ECE 445

Senior Design Laboratory

Design Document

ILLINI VOYAGER

Dynamically equilibrated high-altitude balloon platform for low-cost sensing and remote data retrieval

Team No. 60

Cameron Jones

(ccj4@illinois.edu)

Christopher Xu

(cyx3@illinois.edu)

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1 Introduction

1.1 Problem

Weather balloons are commonly used to collect meteorological data, such as temperature, pressure, humidity, and wind velocity at different layers of the atmosphere. These data are key components of today's best predictive weather models, and we rely on the constant launch of radiosondes to meet this need. The National Weather Service launches multiple high altitude balloons per day at over 100 sites in the U.S., and in March 2022 declared that 9% of sites suffered from a helium or hydrogen shortage.[1] To conserve helium and avoid pollution from constant launches, we may consider extending the range and lifetime of each balloon.

Most weather balloons today cannot control their altitude and direction of travel—after release, they will rise until the gas expansion inside the balloon causes it to pop, for a total flight time of a few hours. If balloons are able to actively control their altitude, each one would be able to collect data from more targeted regions of the atmosphere, avoid commercial airspaces, and importantly, increase range and duration of flights. A long endurance balloon platform also uniquely enables the performance of interesting payloads, such as the detection of high energy particles over the Antarctic, in situ measurements of high-altitude weather phenomena in remote locations, and radiation testing of electronic components. Since nearly all weather balloons flown today lack the control capability to make this possible, we are presented with an interesting engineering challenge with a significant payoff.

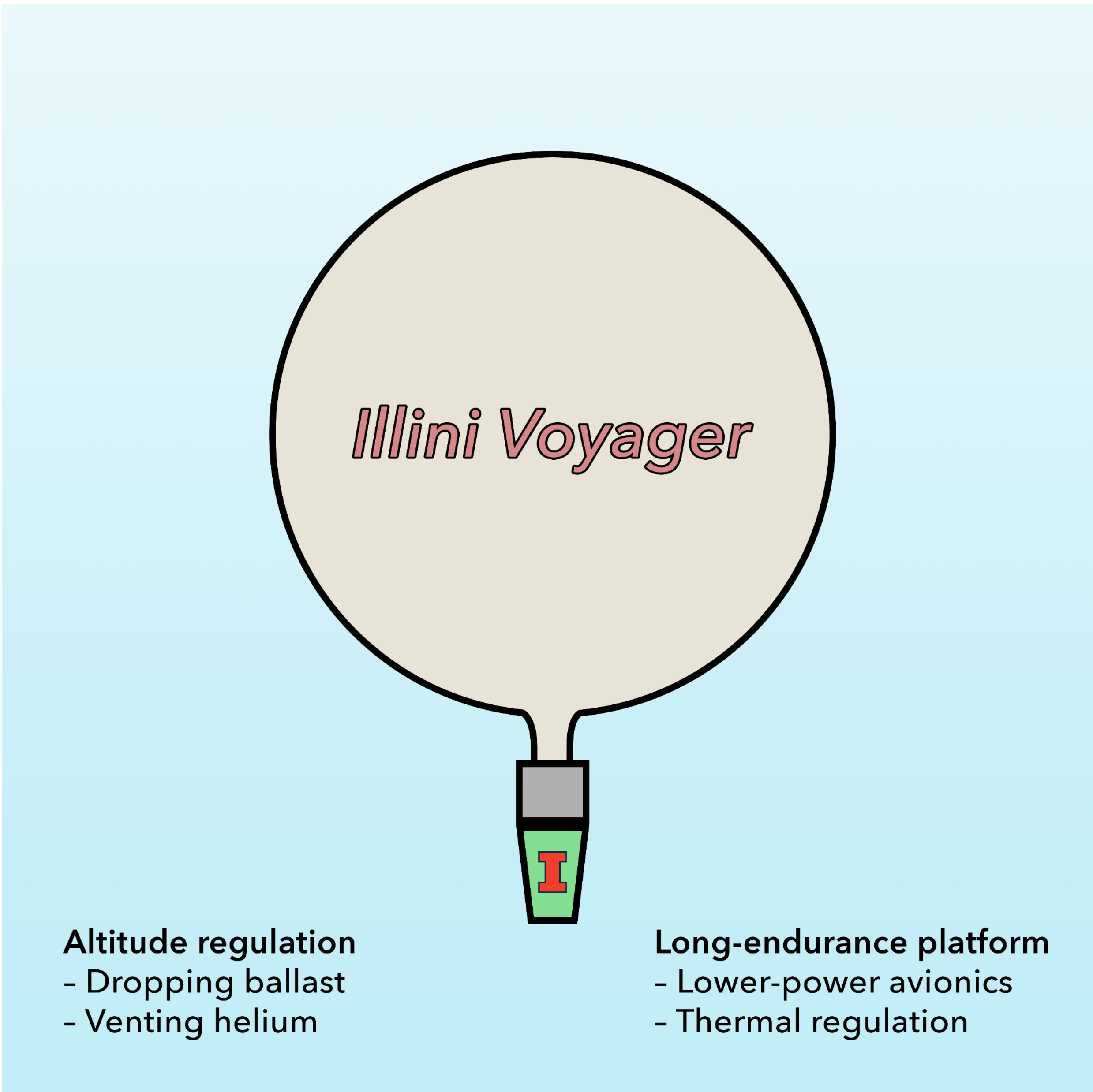
1.2 Solution

We aim to solve this problem through the use of an automated venting and ballast system, which can modulate the balloon's buoyancy to achieve a target altitude range. The venting will be performed by an actuated valve fixed to the neck of the balloon, and the ballast drops will consist of small, biodegradable BB pellets, which pose no threat to anything below the balloon. Similar existing solutions, particularly the Stanford Valbal project, have had significant success with their long endurance launches. We are seeking to improve upon their endurance by increasing longevity from a power consumption standpoint, implementing a more capable altitude control algorithm which minimizes helium and ballast expenditures, and optimizing mechanisms to increase ballast capacity. Given accurate GPS positioning and modeling of the upper atmosphere

