Design of a High Altitude Balloon Satellite

Amare Johnson[1], Madden Pierce[2],
Michael Tyrrell[3], Maria Ivey[4], and Wout De Backer[5]
University of South Carolina, Columbia, South Carolina, 29201, USA

High Altitude Balloon Satellites (HABSAT), large balloons that can float up to the stratosphere in a range of 10 kilometers to 50 kilometers altitude, allow for the gathering of atmospheric data. The HABSAT's are unmanned, which allow for the ability to inexpensively research the atmospheric and weather conditions over a specified area for prolonged amounts of time. A common version of the HABSAT is the weather balloon which is used by the National Weather Service and meteorologists alike to observe and collect data on the weather for society. This paper focuses on the design and development of such a HABSAT that complies within the given requirements of the USC Senior Design Project. The HABSAT designed can reach an altitude of 30 kilometers where it transmits real-time temperature and humidity data, along with HD images back to a ground station SATCOM. This was accomplished through attaching a programmable payload, a radiosonde, which measures the atmospheric conditions, to a weather balloon and parachute. In this case the radiosonde incorporated the use of a Raspberry Pi as the programmable system, since it was crucial to maintain constant communication and data acquisition as efficiently and inexpensively as possible during flight. The balloon lifted the radiosonde and camera configuration into the stratosphere to reach the target altitude of 30 kilometers. During the flight the radiosonde communicated and recorded the atmospheric data back to the ground station SATCOM via radio waves. Furthermore, the telemetry data once recorded was stored on board the radiosonde as backup and was accessed for later analysis after recovery. The HABSAT was tracked during flight through the radiosonde communication link with the ground station SATCOM. Finally, the radiosonde was recovered with a controlled pop of the balloon and deployment of the parachute. In the progress towards a solution, the structural design, communications design, data acquisition design, and recoverability of the design were taken into consideration to successfully and efficiently complete the mission within the regulations and constraints of the mission. These included payload weight restrictions, size restrictions of the balloon, communication restrictions with the ground station, a budget constraint, and time constraint. The design and development of the HABSAT was achieved through the use of commercially sourced products in a 3-month period with a budget of $1250 to showcase the effectiveness and inexpensiveness of a HABSAT.

[1] Undergraduate Student, USC Department of Aerospace Engineering, Student Member
[2] Undergraduate Student, USC Department of Aerospace Engineering, Student Member
[3] Undergraduate Student, USC Department of Aerospace Engineering, Student Member
[4] Undergraduate Student, USC Department of Aerospace Engineering, Student Member
[5] Assistant Professor & Faculty Advisor, Department of Mechanical Engineering, Senior Member

I. Introduction

The following paper summarizes the design process and design selection of the HABSAT that met the given requirements of the USC Senior Design Project in a three-month timespan with a budget of $1250.

A HABSAT is an unmanned balloon that can float throughout the stratosphere to gather atmospheric data and transmit this data back to a ground station team for analysis. HABSATs have an important mission as this data is used by meteorologists to help predict weather patterns across Earth. A standard HABSAT consists of a weather grade balloon, parachute mechanism, structural support, and a radiosonde. The radiosonde is the component that records and transmits the data back to the ground station, while the others serve as the mode of transportation and structural integrity. HABSATs are used on a wide range from hobbyists to government operations to engage in scientific research of the Earth's atmosphere [1].

II. Design Considerations

The design of the HABSAT began with evaluating our mission statement: "Capture HD images from the stratosphere and transmit real-time temperature and humidity data back to a ground station." In addition to the mission statement, certain requirements were imposed by the university as well as by FAA, NFPA, and FCC regulations. Figure 1 below details the various requirements for the HABSAT project. The primary requirements are labelled in red as "killer" requirements to emphasize their importance.

