ECE 445

Senior Design Laboratory

Final Report

ILLINI VOYAGER

Dynamically equilibrated high-altitude balloon platform for long-lasting remote sensing

Team No. 60

Cameron Jones
(ccj4@illinois.edu)

Christopher Xu
(cyx3@illinois.edu)

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Abstract

Illini Voyager is an altitude equilibrating balloon system designed to perform remote sensing for long periods of time in many layers of the atmosphere. It utilizes venting and ballasting actuators to decrease and increase the payload's lift as directed by a control loop. The system is capable of supplying power and a bidirectional data interface to any kind of scientific instrumentation onboard. Due to the extremely cold conditions at the equilibration altitudes, a thermal control system is required to maintain the system's electronics at a survivable temperature. Global communication to the payload is enabled via a satellite modem which reports payload and tracking information back to the ground as well as accepts remote commands. Our system demonstrated full functionality across all of our subsystems and is in preparation for a flight test.

Contents

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 is 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[2]. We are seeking to improve upon their endurance by decreasing the size of the avionics to allow for better thermal performance and more weight for ballast, as well as decreasing the materials costs. Given accurate GPS positioning and modeling of the upper atmosphere wind layers using public tools such as GEFS[3], we can target certain altitudes to

[1] National Weather Service. "Helium Shortage and Radiosonde Balloon Launches." Mar 2022.
[2] A. Suskho, A. Tedjarati, and J. Creus-Costa, "Low Cost, High Endurance, Altitude-Controlled Latex Balloon for Near-Space Research (ValBal). *2017 IEEE Aerospace Conference,* 2017.
[3] National Centers for Environmental Information. "Global Ensemble Forecast System (GEFS)." 2022.

roughly control the direction of travel, making it possible to choose a rough horizontal trajectory and collect data from multiple regions in one flight.

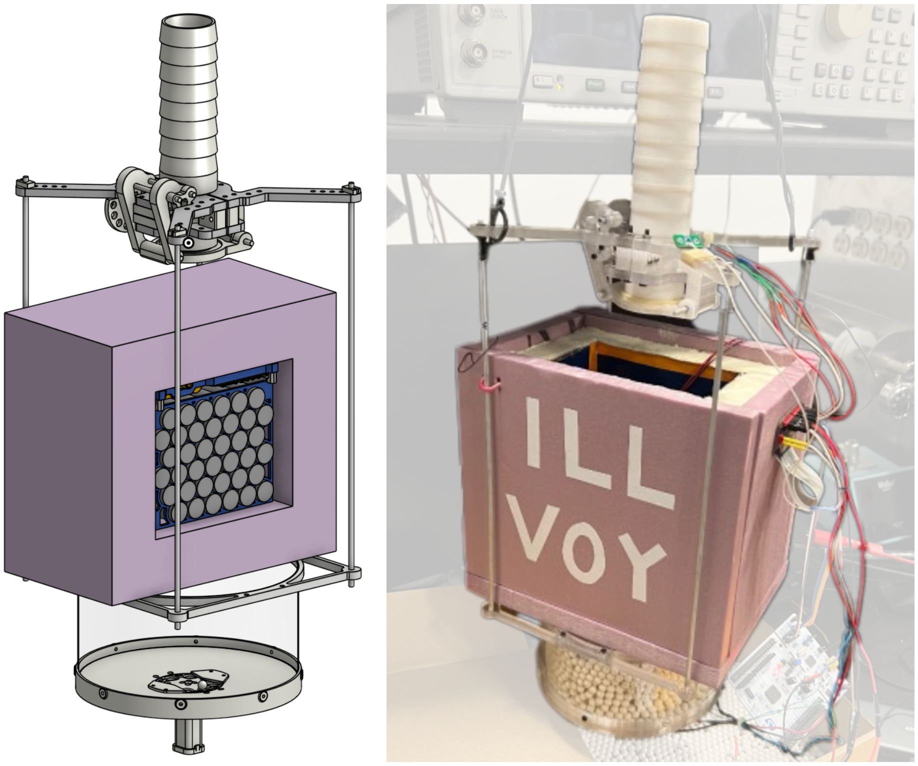

Figure 1: 3D model of the payload alongside the physical prototype. A section of the foam box is removed to display the electronics.

Our solution is a 1500g latex weather balloon (approximately 6 feet in diameter at launch) with a payload attached to its neck, consisting of a valve to seal the helium, a foam box to house the electronics, a clear cylinder to store ballast, and a wheel to drop the ballast. The electronics includes PCBs to collect data, control the system, and communicate with the ground, and is powered by a pack of non-rechargeable batteries.

1.3 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.[4]
- 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.

