Avionics and Power Management for Low-Cost High-Altitude Balloon Science Platforms

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Abstract

High-altitude balloons (HABs) have become popular as educational and scientific platforms for planetary research. This document outlines key components for missions where low cost and rapid development are desired. As an alternative to ground-based vacuum and thermal testing, these systems can be flight tested at comparable costs. Communication, solar, space, and atmospheric sensing experiments often require environments where ground level testing can be challenging or impossible in certain cases. When performing HAB research the ability to monitor the status of the platform and gather data is key for both scientific and recoverability aspects of the mission. A few turnkey platform solutions are outlined that leverage rapidly evolving open-source engineering ecosystems. Rather than building custom components from scratch, these recommendations attempt to maximize simplicity and cost of HAB platforms to make launches more accessible to everyone.

Acronym List

APRS	Automatic Packet Reporting System
COTS	Commercial of the Shelf
CSV	Comma Separated Value
CUSF	Cambridge University Space Flight Center
DC	Direct Current
FAA	Federal Air Administration
GAHPS	Gondola for High Altitude Planetary Science
GPS	Global Positioning System
HAB	High Altitude Balloon
IoT	Internet of Things
$LiSO_2$	Lithium Sulfur Dioxide
NOTAM	Notice to Airmen
PEL	Power Equipment List
PMAD	Power Management and Distribution
RTOS	Real-time Operating System
SoC	System on a Chip
UAV	Unmanned Aerial Vehicle

Introduction

Motivation

This research was initiated as risk reduction for the NASA Gondola for High Altitude Planetary Science (GHAPS) mission. High altitude balloon missions carrying expensive science payloads across harsh, difficult-to-access locations could greatly benefit from improved descent and landing systems with the ability to mitigate landing loads and improve general recoverability.

As a first step, the Glenn Research Center "Rocket University" development program developed a series of payloads of increasing capability to monitor and evaluate various recovery systems as shown in Figures 1 and 2. Comprised mainly of commercial-of-the-shelf (COTS) electronics and open-source software, this paper offers a few turnkey solutions for highly cost-constrained science missions. Rather than re-inventing the wheel, these solutions leverage open-source microcontroller platforms with large ecosystems that offer both flexibility and simplicity.

Balloon Subsystem Basics

A vast multitude of HAB related resources exist online; therefore many of the ancillary subsystems are only briefly outlined here. With many amateur missions focused on videography, this work addresses data acquisition and power management; two disciplines that scale to a wide range of balloon mission.

Figure 1.—Rocket University final launch (left) balloon Inflation, (right) payload being towed to the launch point.

Figure 2.—The data acquisition (DAQ) system for a 2 lb $1,000 launch (bottom) was used again as secondary DAQ for the launch shown in Figure 1.

Power and Thermal Considerations

Payloads endure extremely cold temperatures, making the most common battery types undesirable. As temperature decreases, voltage and overall battery capacity also decreases, often dropping off extremely fast after reaching a specific temperature threshold. With ambient temperatures reaching down to –75 °C, passive insulation and/or active heating can greatly improve battery capacity. Many balloon applications with active heating and radio transmitters also draw current on the order of 1 to 2 amps. Much like cold temperatures, high power draw can also disproportionately reduce battery life.

Lithium Sulfur Dioxide ($LiSO_2$) non-rechargeable batteries have been found to satisfy all of the typical HAB requirements. They can sustain relatively high current draw, are resistant down to –40 °C and their high energy density is desirable for lighter-than-air applications. This particular battery chemistry is rated for many space and medical applications, and they are the primary battery type flown by the Columbia Scientific Balloon Facility.

Using passive thermal insulation alone can capture enough waste heat from the battery bank to maintain –40 °C. Alternatively, on small payloads, chemical heat from hand- warmers are a popular and extremely simple supplemental heat source. Waste heat from transmitters and other onboard electronics can also be used to keep the payload warm. Given the extremely rarified air at high altitudes, heat is primarily transferred by direct thermal conduction and radiation. The lack of convection can be a double-edged sword, helping electronics retain heat in some cases, but also making it difficult to release unwanted heat without the addition of heat sinks or radiators.

Small-scale missions are often airborne on the order of 5 hr, requiring multiple batteries connected in both series and parallel. When building battery banks it's important to consider variations between battery cells, which become exacerbated by high loads and low temperatures. Without sophisticated circuitry, it is generally not advisable to connect batteries into more than two parallel strings. Power across each string is more likely to become increasingly unbalanced, after a single string starts to degrade. This creates a positive feedback loop, which can ultimately lead to a dangerous thermal run-away. With D-cell sized batteries being the limit for most consumer batteries, this puts a natural limit on the amp-hour capacity of amateur flights.

