Streamlining High-Altitude Ballooning Missions: From Payload, to Launch, to Flight

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Abstract—**Building upon the success of the Jet Propulsion Laboratory (JPL), California Institute of Technology's (Caltech) Innovation to Flight (i2F) 2017 Zephyrus Missions, the i2F team has continued making high-altitude balloon (HAB) flights more affordable, reusable, and easier to perform by users of all HAB experience levels. With the creation of the automatic HAB launcher *Talos*, the i2F team has taken what was once a 15+ person job of launching a 5.44 kg (12 lb) payload via a 3000 g (3 m diameter at launch) latex HAB and has reduced it to a single-person task. Furthermore, the time from arrival at the launch site to launching a payload via Talos is still under one hour. The majority of that time is consumed by the inflation of the balloon. The i2F team has additionally overhauled the Zephyrus avionics and communications systems, which are now able to support two-way communications with the ground station while hosting several experiments. This is contained within a 1.2U CubeSat form-factor. The team has additionally designed and built two antenna tracking units for use during operations. This system can uplink and downlink data at a range tested to 160 km (100 miles). The 2018 project campaign for the updated Zephyrus flight vehicle, the Talos automatic HAB launcher, and the long-range two-way telemetry system, was constructed and tested within a span of 10 weeks and on a materials budget of less than $10,000.**

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1. INTRODUCTION

High-altitude balloons have long been used to explore Earth's atmosphere and study the surface of Earth from above. Their applications have bifurcated into two camps, one belonging to hobbyists launching balloons for recreation and simple experimentation, and the other belonging to researchers launching expensive, long-duration missions with support from national laboratories and universities [1] [2]. Over the Summers of 2017 and 2018, student interns at JPL bridged the gap between these discrete camps by developing a low-cost yet reliable high-altitude scientific balloon payload, Zephyrus, and launch system, Talos, to serve the scientific community at JPL and elsewhere. A typical hobbyist stratospheric balloon reaches an altitude of about 35 km (120,000 ft) and operates for two to six hours, depending on ascent rate and weather conditions. This altitude environment and mission time-span is ideal for many scientific experiments and technology demonstrations. By reducing labor costs, time, and expertise required, Talos and Zephyrus enable more researchers to test their innovations and experiments more frequently and with less overhead.

2. ZEPHYRUS

The Zephyrus system is a rapidly reusable high-altitude test platform designed to be compatible with a variety of experiments and instruments with reduced payload integration time. The following section describes Zephyrus iterations V-VIII (the numeral refers to both the Zephyrus payload design, as well as a Zephyrus flight test). For Zephyrus I-IV, please refer to *Project Zephyrus: Developing a Rapidly Reusable High-Altitude Flight Test Platform* [1].

Payload Structure

The latest iteration of the Zephyrus payload consists of one 15.20 x 12.70 x 16.50 cm (6.00 x 5.00 x 6.50 in) polystyrene foam box which contains all flight avionics, communications devices, batteries, and sensors. Holes are cut in the polystyrene foam using a hot-knife on the side of the payload in order to place external power switches for individual components. Having these external power switches greatly reduced time required for pre-flight checks.

Avionics

Zephyrus V—The avionics for the Zephyrus V test were the same used during the Zephyrus I-IV flights. This included a HABduino board connected to an Arduino Mega. For more information, please review the *Project Zephyrus* paper [1].

Zephyrus VI and Zephyrus VII—The Zephyrus VI and VII avionics systems were based around the Raspberry Pi Module 3 computer. A BME280 sensor was attached to record temperature, pressure, and humidity data and a BNO055 IMU was added to log orientation of the payload. A u-blox M8 GPS was chosen for location data as it is similar to the model used in the flight-tested HABduino board. The BME280 and u-blox M8 connected to the Raspberry Pi through I2C pins and the BNO055 through a serial connection. The system was powered by a 6,600 mAh Lithium-ion battery, chosen for its high power capacity and durability in low-temperature conditions. A diagram of the avionics architecture is shown in Figure 1.

