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BalloonSat: A Very Low-Cost ‘Satellite’ Test Platform

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The University of North Dakota has, over the last five years, performed work to significantly lower the cost of the development of a small spacecraft. Despite making significant reductions to CubeSat cost levels, providing increased functionality and customization capabilities, orbital missions still require funding levels that may place them outside the financial capabilities of most K-12 schools along with many colleges and universities. For institutions that can afford CubeSat development, a mechanism is required to allow the institution to gain competency on spacecraft development prior to being a successful proposer for many sources of prospective funding. For both of these reasons, a very low cost CubeSat-like high altitude balloon (HAB) or solar balloon (SB) payload and an associated tracking system solution are being developed.

This paper presents an overview of the BalloonSat design. It describes the composition of the HAB/SB payload and the differences between this design approach and many typical HAB payload designs. One area of particular notoriety of the design, the use of 3D printing to produce the payload frame, is covered in detail. A discussion of the ease of construction, based on the use of 3D printed frame and inserted side panels (mirroring the CubeSat design) is presented. The comparative benefits and drawbacks of this design approach versus foam enclosures and other common HAB payloads are considered. In addition, communication technologies for the HAB/SB and the decision-making process between HABs and SBs are also reviewed in detail. The paper concludes with a discussion of previous and ongoing test missions and an overview of planned future work.¹

I. Introduction

The university of North Dakota has been working on developing a small satellite known as a CubeSat. The objective of the CubeSat program is to lower the cost of creating a 1-U (10cm x 10cm x 10cm, 1.33kg) satellite so that other educational institutions are able to create their own satellites¹. In order to have an affordable way to test these small satellites, as well as to allow K-12 schools to be able to develop their own, a BalloonSat program was

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created. Using a high altitude balloon (HAB) or a solar balloon (SB), a CubeSat-like payload can be carried into a space-like environment and retrieved using a one-way communication and tracking system.

The objective of the BalloonSat program is to create a low-cost satellite test platform that is accessible to K-12 students and which can aid in increasing STEM (Science, Technology, Engineering and Math) discipline participation. During the creation of the BalloonSat, many students will be acquainted with new and exciting technologies like the Raspberry Pi, 3D printing and the APRS protocol. They will also gain a better understanding of hardware-software integration. In addition to educational and enthusiasm benefits, the use of 3D printers and the Raspberry Pi will also eliminate the cost of specialized flight computers and third-party custom part manufacturing.

This paper provides a detailed report of the BallonSat program being developed. It discusses prior work done in the HAB community as well as other educational intuitions. It gives a detailed introduction to the different technologies being implemented (such as the transmission of data packets over amateur radio frequencies, 3D printing and the use of a solar balloon). The application for STEM participation and increasing educational intuitions’ access is discussed. The structure of the payload as well as all the electronic components are also discussed. In addition, the software and data communication link approaches are presented. Finally, the paper concludes with a discussion of future implementations being considered.

II. Background

The BalloonSat project has grown from prior work related to many different technologies. These include the use of the amateur radio system, three dimensional printers, and high altitude balloons such as solar balloons. Many of the different technologies used in the BalloonSat project are discussed in this section.

A. APRS Telemetry

The automatic packet reporting system (APRS) is an amateur radio protocol developed by Bob Bruninga to provide real-time local communications for rapidly exchanging digital data. During the operation of a HAB, the APRS protocol provides a means to track the geographical location of the balloon by providing real time data containing, but not limited to, geographical coordinates and altitude.

In effort to make a low-cost BalloonSat as widely available as possible, APRS is an efficient and convenient solution to provide the necessary real time data needed for successful HAB flights. To utilize the APRS protocol for balloon tracking, an amateur radio technician’s license (which is attainable by taking the FCC amateur radio exam), an appropriate radio receiver and a GPS transmitter (to include within the HAB’s flight system) are required. In addition to these requirements, mapping software and a software terminal node connector (TNC) must be used. The mapping software must have the ability to plot real-time APRS and NMEA (National Marine Electronics Association) format geographical coordinates on a global or regional map. The TNC needs the capability to demodulate the tones transmitted over the amateur radio frequencies and to translate them into APRS packets. The software TNC used in this project is Direwolf. The mapping software used is APRSISCE/32.

