Blending research and teaching through high-altitude balloon projects

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Space environment research, remote sensing, meteorology, electronics, computer control, telemetry, power generation, mechanical and electrical engineering, radio propagation, tracking and recovery all come in to play when designing, building, launching, and recovering a near-space payload. Project coordination, finance, and coordinating with government agencies such as the FAA also come into play. Since its inception in 1998, the UND High Altitude Balloon Project has flown over 40 flights with a recovery rate of greater than 90%. In this paper we will cover the history of the project and discuss the progression of a high-altitude balloon mission concept, through the development of the associated mission architecture, design reviews, and the actual flight of the payload. We will focus on the utility of this approach for exposing students to the systems engineering process, and how we have folded high-altitude balloon activities into university courses and student-driven university projects.

I. Introduction

In the teaching of space technologies such as remote sensing, communications, power generation, tracking, and other related areas, one of the major challenges has always been how to provide students with hands-on experience. Designing "paper spacecraft", i.e. systems that are never taken past the theory or simulation stage is a valuable tool to teach basic engineering concepts, but building and testing actual hardware expands the students' experience to include even more valuable concepts like assembly order, interaction between systems, and making compromises in the design where necessary while staying focused on the over-all mission.

Despite the clear advantage of having students work with actual flight hardware, there are many hurdles in an academic environment to such projects. Placing anything into space is a very expensive proposition. Launching interplanetary probes is typically out of the question from a financial standpoint, and even such 'inexpensive' options as low earth orbit or even ballistic trajectories are so costly that most institutions cannot afford even a single flight, much less yearly or semi-yearly launches.

If some sort of compromise could be found, that would allow student-built hardware and software to be sent to a space-like environment for reasonable cost, the challenges of designing and building working spacecraft could be presented in a more meaningful manner. It was to this problem that the Space Studies department decided to apply high-altitude ballooning.

II. Inception

In 1998 John Graham, an Instructor for the Space Studies department at the University of North Dakota, and John Nordlie, a recent graduate working as a lab assistant, decided to embark on a pilot project to test the feasibility of conducting unmanned high-altitude balloon flights. Initially unable to finance the project through the school, the two funded the pilot project out-of-pocket. Since neither had ever conducted any high-altitude balloon flights before, a search commenced for the necessary information and basic minimum hardware to conduct the flight. A web search led to the balloon pages of AMSAT, the Radio Amateur Satellite Corporation, whose members had also engaged in balloon flights. Though AMSAT was in the process of getting out of the balloon business, their website did provide both details of mission hardware and procedures, and links to other groups of radio amateurs conducting flights at the time.

EOSS (Edge Of Space Sciences) had the most complete set of information online at the time, including not only historical accounts of their flights, but also documentation on such valuable things as procedures and

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government regulations relating to high-altitude balloon flight. Graham and Nordlie decided to base their project on the EOSS online ‘handbook’.

Graham and Nordlie also realized that to have the best chance of success, the project would require a team with a wider experience and skill base. The project was pitched to both the departmental student population and individuals in the local amateur radio community. Many thought the idea was interesting and provided invaluable assistance: an Air Force student provided a surplus drogue parachute, a student working for the FAA in Air Traffic Control volunteered to find and explain the relevant regulations, and radio amateurs provided a transmitter and the electronics skills needed to assemble the payload. The gondola (Fig. 1) was made from an old foam container used to ship fresh fruit, and the flight computer was a microcontroller wired and programmed to send a tracking signal in Morse code as well as trigger a film camera and run a fan connected to a dust collector.