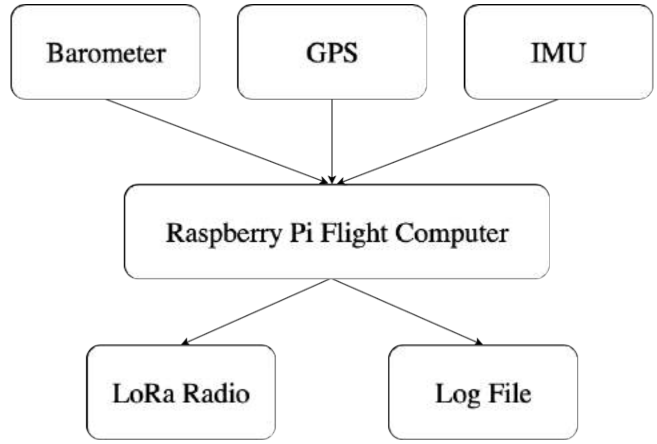

Figure 1. Zephyrus Avionics

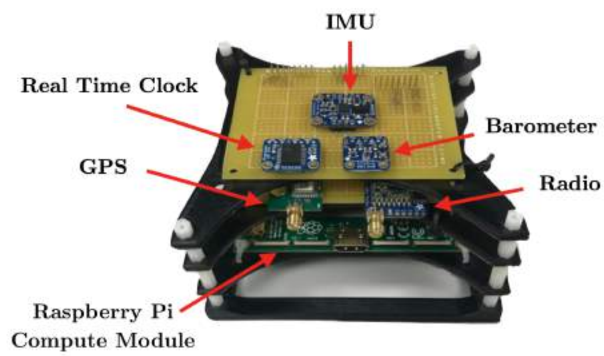

Figure 2. First iteration of the Zephyrus avionics stack

During the Zephyrus VII test flight, the BME280 and BNO055 sensors worked as expected and produced reliable data. Several bugs in the u-blox M8 drivers prevented it from functioning correctly at high-altitudes. The firmware drivers did not correctly account for the u-blox M8's I2C "clock stretching", where it would occasionally hold the bus for longer than expected, causing corrupted data to be occasionally passed to the flight software. The u-blox M8 GPS has several operating modes, including *Pedestrian* for altitudes under 9,000 m (29,527 ft) and *Airborne* for altitudes up to 50,000 m (164,041 ft) [3]. The firmware drivers were written to automatically switch between these modes at about 8,000 m (26,246 ft). Due to incorrect data being processed by the software, the GPS never successfully entered flight mode and was not able to report accurate altitude data above 9,000 m (29,527 ft).

Zephyrus VIII—Zephyrus VIII saw the first implementation of an avionics "stack", which condensed the footprint of the avionics and its components into a 1.2U (12 x 12 x 10 cm) box. A photograph of the stack is shown in Figure 2. The Raspberry Pi Module 3 computer was traded out for the smaller Raspberry Pi Compute Module 3 and the sensors were soldered to prototyping-boards and stacked on top. The u-blox M8 GPS firmware drivers were rewritten to use a software-based "bit banging" I2C protocol due to data corruption caused by the "clock stretching" incompatibility between the Raspberry Pi and GPS sensor.

During this test flight, the u-blox M8 GPS was much more predictable and successfully recorded location and altitude data through the balloon burst. The update rate for altitude and location drastically slowed as the module's altitude increased, and a solution for this will be explored in future

Figure 3. Custom auto-tracker used for Zephyrus VII and VIII flight tests

Zephyrus flight tests.

Communications

The Zephyrus V flight used a RadioMetrix MTX2 transmitting on the 434 MHz band as its primary method of communication, this is expanded on in [1].

The Zephyrus VI-VIII flights all utilized Long Range (LoRa) radio transceivers as their primary methods of communication. Utilizing spread spectrum modulation, LoRa radio allowed the team to receive data on the ground much faster than in previous years' flights and additionally permitted ground stations to uplink commands to the payload. The team operated on both the 434 MHz and 915 MHz bands throughout the summer.

