An Altitude Control System for Flight Control and Stability of HAB Missions

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Our Altitude Control System (ACS) is a flight control system for latex high-altitude balloon (HAB) missions designed to allow controlled venting of helium. In the absence of any mechanism to vent helium, a typical latex HAB will rise at a relatively constant rate until it reaches burst altitude. Our ACS is designed to vent helium at a desired altitude utilizing COTS products and some 3D-printed parts. The ACS was developed to extend flight time at a target altitude for imaging and to expand the scientific research potential for latex HAB missions.

High Altitude Ballooning | Venting | Flight Control | Altitude Control

Introduction

Stratospheric HAB missions offer the opportunity for hands-on engineering, educational engagement, and authentic scientific exploration. However, the full potential for conducting valuable scientific research with HAB flights is often hampered by a variety of factors. A typical latex HAB will rise at a constant rate until it reaches burst altitude, after which the payload usually descends on a round parachute. Typical flight times range from only 90 minutes to 2 hours. Typical flight paths lack any active controls, rather they are governed solely by the winds encountered at different altitudes during the flight, the buoyancy of the balloon, the timing and altitude of the balloon burst, and the size of the parachute. Additionally, typical flight paths spend only a limited time at any altitude, so the payload is always either rising or falling and never dwells at any given altitude. Lastly, the vertical motion of the balloon as it rises.

The ACS is a flight control system for latex HAB missions designed to allow controlled venting of lift gas (in our case, helium). It was developed to address the above-mentioned issues (short flight, no active control, limited time at altitude, and instability) by extending flight time at a selected altitude.

Our main motivations for initially developing the ACS were to extend HAB flight times and enable dwelling at desired altitudes for imaging. An unexpected, but extremely important, side benefit has been dramatically improved stability of the HAB platform itself, which is particularly beneficial for imaging experiments. Such use of the ACS to modify a traditional HAB flight path can expand the overall scientific research potential for latex HAB missions.

Mechanical and Electrical Design

The ACS is a self-contained venting mechanism (Fig. 1) that inserts into the nozzle of a filled latex balloon. Its key components include the nozzle insert, a stopper, an actuator, a Teensy-based microcontroller, and a pressure sensor, along with several power regulation devices housed in a PVC enclosure. Most of the mechanical components are custom designed and 3D printed.

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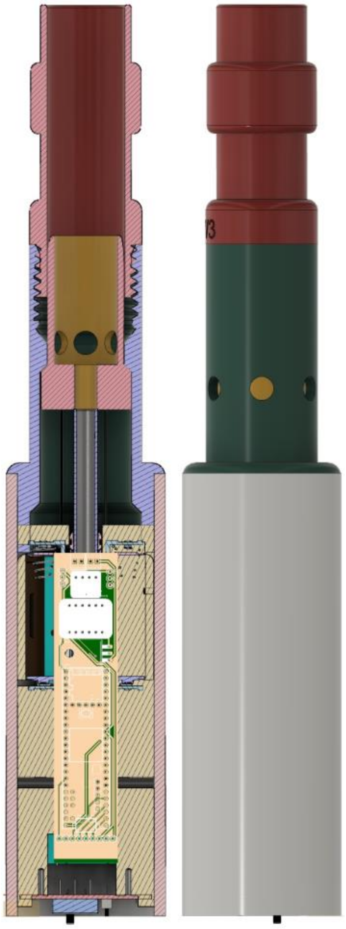


Fig. 1. Adler ACS design views (rendered using Fusion 360)

Mechanical Components

The nozzle insert, stopper, and electronics bay (or “sled”) were all designed and printed in-house, using Autodesk’s *Fusion 360* free online CAD software to develop the design and a *Makerbot Replicator 2* printer to 3D print the parts with PLA plastic.