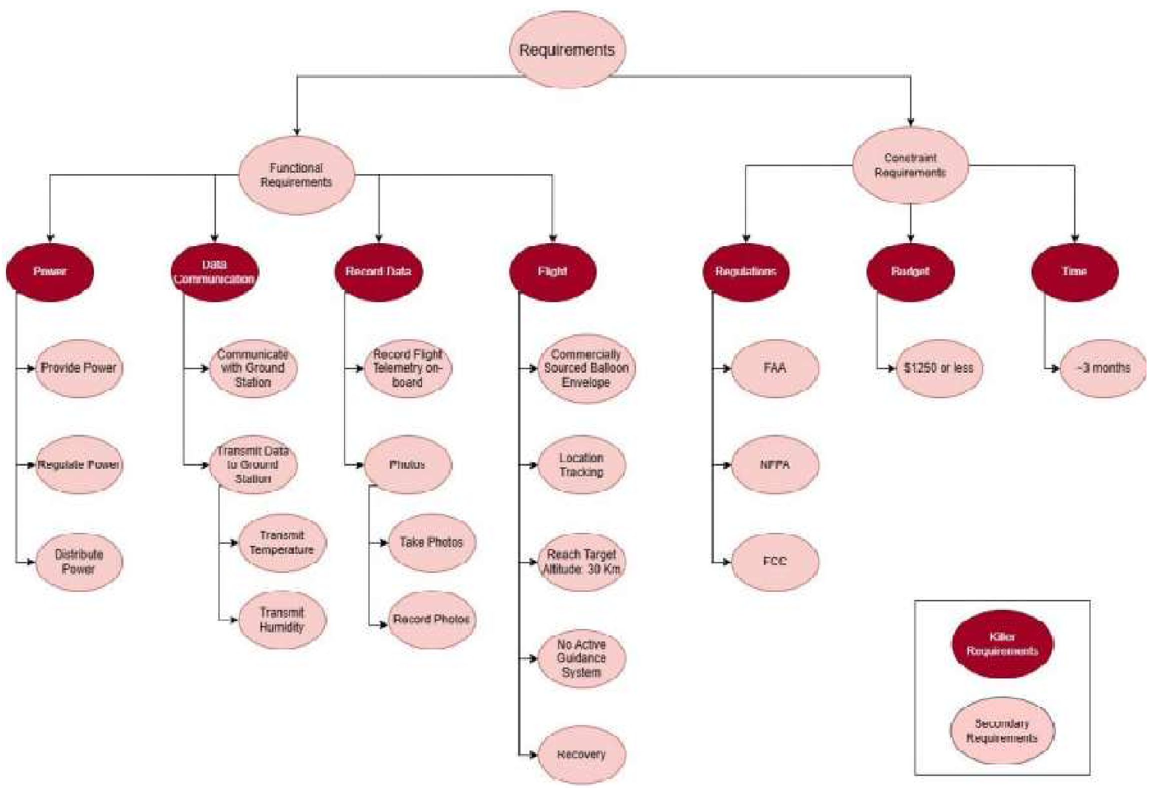

Figure 1: Requirements Discovery Tree

A. Balloon Selection

The balloon selection for the HABSAT was based on the target altitude and ascent time. The Balloon Performance Calculator from High Altitude Science (HAS) [2] [3] was used to find the optimal balloon size. From here it was determined that a 1500-gram balloon would allow the HABSAT to reach the required altitude of 30 km while keeping the total estimated ascent relatively low at around 87 minutes. The specific balloon chosen was also from HAS based on the affordable pricing and the quality guarantees. The HAS balloon also features a long, thin neck which allows it to be easily tied off after inflation.

B. Structural Design

The driving requirements for the structural design were heat insulation, flight stability, and weight minimization. The electrical components used for data collection and transmission can be sensitive to the frigid temperatures in the stratosphere, and the devices must be kept relatively stable during flight in order to ensure the accuracy of the data. Styrofoam was chosen as the material for the electronics housing to provide sufficient heat insulation while minimizing the overall structural mass. To stabilize the HABSAT further, four PVC crossbars were attached to the foam housing. The parachute lines were attached to each end. This configuration increases the coupling between the balloon neck and the payload with the crossbars providing a large moment arm. Air scoops were also included on each of the crossbars to dampen rotations particularly during the first half of the ascent phase where the atmosphere is denser.