The ground stations also benefited from switching to LoRa radio. With LoRa, only an Arduino or Raspberry Pi are needed to decode received data. This allowed the team to easily setup multiple tracking stations in order to optimize the recovery process.

Two Yagi antennas were also used throughout the summer. One was attached to a pan/tilt gimbal (shown in Figure 3) to act as an autonomous antenna tracker. The pan-tilt gimbal is actuated by hobby servos and controlled via a Raspberry Pi. A second Yagi antenna was mounted atop a hill at NASA JPL. These antennas permitted extremely long-distance communication with the balloon, including a transmission distance of about 160 km (100 miles) line-of-sight during the Zephyrus VII flight test.

Data Visualization - Open MCT

Open MCT is a NASA developed, open source, mission operations, and data visualization framework. The Zephyrus project utilizes Open MCT and has tailored it to display GPS and weather telemetry data in the use of high-altitude balloons. Data is downlinked via radio from the payload and uploaded to a server. The platform then fetches this data and makes it available for display. Using a Google Maps API, an

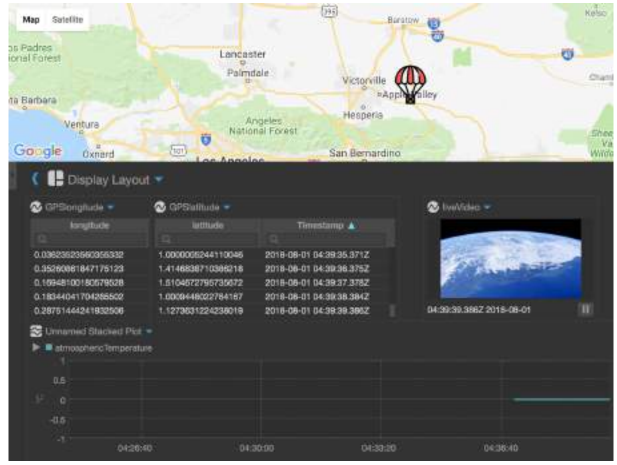

Figure 4. Open MCT example control panel

interactive map was added to the panel.

This web-based framework can be used and adapted for nearly any mission or system that produces telemetry [4]. While the framework was originally developed to support space science missions, it is versatile enough to be used in most domains. The framework has been developed to suit the needs of the Zephyrus flight missions. This interface can visualize live and historical data, imagery, mapping, graphs, and other pertinent data all in a central platform; alleviating the need for operators to switch between different applications to view telemetry data. An example of a Zephyrus mission use of the Open MCT control panel is shown in Figure 4.

Experiments – Thermal Management of HD Cameras

Capturing high-resolution photos and videos creates opportunities to record meaningful data for scientific objectives. GoPro cameras are popular high-resolution cameras for their low cost, durability, low mass, and accessibility. With the goal of the thermal payload to ensure long-term operation of high-resolution cameras, five different GoPro models were flight tested: GoPro Hero 3, GoPro Hero 4, GoPro Session 5, GoPro Hero 6, and GoPro Fusion 360. The GoPro Hero 3 was flown on previous Zephyrus flights and was proven to record at 1080p for the duration of a flight, so it was flown as a control to ensure data collection spanning the duration of a flight [1]. Conversely, the Hero 4 and Session 5 models were flown in previous Zephyrus flights and hypothesized to have failed during flight due to overheating, with the Session 5 failing as quickly as 30 minutes into flight [1]. The GoPro Hero 6 and GoPro Fusion 360 degree camera had yet to be flight tested, so the i2F team flew them with no modifications to study their functionality in the high-altitude flight domain. A copper heat sink was connected to the processors in the Hero 4 and Hero 5 cameras which allowed heat to escape the cameras and exit to the atmosphere. While this strategy would be ineffective at higher altitudes where the air is thinner, the payload would ideally spend enough time at lower altitudes to allow enough heat transfer to keep the cameras operating continuously.