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

- The system must have a power subsystem which supports sustained flight operations and consistent satellite communications for at least 48 hours.

2 Design

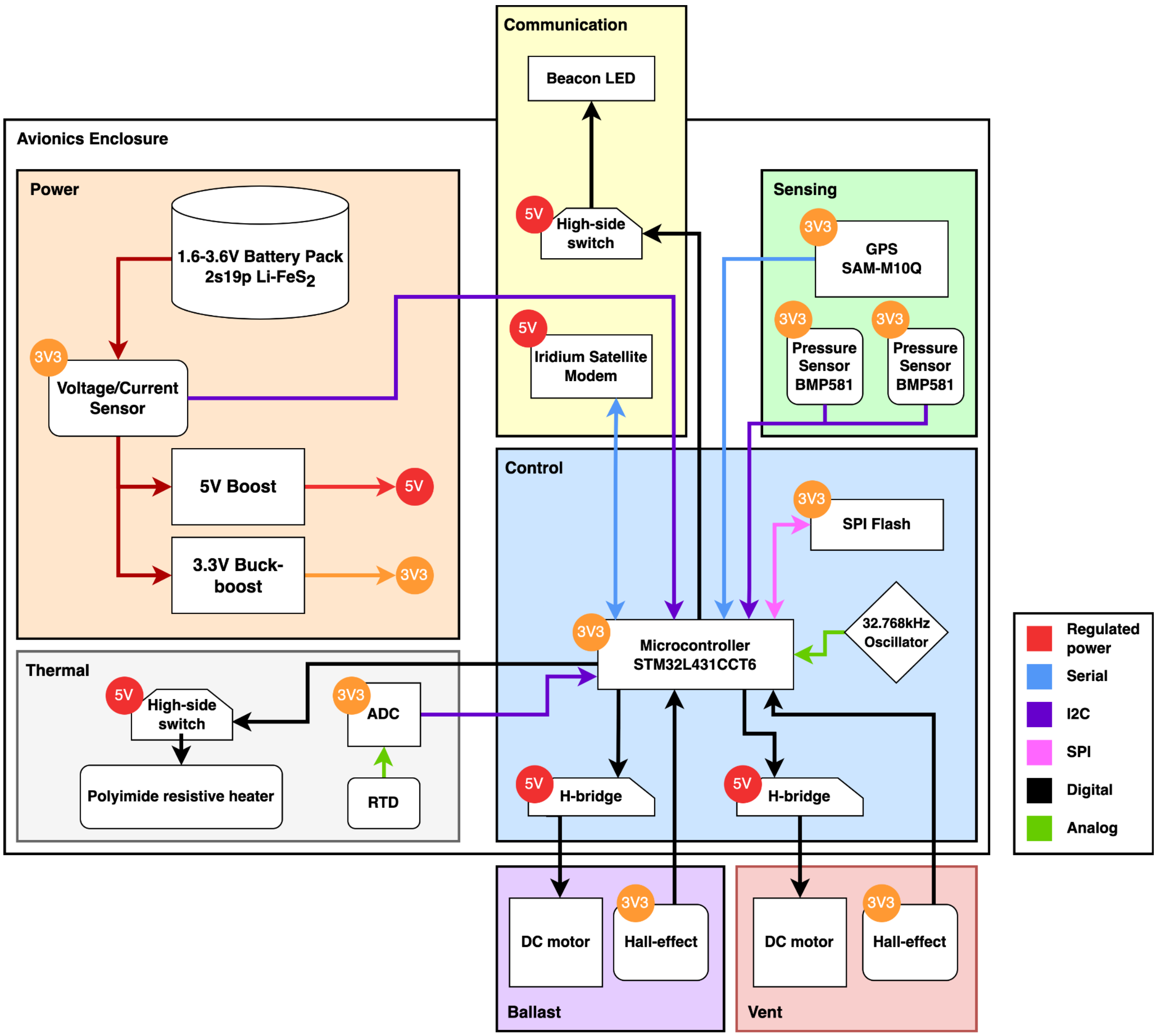


Figure 2: Electronics block diagram.

The avionics system is composed of multiple subsystems which perform functions to keep the payload warm, powered, and communicable. The control subsystem accepts remote commands, collects data, and manages the altitude and thermal equilibration control loops. The communication subsystem flashes a bright LED for safety and allows for remote data retrieval and commanding via a satellite modem. In flight, we access the modem with a custom webserver calling the API provided by the satellite modem. The power subsystem boosts a non-rechargeable battery pack to 3.3V and 5V for the rest of the system. The thermal subsystem keeps the payload warm using a resistive heater and a temperature sensor to maintain a survivable temperature for the electronics and batteries. The vent and ballast subsystems consist of DC gearmotors that either release helium to descend or drop pellets to ascend.