C. Computer System

With the requirement to record and transmit data, the first design selection made for the radiosonde of the HABSAT was the computer system. The computer system runs the commands and instructions for the system on board the radiosonde. Due to the budget and time constraints the computer system needed to be commercially sourced, yet powerful enough to allow tracking, allow recording of the telemetry data of the HABSAT, and allow the ability to transmit the atmospheric data back to the ground station. To accomplish this, a single board computer (SBC) was chosen as it is a complete computer with microprocessors, RAM, and input/output functionality. The SBC that was chosen for the HABSAT was the Raspberry Pi due to its wide documentation of use and ease to order [4]

To fit within the Federal Aviation Administration (FAA) weight regulations for HABSATs, while also being in compliance with the budget for the given mission, the smaller, yet still powerful Raspberry Pi Zero W was selected as the final computer system. The Raspberry Pi Zero W contains a 32-bit processor, 1GHz single core CPU, and 512MB RAM. These specifications were most important for the mission and allowed for the completion of the mission at half the size of the normal sized Raspberry Pi. The Raspberry Pi Zero W allowed for connection of the temperature, humidity, and CO2 sensors, as well as connection to both cameras. A 32 GB SD card was loaded onto the Raspberry Pi Zero W with the required code to allow for data acquisition, recording, and transmission during flight.

D. Camera System

With the requirement to capture HD images or better to visually during the flight, a need for a camera system had to be considered. An HD image quality picture is usually in the range of 720p, 1280 x 720 pixels, or higher. This requirement is important as the higher the image quality the camera can take the more expensive the camera will be. At the same time, to provide the most visual coverage of the HABSAT flight, three different cameras are used at two different orientations: one angled upwards and one angled downwards. Finally, these cameras must be able to operate in the extreme conditions of the stratosphere during the flight. To accommodate these requirements and for the given budget, a singular higher quality camera is chosen with the secondary camera being of lesser quality, both at the HD image range.

The main camera chosen was the AKASO V50X Action Camera. This camera can record 720P quality video with a lifespan of up to 180 minutes with the use of rechargeable 1350mAh batteries. The AKASO V50X has a working temperature of -5 degrees Celsius to 45 degrees Celsius, therefore it is important to note insulation of the camera was needed to ensure operation of the camera as it reached 30 km altitude. This was taken care of through insulation of the radiosonde. Temperatures in the stratosphere can reach around the -50 degrees Celsius mark. This camera was oriented downwards to the side in order to capture the curvature of the Earth as the fight ensued.

The secondary camera selected was the Raspberry Pi Camera Module V2-8. This camera model is a Megapixel camera with 1080p quality photographs that attach directly to the Raspberry Pi Zero W. However, like the AKASO V50X, this camera was insulated inside the radiosonde to ensure proper operation in the extreme temperatures during flight. This camera was oriented upwards to capture the balloon and parachute during the flight.

E. Communications System

To meet the data transmission and tracking requirements of the HABSAT, a form of communication system was needed. For the mission, communication with a ground station team, also a part of the USC Senior Design Project, was needed and served as a constraint on the form of data transmission and communication used.

To operate and track the HABSAT through the communications system used, according to the Federal Communications Commission (FCC), an amateur radio license was needed [5]. Per the FAA, the location of the HABSAT must be reported at least every two hours [6]. These constraints heavily narrowed down the selections of the communications system.

A compromise was made using a GPS receiver and radio transmitter that functioned in the range of 400 MHz to 460Mhz. The transmitter used was a 434 MHz LoRa radio transmitter with a RG174 Tail that was converted into an antenna. On top of this an Automatic Packet Reporting System (APRS) add-on board was used to share and transmit the temperature, humidity, and the carbon dioxide of the atmosphere. APRS works through transmitting the data on a single shared frequency which is repeated to relay stations for widespread consumption [7].

