ODDITY did not reach the target altitude of 35 km, the temperatures that one would expect to see at 35 km are much warmer than what ODDITY experienced at 20 km. Therefore, this test is still useful in verifying that the system can operate in conditions seen up to 35 km. The results show that the internal temperature stayed within the control laws bounds of $18^oC$ to $22^oC$ for the full duration of the flight. The lowest battery voltage that was recorded was 9V a handful of times during the flight. However, as was the case in the dry ice test, the voltage data is truncated and rounded down meaning that it likely didn't fall as low as 9V. These instances also probably occurred during the times that multiple electronics were on as observed with he dry ice test. Overall, these two flight tests show that the heating system was able to achieve the 2nd level of success for survivability.

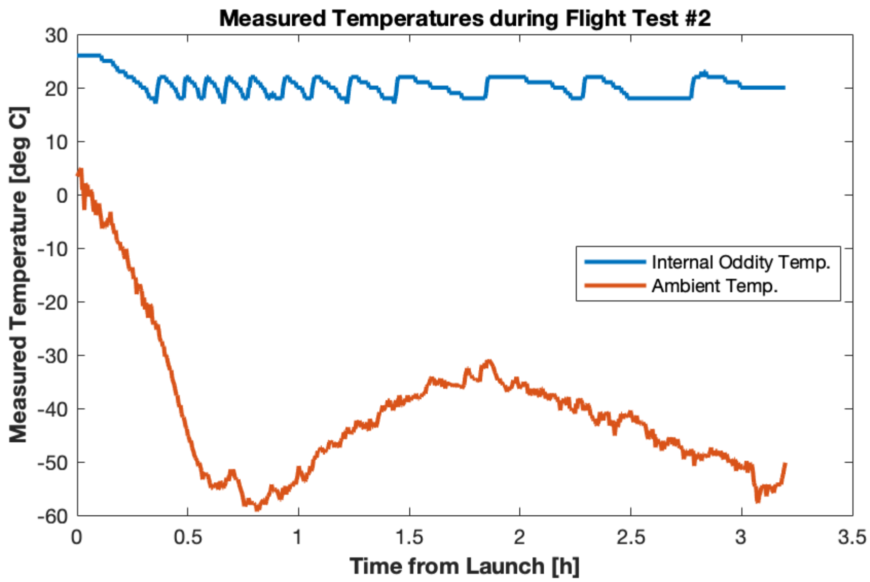


Figure 40: Thermal Control System Performance During Flight Test 2

# 6 Risk Assessment and Mitigation

Authors: Anders Olsen

Project ODDITY had to deal with risks like all projects have to. ODDITY went about dealing with these risks by identifying them, categorizing them, and then actively monitoring and mitigating them.

Before any project risks for ODDITY could be assessed and mitigated they had to be identified. ODDITY identified risks by seeking out potential places where failure could occur. These potential failure points were then noted as risks that should be looked into more deeply. In addition, ODDITY looked for risks that would prevent the group from being able to achieve goals that had been set forth. An example of this is the Test Flight is Unable to Happen risk which was identified when the group made the goal of testing and gathering data about ODDITY in its operating environment. This risk would prevent that goal from happening and was thus identified.

After the group identified a risk to ODDITY, the risk would be categorized. This categorization happened by placing the risk into one of five 'Likelihood' categories and one of five 'Impact' categories as seen below in Fig. 41. By placing the risk into these 'Likelihood' and 'Impact' categories, the team was more easily able to identify the most impactful risks and therefore prioritize the risks and their subsequent mitigation.

| Level | Likelihood | Impact |
|---|---|---|
| 5 | Certain | **Catastrophic:** The entire flight will be rendered useless due to risk |
| 4 | Highly Likely | **Severe:** Very little useable scientific data is able to be used from flight |
| 3 | Likely | **Major:** Some data is able to be gathered, uncertain data accuracy |
| 2 | Improbable | **Minor:** Issues prevent all data gathering, but still overall successful |
| 1 | Extremely Improbable | **Minimal:** Mission is still able to be accomplished with minimal issues |

Figure 41: ODDITY Risk Likelihood and Impact Categories

Based on these categories, the team was able to assign a numerical score to each risk's 'Likelihood' and 'Impact' based on the numbers seen in the 'Level' column in Fig. 41. The 'Likelihood" and 'Impact' values were then multiplied together to assign the risk a 'Risk Level.' These levels of risk and their corresponding scores can be seen below in Fig. 42.

| Score (Impact * Likelihood) | Level of Risk |
|---|---|
| 1 - 5 | Low |
| 6 - 14 | Medium |
| 15 - 25 | High |

Figure 42: ODDITY Risk Levels

These risk levels allowed the group to be able to quickly assess the severity of a risk and helped to streamline the prioritization of risk mitigation. This mitigation looked different for different types of risks to the project. Risks related to project planning and logistics were often mitigated through careful planning and providing ample buffer time for the activity to be completed. This could be seen in the 'COVID-19 Closures' and 'Test Flight does not happen' risks seen in Fig. 43. These risks were mitigated and did not pose significant issues in large part because of the careful planning and buffer time built into the schedule.