Telemetry

The ability to receive live wirelessly transmitted data from a payload is essential for the recoverability of any balloon launch. FindMeSpot is a recommended COTS tracking device, requiring no configuration or operator licenses. Communication via cell phone devices also offers slightly more flexibility, but additional configuration and complexity. Both of these methods are limited to 40,000 ft altitude ceilings. To maintain constant communication up to 100,000+ feet requires higher-powered radios. The most accessible amateur radios require an operator with an amateur HAM license. These licenses require taking an exam from a local amateur radio chapter. Many free online resources and study guides provide an easy way to master the finite pool of possible written quiz questions in a few weeks time. After passing the written test, the basic technician license is granted by the FCC within a few weeks. Additional licenses can be obtained by taking increasingly difficult written exams, allowing the operation of higher-powered radios over a larger range of frequencies.

The most popular balloon radio protocol, Automatic Packet Reporting System (APRS) provides a very succinct transmission including the balloons GPS latitude, longitude, heading, and operator call-sign. By committing to this protocol, the operator is able to leverage a large amount of pre-existing HAM radio infrastructure. Rather than relying exclusively on personal ground station equipment, many other amateur stations are constantly listening for the APRS frequency and protocol. If the signal reaches any of these stations, the signal will be repeated and re-broadcasted to neighboring stations. Eventually the signal will reach an Internet "gateway" where it is published to various web applications and databases. This allows an APRS operator to simply broadcast signals, without the direct need for any receiver equipment. As long as the signal reaches neighboring HAM stations, the call-sign and information will be available in real-time from any Internet connected device. For more direct reception and faster feedback, many affordable handheld receivers are available that can be tuned to filter out all incoming signals except APRS messages from specific call-signs.

If the payload requires more advanced telemetry, leveraging other frequencies and protocols may be more suitable. If a constant transmission (possibly bi-directional) communication link or higher bandwidth is needed, amateur remote control UAV radio components may be a better option. With balloon operations requiring extremely long-distance communication, the most ideal frequencies reside in the UHF range. As a general rule, transmission bandwidth increases and range decreases with increasing frequency. The 900 MHz is ideal for basic telemetry in the 100 to 200 kbps range up to 40 miles away. Radio modems include the RFD900, and Xtend900. These specific models are identified for their drop-in compatibility with existing hobby level UAV ecosystems that are outlined in subsequent sections. They are export controlled, require a basic technician's license, and only necessitate a minimal amount of radio and programming experience.

Balloon and Parachute

For small scale balloon missions Kaymont meteorological balloons are a popular choice. These balloons are selected due to Kaymont's history of providing high-altitude weather balloons to the amateur ballooning community. The balloons are available in a variety of sizes, selected based on the required mass to be lifted and the final float altitude. The smallest balloons are 350 g and suitable for lightweight and low altitude projects. Typically for a 6 to 9 lb chain of payloads, a 1200 to 1500 g balloon will be used. For all balloon sizes fewer than 1500 g, the neck diameter is a standard 3 cm. This is useful when designing your inflation apparatus. A larger neck diameter, which is found on the 2000 and 3000 g balloons will require a larger filling system. Additionally more helium is required for a larger balloon sizes.

The balloon size is only one part of determining how high the balloon reaches before burst diameter. The other factors include the suspended mass of your payload and the lift, which is determined by the amount of helium that is put into the balloon. Kaymont provides a table for reference on the burst diameter and estimated burst altitude for different size payloads with various balloon sizes.

Figure 3.—Inflation of a 1500 g balloon.

Although hydrogen can be used as a source gas for inflation, it is extremely flammable. Helium is preferred for general usage because of its chemical inertness. Typically, helium is sold in pressurized tanks of various sizes. Helium can be acquired through local gas processing companies such as Airgas, Praxair, and Matheson gas. In addition to the helium gas, a regulator is required and a filling system is needed to transfer the gas from the bottle to the balloon. The filling system can simply be a flexible hose connected to a PVC pipe that is just smaller than the balloon neck diameter. Using a simple force gauge, such as a fish scale, lift can be measured during the inflation process.

Simply connect the gauge to the rim of the PVC pipe prior to its insertion inside the balloon neck. The use of latex gloves, and wooden paddles covered in paper (or a tarp over the top of the balloon) is recommended during the inflation process to contain the balloon in light winds as shown in Figure 3. Oil or any other type of residue from direct skin contact may result in premature rupture of the balloon as it expands dramatically at higher altitudes.

Gondola Design

For small-scale ballooning projects the payload box is typically designed using foam core board as shown in Figure 4. The foam-core is cut in such a way that a six-sided box is formed from one piece of board. The board is folded up into a box where all but one side has been glued together using silicone adhesive. The remaining open side will serve as a door to fill the gondola with testing apparatus. Plastic wall anchors typically 10 to 14 sized in the corners of the top and bottom faces of the box. This allows stringing lines to be ran through the bottom to the top of the payload. The area of the payload is determined by the testing components that will be going inside.