B. Three Dimensional Printed Structure

The advent of plastic 3D printing in the consumer market in recent years has created opportunities not previously available. The recent affordability and efficiency of 3D printers has made the technology desirable among those who require custom quality components. For UND’s BalloonSat project, the use of 3D printing has become a staple of its structural design. The ability to 3D print offers the capability for customization of the components and also enables rapid prototyping of designs. The payload housing for the HAB is fabricated piece-by-piece by a consumer model 3D printer, such as a MakerBot Replicator 2 3D Printer. The individual fabrication of each piece culminates in assembly into a final design including a printed frame and inserted side panels.

Prior work in fabricating 3D printed HAB structures has been conducted by the University of North Dakota. Structural designs have been explored and have ranged from traditional to nontraditional form factors. Multiple designs were able to be fabricated quite quickly as a result of the rapid prototyping process offered by 3D printing. The customization of structures (to traditional and nontraditional forms) was also feasible, as 3D printing allowed models to be modified via software as needed. From this, it is apparent that rapid prototyping and customization of structures is cost effective and efficient when a 3D printer is available for use.

Along with the ability to fabricate entirely custom structures, it is worthwhile to note that customized component placement is another useful benefit offered by 3D printing. By utilizing modeling software, such as AutoCAD, it is possible to design a form factor that can be fabricated to accommodate any number of components, in any configuration, that is within the acceptable volume and weight constraints of the structure. By using durable plastics, this enables the structure to house components within pre-cut forms in sturdy and reliable locations.

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Other structural designs using foams like polystyrene were also considered before a decision was made to use 3D printing methods for the payload housing. The typical payload enclosure among HAB enthusiasts is composed of foam. By using foam for the structure material, multiple benefits and drawbacks present themselves. Foam offers an affordable and convenient structure material that floats (aiding in water recovery), but it is brittle in form and it is more susceptible to damage from extreme conditions. By moving from foam to plastic, the durability of the structure is greatly improved in a multitude of conditions, such as freezing or wet environments. Foam also offers the benefit of allowing the placing components in nearly any desired location by modifying the structure. For instance, cuts may be made into the foam to hold components necessary for HAB flight operations. However, the wear and tear of removing and replacing components typically damages the foam structure over time much more quickly than plastic. The final decision to use 3D printing with plastics, instead of foam, was determined by comparing benefits such as customization, rapid prototyping and durability of designs between the two materials.

C. Solar Balloon

The balloon used to lift the payload is one of the most important details of any HAB. The ability to have a low-cost and reliable balloon is imperative to ensure successful test flights. Typically, a latex balloon filled with helium is used to attain high altitudes. For instance, participants in NASA’s BalloonSat Exploring Program sent a HAB to nearly 100,000 ft using a 6-foot-in-diameter latex weather balloon filled with helium. Helium filled HAB solutions do not bode well for developing a low-cost solution, as helium is quite expensive (reported as $3.43 per cubic meter by the United States Geological Survey). In lieu of a helium balloon, a solar balloon solution has been developed and implemented. The solar balloon is built by connecting thin polyethylene sheets with meshing tape and then filling the balloon with air. The polyethylene sheets are typically collected from low-cost and easy-to-obtain garbage bags that are dark in color to allow for efficient heating of the air within the balloon from solar radiation. As the air within the balloon increases in temperature, the balloon begins to increase in altitude while carrying the payload along with it.

D. Inspiring STEM participation

The primary motive for this research is to provide a way for STEM students to have the ability to participate in HAB projects that inspire students to pursue or continue STEM studies and careers. By providing a clear path for a low-cost and convenient HAB project, students are able to pursue HAB projects that may have otherwise been unattainable. Other initiatives similar to this have been and are being conducted. For instance, StratoStar is a company that encourages the use of HABs for STEM education. The balloons they launch are typically launched during special occasions and enable students to get a hands-on experience when working with HABs. Other colleges and universities are also encouraging HAB research for STEM education. Students at Duke University in North Carolina just recently launched a HAB to encourage engineering teamwork and demonstrate synergy of related disciplines. An important skill to learn for success in STEM fields is to maximize efficiency within a project by utilizing each individual’s expertise in their respective field. Through ballooning, students begin to understand the importance of teamwork within a project. Figure 1 shows this happening during a solar balloon launch at the University of North Dakota.