Risks that were related to technical feasibility, however, were mitigated in a different way. The first way that these were mitigated was with a redesign to prevent the issue from being a risk in the first place. This strategy was used with the on board heating system that originally consisted of a single resistor that would dissipate power (risk can be seen below in Fig. 43). Through discussion with Dr. Lawrence and further considerations, it was determined that the single resistor would not be sufficient to mitigate the cold batteries risk. Due to this, the heating system was redesigned to consist of two stainless steel wires wrapped around the batteries and acting as resistors. The other way these technical risks were mitigated was through thorough testing. The best example of this technique being applied was when the group was mitigating the 'Fan cannot remove helium fast enough' risk seen in Fig. 43. To mitigate this thoroughly, the group did numerous tests of the active descent control system. The tests involved measuring the pressure differential created across the axial fan at different ambient pressures between 'Boulder pressure' and the pressure seen at approximately 40km MSL. These volumetric flowrates measured from these tests were then compared to the required volumetric flow rates (see Section 3.1.1: Balloon Dynamics Modelling). These test results were also compared to our CFD models to verify the CFD (see Section 5.1) to further mitigate the risk and prevent it from being an issue.

| Risk | Before Mitigation | After Mitigation | Was it an Issue? |
|---|---|---|---|
| COVID-19 Closures | *Impact:* Severe<br>*Likelihood:* Highly Likely | *Impact:* Severe<br>*Likelihood:* Likely | Slight Issue |
| Test Flight does not happen | *Impact:* Minor<br>*Likelihood:* Likely | *Impact:* Minor<br>*Likelihood:* Improbable | Not an Issue |
| Fan cannot remove helium fast enough | *Impact:* Major<br>*Likelihood:* Likely | *Impact:* Major<br>*Likelihood:* Improbable | Not Expected to be an Issue |
| Insufficient battery power | *Impact:* Major<br>*Likelihood:* Improbable | *Impact:* Major<br>*Likelihood:* Extremely Improbable | Not an Issue |
| Batteries get too cold | *Impact:* Major<br>*Likelihood:* Likely | *Impact:* Major<br>*Likelihood:* Extremely Improbable | Not an Issue |

Figure 43: ODDITY Primary Risks

Throughout the project, ODDITY identifying and mitigating risks to ensure the best chance of success for the project. Of ODDITY's primary risks (Fig. 43), only two were not fully mitigated and therefore impacted the outcome of the project. The first risk that was not fully mitigated was the risk that the fan would not be able to remove helium from the balloon envelope at a fast enough rate. This risk was unable to be fully mitigated because the group was only able to have one successful test flight. This test flight yielded encouraging results that show the fan made an impact and improved the descent performance, however, this was only one test so it cannot be fully relied on to show average performance of the system. Despite this, the risk was significantly mitigated through extensive low pressure testing and CFD modeling to verify its performance at extreme altitudes. Because of this, it has only had a minimal impact on the success of the project and can be further mitigated with more test flights. The other primary risk that was not fully mitigated in this project was the COVID-19 risk. This risk was unable to be fully mitigated because of the nature of COVID-19 and its ongoing effects on all aspects of group interaction. Because of this risk, the group had to be more diligent and deliberate in scheduling ahead of time as well as ensuring all proper protocols were being followed to keep everyone safe.

Despite the group's best efforts to identify all possible risks to the project, there was a large risk that went unnoticed until it impacted the group. This risk was the risk of the gondola board having a failure. The group assumed that the provided gondola board for the test flight would be in working order and would not have issues, but this turned out to not be the case. During the flight, the GPS on the gondola board malfunctioned and prevented the gondola from ever sending the descent control commands to ODDITY. This prevented the group from being able to determine the descent control system effectiveness in flight and therefore limited the success of the test flight. Learning from this surprise risk, the group plans on testing the gondola system prior to the next test flight to ensure all systems are functioning properly so that this issue will not happen again.