Many weeks prior to launch date, a suitable launch location needs to be determined. Aspects of a good launch location include clear open skies in the nearby vicinity, a solid surface to lie out and fill the balloon, and a workspace (or transportable table) to complete any power-on procedures necessary. Standard power outlets are also preferred but not required.
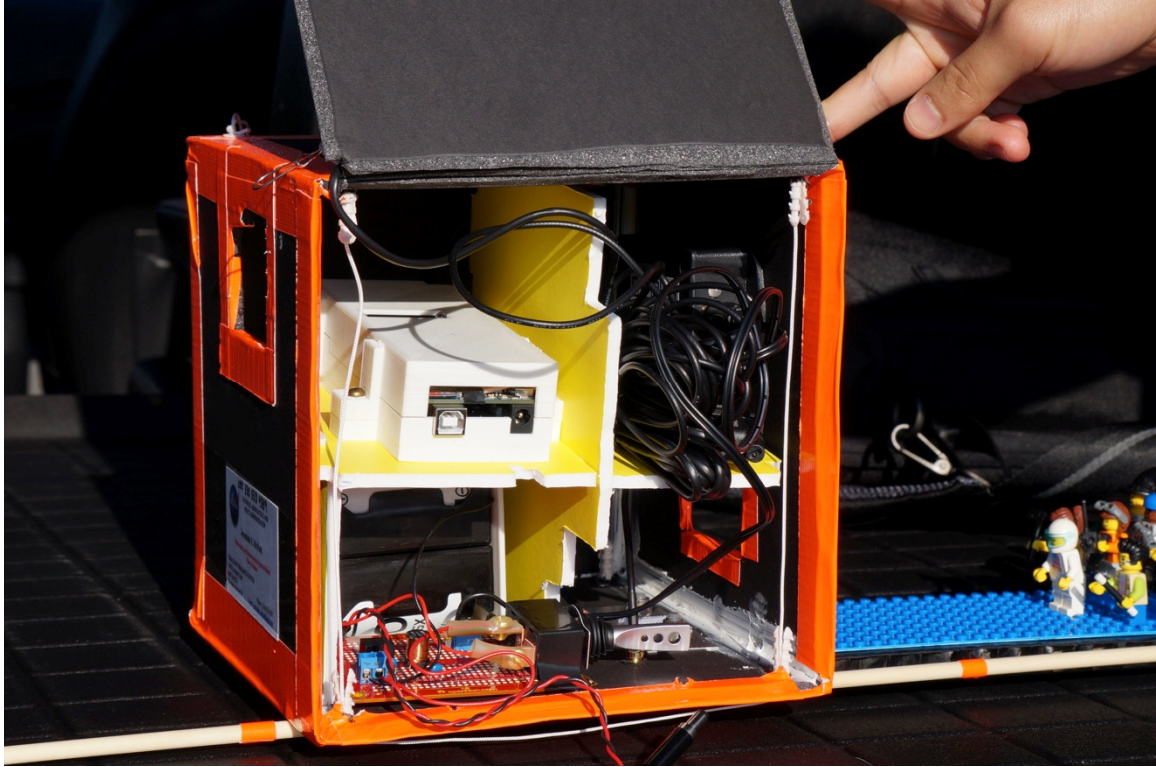
Figure 4.—First Rocket University 2 lb balloon payload, flown on the balloon shown in Figure 3.

A checklist detailing steps required prior to launch is recommended, an example checklist is provided in Appendix B. Once a suitable location has been determined, the specific launch day is usually determined by predicted weather conditions. Long-range forecasts that call for mild to warm temperatures and low ground winds are preferred. There are multiple online sources to predict the trajectory of the balloon and payload. The CUSF Landing Predictor 2.5 (predict.hanhub.org) is an excellent resource. The predictions are more accurate as you approach closer to the planned launch date. The burst calculator on the CUSF page allows you to enter details on your balloon, launch mass, and expected altitude to better refine the prediction. For recovery and safety purposes, the predicted landing site should be one relatively free of metropolitan areas and clear of large forests and bodies of water.

Balloon and Helium Cost

Helium costs roughly $150 for 200 ft^3, not including container and handling costs. A rough estimate of helium cost is shown in Table 1.

TABLE 1.—BALLON CHARACTERISTICS AT 320 m/s ASCENT RATE,
PRICE ESTIMATES FROM KAYMONT BALLOONS

Balloon size, g	Payload weight, g	Nozzle lift, g	Max alt, kft	Balloon price, $	Helium vol., ft^3	Helium cost, ($) x2
350	250	560	85	30	39	60
800	250	970	107	50	65	100
1200	1050	2240	109	70	113	170
1500	1050	2330	112	90	124	190
2000	1050	2470	117	300	143	215
3000	1050	2720	125	400	187	280

Launch Regulations

Developing FAA regulations (as of February 2015) limit small UAS (55 lb) to line of site flight, 500 ft altitude ceiling, daylight operation, operator certification, and additional restrictions in various airspaces (such as 5 mile radii around airports) without notifying air traffic control or further FAA exemption. A separate, "more flexible", set of regulations are under considerations for "micro UAS" class aircraft that fall under 4.4 lb. Although it's unclear how balloon systems overlap with UAS, the development of guided descent and recovery systems certainly fall under both categories, with even more stringent restrictions applied to vehicles used for commercial gain (Ref. 1).