2.1 Control and Sensing

A STM32L431CCT6 microcontroller serves 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.

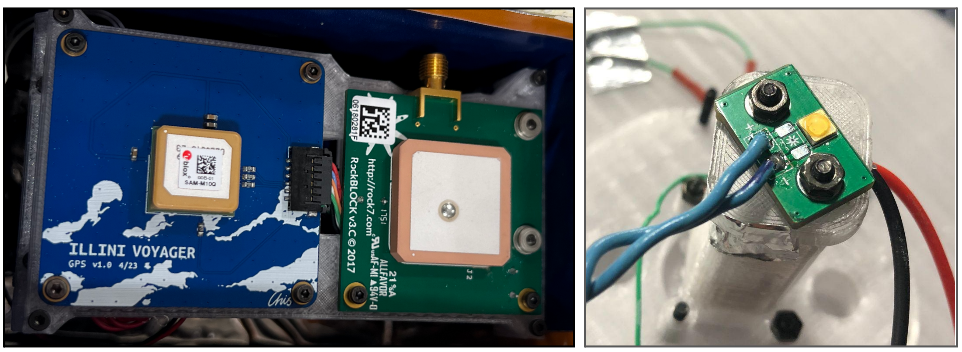


Figure 3
Left: Top view of the avionics, showing the GPS and satellite modem.
Right: Bright wide-angle LED mounted to the bottom of the payload.

2.2 Communications

The microcontroller will communicate via serial to the satellite modem (Iridium RockBlock 9603N), sending packets of 50 bytes back to the ground with a minimum frequency of once per hour, with higher frequency during the first few hours of launch for more diagnostic data. We 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 hook into the Ground Control web API, which is provided by the manufacturer of our satellite modem.

To meet regulations for an unmanned weather balloon, there is a LED beacon visible up to 5 miles at night. The LED is rated to emit 122 lumens for a 150º viewing angle, consuming 855mW. The control subsystem will flash this LED using a high-side driver and an appropriately sized current limiting resistor. We chose to use a high-side driver instead of a low-side MOSFET because of a lower risk of shorting to ground, as the wires to the LED travel a relatively long distance to the outside of the enclosure through several connectors.

2.3 Power Supply

The entire system is powered by 38 $LiFeS_2$ primary (non-rechargeable) batteries in a 2S19P configuration, which provides 51,300mAh capacity at ~3V. This system distributes power to the actuators, sensors, and control electronics at the correct voltages while monitoring the voltage and current in order to detect and report subsystem failures. The batteries are 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. Solar cells would also present a challenge since the balloon would obscure the payload from sunlight for most of the day, thereby reducing charging capability.

We utilize a buck-boost converter to supply 3.3V to the sensors and other core avionics hardware, and a 5V boost converter to power the vent and ballast gearmotors, heater, LED beacon, and satellite modem. In order to pick optimal external component values, we simulated the designs for our two power converters in TI WEBENCH.

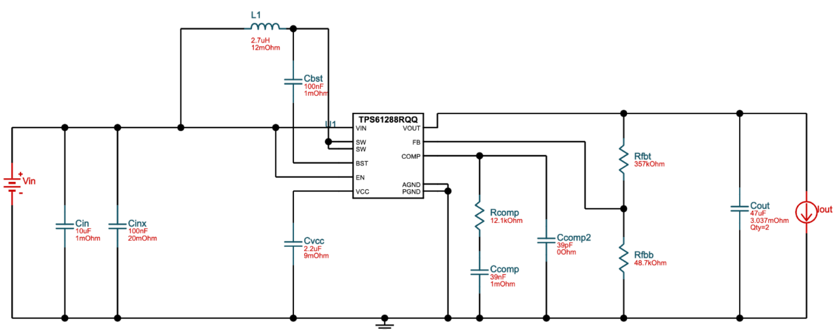


Figure 4: 3.3V buck-boost converter (94.6% efficient @ 2A load)

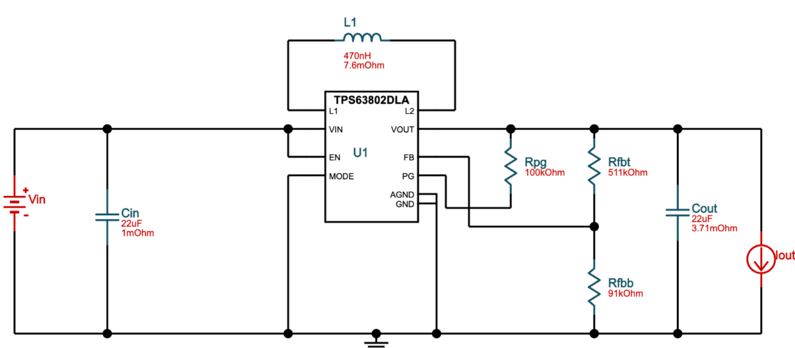


Figure 5: 5V buck converter (90.3% efficient @ 1A load)