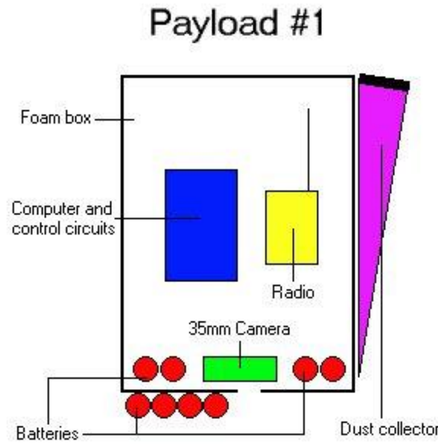

Figure 1. Payload 1 layout

As with most first attempts at anything technical, the project ran into its share of troubles. Procedural details on measuring nozzle lift during filling had not yet been worked out, so filling the balloon to the correct lift was hit or miss. The filling equipment, assembled from plumbing and compressed air parts, functioned but was not ideal to the task. None the less, the balloon was successfully launched and tracked, which was the goal for that flight. Unfortunately the radio battery died shortly before the balloon burst and the tracking and recovery team were unable to locate where the gondola landed. Despite these disappointments the team considered the flight a valid proof of concept. The Space Studies department agreed, and provided funding for additional flights.

III. Success and expansion

During the winter of 1998, the second payload was constructed. Functionally a copy of the first, it incorporated a more durable gondola and an improved power system. This was launched in May of 1999, and ended with the first successful recovery. Additional flights in June and July of that year built confidence and attracted interest by more students and other departments within the University. In October, the payload was redesigned to use both the Morse code beacon and a new GPS-based Automatic Position Reporting System (APRS) system, which greatly improved the ability of suitably equipped radio amateurs to track the exact position of the gondola. Success with this payload led to the teams’ first night flight in November of 1999. A low-light camcorder was lofted in an attempt to capture the Leonids meteor shower. Cold temperatures and a miscalculation in the amount of helium required caused a lower rate of ascent, to an altitude of only 30,000 feet when the flight computers’ timer triggered the cut-down mechanism. When the balloon was released the parachute failed to deploy, which resulted in a crash and the destruction of the camcorder and dust collector experiment. Amateur radio chase personnel also expressed their displeasure at having to work through the night, so plans for additional night flights were discarded.

The year 2000 saw the University of North Dakota School of Engineering and Mines (UND SEM) join the project. Students in Electrical Engineering designed, built, and programmed experiments which logged temperature inside and outside the gondola, and recorded data from a Geiger counter (Fig. 2). The radio amateurs provided a 440 MHz voice repeater system for the gondola, and a new camcorder was added for the final flight in September. 2000 was the groups’ most active year, seeing seven flights completed out of a planned nine during the season. Despite the successful outcome of all attempted flights, some group members began to exhibit signs of burn-out, and many chase team members expressed feelings that the project was consuming a disproportionate amount of their free time. It was decided to reduce the number of flights in future years to a more manageable number.

In 2001 the group limited the number of flights to four. A new, more powerful flight computer was tested, more still and video cameras were sent up, a model rocket was launched from the gondola, and an experiment to sample the air for atomic mercury was flown. In the middle of the flight season the group lost John Graham, who left the University to pursue other interests. This was quite a blow to the group, as Graham was both a founding member and a driving force behind the project.

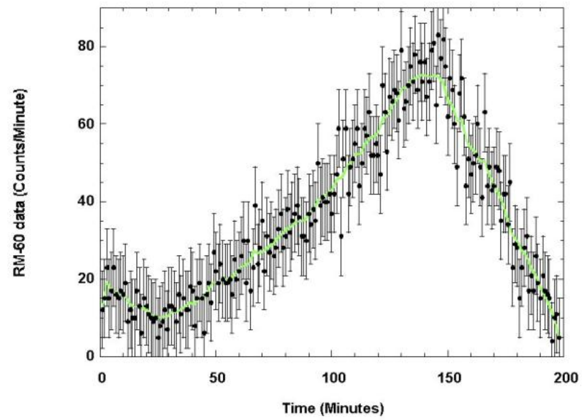

Figure 2. Geiger counter data vs. mission time

For 2002 the group partnered with the UND Energy and Environmental Research Center (EERC) to continue experiments to capture and measure atomic mercury in the upper atmosphere. All four flights conducted in 2002 carried an advanced trap system based on gold-coated sand and a calibrated air pump, as well as APRS tracking gear and a flight computer connected to a cut-down mechanism.