[1] National Weather Service. "Helium Shortage and Radiosonde Balloon Launches." Mar 2022.

wind layers using public tools such as GEFS[2], we can target certain altitudes to roughly control the direction of travel, making it possible to choose a rough horizontal trajectory and collect data from multiple regions in one flight.

1.3 Visual Aid



[2] National Centers for Environmental Information. "Global Ensemble Forecast System (GEFS)." 2022.

Our solution consists of a large latex weather balloon with a payload module attached to the neck, which consists of a vent actuator, avionics bay, ballast hopper, and ballast actuator. The above visual aid provides a simplified view of our system in flight.

1.4 High-level requirements

- The system must be able to modulate its equilibrium altitude by venting helium and dropping ballast as directed by an automated control algorithm, compensating for the initial lift surplus as well as temperature fluctuations that can create up to a 10% change in lift over a diurnal cycle.[3]
- The system must make reports with system health and location data at least every 10 minutes, as well as accept remote commands all via a satellite modem.
- The system must have a power subsystem which supports sustained flight operations and consistent satellite communications for at least 48 hours.

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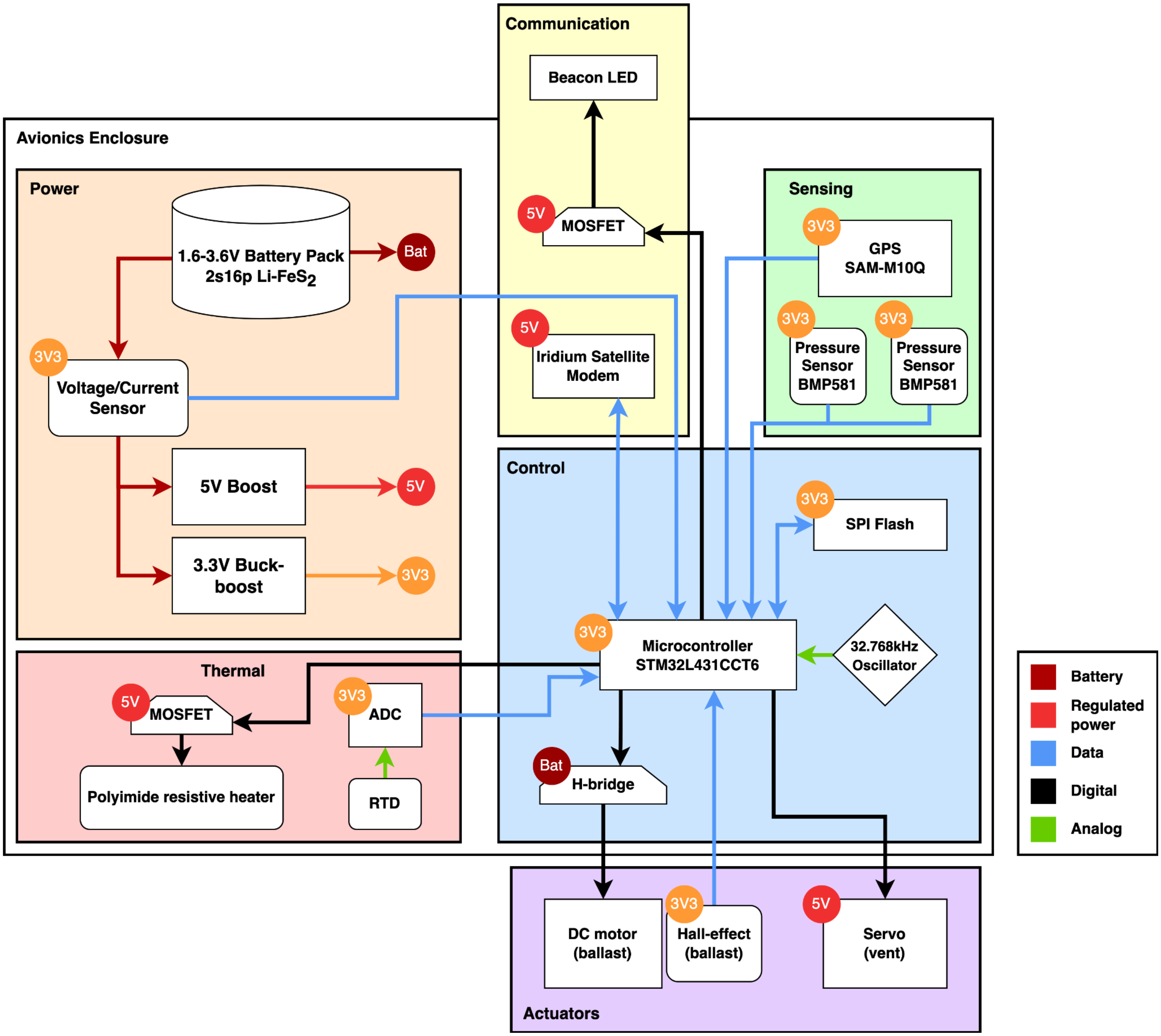
[3] Toyoo Abe et al, "Balloon Systems," in *Scientific Ballooning.* New York: Springer, 2009, pp. 46-47.

