ECE 445

Senior Design Laboratory

Project Proposal

ILLINI VOYAGER

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

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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

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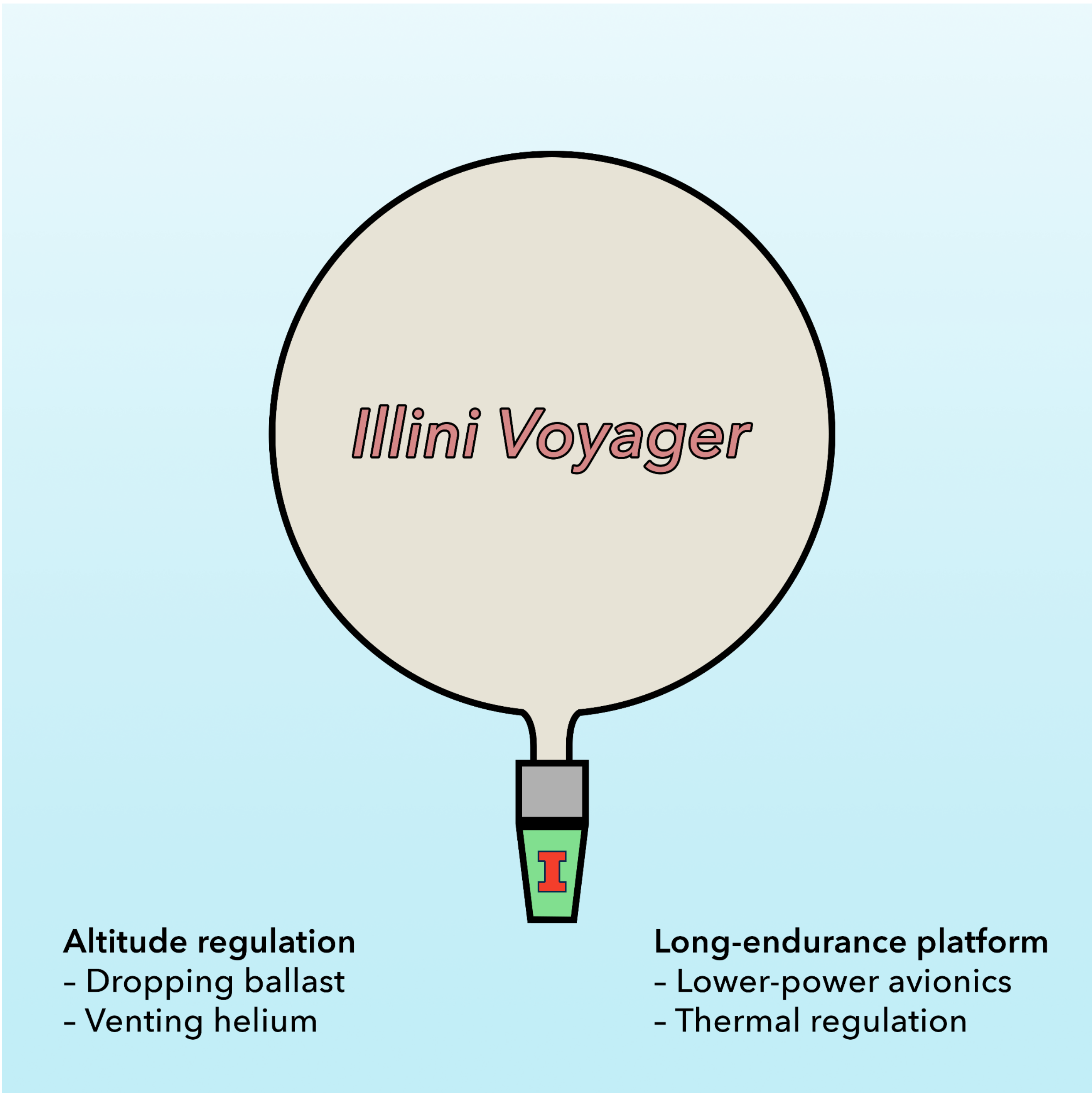
[1] National Weather Service. "Helium Shortage and Radiosonde Balloon Launches." Mar 2022.

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.