# 7 Project Planning

Authors: Alex Larson, Thania Ruiz

## 7.1 Organizational Chart

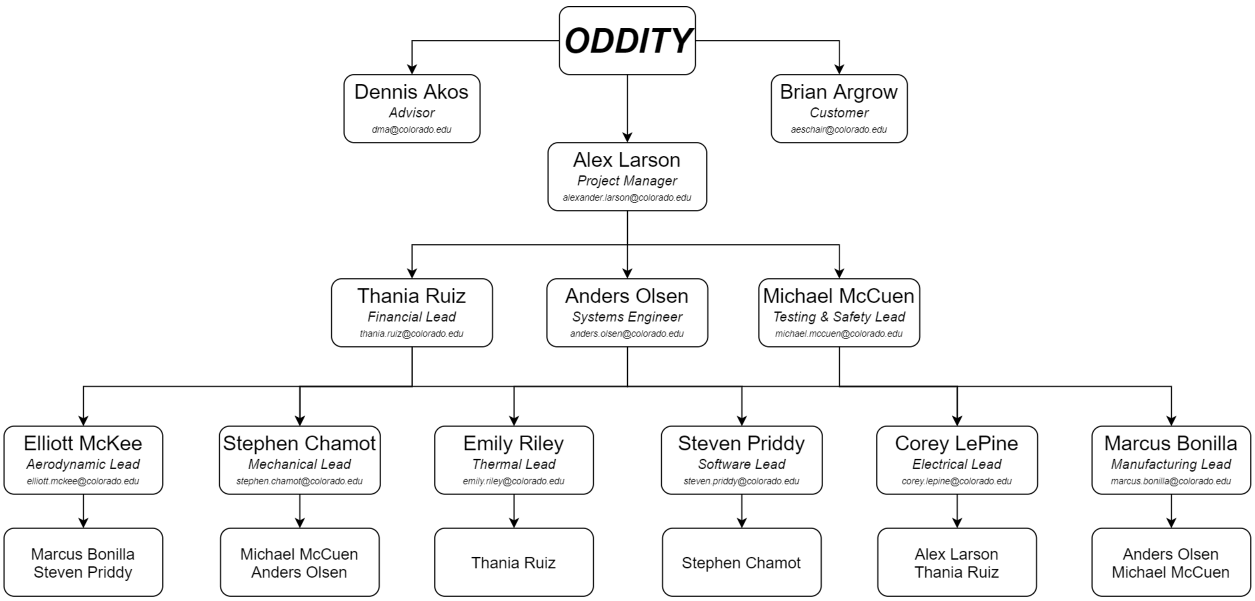


Figure 44: Project ODDITY Organizational Chart

Figure 44 shows the Organizational Chart (OC) for Project ODDITY. At the top of the organization structure is the project, flanked by Dr. Brian Argrow, the customer, and Dr. Dennis Akos, the faculty advisor. The next tier contains Alexander Larson, the group's elected project manager who has been instrumental in ensuring Project ODDITY remains on schedule and successful in its tasks. Below Alex are the high level leads: Thania Ruiz who is in charge of all financials for ODDITY, Anders Olsen who is the systems engineer for the project, and Michael McCuen who heads testing and safety for ODDITY. The fourth tier is the most important tier and it includes the system leads for Project ODDITY. Elliot McKee is the aerodynamic lead and has been spearheading CFD modeling for the group, Stephen Chamot is the mechanical lead and has been responsible for the CAD models and designs used by the group, Emily Riley is the thermal lead and has lead the development of the thermal models for ODDITY throughout predicted flight paths, Steven Priddy is the software lead and has largely driven the development of the control and communications code needed for ODDITY to function, Corey LePine is the electrical lead and has developed power budgets and and PCB designs for the project, and finally Marcus Bonilla is the manufacturing lead and has been aiding Elliot with CFD and Stephen with mechanical calculations while also coordinating the manufacturing efforts associated with making an ODDITY unit.

## 7.2 Work Breakdown Structure

Project ODDITY's Spring 2021 Work Breakdown Structure (WBS) is shown below in Figure 45. This WBS contains the major overall tasks that had to be accomplished in the Spring Semester. The first of these is 'Component Testing/MFG' which encapsulates the testing and manufacturing of four of the critical project elements discussed throughout this report with the exception of the neck attachment. It does not appear here as this CPE did not require serious testing to verify and its construction would be dependent upon the other 4 CPE's, but one can see that it's construction planned into the "Building ODDITY" phase. As one can see by the green outline around each box, this section has been entirely completed which allowed the group to move onto the "System construction" and "System Testing" portions of the project. "System

Construction" is broken down into two parts. These parts are "Building ODDITY" which is comprised of the tasks necessary to assemble an entire ODDITY unit and bring all sub-systems and CPE's together to work cohesively and has been completed at this point in time, whereas the "ODDITY Assembly Guide" is still being written and edited to provide to the customer once the project has fully come to a close. The "Systems Testing" grouping involves testing assembled ODDITY sub-systems and even full ODDITY units in low temperature and low pressure environments to ensure that component integration was successful and to garner new information for further refinements to the system. These systems level tests have now all been completed leaving only flight testing to be conducted, which is covered in the next set of task groupings. "Flight Testing" is a culminating point in the project where the entire ODDITY unit has been constructed and thoroughly tested. These flight tests will help to further verify the success of the ODDITY project in it's actual working environment. As was discussed previously, a flight test has already been conducted but due to GPS failures occurring in hardware outside the influence of the group the test did not yield many useful results at all. However with one last flight test planned before the semester comes to a close, the group hopes to fully finish off these last remaining tasks found under the "Flight Testing" grouping. The final section of the Spring WBS is the 'Spring Deliverables' grouping. These deliverables have been completed in parallel to the previously discussed sections, which as one can see have all been completed with the exception of this assignment, "Project Final Report" and will be completed once this document is turned into the PAB for grading.