2 Design

2.1 Block Diagram

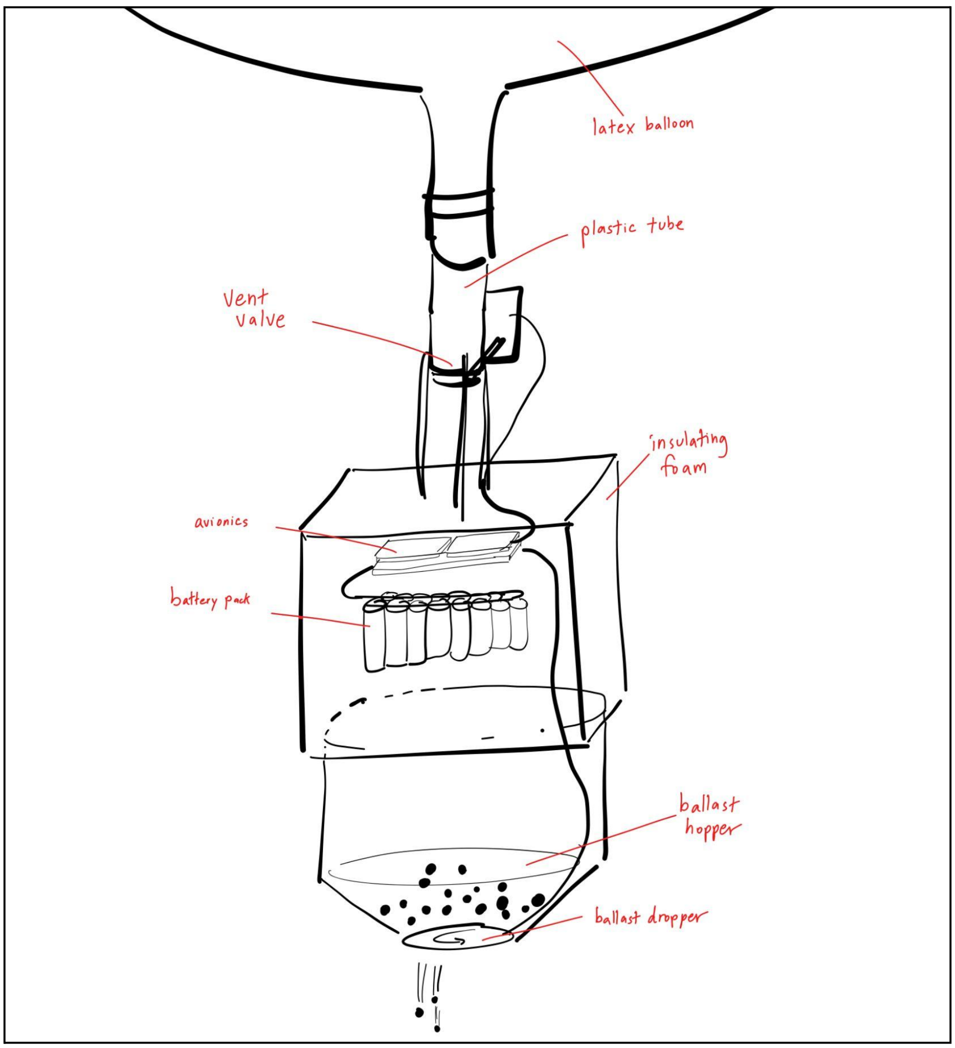


The avionics system is composed of multiple subsystems which perform functions to keep the payload warm, powered, and communicable. The control subsystem is the brains of the avionics, which accepts commands, collects data, and manages the altitude equilibration control loop. The communication subsystem allows for remote data retrieval and commanding via an Iridium

RockBlock 9603 satellite modem. The actuator subsystem enables venting and ballast dropping actuations through a DC gearmotor and a servo that has been modified for operation in cold environments. The thermal subsystem keeps the payload warm by using a heater and a temperature sensor to maintain a survivable temperature for the electronics and batteries. The power subsystem consists of the battery bank as well as a 3.3V buck-boost and 5V boost to supply the necessary power rails for the system. The ground subsystem software provides ground connectivity via the satellite modem provider's API interface to send and receive commands from the balloon while in flight.

2.2 Physical Design

Initial sketch of the structure and physical layout of components:



The entire system will be suspended from a plastic tube lashed to the opening of the latex weather balloon. The vent valve and its actuator is attached to the opening of the plastic tube. An insulating foam box is rigidly attached underneath the valve, where the avionics and battery pack is stored in a warmer environment. The avionics will consist of 3 boards: the main board that consists of the microcontrollers, power converters, and sensors, then the GPS and Iridium modem boards on top of the main board in order to receive better satellite connectivity. The ballast subsystem is below that, which consists of a plastic hopper feeding BBs to a rotary dropper.

Plastics considerations

Our structure will consist of plastic components for their higher strength-to-weight ratio. However, we will need to pick materials that are resistant to low temperatures and UV radiation. We will also avoid using materials with high thermal expansion for dimension critical components.