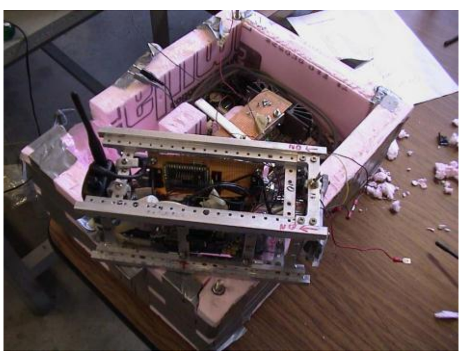

Figure 3. SEM Microsatellite bus

In the 2003 flight season, the group once again joined with UNDs' School of Engineering and Mines. Instead of individual experiments, the SEM students designed and built a micro-satellite spacecraft (Fig 3). When the SEM encountered problems finding an affordable launch to orbit for the spacecraft, it was decided to loft the package on a high-altitude balloon to allow testing of the system in a near-space environment. The microsatellite bus was flown three times, in April, June, and August. One additional flight was conducted in June 2003, carrying a payload built by children at a local science center. That flight was less about obtaining data or testing engineering concepts, and more about public outreach and fostering interest in space and high-altitude ballooning.

By 2004 the group had begun to lose some momentum. This was partially due to Grahams' departure, and also increasing duties of some of the faculty and staff at the University. The number of students involved was also on the wane, so only a single flight was conducted that year. An Amateur TV payload, constructed by the Concordia College balloon group in Morehead, MN (headed by Dr. Paul Seifert), was lofted in August.

2005, 2006, and 2007 saw launches of balloons carrying small 'balloonsat' payloads built by area high school students. Problems with the APRS system caused the loss of some of these flights. Later in 2007 a new light-weight tracking system was tested, but it too succumbed to glitches and the gondola was lost.

2008 and 2009 saw little activity by the group, but the addition of Dr. Ron Fevig to the Space Studies faculty breathed new life into the stagnating project. A search to add a new group of students to the project began.

In 2010 the group once again worked with the SEM to use ballooning as a method of accessing near-space. Students designed hardware and software for their SEM coursework, bringing a formal systems-engineering approach to the projects. The group also began working with Dr. Vadim Rygalov of the Space Studies department on some life sciences projects on which he was conducting research: a small greenhouse containing two plantlets was flown and recovered, after which the one surviving plant was grown to maturity.

IV. Design process

The first logical step of any balloon mission is to ask, "What do we want to accomplish?" For most flights, this means to carry a sensor, instrument, or mechanism into the near-space environment and recover it safely. The planning of the flight will be dictated by the goal or goals: lofting a greenhouse containing plants to test their reaction to altitude will be different than flying a radio repeater to test its range at high altitude.

After the purpose of the mission has been established and agreed upon, a brain-storming session is usually conducted to come up with ideas on how to accomplish the goal, what hardware and software will be needed, and how the mission should be structured. Free flow of ideas is key here, and many students find this the most enjoyable and creative part of the process. Faculty typically intervene only when students are getting wildly off-track, or try to squash others' ideas while the brain-storming is still going on.

With brain-storming complete, the faculty usually step in to start culling the less practical ideas and moving towards a design with a reasonable chance of actually being built, usually based on cost, time, complexity, and their experience with past projects.

When the over-all design has been hashed out, the tasks are divided up between team members. Students typically carry the largest load in terms of designing and building hardware and writing software, since this is a major part of their educational process. Learning what things need to be changed when going from a design to a working system, how to coordinate and cooperate with other members and other teams, follow budgets (both monetary and time), all while keeping an eye on the over-all key concepts and mission purpose are all real-world skills that will be absolutely necessary in their future careers.

In systems engineering, a formal process is followed, making use of design reviews to assure students make progress while staying on task and on time, and conduct proper analyses and testing. One vital concern is that any changes to the design of any component or subsystem during the process are communicated to the group as a whole so that impact on other teams' and students' work can be assessed and managed. Many students do well in design and analysis, some are adept at changing designs and trouble-shooting, and a few are even able to manage their time well and finish their tasks early. From a teaching standpoint, a student who is well challenged usually learns more and gets more out of the project than one given a trivial task that is easily accomplished in a short time. The object is not to set the student up to fail, but to give each student a challenge suitable to their level of skill and stamina.