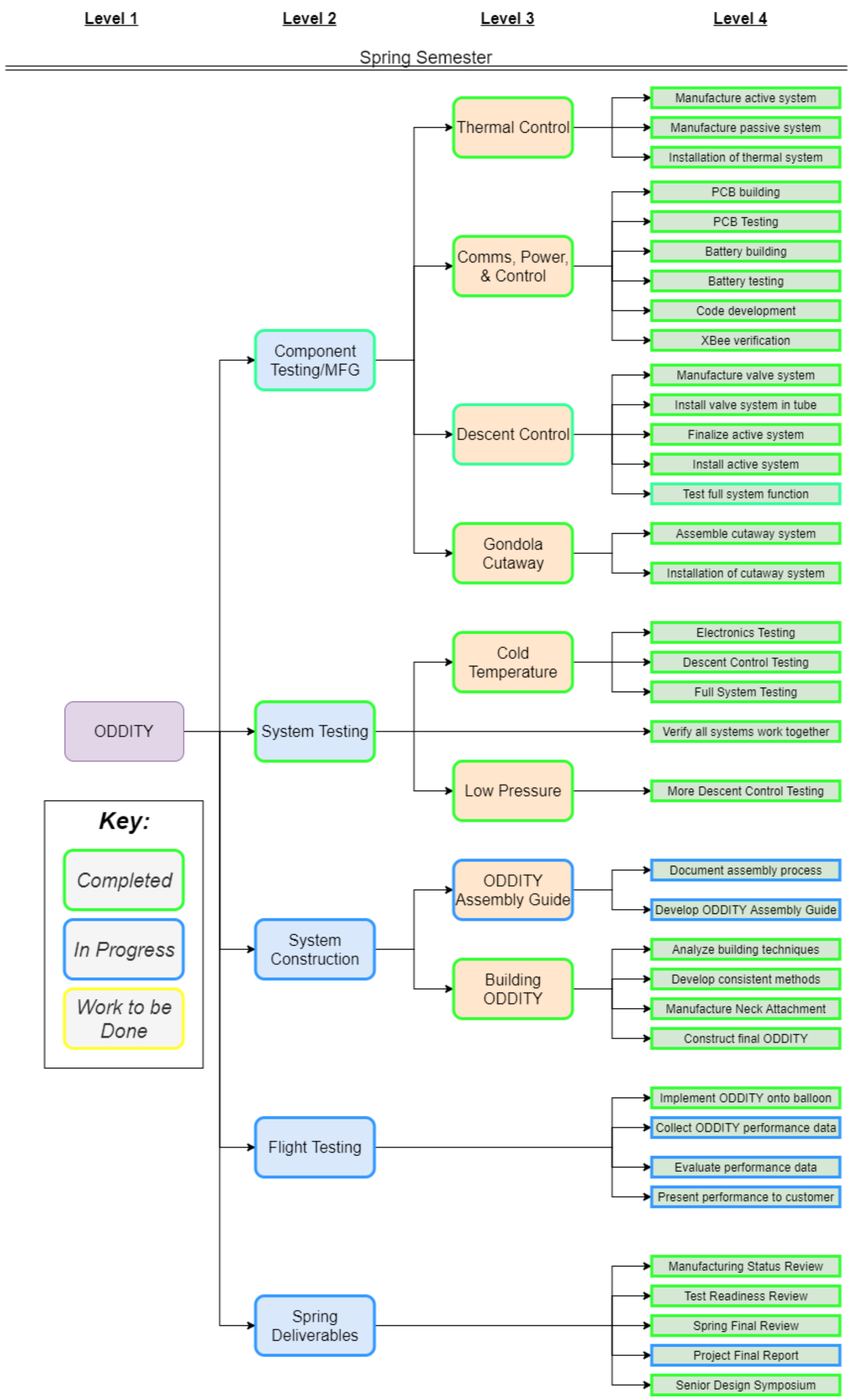


Figure 45: Spring Semester Work Breakdown Structure

## 7.3 Work Plan

In order to accomplish the work and individual tasks that were discussed in the last section, a Gantt Chart was developed to help keep track of all activities and schedule them such that the project can be completed within the confines of the class. Generally the Fall and Spring schedules were developed separately, so that is the way that they will be presented here.