	Min temp (ºC)	Thermal expansion (10^-5 in/inºF)	Impact strength (ft-lbs/in)	UV resistance	Notes
PETG	-40	3.8	1.7	fair	3D printed, thermoformed
UHMWPE	-40		16.8	fair	Soft, slippery,
HDPE	-70		1.5	ranges	Sheets and bottles
Acrylic	-40	3.4 – 4.2	0.3	good	Lasercut, sheets, tubes
PTFE	-200	7	3.5	good	Soft, slippery
Acetal	-40 – 50	4.7 – 6.8	1-1.5	poor	Hard, machineable
Polycarbonate	-40	3.7	12 – 18	fair	Sheets
PLA	-40		1.8	fair	Non-toxic, porous

2.3 Control Subsystem

A STM32L431CCT6 microcontroller will serve as our flight computer and has the responsibility for commanding actuators, collecting data, and managing communications back to our ground console. An internal watchdog timer will reset the microcontroller to recover from system faults. The controller will use GPS, pressure, and temperature data to determine how to best actuate the vent valve or ballast in order to follow the planned trajectory. This subsystem automatically manages sensor data acquisition, sending data reports, receiving and responding to commands, the thermal control loop, and most importantly, the altitude maintenance control loop.

Requirements Table

	Acceptable range	Verification
Pressure/Altitude measurement	Range: 0 m to 20000m Accuracy: 100 m Rate: ≥1 Hz	Check datasheet
Control loop rate	≥1 Hz	Microcontroller should finish all routine operations within 1 s
Output latency	≥1 second	Heater, ballast, and vent should get the planned signal within 1 s
RTC time	Within 5 minutes of real time	Run the system over 24 hours and compare RTC time with external time.
Power draw	<40mA at 3.3V	Monitor while powered from a bench power supply, running all operations.
Altitude control	Maintain within 5000m of desired altitude	Verified in simulation and during actual launch
GPS connectivity	Maintain lock at 30˚ tilt from horizontal	Tilt the receiver in any direction and check GPS lock quality

2.4 Communications Subsystem

The microcontroller will communicate via serial to the satellite modem (Iridium 9603N), sending small packets back to us on the ground with a minimum frequency of once per hour. There will also be a LED beacon visible up to 5 miles at night to meet regulations for visibility at night. We have read through the FAA part 101 regulations and believe our system meets all requirements to enable a safe, legal, and ethical balloon flight.

Requirements Table

	Acceptable range	Verification
Ground control latency	More than once per minute, and configurable	Send and receive a message over satellite modem every minute
Connectivity	Up to 30º tilt from horizontal	Tilt the modem in any direction and check sending/receiving

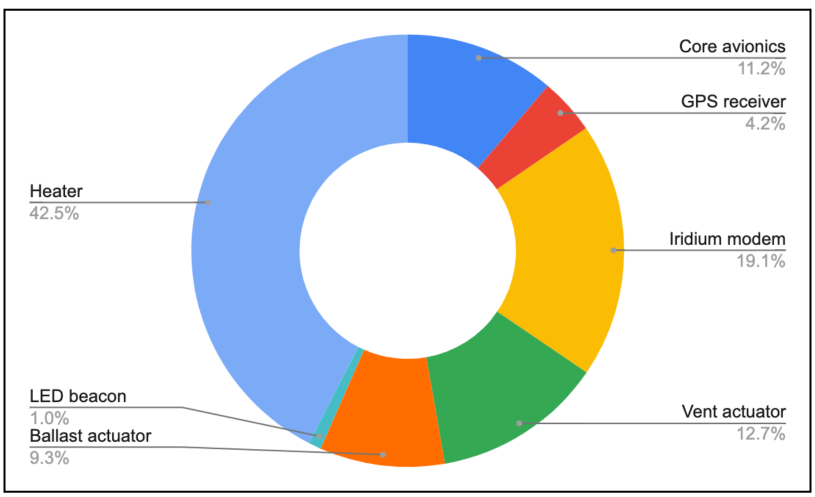
2.5 Power Subsystem

The entire system will be powered by 32 $LiFeS_2$ batteries in a 2S16P configuration, which would provide 48000mAh capacity at ~3V. This system will distribute power to the actuators, sensors, and control electronics at the correct voltages while monitoring the voltage and current to report back in case of failures. The system is not rechargeable due to the relatively low power requirements of our system, in conjunction with the higher mass penalty for rechargeable batteries, solar cells, and maximum power point tracking (MPPT) hardware.

We will use a buck-boost converter to supply 3.3V to the sensors and GPS, and a 5V boost converter to power the vent actuator servo, heater, LED beacon, and satellite modem. The ballast actuator will be powered off of the raw battery power.

Power Budget

Energy Storage						
Series #	2					
Parallel #	16					
Cell capacity at op. temp (mAh)	3200					
Nominal cell voltage (V)	1.4					
Cell mass (g)	14.5					
Cell Count	32					
Pack voltage (V)	2.8					
Total capacity (mAh)	51,200					
Total energy (Wh)	143.36					
Pack mass (g)	464					
Power Consumption						
Component	**Op. voltage (V)**	**Current draw (mA)**	**Duty cycle (%)**	**Peak power draw (W)**	**Avg power draw (W)**	**In avionics bay**
Core avionics	3.3	40	100%	0.132	0.132	Yes
GPS receiver	3.3	15	100%	0.050	0.050	Yes
Iridium modem	5	45	100%	0.225	0.225	Yes
Vent actuator	5	300	10%	1.500	0.150	No
Ballast actuator	5	220	10%	1.100	0.110	No
LED beacon	2.8	40	10%	0.112	0.011	No
Heater	5	200	50%	1.000	0.500	Yes
				0.000	0.000	
				0.000	0.000	
				0.000	0.000	
				0.000	0.000	
				0.000	0.000	
				0.000	0.000	
Totals				**4.119**	**1.178**	
System Lifetime						
Total energy storage (Wh)	143.36					
Average power draw (W)	1.178					
Average power dissipation in bay (W)	0.907					
Peak power dissipation in bay (W)	1.407					
Average current draw per cell (mA)	26.29					
Peak current draw per cell (mA)	91.93					
Lifetime (hours)	121.73					
Lifetime (days)	5.07					