Before launch, it's highly recommended to file a Notice to Airmen (NOTAM) with the FAA and any local regional airports.

Avionics for Multiple Cost Levels

Microcontrollers and systems on a chip (SoC) have improved significantly in compute power, accessibility, and cost over the past few years. Initially driven by hobby electronics, extremely broad communities of developers have emerged, blurring the lines between amateur and professional systems for many applications. The new economies of scale, trickle-down smartphone technology, Internet-of-Things (IoT) movement, and beginner friendly developer tools have made high-performance sensing platforms accessible to anyone.

The choice of hardware outlined here is separated into various pricing tiers, each optimized for rapid development time and extensibility.

Sub $300 Launches

Pico-HABS represent the most extreme type of balloon flight possible. These payloads are measured on the order of grams, and designed to be neutrally buoyant with the lift generated from large party balloons. Although they cannot reach extremely high altitudes, or carry any consequential amounts of payload, they can be outfitted with extremely basic sensors and communication equipment. Successful launches costing less than $100 have been demonstrated with balloons capable of traveling 30,000 ft high and over 4000 miles in a single flight, while maintaining radio contact (Refs. 2 and 3). Although extremely limited individually, these balloons could potentially serve useful purposes in distributed swarms.

Micro-HABS have been popularized by high school and colleges, and are often used to take still and video footage from up to 100,000 ft for less than $300. These payloads require larger latex balloons, with significantly more helium.

It should be noted that missions with payloads weighing a few pounds should be cognizant of safety concerns, avoiding highly trafficked air space and landing zones.

Higher cost launches, outlined below, also often fall under the 6-lb category, however the exponential increase in helium and balloon cost places them in their own category.

Sub $1,000 Launches

The first Rocket University avionics demonstrator was designed to characterize flight loads throughout the entire mission profile and maximizing the chances of recover ability, while staying under $1000, itemized in Table 2. An Arduino Mega was chosen as the main flight controller, due to its extremely large ecosystem of drop-in sensors, firmware/drivers, documentation, flexibility, development tools, and low-cost. Slightly more advanced users could also create a very similar system using the Beaglebone microcontroller and ecosystem. The Raspberry Pi platform is less strongly recommended for balloon applications, as it is better suited for desktop applications requiring a full operating systems and less geared towards integration with sensors and other peripherals.

TABLE 2.—LAUNCH 1 PRICE BREAKDOWN

Part	Function	Cost
Arduino mega	Microcontroller	$40
microSD card (16 GB)	Data storage	$10
Razor 9DOF	Inertial measurement unit	$75
GPS	Navigation	$50
GPS antenna	Antenna	$15
Spot tracker	Back-up tracker	$75
MicroTrak	APRS tacker/radio	$250
Connectors/cables	Misc	$20
Parachute	Impact reduction	$15
Subtotal	(One time cost)	$550
Balloon	Lifting vehicle	$90
Helium	Lifting gas	$200
$LiSO_2$ batteries (x4)	Power	$70
Total		<$1000

The following parts lists outlines an example build for a system capable of measuring, temperature, pressure, altitude, acceleration, orientation, heading, location, and video, with doubly redundant tracking mechanisms. The system is capable of data logging as well supporting additional sensors across a range of communication protocols (SPI, Serial, I2C, One-Wire, ADC, and more...). An additional 3 lbs of payload could be lifted with the given launch configuration, or an additional 8 lbs, distributed over two payloads with additional helium.

This budget is highly sensitive to payload weight, since balloon envelope and helium costs exponentially increase with weight. Based on the table above, subsequent launches would only cost half the up-front cost, assuming the payload is recovered.

Arduino Programming

The full Arduino source code used by Rocket University can be found in Appendix A. As a brief explanation, the code can be split into two distinct groups. The header script and setup() function are run once during power-on. In this section the programmer must import the required libraries to drive communication and sensors. Next, digital and analog pins from the Arduino are assigned to variables, and baud rates are chosen for serial communication. The first serial port is used to communicate with the PC over USB, and second is used to communicate with the dedicated Razor Inertial Measurement Unit (IMU), and the third and final serial port communicates with the GPS module. The rest of the code resides in the loop() function that runs repeatedly (and synchronously) until the Arduino is powered off. Each sensor is broken into a sub-function, which reads and logs the data. These functions can do basic calculations on the readings in real time, and format the data to be logged to the SD card every process loop.

$1,500+ Launches

The second avionics design is geared towards more advanced payloads requiring more challenging requirements. Although the sensors involved are comparable to the previous price tier, this COTS system requires much less configuration out-of-the-box. As a drawback, it's a much more complicated system to extend towards custom applications. Drawing from the amateur unmanned aerial vehicle community, it excels when requirements include constant two-way telemetry, remote control, asynchronous sensor sampling, sensor fusion, and even autonomous flight. The system is centered on the Pixhawk open-source UAV ecosystem and a breakdown of costs is shown in Table 3.