Figure 1. Solar Balloon Launch at UND.
Students at the Massachusetts Institute of Technology have contributed the HAB community in a related way. A team of two students from the institution fabricated a HAB for about $150 USD in 2009 that was able to capture photos depicting the curvature of the Earth\textsuperscript{13}. For students wishing to perform research and participate in projects outside of events, DIY guides and kits for hobbyists and enthusiasts alike are available. High Altitude Science in Colorado Springs offers a full weather balloon kit that provides all the necessary materials to get started in high altitude ballooning\textsuperscript{14}. In addition, DIY guides for off-the-shelf materials can provide a much cheaper alternative than prepared kits. However, despite these options, the accessibility for HAB projects is still limited by the cost of components and the difficulty of understanding projects that have not been laid out clearly for the K-12 target.

Once a student is able to work with a HAB, a variety of benefits are enjoyed. The student will gain experience in developing problem solving skills and working in a hands-on environment. Developed skills like these have been observed in students participating in HAB projects. For instance, The Forestview Middle School in Minnesota has recently started a HAB project for students to participate in\textsuperscript{15}. During this project, the students have been reported to show more interest in STEM fields and have increased participation in academic activities. Aside from the hands-on-experience and problem solving skills students will develop, they also have the ability to participate in events exclusively for HAB enthusiasts. For instance, the Global Space Balloon Challenge (GSBC) is a worldwide event held for HAB students and enthusiasts that encourages teamwork when solving problems\textsuperscript{16}. Events like these may help to encourage STEM students to further pursue the sciences and engineering.

III. Overview

This project has had many layers of customization come together to make an experience that is truly rich and unique, serving as a model for prospective replication. It has made use of 3D printing to fabricate the structure of the BalloonSat. Students may customize the 3D structure, such as adding their name, their school’s mascot to the side panels or completely modify the design to fit their particular payload. Using the 3D printer also reduces the need to have custom parts made, which can become expensive and can lead to delay in the project. Figure 2 shows how the parts of the BalloonSat system work together. This modularity allows the unit to be extremely customizable and easy to create. The sides, posts and top and bottom panels are 3D printed. This allows the integration of a release mechanism which is connected to an Arduino and controlled by software. The Raspberry Pi, a very popular and compact computer for DIY projects which is commonly available to many educational institutions, is also used. The Raspberry Pi and Arduino also provide the benefit of having large, active and friendly user communities.

![BalloonSat Diagram](image.png)

**Figure 2. BalloonSat Diagram.** The components that comprise the BalloonSat.

The BalloonSat allows customization of the payload design. This customization can come in a physical form, such as structural design, or in a digital form, such as software. For example, when replicating the project, different types of printer filament, colors for filaments, or different designs for side panels may be used. The structure can be modified to accommodate a larger payload (which is an example of modifying the structure to meet specific needs). The
software can be manipulated so that the BalloonSat behaves in specific ways to support a wide array of situations. Software modifications may include the use of different parameters to terminate the flight. Modifications such as these would differ from the software that was originally packaged with the source code from the original project. Sensors can also be included to supply various types of needed data to the software.

IV. Structure

The BalloonSat was fabricated with four fundamental goals. It had to be light, inexpensive, easy to reproduce, and customizable. This challenge led to many different approaches being considered, but ultimately the 3D printing approach seemed to be the most beneficial, due to it being easy to use, inexpensive, and highly customizable. These same four fundamental goals led to the selection of many commercially available electrical components. Using commercially available components means that they are typically economical and easy to use. The Raspberry Pi and Arduino are very good examples of this: they have an active community and are some of the most affordable microprocessors on the market.

A. Construction of the BalloonSat

To construct the BalloonSat, work started by constructing the outer box and then moving on to make the interior elements. What was produced was a 3D template that can be used to print the four corner posts, the top, and bottom panels of the box. All of these are easy to print and don’t require the best 3D printers on the market. These outer pieces are all connected using screws and this provided a solid starting point (see Figure 3). From here, the next step was looking at the customization aspect of the BalloonSat. Customization is offered through the versatility of 3D printing by enabling custom parts to be fabricated. This customization also serves as a teaching aid by allowing students to explore and see which materials would be best for a system for high altitude operations.