Requirements Table

High level: The power subsystem must have enough battery capacity to meet the high-level requirement that the system must survive for at minimum 48 hours. It must take into account battery derating at the operational temperature and may last significantly longer at our discretion in the case that the system survives more than 2 days in flight.

	Acceptable range	Verification
5V supply	Does not drop below 4.5V at 3A	Apply a simulated 3A load using a load tester or carefully sized resistor
3.3V supply	Does not drop below 2.7V at 200mA	Apply a simulated 200mA load using a load tester of carefully sized resistor
Current measurement	Within 10mA accuracy	Compare with known current draw from power supply
Voltage measurement	Within 0.1V accuracy	Compare with multimeter reading

2.6 Thermal Subsystem

At the altitudes where we expect to cruise, the temperature can be as low as -60ºC, which can decrease the performance of the electronics, especially the sensors and batteries. To keep the batteries close to their nominal capacity and ICs well within the temperature rating of around -40ºC, we will design into the avionics bay a polyamide resistive heater that will be part of a thermal control loop. The avionics will be housed in a small foam chamber designed for low thermal conductivity to minimize the heating requirements of the system.

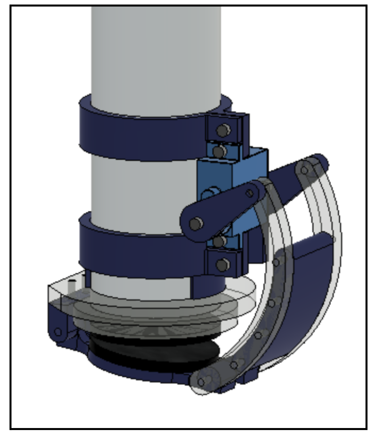
Requirements Table

	Acceptable range	Verification
Temperature measurement	Range: -80ºC to 20º C Accuracy: ±5ºC Rate: ≥1 Hz	Measure known temperatures with an external RTD at 1 Hz, use dry ice to test to -78.5ºC.
Temperature regulation with heaters	Maintains -20˚ C internal temperature over ambient temperature range (-60 or -70˚ C at the lowest)	Test inside an insulated foam box that is surrounded by dry ice

2.7 Actuator Subsystem

Vent Valve and Cut-down

A servo actuates a valve that allows helium to exit the balloon, decreasing the lift. This will allow the balloon to fall to a lower altitude, or to maintain the altitude during higher temperature fluctuations. The same servo, if driven far enough in one direction, will detach or cut down the balloon in case we need to end the flight early. If the balloon is under free fall, a parachute will automatically deploy to control the descent. We chose to use the same actuator for venting and cut down to save weight for ballast. To save energy, the valve uses an overcenter mechanism to lock into a sealed state with no additional actuator torque. We will also use quantized bursts of air release in order to more accurately control the amount of air released.



Requirements Table

	Acceptable range	Verification
Seal leakage	≤5%	Fill a balloon with helium and record volume lost over a 48 hour period with the valve sealed
Vent mass flow	Fast enough to stop the initial 3 m/s ascent rate from the ground to 20 km altitude.	Verified in simulation and during flight
Quantized release of air	Bursts of less than 1 second	Intrinsic to design
Peak power	≤10W at 5V	Operate valve repetitively using bench power supply
Quiescent power	≤5mW	Measure the current of the servo with no applied torque

Ballast Dropper

A small DC gearmotor will spin a wheel at the bottom of the balloon payload to drop 0.25g biodegradable BB pellets. As the total weight of the system decreases, the balloon will gain altitude, and this is how we compensate for decreases in lift due to lower temperatures and helium leakage. We will design the payload to maximize the amount of ballast we can carry in order to maximize the range of the balloon. The ballast system should drop ballast at a consistent or highly controllable rate in order to know the amount of ballast dropped: through inherent mechanism design or with a sensor.

Requirements Table

	Acceptable range	Verification
Drop ballast at a rate of 1 gram per second or higher	≥1g/s	Average drop speed over a test interval by counting BBs
Reliability	No jams, or recover from jams, for 48 hrs or more	Test system with a way to detect ballast drop
Under 5W peak draw	<5W power draw	Test power draw during actuation events

2.8 Ground Subsystem

We will maintain a web server which will receive location reports and other data packets from our balloon while it is in flight. This piece of software will also allow us to schedule commands, respond to error conditions, and adjust the control algorithm while in flight. We will hook into the Ground Control web API, which is provided by the manufacturer of our satellite modem.

Requirements (qualitative)

- The ground subsystem must consist of a web server and client side user interface.
- The ground subsystem must receive and parse the latest data packets from the balloon, and allow for the construction and transmission of commands to the balloon via the Ground Control satellite modem web API.
- The ground subsystem must log all data and provide tools to predict balloon trajectory.