This combination allowed for proper tracking and data transmission of the HABSAT as it ascended to the 30 km altitude target.

F. Sensor System

In flight, data acquisition was needed to gather the temperature, humidity, and carbon dioxide of the atmosphere. Two main sensors were used to gather this data. For the temperature and humidity data acquisition DHT22/AM2302 Digital Humidity and Temperature Sensor Module were used. For the carbon dioxide sensor, a Senseair K30 sensor was used. These sensors were placed on the outside of the radiosonde while connected to the Raspberry Pi Zero W. The data gathered from the sensors were then stored onto the Raspberry Pi Zero W and then transmitted to the ground station for analysis.

The DHT22/AM2302 sensors operate in a temperature range of -40 degrees Celsius to around 80 degrees Celsius. The temperature accuracy of these sensors is ± 0.5 °C. For the humidity range, these sensors operate in the range of 0 to 100%RH. The humidity accuracy for these sensors is ±2%RH.

The Senseair K30 sensors operate in a temperature range of 0 degree Celsius to 50 degrees Celsius. The Senseair K30 sensor has an accuracy of ±3% carbon dioxide.

These sensors successfully completed the requirement of data acquisition and allowed data transmission for analysis by the ground station team.

G. Power System

The Raspberry Pi Zero W is powered by two lithium AA batteries, providing 3.7 volts each. The batteries are housed in a plastic holder and wired to the Raspberry Pi Board, which then routes power to each of the sensors as well as the secondary camera. The primary camera has an internal battery which provides 1350 mAh of power. This is enough to power the primary camera for about 180 minutes while capturing footage at 1080p resolution.

H. Risk Assessment

The risks and mitigation approaches will now be discussed for the final design. The main risks associated with this design are as follows:

1. Thermal Protection Failure
2. Aerodynamic Instability
3. Telemetry Failure
4. FAA Regulation Compliance
5. Parachute Failure
6. Premature Balloon Burst
7. Battery Failure
8. Structural Failure
9. GPS Failure
10. Ground Station Failure
11. Compressed Gas Safety

Thermal Protection failure refers to the sensitivity of the components inside the payload. The HABSAT is required to reach an altitude of at least 30 km, where temperatures can range from –55 C to –5 deg C. The payload needs to be properly insulated to ensure each feature can be performed as expected. If not, the drastic drop in temperature can risk the camera performance and quality, the battery performance, and electronic component failure of the Raspberry Pi. However, this risk poses less concern due to the use of Styrofoam housing and the possible inclusion of heat packs. Freezer testing of the insulation will be conducted to verify performance before launch.

Aerodynamic Instability concerns the risk of the payload spinning or tilting. Instability risks the quality of the antenna connection as well as the quality of the images gathered. For risk mitigation, the design includes a crossbar with air scoops attached to the payload. This design keeps the payload more stable and resistant to rotation.

Telemetry failure concerns the HABSAT's inability to transmit real-time data. Requirements for the project include the ability to transmit real-time temperature and altitude data to the Ground Station during the mission. Risk mitigation includes stabilizing the payload, and ensuring the strength of the satellite for the ground station and the Raspberry Pi Zero W. All transmitted data will also be backlogged onboard.

Regulation compliance is critical to ensure launching within schedule. Failure to comply with regulations means the HABSAT cannot be launched regardless of a finished product or not. Risk mitigation includes ensuring we meet the payload weight, balloon size, and launch location/day restrictions. Regulations referred to include the FAA part 101 for Unmanned Free Balloons.

Parachute failure risks the integrity of the payload and puts others at risk. In the event the parachute doesn't deploy, the payload would experience a rapid descent that would damage the components inside on impact as well as potential damage in the landing area. Drop testing is the best risk mitigation approach.