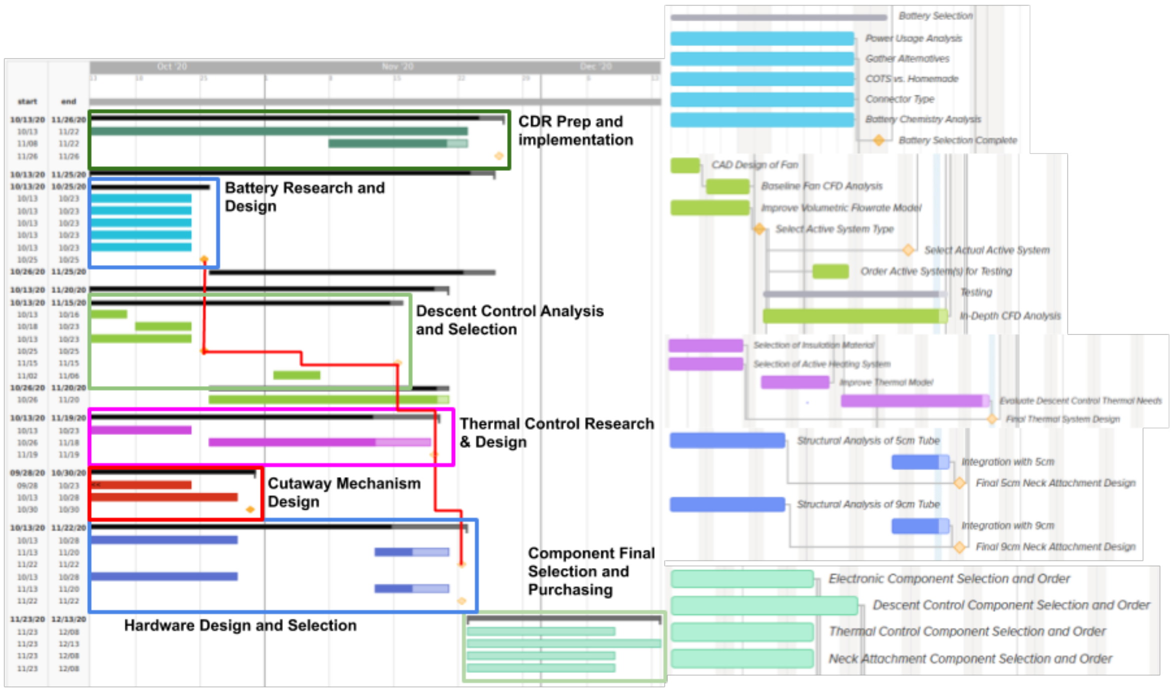


Figure 46: Project ODDITY Gantt Chart for Fall 2020

As one can see by inspecting Figure 46 each set of tasks is broken up by color and in accordance to the project CPE sub-systems. The red line represents the critical path, which connects certain due dates and milestones which represent most critical elements of the project that will effect scheduling and timing of other project elements and shift the overall schedule time line. On the right of the diagram one can see zoomed in images of the task groupings that fall on the critical path. This particular chart represents the time between PDR and the end of the semester where the group began with emphasis on battery selection as this would set up all capabilities of the system going forward and the PAB had expressed particular concern in this area. This task grouping went rather smoothly which set up both the descent control and thermal control design up well knowing their limitations as far as power supply. The descent control analysis and selection phase was extremely critical to achieving project objectives and also influenced the operation of the remaining sub systems. Unfortunately this phase gave the group the most trouble and lasted a bit longer than originally intended. This did effect completion dates of other sub systems, however most analysis was able to be completed simultaneously despite the delay. Descent control selection led into final thermal control analysis and design as thermal considerations were able to be made of the descent control system upon completion. Alongside all of these phases the hardware design was being refined and added to, to reflect ongoing project decisions that were being made. Once all sub system analysis and design work had been completed and related presentations and coursework were given, the hardware design could be finalized and the group could move onto the final phase of the semester which was sub system finalization and component testing. Upon completing this final fall task group, the projects group could move onto winter break testing plans and Spring semester manufacturing and sub system testings plans.

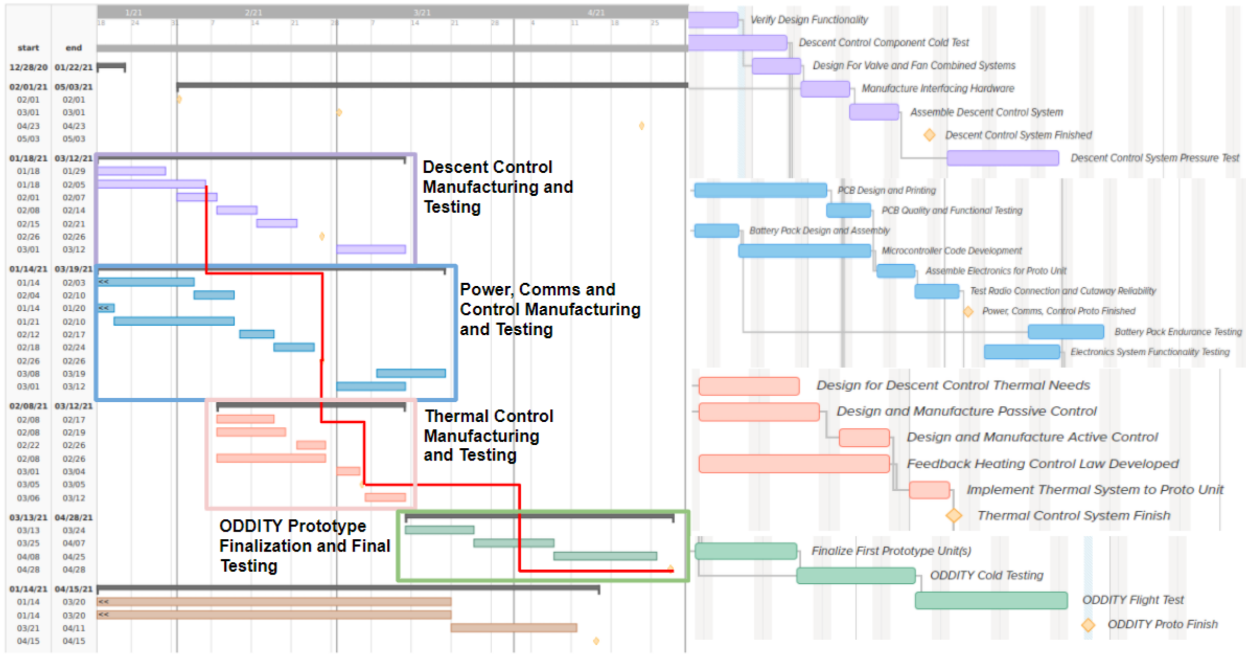


Figure 47: Project ODDITY Gantt Chart for Spring 2021

Figure 47 depicts the groups Spring 2021 Gantt Chart and work plan as it has been conducted and completed up until this point. The task groupings and critical path follow the same formatting as the previous Gantt Chart. Schedule was mostly driven and shifted by MSR and TRR completion dates, where the group completed almost all manufacturing by TRR and was able to display their readiness to move into the testing phase. As one can see Descent Control and CPC task groupings were largely able to be completed in parallel where as the Thermal Control tasks were dependent on Descent Control progress and decision making, which is why the beginning of these tasks had to be offset from the beginning of the semester. Unfortunately building in visual representation of margin is the one feature that this Gantt software (TeamGantt) lacks in. So with this in mind, when scheduling lengths of each task, more time was given than thought would be necessary to account for various scheduling delays and act as a form of built in margin. Furthermore, each milestone that marks the end of each task group was scheduled with about 3 to 5 days worth of margin after the the last task in the group was meant to be complete. The schedule was constructed in this way in hopes that delays and deviation from the schedule could be kept to a minimum and ensure the best possible chances of achieving a flight test by the end of this semester. As a couple of flight tests were conducted within the last couple weeks, this effort was largely successful, but not without obstcles and bumps along the way. But these obsticles and bumps will be addressed more in the Lessons Learned section of this report.