Our power subsystem must contain enough energy to operate the payload for at least 48 hours according to our high-level requirements. We utilized a power budget with current draw estimations to determine that with our 38 $LiFeS_2$ cells, we should expect a lifetime of at least 3.5 days. This power budget is dependent on conservative assumptions for heater performance at high altitudes, which will enable us to operate longer if the power draw is lower in practice.

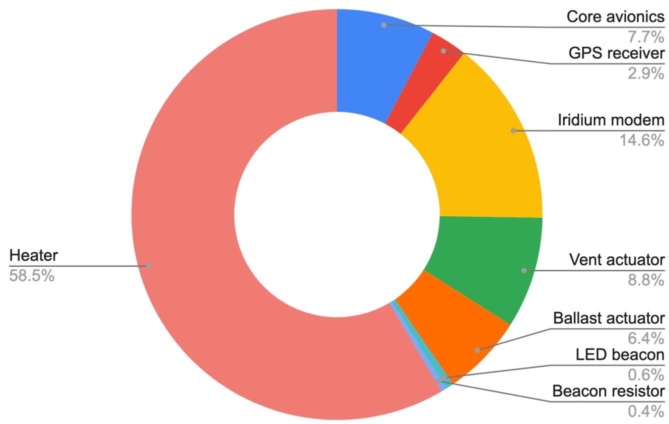


Figure 6: Breakdown of estimated energy consumption. Refer to Appendix B for the full power budget.

2.4 Thermal Regulation

At the altitudes where we expect to cruise the temperature can be as low as -75ºC, which can decrease the performance of the electronics, especially the sensors and batteries. Drawing high current from the battery at low temperatures can result in a lower pack capacity, reducing our potential flight time. To keep the batteries close to their nominal capacity and ICs well within the typical temperature rating of -40ºC, we design into the avionics bay some polyamide resistive heaters that are part of a thermal control loop. The avionics is housed in a small foam chamber designed for low thermal conductivity to minimize the heating requirements of the system. There is pink XPS construction foam ½ inch thick on the exterior, and 1 inch of closed-cell polyurethane spray foam on the interior to minimize the thermal conductivity given constrained mass. The heaters are weaved through the battery stack and are regulated such that a temperature probe glued to the pack maintains above -20˚C. The bottom and side inner faces of the enclosure are covered with aluminized film (Mylar), which act as a thermal diode to allow heat to radiate in during high solar irradiation and reflect some of the heat radiating from the electronics.

2.5 Vent Valve

A gear motor 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 temperature increase. To save energy, the valve uses an overcenter mechanism to lock into a sealed state with no additional actuator torque. We use quantized bursts of air in order to more accurately control the amount of air released. To open the valve to a consistent angle each time, there is a magnet mounted to the linkage and two hall-effects switches, one at the open position and one at the sealed position. For opening and closing the valve, the control subsystem drives the motor until the hall-effect at the opposite side detects the magnetic field.

2.6 Ballast Dropper

A small DC gear motor spins 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, which is how the system compensates for decreases in lift due to lower temperatures and helium leakage. We minimized the mass of the rest of the payload to maximize the amount of ballast we can carry in order to increase the range of the balloon. The ballast system drops ballast at a controllable rate using a magnet attached to the rim of the wheel, which is detected by a hall-effect switch every rotation.

2.7 Structure

The entire system is 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.

2.7.1 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. PTFE is used for the barbed tube interface to the balloon for its extreme temperature stability and ability to avoid ice formation. This tube supports the entire payload from the balloon, so it must not degrade from the harsh conditions. Ice forming at the tube opening to the vent would likely interfere with the operation of the vent and would also be detrimental. Polycarbonate is used for the main structural components because of its fair UV compatibility and high impact resistance. Acrylic is often used in similar applications as polycarbonate and is even more UV resistant, but it is much more brittle. The balloon will be subject to high winds, and the material should be able to flex a little bit without snapping. PETG is used for the more intricate components such as the ballast wheel or vent linkage for ease of manufacturing with 3D printing. It has fair UV resistance compared to other common 3D printing thermoplastics, and it is impact resistant like polycarbonate.

2.9 Tolerance Analysis

2.9.1 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 about 1.7W, with most power going to the heater and satellite modem.

The cells have a nominal capacity of 3000mAh at 1.5V, so our 2S19P pack would ideally contain 171Wh 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.[5] 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.