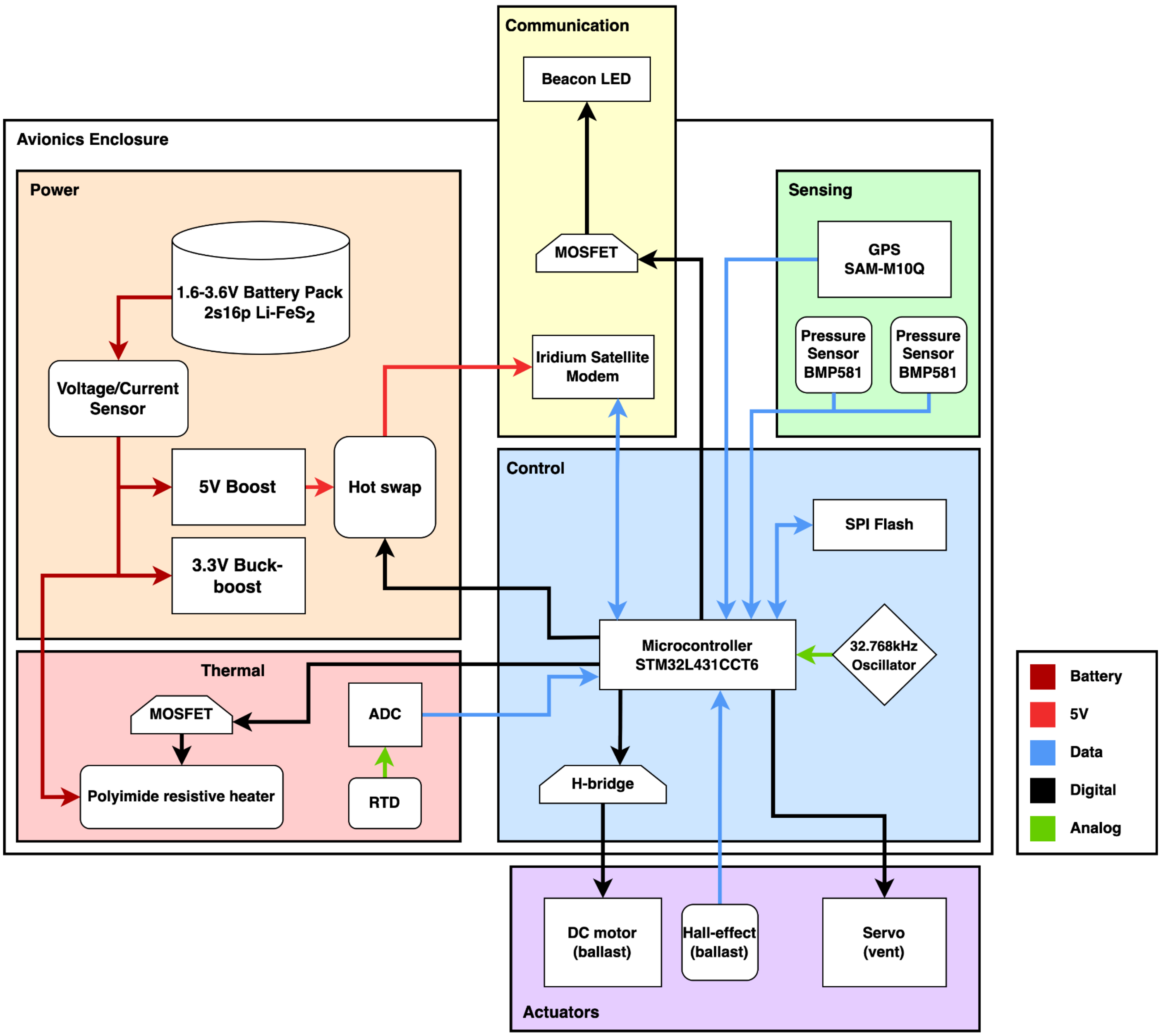
1.4 High-level requirements

- 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.

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

2 Design

2.1 Block Diagram



2.1 Subsystem Overview

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. We chose to use the same actuator for venting and cut down to save weight for ballast. To save energy, the valve contains an overcenter mechanism so it locks into a sealed state with no additional actuator torque.

Actuator Subsystem: Ballast Dropper

A small DC gearmotor will spin a wheel at the bottom of the balloon payload to drop 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.

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.

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.

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.

Communication 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.

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.

2.2 Subsystem Requirements

Vent Valve and Cut-down

- The vent must release helium fast enough to slow the initial ascent from the ground to a 12-20 km cruise altitude. This release rate will depend on the initial lift, which we will .
- The valve seal must not leak a significant amount–losing no more than 5% of lift due to the seal alone—in a 48-hour period.
- The valve mechanism must allow for quantized release of air, such as in series of short bursts, in order to predictably control the volume of air released.
- The valve actuator should draw negligible power when not in use, and under 5W peak.
- The valve actuator also serves to cut down the balloon controllably.
- The balloon must have an automatically deployed parachute to arrest descent rates upon loss of lift due to leakage or the balloon popping.

Ballast Dropper Requirements

- The ballast system must drop ballast at a rate of 1 gram per second or higher
- The ballast system must 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.
- The ballast dropper mechanism must not jam if operated intermittently over a 48-hour period, or be able to detect a jam and run infallible de-jamming sequences during testing.
- The valve actuator should draw negligible power when not in use, and under 5W peak.

Power Requirements

- 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 last significantly longer at our discretion in the case that the system survives more than 2 days in flight.
- The power subsystem must be able to provide 3.3V with up to 200mA current draw.
- The power subsystem must be able to provide 5V with up to 2A current draw.
- The 5V supply for the satellite modem must be gated through a current-limiting hot swap to enable lower power consumption and protect against faults.
- The power subsystem must report back current and voltage measurements from the batteries to detect charge state.

Thermal Requirements

- The resistive heater and insulating box must keep the enclosure temperature consistently above freezing while drawing less than 1W during use at night.

Control Subsystem Requirements

- The control subsystem must automatically manage sensor data acquisition, sending data reports, receiving and responding to commands, the thermal control loop, and most importantly, the altitude maintenance control loop.
- The control subsystem must

Communication Requirements

- The communications subsystem must utilize satellite connectivity to enable data reports every 10 minutes or more frequently as needed, as well as command uplink.
- The communication subsystem must maintain connectivity despite the dynamic environment of the upper atmosphere which may cause balloon motion.

Ground Requirements

- 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.

2.3 Tolerance Analysis

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

Another limited resource is the amount 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.

"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

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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.

weather balloon. As a proof of concept, we can demonstrate dropping ballast at a consistent mass rate and similarly venting air controllably.

3 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

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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."

notifications to authorities prior to and during a balloon operation.[10] To meet these requirements, we will be 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.

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[10] Code of Federal Regulations. "Part 101."