This Spring Gantt Chart begins with fan component pressure and cold testing which was extremely critical to the remainder of the schedule and finishing an ODDITY prototype in a timely manner. These tests began over winter break given the hugely important implication of the results in regard to the project design. Thankfully these preliminary tests gave the team necessary confidence to move on with the design choice made and continue development of the project. Beginning in the spring semester both manufacturing and testing processes for descent control and CPC sub-systems began with the two phases will ending in the integration of the two systems onto the ODDITY hardware neck attachment, and subsequent testing of the systems once assembled. After the major descent control design choices were made, manufacturing of the thermal control hardware begun as well as the evaluation of the axial fan and it's thermal needs. This stage came to a close by conducting system low temperature tests to ensure that the designed thermal system had the ability to monitor and control temperature in the insulation tube as intended. After these main stages of manufacturing are complete, final assembly of an ODDITY unit will be done and full unit testing will begin. The two main tests in this stage was completing more in depth low temperature tests of the full ODDITY unit and attempting to conduct a flight test which would put the ODDITY to use in it's intended environment. One final note about this Spring 2021 work plan is that full documentation of ODDITY manufacturing procedures will be taken and a manufacturing guide will be developed in parallel with the rest of the project task groups. This will be done in order to carefully and meticulously document the procedure of assembling and integrating each sub-system as it is being made.

## 7.4 Cost Plan

| *ODDITY Parts* | *Quantity* | *Cost* | *Total* | *Uncertainties* |
|---|---|---|---|---|
| *Electronics* | | | $99.68 | $6.42 |
| Arduino Nano | 1 | $12.90 | $12.90 | $3.52 |
| Xbee Zigbee 3 | 1 | $16.21 | $16.21 | $1.60 |
| ASP CR123A Batteries | 4 | $1.90 | $7.60 | $1.00 |
| Transistors | 4 | $0.45 | $1.80 | $0.00 |
| Temperature Sensor Resistor | 1 | $0.06 | $0.06 | $0.10 |
| Voltage divider Resistors | 3 | $0.31 | $0.93 | $0.00 |
| **Solder Flux** | **1** | **$26.99** | **$26.99** | **$0.00** |
| Current Limiting Resistors | 1 | $0.19 | $0.19 | $0.20 |
| Printed Circuit Board | 1 | $33.00 | $33.00 | $0.00 |
| *Thermal Control Parts* | | | $33.50 | $3.00 |
| **Insulation (6ft)** | **1** | **$19.20** | **$19.20** | **$2.00** |
| **Active Stainless Steel Wire** | **1** | **$8.65** | **$8.65** | **$0.00** |
| Thermal Tape | 10 | $0.37 | $3.70 | $0.00 |
| Temperature Sensor | 1 | $1.95 | $1.95 | $1.00 |
| *Descent Control Parts* | | | $33.53 | $4.50 |
| Servo | 1 | $7.98 | $7.98 | $0.50 |
| Sealing Valve | 1 | $2.00 | $2.00 | $1.00 |
| **Foam Tape** | **1** | **$12.23** | **$12.23** | **$0.00** |
| Axial Fan | 1 | $11.32 | $11.32 | $3.00 |
| *Cut Away Mechanism Parts* | | | $0.50 | $0.10 |
| Burning Resistor | 1 | $0.50 | $0.50 | $0.10 |
| *Balloon Attachment* | | | $12.00 | $7.00 |
| **Nylon Bolts** | **1** | **$27.99** | **$27.99** | **$0.00** |
| **Sealing Glue** | **1** | **$4.75** | **$4.75** | **$0.00** |
| **Mounting tape (3ft)** | **1** | **$6.99** | **$6.99** | **$0.00** |
| Diffuser Neck Attatchment | 1 | $2.00 | $2.00 | $3.00 |
| Balloon Neck Plastic Tube (5 cm) | 1 | $4.00 | $4.00 | $2.00 |
| Balloon Neck Plastic Tube (8 cm) | 1 | $6.00 | $6.00 | $2.00 |
| | | Total | $179.21 | $21.02 |

Figure 48: Project ODDITY Cost Plan

In the figure 48 shows the costs of all the major components of project ODDITY. It is separated into each subsection of our team along with the uncertainties of the items. The uncertainties of the costs relates to difference in the lowest and highest cost found. These uncertainties are included due to the possibility that the original provider is out of stock and the item must be purchased through a different provider which has a higher cost of the item from the originally predicted price. Per customer requirement the maximum cost for project ODDITY is $200.00 in the last row of the figure above shows the total and the total of all the uncertainties in the costs, adding the total with the uncertainties, project ODDITY is about 23 cents over budget. However, in the figure above there are several items that are bolded those are items that were bought it bulk and can be used to construct more than one ODDITY unit.