2.9.2 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:

$$m_{\mathrm{B}} = m_{\mathrm{t}} K_{\mathrm{B}} \sum (1 - K_{\mathrm{B}})^{n-1}$$

with $\mathbf{m_t}$ being the total mass of the system and $\mathbf{K_b}$ being the daily change in lift. [6]

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

[5] Energizer. “ENERGIZER L91 Ultimate Lithium.” Form No. EBC-4201T9X-B.

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

can lift a payload of 1500 grams, we believe that we have enough tolerance for the mass of structures and actuators.

3 Verification

3.1 Controls

We are able to verify that with the current amount of helium and ballast stored at launch, even a simple controller can maintain the altitude of the balloon within 5 km altitude of the target. We simulated the system in python using the ideal gas law for the helium in the balloon and the atmos python package for the atmospheric model, which includes temperature fluctuations from day to night.

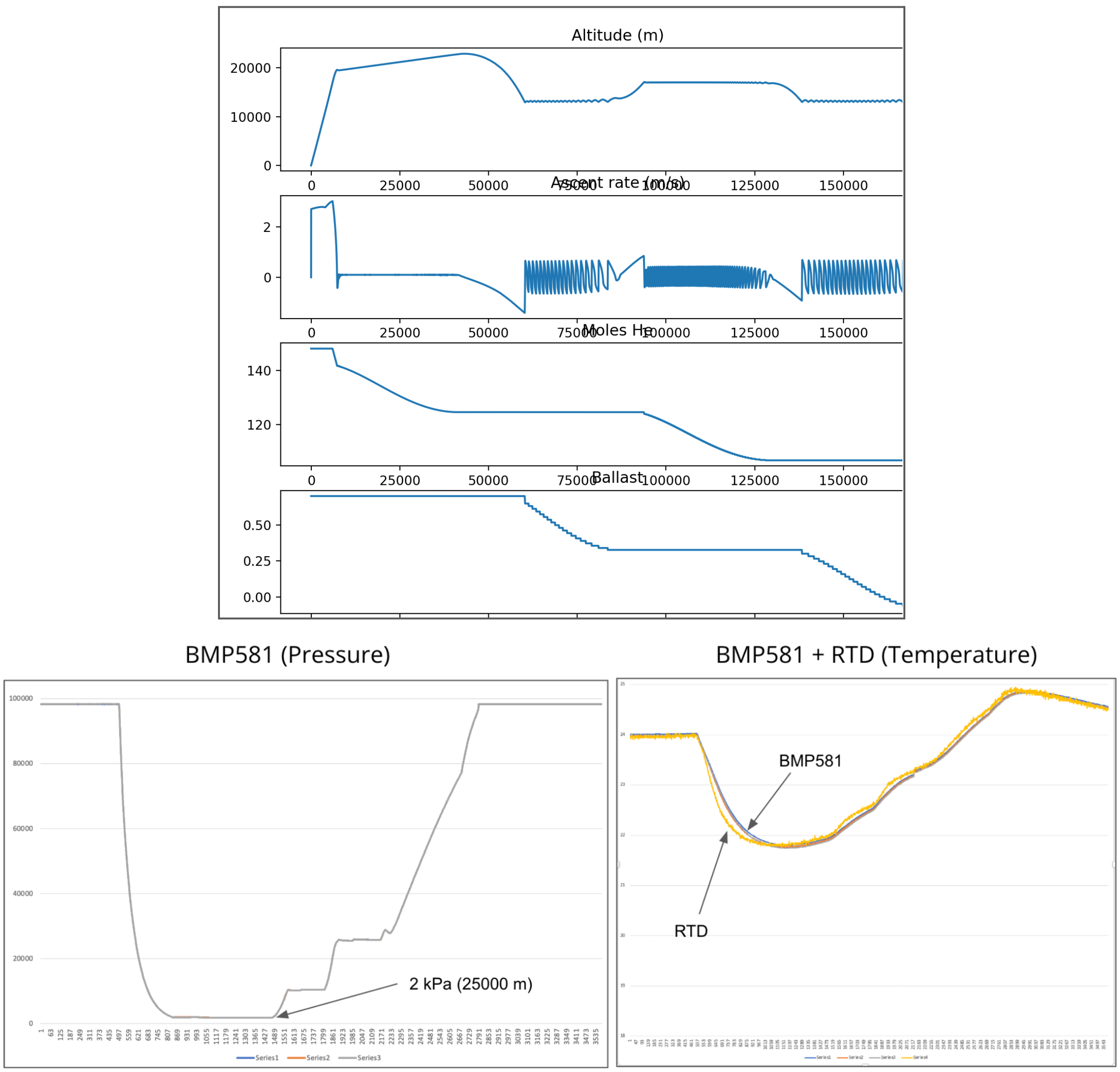


Figure 7

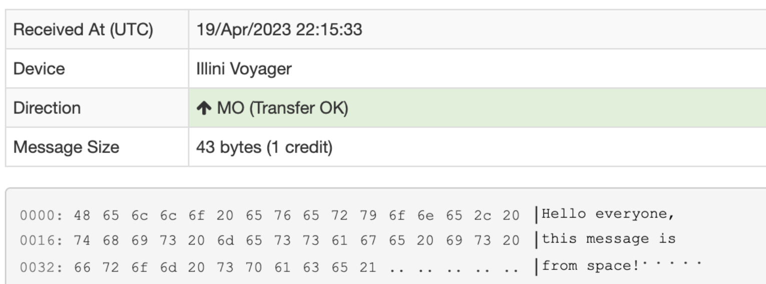
Top: Simulation of 48 hours of flight with a simple controller.

Bottom: Pressure and temperature logs from a test inside a vacuum chamber.

For the sensors on the main board, we were able to test our BMP581 pressure and temperature sensors, as well as the platinum RTD. They agree well throughout the pressure range that we expect from sea level to 20 km.

3.2 Communication

The communication subsystem is crucial to the operation of the payload, as it allows us to receive data back on the ground, as well as command the payload. We tested the Iridium 9603N satellite modem with foam obstructions similar to what it will see during flight, and delivered multiple packets both from and to the device. We were able to forward these packets on to a web server, proving out the ground station's ability to receive data end-to-end.



Received At (UTC)	19/Apr/2023 22:15:33
Device	Illini Voyager
Direction	MO (Transfer OK)
Message Size	43 bytes (1 credit)

```