2.9 Tolerance Analysis

Battery energy

One of the limiting factors in flight duration is the amount of stored electrical energy in the non-rechargeable Li-FeS_2 batteries. These will almost continuously power the resistive heater, GPS receiver, and control circuitry, as well as short bursts of power for sending data over satellite modem and actuating the vent and ballast. For the components currently selected, we can expect to draw an average of roughly 1W, with most power going to actuators and satellite modem.

The cells have a nominal capacity of 3000mAh at 1.5V, so our 2S16P pack would ideally contain 144Wh of energy. For a 48-hour flight, we will be able to draw an average of 3W, which is much more than expected. However, the batteries will derate at low temperatures. According to the Energizer L91 datasheet, capacity drops to 1500mAh at -40º C.[4] In this case, we can only draw an average of 1.5W. The extra capacity in our system allows for a faulty heating system, as well as additional unforeseen power draw if we have to increase our data transmission rate or if there are higher than expected vent and ballast drop events.

Ballast mass

Another limited resource is the quantity of preloaded ballast. For balloons with approximately the same internal and external pressure, which includes latex weather balloons, the total mass of ballast $\mathbf{m_b}$ used over **n** days can be calculated as:

$$m_B = m_t K_B \sum (1 - K_B)^{n-1}$$

with $\mathbf{m_t}$ being the total mass of the system and $\mathbf{K_b}$ being the daily change in lift. [5]

With a requirement to compensate for a 10% change in lift every night due to temperature difference, we set K_b to 0.1. For a 48-hour flight, there would be 19% of the total system mass used for ballast. For 6 days, that would be about 47%. With a standard weather balloon size that can lift a payload of 1500 grams, we believe that we have enough tolerance for the mass of structures and actuators.

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[4] Energizer. "ENERGIZER L91 Ultimate Lithium." Form No. EBC-4201T9X-B.

[5] Toyoo Abe et al, "Balloon Systems," in *Scientific Ballooning.* New York: Springer, 2009, pp. 46-47.

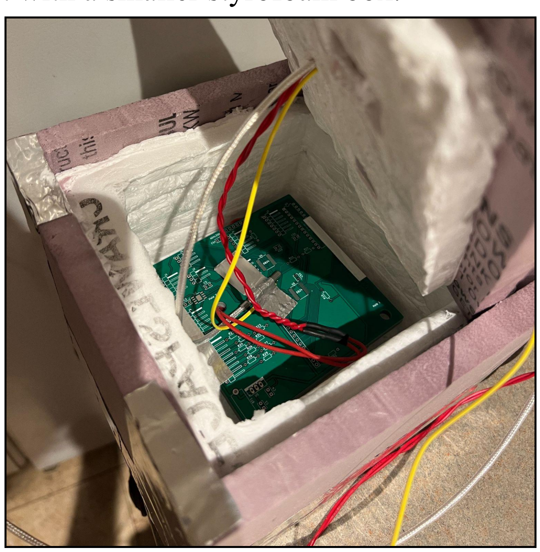
3 Testing

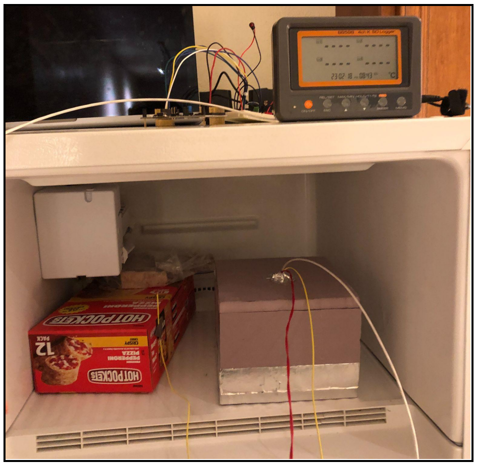
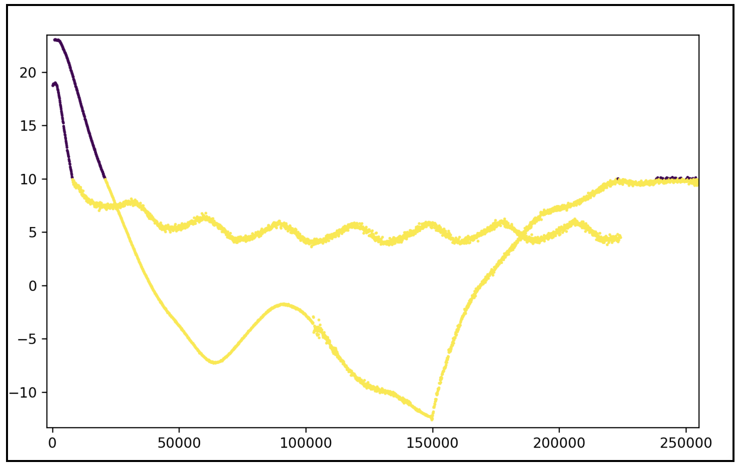
3.1 Valve testing

We filled up a 36” latex balloon and recorded a timelapse to detect leakage of air through the valve assembly. The first test resulted in deflation over 1 hour 45 minutes due to leakage in the pipe connection. In the second test, we connected the balloon and valve to the same pipe and was able to last 49 hours with nearly no volume change. With the success of the second test, we will be moving forward with this valve design and plan to test again with helium.
Timelapse

3.2 Insulation and heating testing

We built a 120 x 120 x 70mm box out of pink insulation foam and polyurethane spray foam, then left it in the freezer at -10ºC to -15ºC. There are a few blank PCBs, a 1W polyimide heater, a thermocouple, and a RTD inside the box to attempt to control interior temperature to 10ºC. We also conducted the same test with a smaller styrofoam box.