TABLE 3.—LAUNCH 2 PRICE BREAKDOWN

Part	Function	Cost
Pixhawk	Flight controller	$240
microSD card (32 GB)	Data storage	$20
RFD900	Radio transciever	$200
uBlox NEO-M8N	GPS and antenna	$90
Action video cam	Video sensor	$200
Spot tracker	Back-up tracker	$75
Rubber duck and yagi	Flight/ground antenna	$60
PMAD	Power distribution	$80
Connectors/cables	Misc	$30
Parachute	Impact reduction	$16
Subtotal	(One time cost)	$1,000
Balloon	Lifting vehicle	$90
Helium	Lifting gas	$200
LiSO$_2$ batteries (x6)	Power	$100
Total		<$1400

Pixhawk Programming

Programming of the Pixhawk is largely beyond the scope of this paper. The C++ code runs on a real-time-operating-system (RTOS) called Nuttx. Not only is the processer much faster than the Arduino, but also the flight controller performs many operations asynchronously allowing the system to log at a much higher rate. The Pixhawk is a fully autonomous flight controller right out-of-the-box, but can also be used simply as a data acquisition and telemetry system if active motor control is not necessary.

Programming requires an understanding of Git version control, C++, and familiarity installing, editing and running terminal scripts, and compiling source code with provided build chains.

At a minimum it's recommended to log all data after power on by modifying `ROMFS/px4fmu_common/init.d/rc.logging` line 14 to:

```
sdlog2 start -r 10 -e -b 12 -t
```

```
usage: sdlog2 {start|stop|status} [-r <log rate>] [-b <buffer size>] -e –a

-r      Log rate in Hz, 0 means unlimited rate

-b      Log buffer size in KBytes, default is 8

-e      Enable logging on app start (if not, can be started by command)

-a      Log only when armed (can be still overriden by command)

-t      Use GPS timestamps to create folder and file names
```

Power Management and Distribution

The Power Management and Distribution device (PMAD) is responsible for conditioning and supplying electrical power from the battery to all electrical subsystems (sensors, avionics, cameras, etc.). In doing so, it must be able to function over the entire flight profile operation, be designed and built so as to withstand the harshness of high altitudes, desert environments, and potential high-G loading, offer protection against electrical faults, whether occurring in a subsystem, the battery, or in the PMAD itself, and ease of use.

Sub $1,000 Launches

When the only electrical load is a single Arduino microcontroller with various sensors attached, its electrical demands can be met using an array of D cell batteries. For this implementation, only a buck DC-DC buck converter and output-smoothing filter are all that are necessary as depicted in Figures 5 and 6. The Arduino is capable of accepting a wide range of voltage inputs, however extra power is not dissipated efficiently. A buck converter can drop the battery pack voltage to a nominal 12 VDC for microcontroller operation and an output filter can suppress ripple due to switching on the output. The final manufactured version is shown in Figure 7.
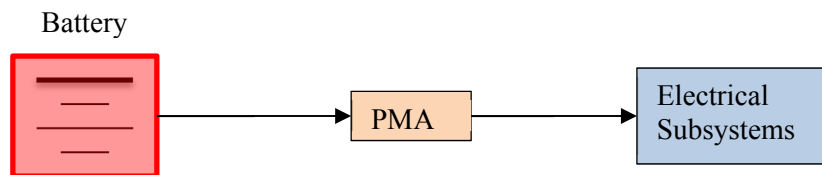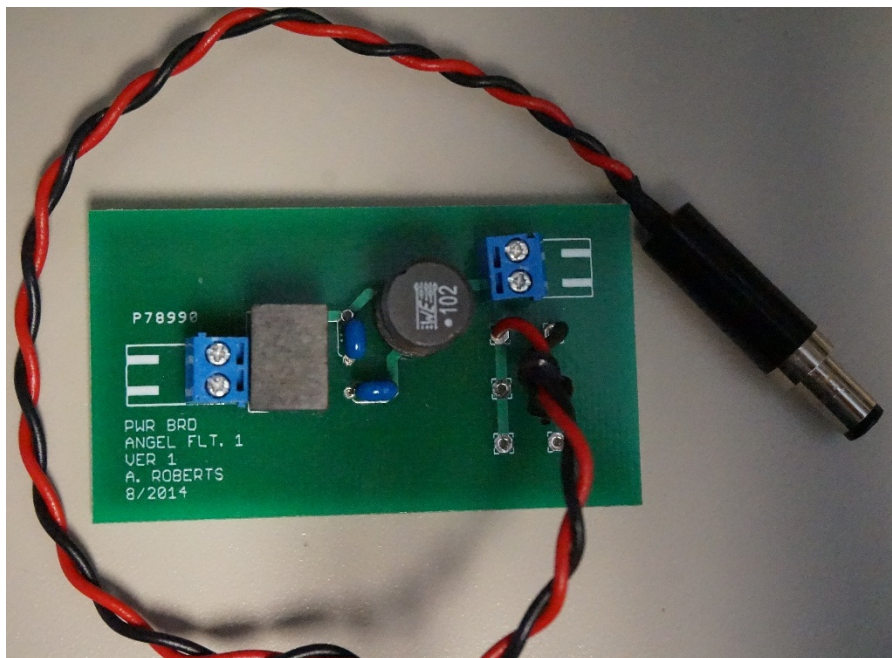

Figure 5.—PMAD connectivity block diagram.