Next, work moved onto the interior elements of the BalloonSat. These included the electronics, the wiring, and the mounting of all of the components. The core of the electronics system consisted of the Arduino and the Raspberry Pi. Together, these two boards provide flexibility and computational power for the BalloonSat. The design used the Arduino’s built in power regulator to draw from a 9v battery that would power both the Arduino and the Raspberry Pi. Also, a temperature sensor and servo were connected to the Arduino. The software for the Arduino was simple. If the temperature dropped below -10 degrees Fahrenheit, then the servo will be activated to release the balloon. The temperature termination condition was used because electronics may stop working at temperatures below this low of a temperature. Eventually, if that temperature is never reached, the servo will be turned on to trigger the descent of the balloon after a certain amount of time. The main function of the Raspberry Pi is to take aerial photos with an attached camera and to log temperature readings while airborne. This allows the collection of data that can be reviewed when the BalloonSat is recovered.

The final problem that had to be solved was mounting all the components in a small area while ensuring ease of installation. A double surface table inside of the BalloonSat that was mounted with four screws to the bottom sheet of the box (see Figure 4) was used. This was useful because assembly could be done outside of the structure where components could be inserted with ease. A Raspberry Pi, Arduino, two temperature sensors, and a camera can be attached to the table and then the table assembly can be attached to the bottom outer sheet of the BalloonSat. A hole
was included in the center of the bottom outer sheet to allow the camera to look downward towards the Earth. The camera had a wide viewing angle so a lens was put in to provide more focused pictures.

B. Raspberry Pi

A Raspberry Pi Model B 3 is housed within the BalloonSat structure and has the primary function of capturing downward-facing photos with a connected camera while the HAB is airborne. Captured photographs are taken intermittently throughout the HAB’s flight and are stored on the SD card’s local file system. The Raspberry Pi also has the capability to log ambient temperature readings via a temperature sensor that is also mounted within the BalloonSat structure. In addition to the current functions of the Raspberry Pi, the system is also open for modifications and the addition of supplemental components. For instance, a humidity or pressure sensor could be added to the system to enable a wider range of data collection.

C. Raspberry Pi Camera Module V2

The camera used by the Raspberry Pi is a standard camera manufactured by the makers of the Raspberry Pi. The camera is able to capture 8-megapixel photos and can send the image data to the Raspberry Pi via a 15 cm ribbon cable to the CSI port.

D. Raspberry Pi Temperature Sensor

A digital temperature sensor is housed within the BalloonSat structure and connected to the Raspberry PI. It has the primary function of logging temperature data during flight. Temperature data is collected intermittently throughout the HAB’s flight and stored on the local file system where it can be reviewed once the BalloonSat has been recovered.

E. Arduino UNO

An Arduino UNO is housed within the BalloonSat structure and controls power regulation and the termination of flight of the BalloonSat. Power regulation is necessary to control the amount of energy flowing into the system so that electronic components can be operated properly. A servo motor is also mounted within the BalloonSat structure and is used when the BalloonSat should trigger the balloon release - this is known as termination. Termination conditions occur when the balloon has reached an altitude where the temperatures are less than -10 degrees Fahrenheit or the balloon has remained airborne for a certain amount of time.

F. Analog Temperature Sensor

An analog temperature sensor is mounted to the BalloonSat structure and is connected to the Arduino UNO. The primary function of this temperature sensor is to provide temperature data to allow the software to check the temperature termination condition. Software running on the Arduino will continually check the ambient temperature to ensure the HAB will not remain in conditions where the electrical components may begin to fail due to cold temperatures.

G. Servo Motor

A servo motor is mounted to the BalloonSat structure and maintains a physical connection between the balloon and the BalloonSat. Its primary function is to control the release mechanism of the BalloonSat when a termination condition has been satisfied. When a termination condition is met, the servo motor rotates about 90 degrees to release the BalloonSat from the balloon.

V. Communications

An important aspect about the BalloonSat system is the ability to track and retrieve the payload. Without a good communication link and GPS capable mapping software, it may be difficult to retrieve the payload reliably. Therefore, any tracking procedure that is developed has to be tested and proven reliable. APRS was chosen due to the coverage offered and the ability to listen to an APRS transmitter with a handheld transceiver. The mobile station will allow for precise tracking and recovery while a ground station can provide a stationary point for collecting data.

A. APRS Overview

The automatic packet reporting system provides a means to gather real-time data associated with the location of a HAB. The APRS is an amateur radio service that is free and requires that the operator of the transmitting station be licensed by the FCC. To make use of services offered by APRS, specific equipment is required to collect the relevant
data. A GPS transmitter must be attached to the HAB to collect and transmit the position data over APRS. To receive the data, a ground station must be able to receive and record the HAB’s geographical data. By these means, the tracking of a HAB can be done either at a ground station or a mobile station pursuing a HAB in a chase vehicle.