0000: 48 65 6c 6c 6f 20 65 76 65 72 79 6f 6e 65 2c 20 |Hello everyone,
0016: 74 68 69 73 20 6d 65 73 73 61 67 65 20 69 73 20 |this message is
0032: 66 72 6f 6d 20 73 70 61 63 65 21 .. .. .. .. .. |from space!.....
```

Figure 8: Example of transmitted Iridium SDB packet

Another part of the subsystem important for regulatory compliance is a bright beacon LED which sits at the bottom of the payload. This beacon LED must be visible for 5 miles, and was deemed acceptable due to its lumen rating of greater than 136 lumens at our operational current and wide viewing angle.

3.3 Power

5V Power Rail

Component	Peak current draw (mA)
Heater	400
Iridium	500
Beacon LED	373
Total	1,273

3.3V Power Rail

Component	Nominal current draw (mA)
Control subsystem	41

Our power subsystem was validated by operating the system at full power without appreciable sag in the supply voltages. This was done by turning all sensors on, as well as the actuators, satellite modem, heaters, and beacon. With all of these subsystems enabled, we still maintained tight voltage tolerance and did not exceed any current limitations on our supplies. We performed a test with a spare $LiFeS_2$ flight battery, and determined that the batteries could readily support the required loads without voltage drop that would exceed the buck-boost or boost converter recommended operating conditions.

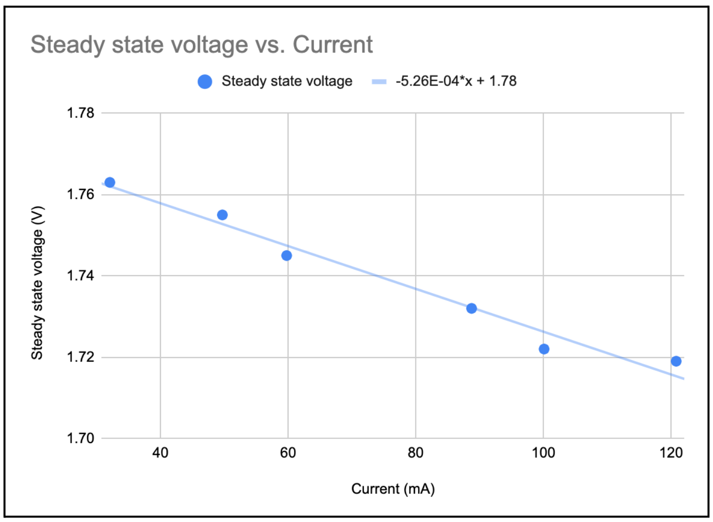


Figure 9: Collecting steady-state cell voltage under load

3.4 Thermal

We were able to test our system in a freezer to compare with a similarly sized styrofoam box, proving that the pink XPS and urethane foam combination we selected is a better thermal insulator. Both boxes with thermocouple probes were placed into the freezer at around -8 ºC, then the freezer was unplugged to any effect of the freezer's cooling effort. This caused the steady state temperature of the entire system to increase slowly, but it is clear that the custom foam box has a higher thermal resistance because the change in temperature with respect to time is consistently lower than the styrofoam.