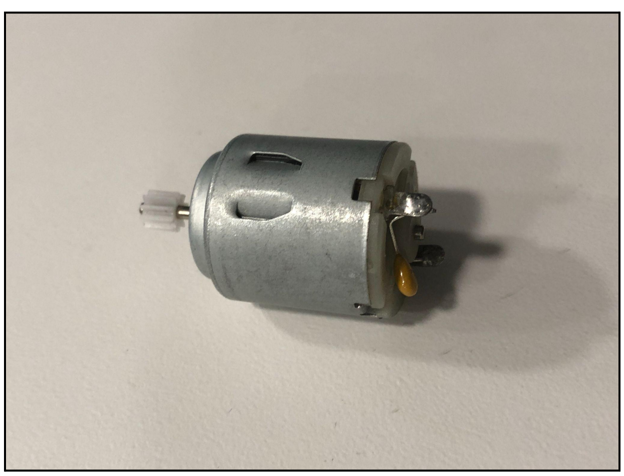
 

RTD temperature data on the right, with temperature in ºC plotted against an arbitrary data collection timestep. The heater is on a bang-bang control, turning fully on when the RTD measurement is below 10ºC and turning off above. The two series of data correspond to the custom foam box and the styrofoam box, with the one starting at 23ºC being the custom box. The heater did not turn on for the custom box until the 150000 mark, but we can confirm that the custom box has a higher thermal resistance than the styrofoam box from the shallower line during the initial cooling from room temperature and a higher equilibrium temperature at the end.

In the future we hope to conduct more robust but similar tests to characterize the thermal insulation and qualitatively compare different designs.

3.3 Motor current testing

To size the motor for the ballast actuator, we applied various voltages to a small DC motor using a bench power supply and recorded the current. These values help us determine the power budget.



Stall and free current for the motor above:

	1V	2V	3V	4V	5V
Stall current (A)	0.496	0.962	1.370	1.82	2.2
Free current (A)	0.070	0.080	0.096	0.098	0.102

4 Cost and Schedule

4.1 High-level Cost Analysis

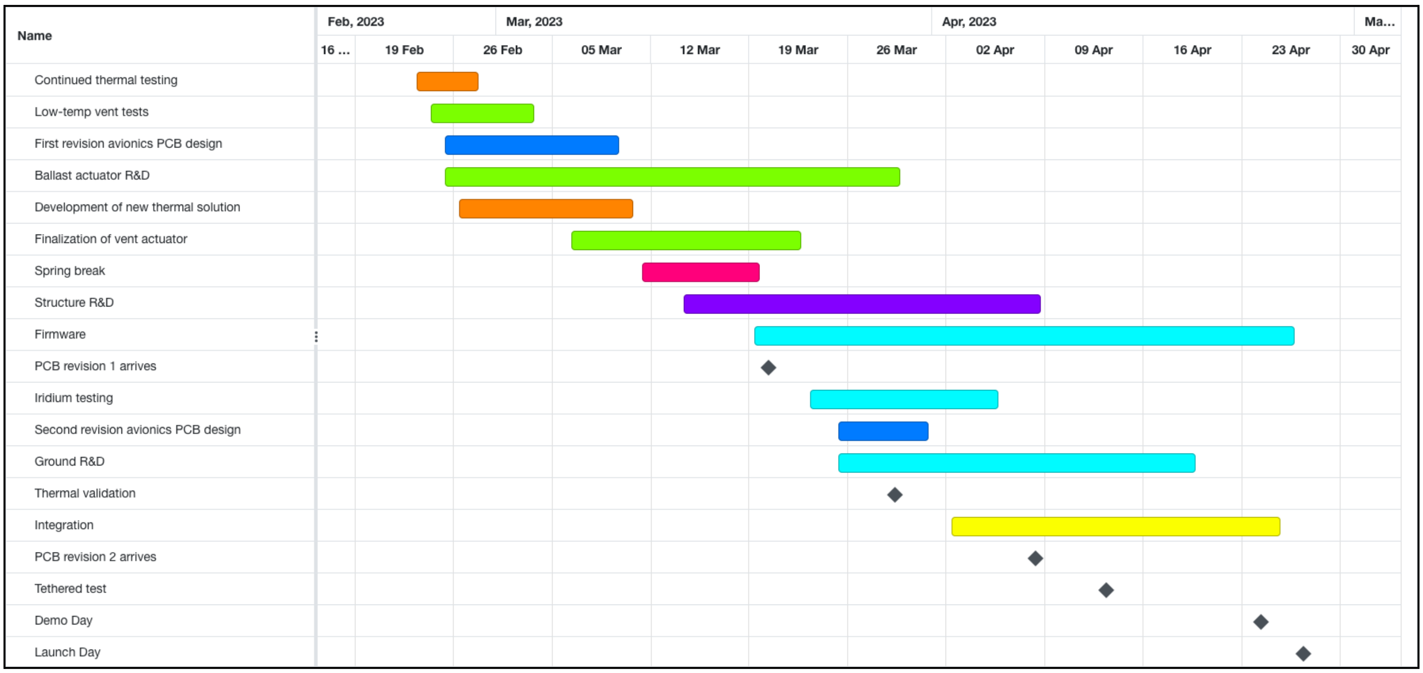
Major Expense	**Cost**
Latex high-altitude weather balloon (1500g, 120 ft^3)	\$115 x 2
Helium tank rental (100-200 ft^3)	\$400 - 1000
Iridium satellite modem and subscription	\$350
$LiFeS_2$ primary batteries (32-40 cells)	\$140
Avionics components: MCUs, sensors, power electronics, passives	\$200
4-layer flight controller PCB (2 revisions)	\$100
Plastic and composite structure	\$60
Biodegradable BBs (ballast)	\$50
Parachute and rigging	\$40
Sealants and gaskets	\$30
Actuators (DC motor, servo)	\$30
Labor cost (assuming \$35/hr and ~12 hour workweeks)	≈ \$10,000
Total	≈ \$11,700 - 12,300