| ODDITY Budget | Costs | Margin |
|---|---|---|
| ODDITY Maxumum Budget | $200.00 | - |
| ODDITY Total Cost | $179.21 | 89.61% |
| Total Cost w/ uncertainties | $200.23 | 100.12% |
| Surplus Budget w/out uncertainties | $20.79 | 10.40% |
| Surplus Budget w/ uncertainties | -$0.23 | -0.11% |
| | | |

Figure 49: Project ODDITY Cost Margins

The maximum budget for Project ODDITY is shown in figure 49 along with the margins for the initial cost and the cost with the uncertainties applied. As seen above only 89% of the budget is used and having 10% of the budget to make further adjustments after the adjustments that were made since the fall semester to components in the project. With the uncertainties applied these values do change, and the budget exceeds the margins by 0.12%. As mentioned before there are some items that must be bought in bulk and can be used for several ODDITY units.

# 8 Lessons Learned

Authors: Alexander Larson, Anders Olsen

Overall project ODDITY was a great success for the project team and was a fantastic experience, however, this did not go without some bumps along the road. The largest of these which impacted everything from schedule to personnel allowed to work on the project in in-person capacities was COVID-19. This is a risk and problem that was monitored and mitigated to the best of the groups ability since the beginning of the project, but as the project went on it became clear that even the mitigation efforts taken into consideration particularly on the scheduling side of things was not quite enough. When building out the spring semester project plan in particular large amounts of margin were built into each task, especially when dealing with complex tasks that required an in-person element to complete. With such tasks, which mostly included manufacturing and testing tasks, at least a week margin was built into the task when scheduling it into the project plan. The PM imagined that this mitigation strategy would be fairly sufficient to overcome COVID delays as some tasks would not use up this entire margin and allow for more margin to tack onto more critical tasks that lie upon the critical path. However, almost all of these tasks that required an in person element took as long if not slightly longer than the projected finish date including margin. In general, things like time to gain access to a facility or arrange use of specialized equipment with reduced personnel were anticipated well, however, it was the small and tiny interactions that added up over time. For example tracking down information from a TA, PAB member, or other faculty source proved to be more of a lengthy and difficult process then first imagined. Fairly straight forward questions concerning the behavior or performance of a certain component that should and could have been quickly answered in a matter of minutes with a simple face to face conversation turned into a matter of days and sometimes weeks to get clear answers on such matters via email and virtual meetings. Just setting up lines of communication could prove to be difficult and time consuming let alone when exchange of information and ideas were necessary. Even shipping and supply chain impacts due to COVID took its toll on the project. All components were sourced from within the US in order to try and mitigate these types of delays, but even still the ongoing electronics shortage largely effected the delivery of many electronic components. Batteries that were ordered at the beginning of the semester did not show up for another month and a half after purchase, and even PCB's ordered for manufacturing could end up having a turn around time of a week and half instead of 3 to 4 days as originally projected. These days and weeks spent tracking down information and waiting on extended turn around times were not a huge hit on an individual basis typically but once they started adding up it definitely impacted the project scheduled to such an extent that the inclusion of certain end of life tasks had to be reevaluated. Advice that the team and PM would give to future project teams who might find themselves in a similar limited in person interaction situation, is to not underestimate the impact virtual work can have on schedule. Virtual work, while convenient in certain situations, can be extremely time consuming and days and weeks built into a project schedule can be lost very easily while navigating this virtual work space. Therefore make sure to include what may seem like excessively large margin when building out a project plan, because it may limit you in what you can do with the allotted time, however it will at least help to ensure that a team can accomplish the tasks that are planned for originally.

Continuing with this theme of scheduling, a lesson could also be derived from the manner in which resource allocation and assignment of responsibility was handled throughout the project. If one looks back to Figure 44, project ODDITY's organizational chart, they will notice that most everyone appears on the chart twice in separate locations and tiers of the chart. This was done deliberately in order to maximize team communication and flow of information across sub-teams. However this cross in personnel could lead to certain individuals work loads filling up quickly depending on the given stage of the project. For example for the period in time where an aerodynamic model was still being refined for the descent control team and the manufacturing was beginning to ramp up simultaneously, Marcus could find himself overloaded pretty easily. Most of the time resource management and assignment was handled on a whole team capacity, so when complexities such as these began to pop up this process could become very time consuming. Similar to the previous lesson that was discussed, individual such as these were not a big deal, but over time they could definitely add up and take away from precious lab time that could be used accomplishing some project tasks. Upon reflection of this, it would have been very desirable to arrange for reoccurring sub-team meetings where smaller scale resource management could be conducted and more focused discussion on the plan or execution of a given task could be had internally by the responsible sub-team. This would allow for more efficient use of the team wide meeting time but also give sub-teams the more regular opportunity to discuss progress and challenges outside of the group setting which certainly could have made the overall process more efficient.