Figure 6.—PMAD for arduino power conditioning, approximate length: 3 in.

$1,500+ Launches

A more sophisticated PMAD can expand on this topology by extending the number of converters to offer various voltage and power levels to serve the greater number of loads. A number of assumptions were made prior to design for this mission: radiation shielding would not be required, current and voltage ratings for components would exceed, at minimum, 150 percent of the peak operating conditions, the design would be robust against all load operations, thermals would be passively managed, startup and recovery-from-fault times would not cause erroneous operation, and that the PMAD be one self-contained unit with dedicated peripheral terminals for each subsystem. It is advised to create a Power Equipment List (PEL) to account for the current, voltage, and power needs for each electrical subsystem during the entire mission profile. This information can be used to determine the component sizing and ratings on the PMAD. All components chosen were selected for being able to operate over the entire mission environment in terms of survivability in extreme temperature and pressure.

In addition to the power supply circuitry, the PMAD outlined below has the capability to output, in real-time, the supply voltage and total load current measurements to a Pixhawk controller. This information is useful in assessing the power demands of the subsystems and the effects of extreme environments on their operation.

The PMAD is protected against electrical faults through design. Shorts occurring on any of the subsystem outputs trigger an output shutdown of the DC/DC converter responsible for supplying that particular load. The PMAD itself has a fused input to protect against any accidental electrical shorts that might unexpectedly occur. The battery has a fused output as well and uses internal diodes to eliminate the potential for cell reversal. Therefore, no emergency shutdown circuitry is required due to the battery's own internal protection.

Operator ease-of-use is integrated in the design by addressing how external users interact with the device. Consideration was given to how the PMAD was integrated, how it could be powered on and off, and confirmation of power. Keyed connectors were chosen so corresponding connections could only be made the correct way. Connectors were selected to be mechanically locking or very secure to minimize the risk of coming separated in flight. Board (and subsystem) power status is indicated using an LED and power is controlled through a clearly marked rocker switch.

All parts of the PMAD can be found from commercial electronics distributers such as Digikey, Mouser, or Sparkfun. Circuit design and printed circuit board layout were done using Cadsoft's EAGLE design tool (http://www.cadsoftusa.com/). This is a power schematic capture tool that allows complex electrical design and includes libraries of all basic electrical components as well as many commercial parts. EAGLE offers users the user the ability to expand on its usefulness by allowing custom code execution to add functions, unique part creation, and large user community. The layout functionality allows the user to export all of the most common manufacturing files in use by board houses. The circuit boards were manufactured by Advanced Circuits (http://www.4pcb.com/).
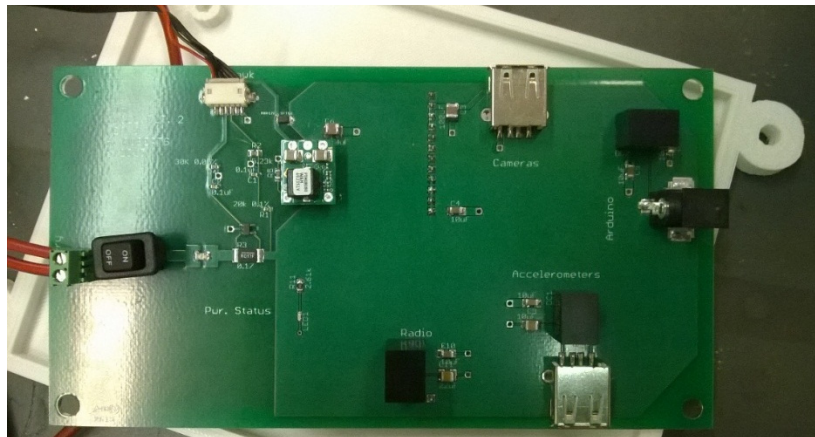

Figure 7.—PMAD for the final Rocket University flight, approximate length: 12 in.

Data Analysis

Post-processing the results of a flight often involves processing numerous hours of raw sensor data. If all sensors are not logging to a centralized source, it is important to have a baseline event to properly sync each source. For example, multiple independent accelerometer sensors can all be synced with a small 'kick' before launching. Since every sensor cannot be turned on at the exact same time, this small acceleration can used to match all sensors up to the same event in time, much like a movie clapperboard.