Electronics

The electronic components are assembled onto a custom-designed PCB and mounted onto a 3D-printed sled (Fig. 2). The electronic system is composed of the Barometric Pressure Sensor MS5609, Actuonix Linear Actuator L12-50-210-6-R, and the Teensy 3.5 Microcontroller. These devices were chosen because of their reliability under stratospheric conditions. The barometric pressure sensor operates between 10 to 1200 mbar, at temperatures ranging from -40 to +85 °C. Similarly, the linear actuator was chosen due to its low operating voltage demands and its high torque ratio. The Teensy 3.5 Microcontroller was chosen for its high processing capacity as well its large flash memory capacity. Additionally, the Teensy 3.5 Microcontroller can readily record data to a removable SD card.

With outside temperatures reaching below -50^{0}C for extended periods during flight, a major challenge has been maintaining operational temperatures. By using lithium thionyl chloride batteries, an outer insulation layer, and a nichrome wire heated wrap, functional temperature can be maintained.

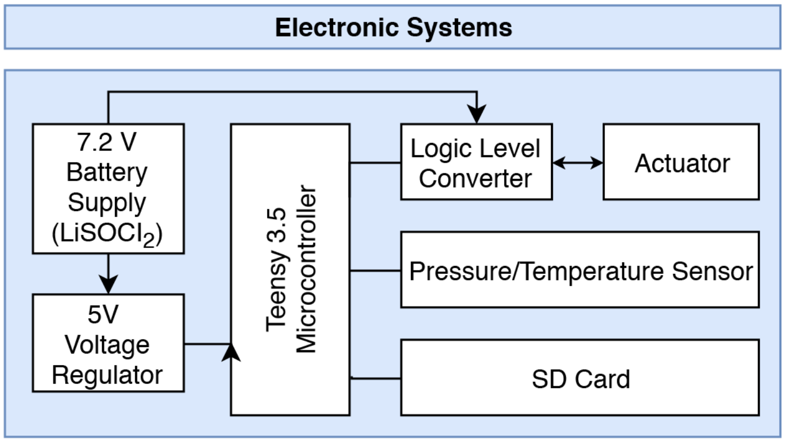


Fig. 2. Block diagram of electronic systems on the PCB

Software Control & Implementation

The Teensy 3.5 Microcontroller has been programmed to capture sensory readings from the barometric pressure sensor and logically reposition the linear actuator at different positions. Each of the different positions of the actuator provides a different venting rate of helium from the balloon.

The unit is preprogrammed with a mission profile describing the desired sequence of operations. A typical example might be to retract the actuator to its open position at a chosen altitude to allow lift gas to vent, followed by closing the vent once neutral buoyancy has been detected (based on the rate of change of altitude). After a chosen amount of time has elapsed according to the mission requirements, the actuator reopens the vent to begin descent (Figs. 3 & 4).