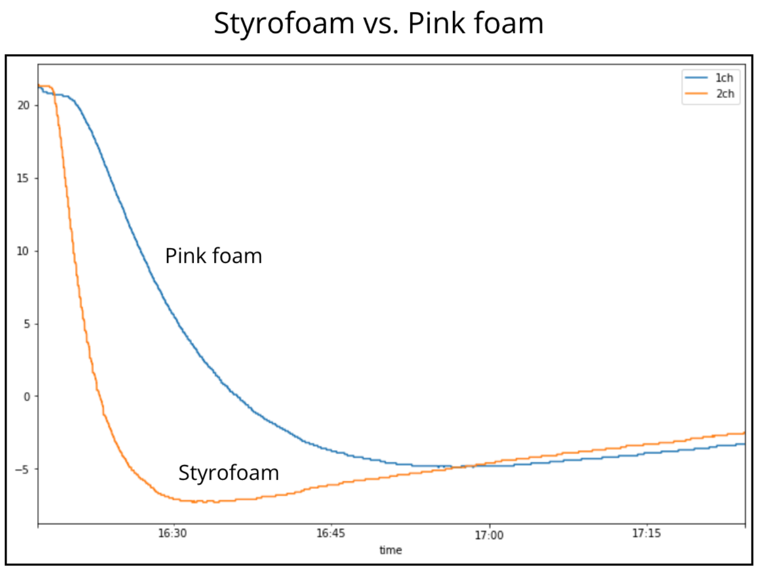


Figure 10: Plots of temperature vs. time comparing our custom box with styrofoam.

3.5 Vent Valve

We filled a 36" latex balloon with air 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 our final vent assembly, we connected another 36" latex with helium, and used soapy water to determine if there were any leakes around the seal. With no leaks detected using soapy water during a 10 minute test, we deemed the valve adequate for flight.

Figure 11: Testing the vent assembly with helium by the ECEB tank cage

3.6 Ballast

We were able to drop over 15,000 BBs (4.5kg) without jamming to verify that the ballast mechanism would continue operating during flight. For each trial of 5,000 BBs, the system was placed over a glass jar and operated at full speed, with a video camera pointed at the side. The ballast rate and consistency can be determined using the audio track of the footage.

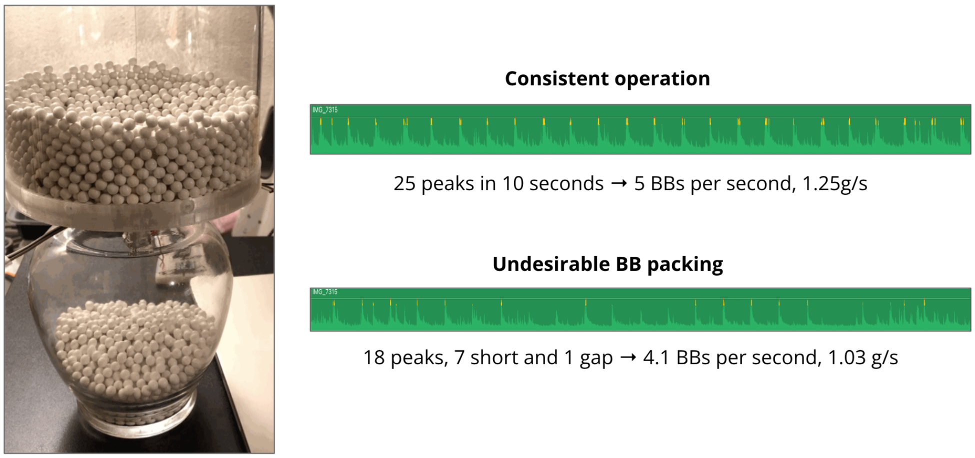


Figure 12: Audio analysis of ballast dropping.

During most of the operation, there are consistent peaks in volume from the two BBs simultaneously dropping into the jar. From analyzing the period of these peaks we determine that about five BBs drop every second, which corresponds to 1.25 grams/second. We noticed that at a certain fill level the packing of the balls forms a self-supporting arch structure that stops the flow of BBs from one or both ports. In this case, the audio sometimes shows shorter peaks or no sound at all, which indicates that only one or no BBs were dropped in that period. However, the motor continued to spin and agitate the hopper, so the ballast system can continue operating. During the undesirable packing the average rate was still 1.03 grams/second, which meets our initial requirement of 1 gram/second.