Post-Processing

Working with extremely large data sources often requires manipulating and 'cleaning' data using table-wide data transformations. Sensors may reset mid-flight, sample at various rates, or momentarily return invalid values. In order to process data for analysis purposes, it can be necessary to perform string and float manipulations, interpolations, etc.

While this will vary from project to project, it's important to be mindful of post-processing tasks while designing how each sensor reports data. Many sensors report floats even when throwing errors, making it difficult to search and distinguish between valid and invalid values during post-flight analysis. This can be avoided by logging errors with easily distinguishable strings or values that can easily be searched and removed later. It is also vital to timestamp and format all data in a syntax that is easily parse-able, based on the analysis tool of choice, otherwise it can be impossible to synchronize disparate logs with hundreds of thousands of entries. Excel, Python, and Matlab are all excellent choices for post processing. The example source-code used by Rocket University can be found in Appendix A.

Visualization

Even with perfectly synced data, it can be difficult to fully understand or appreciate the data in the form of a comma separated value (CSV) table. Plotting the data as a time-series can be helpful for analysis, and more advanced visualizations can be help in grasping the full context.

Processing, (processing.org) is a programming language and development environment designed with visualization in mind. For this project, it was used to sync video footage with visualized sensor data.

This particular program, shown in Figure 8, displays the accelerations, temperature, speed, altitude, and orientation in multiple contexts. There is a video component showing a picture- and-picture view of both camera angles, accelerations plotted as vectors, data shown as raw values, altitude shown both as a moving graph and overlaid on a map with speed, and a 3D rendering of payload orientation. The source-code for this visualization can be found in Appendix A. In order to properly sync the data with the video, all of the data was consolidated into a single table, where data was reported in to a new row every 0.2 sec. The program embeds the video and syncs the frame-rate with rows of sensor data from a CSV. At 30 frames per second, it reads a new row from the CSV file every 6 frames, updating the display. Playback controls are also provided, to allow the user to skip to any segment of the video/database. This requires a video file that starts and stops exactly with the beginning and endpoints of the data file. This way jumping to the halfway point corresponds to exactly halfway down the CSV file, and halfway through the video.

Data Dissemination

Two recommended services for online data dissemination include Github and Google Fusion Tables. Github allows for version control of plain text files (code, output) and a repository for any other type of file. Google fusion tables can be used exclusively for sensor output CSV's and provides a convenient way to share and visualize data in a single place, as demonstrated in Figure 9. It is especially usefully for plotting time series data, and plotting GPS data directly on an interactive map.
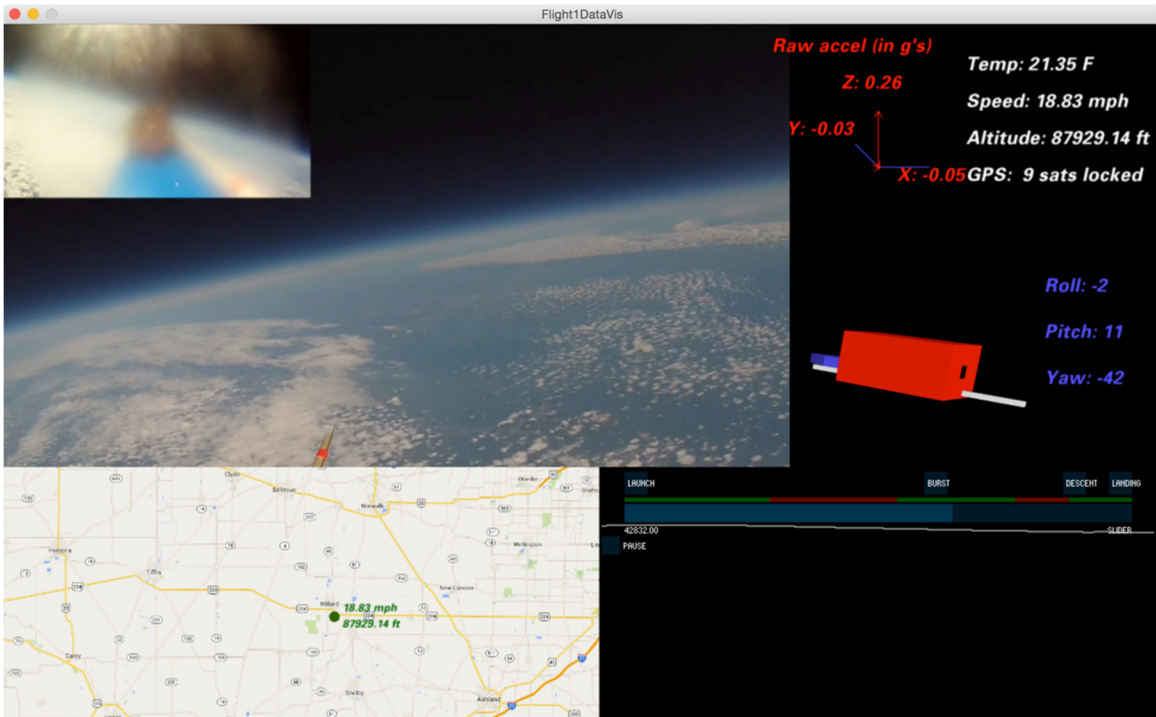
Figure 8.—Custom processing visualization based on the data from the payload in Figure 4.
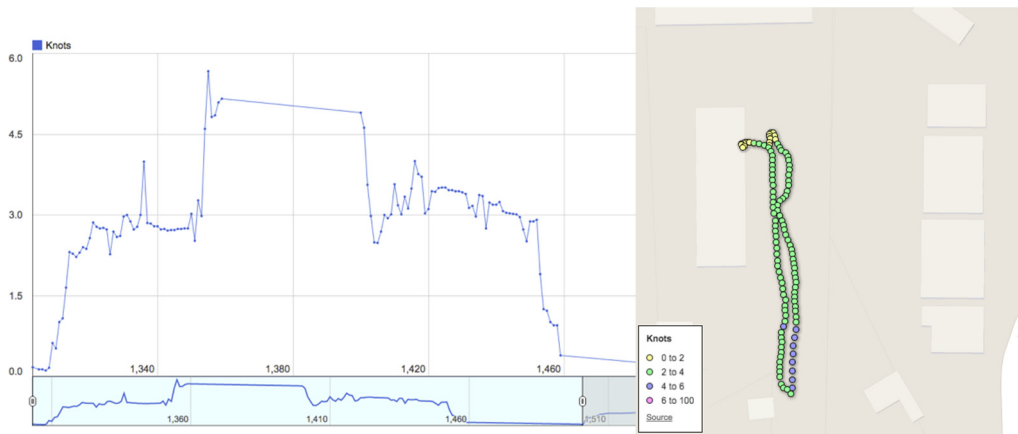Map data copyright Google 2015.