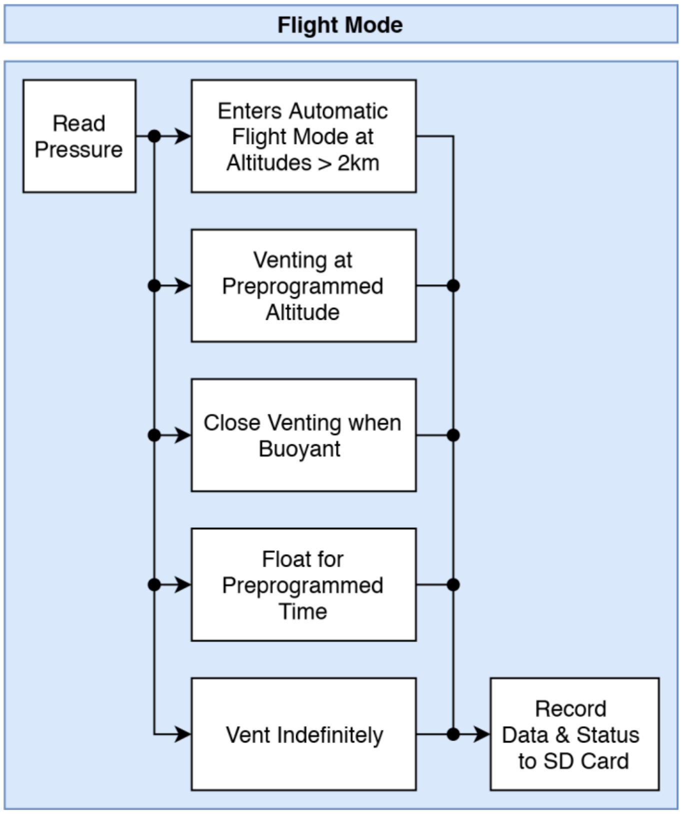


Fig. 3. Block diagram of a typical HAB flight profile using the ACS

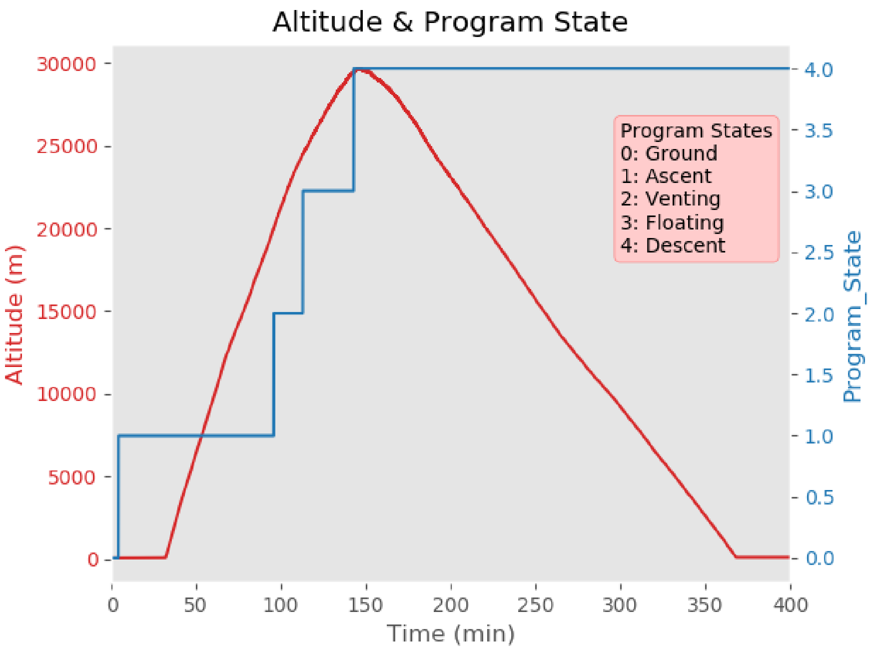


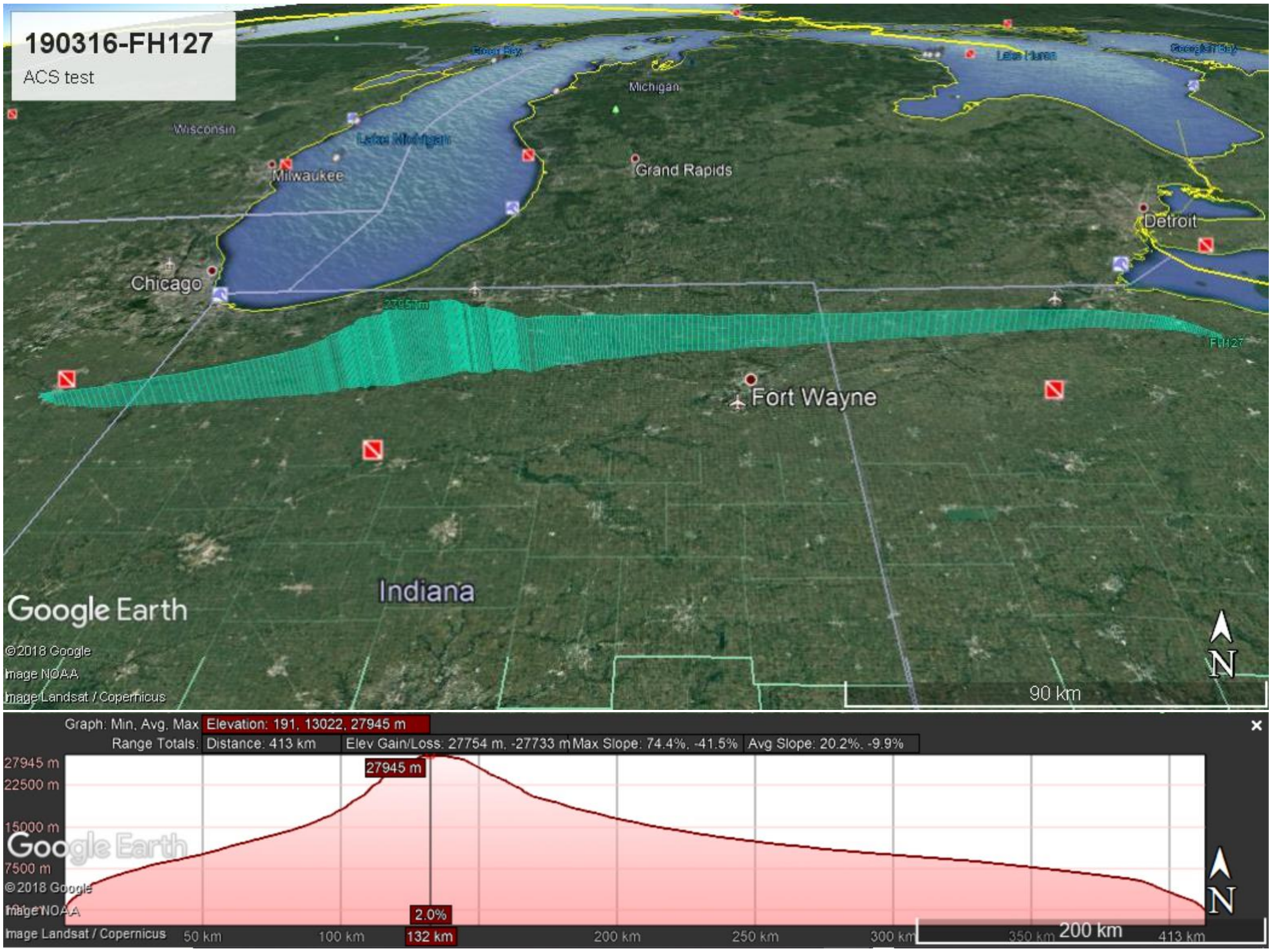
Fig. 4. ACS program states at different HAB altitudes over a typical flight

Flight Results

The ACS has been flown on more than a dozen test flights to date with a variety of flight profiles.

For our test flights, a “venting over the top” mission profile opens the vent at ~18,000m and allows helium to escape continuously from then on. This is the simplest type of profile using the ACS and most of our earlier tests followed this basic profile, though not always intentionally. As previously noted, we had some challenges with the system operating during prolonged exposure to the extreme low temperatures at high altitudes. On some of our test flights, we had programmed the ACS to close once a certain amount of time had passed after its initial venting, but it instead froze up and would not execute this step, so the balloon ended up simply continuing to vent slowly until the payload reached the ground.

A typical profile for an imaging mission is to open the vent as the balloon approaches an altitude of 20km (~65,000ft), then close the vent once neutral buoyancy is detected, dwell with the vent kept closed for 30 minutes, then reopen the vent and descend slowly until the payload reaches the ground. This was the profile used in the most recent ACS test flight on March 16, 2019 (Fig. 5). As programmed, the vent opened at the correct altitude, but closed prematurely (that is, while it was still ascending, before reaching neutral buoyancy), due to some outlying data points. It dwelled for 30 minutes before venting again (as programmed). This has prompted us to refine our filtering algorithm for determining when neutral buoyancy has been reached. (Due to the early vent closure, our balloon ascended higher than planned. That combined with the subsequent very slow descent helped us set a new downrange distance record for ourselves of roughly 400km from the launch in Kankakee, IL, to the landing just shy of Fremont, OH!) Otherwise, the ACS performed as intended.