4 Costs

4.1 High-level Cost Analysis

Major Expense	Cost
Latex high-altitude weather balloon (1500g, 120 ft^3)	$115
Helium tank rental (219 ft^3)	$215 ($415 retail)
Iridium satellite modem and estimated subscription	$350
$LiFeS_2$ batteries (38 cells)	$140
Avionics components: MCUs, sensors, power electronics, passives	$200
4-layer flight controller PCB and various 2-layer breakouts	$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 Components Cost Analysis

Part Number	Description	Quantity	Cost
STM32L431CCT6	32-bit microcontroller	1	$5.96
RockBlock 9603	Iridium satellite modem	1	$274.95
SAM-M10Q-00B	GPS module with antenna	1	$31.50

BMP581	Pressure sensor	4	$3.64
TPS63802DLAT	3.3V buck-boost converter	1	$3.00
TPS61288RQQR	5V boost converter	1	$6.18
INA232AIDDFR	I2C current/voltage sense	3	$2.63
DRV8231ADDAR	Bidirectional motor driver with FETs	2	$1.94
ADS1119IPW	ADC for RTD sense	1	$6.47
Total			$354.39

5 Conclusion

Through multiple revisions of hardware tested at conditions similar to those found at our equilibrium altitude, the Illini Voyager system has proved its capabilities and met all of the design goals we set. The avionics package is fully operational, can transmit and receive over satellite modem, and can operate all portions of the system. The two actuators—vent and ballast—have been tested to be reliable in a variety of environments, and can readily support the dynamic altitude control requirements of the payload. While there are still integration, firmware, and regulatory activities that have to be performed prior to a fully-fledged launch, we have developed a system which is able to fly.

5.1 Ethical considerations

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.[7] 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.[8] 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 is 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.[9]

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

[7] National Weather Service. "Helium Shortage and Radiosonde Balloon Launches." Mar 2022.
[8] IEEE. "EEE Code of Ethics."
[9] Energizer. "L91 Product Safety Data Sheet."

any people, animals, or property beneath the balloon during a ballast drop.[10] 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.[11]

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.

5.2 Future work

While our ECE 445 course requirements are coming to a close, our intent is to follow through and launch the Illini Voyager system pending FAA, ATC, and university approval.

Go Illini Voyager!

[10] The Airsoft Trajectory Project. "Physical Characteristics of Pellets."
[11] Code of Federal Regulations. "Part 101."

References

[1] National Weather Service, “Helium Shortage and Radiosonde Balloon Launches,” Mar 2022.

[2] A. Suskho, A. Tedjarati, and J. Creus-Costa, “Low Cost, High Endurance, Altitude-Controlled Latex Balloon for Near-Space Research (ValBal). *2017 IEEE Aerospace Conference,* 2017.

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

[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.

[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.”

Appendix A: Initial Design Requirements

A.1 Control

	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

A.2 Communication

	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

A.3 Power

	Acceptable range	Verification

5V supply	Does not drop below 4.5V at load	Operate the satellite modem, beacon, and both actuators
3.3V supply	Does not drop below 2.7V at load	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

A.4 Thermal

	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

A.5 Vent

	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

		gear motor with no applied torque

A.6 Ballast

	Acceptable range	Verification
Drop ballast at a rate of 1 gram per second or higher	$\geq$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

Appendix B: Power Budget

Energy Storage						
Series #	2					
Parallel #	19					
Operational temperature (C)	-25					
Cell capacity at room temp (mAh)	3200					
Cell capacity at op. temp (mAh)	2700					
Nominal cell voltage (V)	1.4					
Cell mass (g)	14.5					
Cell count	38					
Pack voltage (V)	2.8					
Total capacity @ cell voltage (mAh)	51,300					
Total energy (Wh) / (kJ)	143.64	517.10				
Pack mass (g) / (lbs)	551	1.21				
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	50	100%	0.250	0.250	Yes
Vent actuator	5	300	10%	1.500	0.150	No
Ballast actuator	5	220	10%	1.100	0.110	No
LED beacon	3	350	1%	1.050	0.011	No
LED beacon current-limiting resistor	2	350	1%	0.700	0.007	Yes
Heater	5	400	50%	2.000	1.000	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				**6.782**	**1.709**	
Lifetime Statistics						
Total energy storage (Wh)	143.64					
Average power draw (W)	1.709					
Peak power draw (W)	6.782					
Average power dissipation in bay (W)	1.439					
Peak power dissipation in bay (W)	3.132					
Average current draw per cell (mA)	32.12					
Peak current draw per cell (mA)	127.47					
Lifetime (hours)	84.05					
Lifetime (days)	3.50					