Premature balloon burst takes into consideration the budget. With the purchase of only one balloon, it's critical to be extra cautious with the balloon. Risk mitigation means taking care when inflating the balloon before launch and wearing latex gloves. After launch there is little to be done about this risk.

Battery Failure was partially addressed in the Thermal failure sections, but another consideration is battery failure of components due to prolonged ascent time. In particular, the battery life of the GPS needs to last long enough to ensure recovery. Risk mitigation included choosing a 1500 g balloon to decrease ascent time.

Structural Failure considers the unintended detachment of the payload from the stabilization crossbar or the separation of the balloon from the payload assembly during ascent. Risk mitigation includes ensuring proper connections. After the components are placed inside, the Styrofoam housing should be securely attached to the structural beams using zip ties and the suspension lines of the assembly should be able to withstand the weight of the payload.

GPS failure results in failure to retrieve the payload. Part of the requirements include retrieving the payload to analyze the data later. Risk mitigation includes tracking the HABSAT during the flight and following during descent. The stabilization crossbar will also assist in this.

The Ground Station Failure concerns the risk of failure of receiving transmissions, which is a key requirement. The design and building of the ground station is overseen by a different Senior Design team. This risk considers the unexpected damage or failure of the ground station, after initial testing. As the ground station is the responsibility of another team, outside of testing and launch day risk mitigation is difficult.

Compressed gas safety concerns the handling of the helium during inflation. It's important for team members to be aware of the potential risks from handling helium near electrical components and careless wiring. Risk mitigation includes mandatory Compressible Gas Safety classes provided by the University of South Carolina.

III. Bill of Materials and Weight

A. Budget Breakdown

After completing the preliminary design phase and identifying the risks, the required components could be identified. The required materials have been organized into a comprehensive bill of materials to keep record of the parts being ordered. Table 1 shows a simplified breakdown of the project budget, organized into the HABSAT's subsystems. The costliest components for this design were the helium needed to fill the balloon and the electronic components of the Rasperry Pi Zero W system with the sensors, GPS, radio transmitters, and the APRS add on board.

Subsystem	Price
Balloon	$378.16
Parachute	$53.40
Camera	$124.60
CPU	$364.87
Data Acquisition	$70.28
Structural	$70.65
Total	$1,061.96

Table 1: Budget Breakdown

B Weight Distribution

One of the most important factors to consider when designing a weather balloon, as with any flying device, is weight. To comply with FAA regulations, the maximum target weight for the payload design was 6 lbs[8]. Similarly to the method used for the budget breakdown, the weight of each component was calculated and organized into the HABSAT's subsystems. The weight of the balloon itself was neglected here as FAA regulations only constrain the payload weight. Table 2 below displays the weight breakdown for the HABSAT.

Subsystem	Weight (oz)
Parachute	2.4
Camera	19.15
CPU	4.66
Data Acquisition	0.847
Structural	32
Total	59.057

Table 2: Weight Breakdown

IV. Conclusion

This HABSAT system is designed to reach the stratosphere and measure and transmit real-time weather data, as well as capture HD video during the flight. The design has applications for meteorological analysis, wildfire monitoring, and climate studies. This project also aims to demonstrate that reliable weather data can be obtained using a low-cost system. Overall, this project has served to advance the USC Senior Design Project group's engineering knowledge and created a foundation for designing and manufacturing under a given timeline and budget.

V. References

[1] Wikipedia, "Highaltitude balloon" [Online].
[2] High Altitude Science, "Weather Balloon 1500 g." [Online]
[3] High Altitude Science, "Balloon Performance Calculator" [Online]
[5] Federal Communications Commission, "Amateur Communications & Operations FAQ" [Online]
[6] Federal Aviation Administration, "Section 6. Unmanned Free Balloons" [Online]
[7] APRS.org, "Automatic Packet Reporting System" [Online]
[8] National Archives, "Code of Federal Regulations; Title 14, Chapter I, Subchapter F, Part 101" [Online]