B. Collecting HAB Location

The geographical location of a HAB is transmitted via the attached GPS transmitter over APRS. Once the transmitted data has been received by a listening repeater, the transmitted data can then be re-transmitting over amateur radio frequencies. Data transmitted over the APRS network may be received by a radio tower or received by internet gates (or I-Gates), where the transmitted data is uploaded to the internet. Collection and interpretation of the data is handled by either the ground station and/or the mobile station.

C. Ground Station Operation

The purpose of a ground station is to maintain a stationary point of data collection pertaining to the geographical location of a HAB. A ground station configuration starts with a radio transceiver that is capable of receiving on APRS radio frequencies (typically 144.390 MHz). When a transmitter reports its location on the APRS network, the receiver will receive the location of the GPS transmitter and provides this data as a series of audible tones. By connecting the transceiver’s audio output to a desktop or laptop computer’s audio input, software can be used to demodulate these tones into meaningful information. In addition, mapping software can graphically label the location provided by the geographical data of the HAB transmitter.

To demodulate tones, a software terminal node controller (TNC) known as Direwolf was used. By connecting the transceiver’s audio output into a desktop or laptop sound card’s audio input, tones can be demodulated and represented as meaningful, textual data.

To be able to graphically label the location of the HAB, mapping software known as APRISCE/32 was used. It is possible to pair APRISCE/32 and Direwolf together via socket protocols to enable communication between the two programs. Through this, Direwolf is able to send the geographical data to APRISCE/32. The mapping software can then plot the geographical coordinates on a global map.

D. Mobile Station Operation

The purpose of a mobile station is to provide a means to chase a HAB after it has been launched. Chasers must maintain real-time knowledge of the HAB’S geographical location. A mobile station configuration is quite similar to a ground station except for a few key differences. The first is that a mobile computer must be used and the second is that a GPS unit must be attached to the mobile computer to maintain the chasing vehicle’s location relative to the airborne HAB. In addition, using a transceiver to collect APRS data is typically required as internet connectivity may be limited while mobile.

E. Packaged High Altitude Balloon Tracker Program

The graphical user interface (GUI) is an easy to use, in all one program, via which any GPS capable computer can manage real-time flight data for a HAB. The GUI will have a documentation library, hardware tester, an integrated version of Direwolf, and possibly an integrated version of the APRISCE/32 software. The documentation will include guides on how to best use the software as well as on best practices when tracking a BalloonSat. The hardware tester will make sure that a COM/NMEA GPS device is detected and advise whether it has locked onto its current position. At this point, any COM/NMEA GPS enable device should work, but a list of compatible hardware will be created to make the setup process less difficult. Adding an APRS beacon tester is still being considered, however the APRISCE/32 software makes it easy to check whether or not the beacon is operational and therefore just the GPS tester has been implemented. Once the hardware has been properly configured, the program can be started with ease. Choosing the start button on the GUI will automatically start Direwolf in the background. After an initial delay, the APRISCE/32 will also start running. It will preconfigure to start tracking the mobile user’s current position and the position of the APRS beacon.

VI. Conclusion

Balloon payloads make for excellent low-cost satellite test platforms. They are great teaching aids and have the potential to spark creativity within students. They can incorporate new technologies such as 3D printing and tiny low cost computer boards (such as the Raspberry Pi or Arduino). They can also help people learn about APRS
communication and tracking. Finally, they can be used to help students learn how to design software and gain useful problem solving skills.

The initial design is being prepared for launch. It is planned that, soon after initial testing, an open source guide will be released to allow others to replicate the BalloonSat project. This guide will include all of the 3D printing templates, the website URLs to buy the required components (such as wires, computer boards, batteries, etc.), blueprints for assembly and even software that can be used for the Raspberry Pi and Arduino. Also, the high altitude balloon tracker program will allow students to easily connect to their BalloonSat. The planned integration of Direwolf and the APRSISCE/32 into the BalloonSat tracker will allow for an all in one tracking software package. In the future, a plan is in place to add a two-way communication link, which should allow for commands to be sent to and from the BalloonSat. The two-way communication link will allow a vast array of different research projects to be explored. Also in the future, several test missions to perfect the project are planned, seeing as how the first run might not be ideal.

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