Integration and testing always seems to prove a challenge to students. It is always stressed during the entire project that unforeseen problems will arise when different components of a complex system are brought together for the first time. Chasing system bugs can be a daunting task even for experienced engineers, and students' inexperience usually lead them to underestimate the amount of time required to tune and tweak a system until it will run with a reasonable level of reliability. Faculty try to build an adequate amount of time into the schedule for this very important task, but it can be difficult especially when schedules slip and deadlines loom. Many senior engineering students have stories of soldering wires and writing software in a hotel room at 3:00 am with a launch impending close to dawn the next day. While some faculty feel this is also part of the educational process, it is always stressed that people do not do their best work under those sort of circumstances.

While the hardware and software are being developed, other aspects of the over-all mission must be addressed. Design specifications can tend to creep, but certain ones like the total mass of the gondola will be critical in making decisions on things like how large a balloon will be needed, how much gas will be required to fill it, and what category will it fall under in terms of the rules and regulations imposed by the relevant governing body, such as the Federal Aviation Administration in the U.S. Some team members will be tasked with finding and coordinating a launch site, filing required paperwork with the FAA, ordering helium and balloons, and coordinating schedules with chase teams, all while keeping an eye on weather forecasts. It is stressed to the students that every detail in the mission is equally important: any single thing not taken into account could cause the cancelation or loss of the mission. While some things like the weather are not under control, others such as the development state of hardware and software are, and setting reasonable deadlines and reviews helps keep these items on track.

When the flight date is close, logistical planning becomes more important than ever. The emphasis stays on keeping things on a formal level when possible. Written checklists are encouraged, deadlines are set for mandatory successful tests of systems and subsystems (while ideally leaving adequate time to make adjustments and changes), and backup/fallback plans are put in place so that when problems are encountered, the entire mission is not put in jeopardy due to a single component not being ready in time. For example, an experiment that is not ready may be left off the gondola, so long as its absence won't cause problems with other systems.

Fly days bring nerves and excitement. It is the task of the faculty on these days to try to keep things calm and controlled. Safety is always the primary consideration, though most students of college age have themselves under a good degree of control. However cases of 'go-fever' are common and the emphasis must always be to take time and do things correctly. Systems that don't work on the ground will seldom work in flight, and while it takes courage and self-discipline to delay or even cancel a flight, it's important that the students know and understand when it's the right thing to do.

What role individuals will play during the flight must be decided upon before the launch. Many students enjoy the thrill of the chase, and the faculty encourage them to do so while keeping in mind that safety is always paramount. Pairing students with more senior members of the group can help with this. Some people will need to stay at the launch site to collect gear and pack up after the balloon is successfully launched. Experienced members try to make sure that all details are looked after.

Senior members of the group also try to keep things on an even keel when tact is called for, such as when a gondola parachutes onto private property and the situation must be explained to landowners who might not share the students' enthusiasm. Our group has always found that a cash reward for the return of a gondola can help keep all parties involved in good spirits. A briefing to the students (and other chasers) to remember to conduct themselves as respectful and gracious guests when on private land is usually a good idea.

Whatever the result of the mission, a debriefing is always conducted. Sometimes, this is just after payload recovery, sometimes it's later depending on time of day and the energy level of the group. The importance of preserving data and recording observations and thoughts that fade rapidly from memory is emphasized. The group meeting is also a good time to go over "lessons learned", as well as offer congratulations if the mission was a success, or to emphasize that we learn more from our failures than our successes if things did not turn out quite so well. All this is recorded into reports and papers, not only to preserve data and present results but to save valuable knowledge for use during future missions. This also gives the experienced students a chance to serve as mentors to new students joining the project later, which reinforces the learning process as well as contributes to the body of knowledge.

V. Conclusion

The process of planning, designing, building, testing, flying, and recovering unmanned high-altitude balloons can be quite an involved and complex task. Using this task as a real-world example for teaching students in science and engineering, using a hands-on approach, has been very valuable in the education and training process. Students have found the process to be interesting, exciting, frustrating, daunting, challenging, exhilarating, sometimes heart-breaking, but always an educational experience. To the authors' knowledge, no student involved in the project has ever considered it a waste of their time.

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