Figure 9.—Google fusion table (left) speed vs. time (right) GPS path colored based on speed.
Map data copyright Google 2015.

Final Remarks

Balloon payloads offer extremely low-cost scientific platforms. The advent of widely available inexpensive sensors, computers, and open-source hardware/software has greatly reduced the barrier to entry for planetary research.

The lightweight, inexpensive sensor packages outlined in this paper can scale to payloads of any size. These systems were originally intended for passive monitoring systems, however the final avionics system outlined could be used to control an active descent system.

Balloons have made a resurgence in both commercial and scientific applications. Exciting projects such as Google Loon are poised to play a large role in extending Internet connectivity to developing countries, proving that balloons can have significant and impactful real-world applications (Ref. 4).

Appendix A—Source Code

Flight 1

The entire source code can be found on github.
https://github.com/jcchin/ANGEL

Helium Calculator https://github.com/jcchin/BalloonPy

Flight 2

The entire source code can be found on github at:

https://pixhawk.org/dev/quickstart
https://github.com/jcchin/firmware

Processing

The entire source code can be found on github at:

https://github.com/jcchin/ANGEL/tree/master/RAZOR/Processing/Flight1DataVis

Appendix B—Weather Balloon/Payload Launch Inflation Checklist

Parts Lists Inflation	
2 Balloons (1 is spare)	adjustable wrenches
Helium, 2 tanks (K bottles)	pliers
Helium truck rack and rope	fish-scale
Pressure Regulator	digital scale (w/ spare 9 V battery)
4 – wooden paddles (1' by 3', wrapped in paper)	tape measure
Latex gloves (6 pairs)	Water container (counter balance determination)
Cotton gloves (6 pairs)	String (for tying off balloon) 100 lb test Dacron
hose and gas feed adaptor with valve	scissors
hose clamps (1 for balloon and 2 for the hose)	knife
tarp	duct tape
parachute	water – in container
big wrench (for regulator, gas feed)	wooden spreaders for parachute (if needed)
small balloons for weather check	

Balloon Inflation

_____	Attach regulator to He bottle and attach hose,
_____	Prepare water as balance, determine required mass from below
_____	Lay out tarp and balloon so that it is close to the other end of the hose
_____	Attach L-shaped fitting to balloon secure with hose clamp
_____	Attach Fishing scale and weighted water container
_____	Unwrap balloon and layout on tarp, check for kinks/tears
_____	Start filling balloon slowly at first, and continue raising inflation rate until lift matches water weight. Stretch out balloon on tarp,
_____	Use covered wooden paddles to stabilize balloon from wind drift.
_____	Once inflated, (balloon lift is equal to weight of water container) remove balloon from inflation assembly, fold over balloon nozzle, tie off with string (leave enough string to attach payload), wrap with duct tape.
_____	Prepare and launch small helium balloon for wind assessment
_____	Attach payloads.
_____	Arrange payloads such that the line between all elements has no slack.
_____	Release balloon.

Balloon Lift Worksheet

	112 kft
Total Balloon Lift	2330 grams
- Balloon Mass	1500 g
- payload mass	1050 g
Net Lift to reach altitude at 320 m/s	1280 g

References

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