A final important lesson the the group learned was the importance of risk mitigation and keeping up with the risks. As discussed earlier, the risk of COVID-19 impacting the performance of the group and different tasks in the project was significant. This result, however, was only possible due to the mitigation efforts performed by every team member so that this risk was not more impactful and disruptive for the project. Overall, the group was very effective with identifying and mitigating new risks, however, these efforts became a bit more lax towards the end of the semester. This was seen during the first test flight of ODDITY when the GPS unit on board the gondola gave out. This gondola unit was given to use by the HYFLITS team, so the project group assumed that it was fully functional and would not be the weak link in the system. The group should have acknowledged that any and all electronics can have issues and should have performed more pre-flight testing of the electronics we were not in charge of to catch any issues like this. This lesson was learned in the first test flight and because of that did not pose a problem during the second test flight.

# 9 Individual Report Contributions

## 9.1 Alexander Larson

Alex contributed to writing section 1, 2.2, 2.5, 7.1, 7.2, 7.3 and 8 of this report. These sections are mostly comprised of the high level aspects of project ODDITY as well as the project management and planning portions of the report. As the PM of the group it was his responsibility to cover these topics, as well structure the report and the overall global cohesion of this document. He also helped with general report proofreading and editing.

## 9.2 Corey LePine

Corey LePine wrote sections 3.2 and 4.2 of this report, which were the final design and manufacturing sections of the electronics subsystem. As electrical lead, Corey was in charge of creating and meeting the power budget, designing ODDITY's circuit, designing and integrating (with aide from other members) the custom PCB, and was aided in the design, assembly, and testing of the battery packs.

## 9.3 Stephen Chamot

Stephen Chamot wrote sections 4.1 and 4.6 of this report. As the mechanical lead, Stephen was in charge of all mechanical designs and designed most of the CAD for ODDITY as well as performed the preliminary data simulations and data analysis on many of the tests throughout the project.

## 9.4 Michael McCuen

Michael McCuen helped to write section 5.4.1 and 5.4.2. He also created Figure 34, which diagrams the test setup used in the thermal chamber. He also helped with general report editing.

## 9.5 Thania Ruiz

Thania Ruiz wrote part of the Thermal Control portion of the Final Design, mainly the Thermal Insulation subsection and part of the Thermal Active Heating section. Thania also wrote the Thermal Control COTS section and part of the Custom Manufacturing subsection. As CFO of Team ODDITY, Thania wrote the Cost Plan subsection within the Project Planning section. Overall, Thania was mainly part of the Thermal Control sub-team and assisted in the battery design and testing.

## 9.6 Marcus Bonilla

Marcus Bonilla wrote the neck attachment sections in the final design, manufacturing and the levels of success. He also helped write some of the final design and manufacturing section of the descent control. Marcus also helped in the general editing of the report.

## 9.7 Steven Priddy

Steven Priddy helped write the Cutaway Mechanism subsections of the Final Design and Manufacturing sections. Also, he was responsible for the Communications levels of success section which described how Team ODDITY met met those levels of success. In general, Steven wrote most of the arduino code for ODDITY testing and had to make modifications for the existing HYFLITS gondola board to implement additional logic for ODDITY's purposes.

## 9.8 Emily Riley

Emily Riley helped write part of the Thermal Active Heating section in the Thermal Control portion of the Final Design. She also wrote about the insulation in the Custom Components portion of the Thermal Control Manufacturing section. Emily also wrote most of the Survivability Verification and Validation section which includes both Level 1 and Level 2. Emily also performed the majority of the thermal modeling and comparison to experimental data and helped with thermal and full system testing.

## 9.9 Anders Olsen

Anders Olsen helped to write the Project Objectives and Functional Requirements section of the PFR document. In this section, he was responsible for the critical project elements, functional requirements, and measures of success sections. He also helped to write the Descent Control section within the Manufacturing section, focusing on the COTS Components parts. Anders also was solely responsible for the Risk Assessment and Mitigation section. Finally, he helped to right the Lessons Learned section.

## 9.10 Elliott McKee

Elliot McKee wrote the Decent Control portion of the Final Design Section. Additionally, Elliott wrote the Descent Control Verification and Validation sections. Elliott handled much of the final descent control testing and analysis leading up to the final versions presented in this SFR, and used in the system design. Handled low pressure testing, with much assistance from other team members, worked on finding discrepancies between the modelled and CFD simulated systems. Handled most processes and modelling related to CFD.

# 10 Appendix

## 10.1 Thermal Control Trade Study

| | Expanded Polystyrene | Polyiso-cyanurate | Extruded Polystyrene | Armaflex Polyethylene |
|---|---|---|---|---|
| *Metric* | *Score* | *Score* | *Score* | *Score* |
| **Density (35%)** | 3 | 4 | 5 | 3 |
| **Thermal Conductivity (35%)** | 2 | 5 | 4 | 3 |
| **Temperature Range (20%)** | 2 | 5 | 1 | 5 |
| **Cost (10%)** | 1 | 4 | 5 | 5 |
| | | | | |
| **Weighted Score** | 2.25 | 4.55 | 3.85 | 3.6 |

Figure 50: Insulation Trade Study

# References

[1] Larson et al. Optimal Descent Device for In-Situ Turbulence AnalYsis (ODDITY) Fall Final Report, 12/11/2021 (not published).

[2] Engineering ToolBox, (2003). U.S. Standard Atmosphere. `https://www.engineeringtoolbox.com/standard-atmosphere-d_604.html` Accessed 4/30/2021.

[3] CR123A Batteries , (2016) Safety Data Sheet `https://sep.yimg.com/ty/cdn/theshorelinemarket/SDS-CR123ABatteries.pdf`