Graph: Min, Avg, Max Elevation: 191, 13022, 27945 m

Range Totals: Distance: 413 km Elev Gain/Loss: 27754 m, -27733 m Max Slope: 74.4%, -41.5% Avg Slope: 20.2%, -9.9%

Fig. 5. Ground track and elevation profile for March 2019 ACS test flight

For our upcoming first mission flight over Chicago, unlike our previous test flights where we launched far south of the city, we have two major added factors: (1) Lake Michigan, which lies east of the city, in the direction of most flight tracks; and (2) the complex airspace around Chicago's airports, including the Class B controlled airspace around O'Hare International (ORD), Class C controlled airspace encompassing Chicago Midway (MDW), and a number of smaller public and private airfields. Without the ACS, there is low chance of launching far enough from the city to address the airspace constraints while simultaneously reaching optimal altitude over the city AND clearing the lake on descent (Fig. 6).

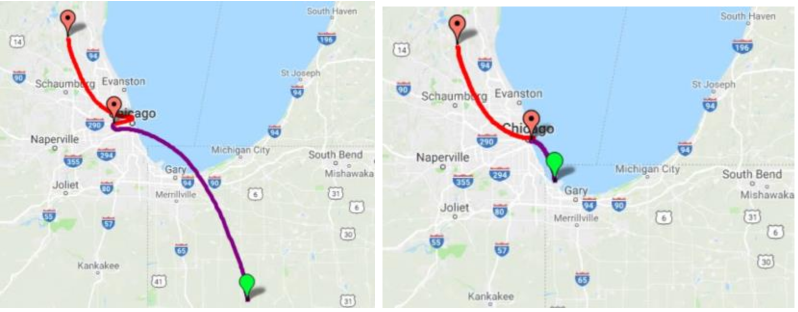


Fig. 6. Ground track predictions for a vented (with ACS) vs. traditional (to burst) HAB flight, using NOAA Balloon Prediction 0.0.5.6 software

One observed benefit of achieving neutral buoyancy in our test flights has been to dampen - indeed nearly eliminate - swaying, rotation, and instability of the balloon payload. An ascending HAB moves with the wind. It therefore experiences no forces from horizontal airflow. At typical ascent speeds (~5m/s), however, it experiences vertical airflow with forces equal to the buoyancy. Since a latex HAB is far from rigid, it wobbles and deforms under the influence of the vertical airflow. The power delivered to oscillatory modes is proportional to the third power of the vertical velocity, while the amplitude of motion scales as the 3/2 power. By lowering the ascent/descent speed we have achieved angular velocities as low as a few×0.1°/sec for extended periods of time (Fig. 7). Payloads flown on latex balloons are notoriously unstable. Thanks to the stability achieved with this system, we have been able to perform relatively long exposure nighttime Earth imaging missions for light pollution research.