4.2 Avionics Parts Cost Analysis

Part Number	**Description**	**Cost**
STM32L431CCT6	32-bit microcontroller	\$5.96
RockBlock 9603	Iridium satellite modem	\$274.95
SAM-M10Q-00B	GPS module with antenna	\$31.50
BMP581	Pressure sensor	\$4.12

TPS63802DLAT	3.3V buck-boost converter	$3.00
TPS61288RQQR	5V boost converter	$6.18
INA232AIDDFR	I2C current/voltage sense	$2.63
Total		$328.34

4.3 Schedule (Gantt chart)



Worst case goal

If we cannot obtain helium gas at a reasonable price or in case of unexpected delays in one of the subsystems, we will conduct ground tests with as much hardware as possible to verify the complete subsystems. The highest priority is a reliable avionics system and the actuation of our vent and ballast subsystems as those are the main additions we propose adding to a conventional weather balloon. As a proof of concept, we can demonstrate dropping ballast at a consistent mass rate and similarly venting air controllably.

5 Ethics and Safety

With any weather balloon launch where there is no expectation of recovery, there is an ethical question surrounding the environmental impact of these activities. The polymers, metals, and other compounds—particularly in the batteries—are potential pollutants that would be released into the environment. Since the trajectory of the balloon cannot be perfectly predicted, such a release is difficult to limit to areas where it would have minimal impact. That said, hundreds of radiosonde launches are conducted each day by the United States, with latex balloons and styrofoam pieces getting scattered around the launch sites.[6] The goal of this project is to explore ways we can limit this environmental impact through extending the lifetime of a given balloon, and providing a semi-permanent mobile platform to collect important weather data. The IEEE code requires prompt disclosure of anything that might endanger the public or the environment.[7] In this case, the environmental impact of a single balloon launch is limited, and with the data collected, we can push forward with reducing the total impact of the world's collective radiosonde launches. The balloon will be marked as a scientific payload which will not cause harm, to ensure that we do not cause distress to anyone who finds it. We are also taking steps to minimize the environmental impact of the balloon as a whole, by reducing usage of styrofoam as insulation which readily breaks apart, as well as limiting ourselves to nontoxic battery chemistries.[8]

The requirement to drop ballast creates both a safety and environmental concern which we've addressed by selecting biodegradable airsoft BB's as our ballast. These present unique advantages, for example, that each BB has a well defined mass, thus dispensing a fixed number results in a known change in lift. Second, these BB's will quickly degrade in the environment, alleviating any pollution concerns. Third, they have such a small mass (0.2-0.25g) that their terminal velocity is low with respect to their mass, which means they do not present a hazard to any people, animals, or property beneath the balloon during a ballast drop.[9] If the balloon were to pop or otherwise deflate due to helium leakage or a cut-down command, it would fall on a parachute integrated into the system to safely bring it to the ground.

From a regulatory perspective, the expectations for this project are outlined in FAA Section 101, which covers requirements for control, communications, radar reflectivity, visibility, and notifications to authorities prior to and during a balloon operation. Our balloon will likely be exempt from Section 101 if the payload is less than 6 lbs, has a weight/size ratio less than 3 oz/in^2 on any surface, and requires less than 50 lbs of force to separate.[10]

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[6] National Weather Service. "Helium Shortage and Radiosonde Balloon Launches." Mar 2022.
[7] IEEE. "EEE Code of Ethics."
[8] Energizer. "L91 Product Safety Data Sheet."
[9] The Airsoft Trajectory Project. "Physical Characteristics of Pellets."
[10] Code of Federal Regulations. "Part 101."

However, we still plan to adhere to Section 101 by notifying air-traffic controllers prior to the launch of this balloon, and cooperate with any requested position reports. The balloon will be made to present a large radar cross section within the frequency ranges requested by the FAA, and to further increase visibility while flying below 60,000 feet, it will utilize a beacon LED which will flash once per second. We will optimize our control algorithm to minimize or otherwise avoid time spent in the altitude corridor where commercial aviation is most prevalent. Following all of the stipulations outlined in section 101, as well as going a step further with our own safety precautions and monitoring of the balloon at all times is the process by which we will mitigate concerns from regulatory, ethical, and safety standpoints.

Citations

National Weather Service. “Helium Shortage and Radiosonde Balloon Launches.” Mar 2022.

National Centers for Environmental Information. “Global Ensemble Forecast System (GEFS).” 2022.

Toyoo Abe et al, “Balloon Systems,” in *Scientific Ballooning*. New York: Springer, 2009, pp. 46-47.

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