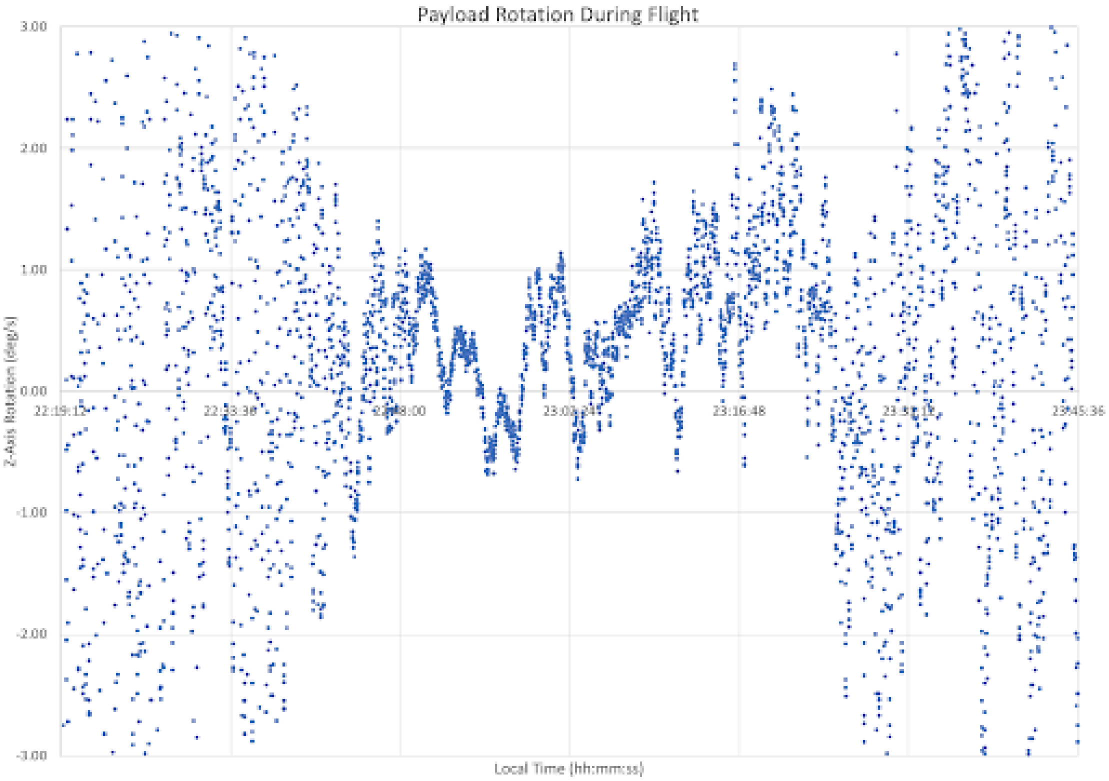


Fig. 7. Payload rotation per IMU data during an ACS flight

Lessons Learned & Future Design Improvements

We learned some important lessons over the course of designing and testing the ACS. Number one, it's cold up there! Other HAB teams have encountered issues with payload systems due to frigid stratospheric temperatures, including other efforts at controlling altitude through venting (4). By adding a heating element around the housing for the electronics, we were able to maintain the temperature within an operational range.

Our previous design of the ACS was an integrated venting and cutdown system. The previous nozzle insert that was positioned inside the balloon nozzle was essentially the same as the current design, except that instead of being threaded to screw into the venting tube, it had a series of flanges at the (now threaded) end (Fig. 8). Knobs at the end of the flanges were shaped to nest into a circular groove set around the inside circumference of the venting tube. When the actuator was extended, the stopper was positioned within the flanges, such that it pressed them outward and held them in the groove of the venting tube. Only when the actuator was fully retracted was the stopper finally clear of the flanges, at which point the weight of the payload was sufficient to pull the flanges free from the venting tube, separating the payload (with the ACS and parachute still attached) from the balloon, so it would then descend in the traditional manner (minus the usual turbulence that accompanies a balloon burst). It worked well in our many lab tests, but unfortunately it did not work during actual HAB flights. We have various theories for why it did not work in practice (cold temperatures being our leading suspect), but after many unsuccessful efforts to correct the issue, we finally abandoned this design in favor of our current, non-cutdown design, which is actually an earlier design that had tested successfully during flights.

Fig. 8. Previous design of ACS nozzle insert, for integrated venting & cutdown system

As mentioned earlier, during our last test flight in March the ACS stopped the initial venting stage prematurely, i.e., before it reached neutral buoyancy, due to some stray data points (dA/dt) resulting from normal turbulence experienced as the balloon was ascending. To correct this issue for future flights, we are updating the Adapted Filters in our software to take data more frequently and to average over a larger data sample.

To help inform future design improvements, as well as enable us to refine our balloon track predictions for future ACS flights, we plan to categorize the venting flow rate for different program states of the ACS. Additionally, we have designed an airflow barrier (still to be tested) to help block venting helium from blowing into the electronics sled, as an added mechanism to help prevent the electronics from getting too cold.

Conclusion

There are numerous applications for active image stabilization from HAB flights. One such application is mapping urban light pollution. This has historically been a difficult process that required either costly aerial surveys or satellite imagery with limited data quality. However, HAB flights, with an effective camera stabilization system, offer the potential for this process to become far cheaper and more accessible for not only researchers, but also hobbyists and citizen-scientists alike. This project is currently being adapted in an effort to map the light pollution of the Chicago area in order to expand our understanding and quantification of light pollution for research.

Acknowledgments

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