The thermal-testing payload was a 15.20 x 12.70 x 16.50 cm (6.00 x 5.00 x 6.50 in) polystyrene foam box with holes cut out on two faces to reduce mass and increase airflow to the copper heat sink to aid convection. Previous flights have indicated a difficult thermal environment as a result of low

Figure 5. Picture taken by GoPro Hero 6 looking South over the Mojave Desert on Zephyrus VII (not corrected for lens distortion)

air density to dissipate heat and very little atmosphere to protect from incident solar heat. Camera failures were the most notable result that drove the need for a more advanced thermal control system. A 15.20 x 15.20 x 0.08 cm (6.00 x 6.00 x 0.03 in) copper sheet was placed at the bottom of the thermal payload and two 15.20 x 7.60 cm (6 x 3 in) copper fins were attached using thermal paste and aluminum right angle brackets. The heat sink was central to all five GoPro cameras tested as part of the experiment. This payload was successfully flown three times and the payload box remained intact in each iteration.

For the thermal payload, a camera was successful if it recorded the entirety of the flight, from launch to landing. The only camera to record the full flight was the GoPro Hero 3 with a resolution of 1080p. The GoPro Session 5 survived 15 minutes longer than in previous Zephyrus Missions, and the Hero 4 connected to the heat sink had no noticeable differences [1]. The GoPro Hero 6 and the GoPro Fusion 360 both recorded in 5.2k and survived longer than the Hero 4 and Session 5 (seen in Figure 5). It was predicted before the launch that the GoPro 360 camera would overheat first due to its compact size and higher power requirements. The 360 camera was able to record through the balloon burst and halfway through the descent stage. This exciting result opens up opportunities for incorporating high-resolution 360-degree footage into virtual reality environments as an education tool and for immersive data analysis.

3. TALOS

The motivation for developing an automatic high-altitude balloon launching system lies in the difficulty involved with launching large balloons (3000 g) by hand. Traditionally, the launch process requires a team of 15+ people 2 to 3 hours to successfully launch a balloon. With Talos, the driving requirement was to allow a single person to launch a HAB in under an hour, including setup, inflation, and launch. Four iterations of Talos (Mk. 1 through 4) were designed, built, and tested. Each had four main subsystems: structure, external environmental sensor suite and controls, pressure systems, and transportation. The following sections outline how the design of Talos evolved with respect to each subsystem.

Structure

The structure of each Talos iteration served the general purpose of supporting the balloon, pressure systems, and electronic systems through all phases of inflation, while being portable to and from the launch site. The methods and mechanisms developed to accomplish this varied by iteration.

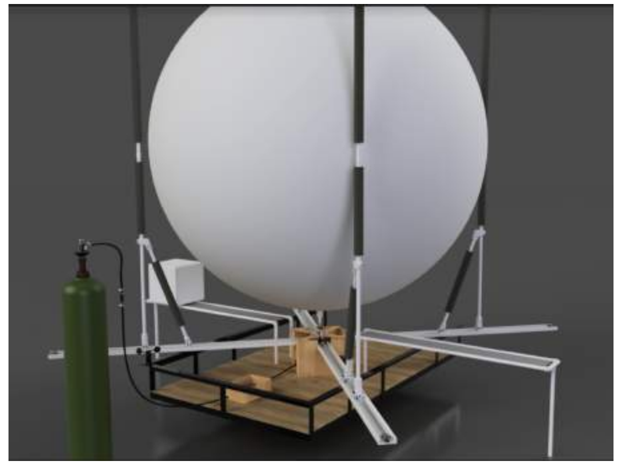

Figure 6. Talos Mk. 1 CAD rendering (balloon shown is 3 m in diameter)

Talos Mk. 1— The structure of the first iteration auto-launcher was designed to hold the balloon in place during inflation. That mechanism consisted of four 2.74 m (9 ft) tall polyvinyl chloride (PVC) poles wrapped in foam which actuated outwards on a motorized chain-and-sprocket system to hold the balloon in the same spot as its radius increased during inflation. Since this would only be effective after the balloon reached neutral buoyancy, a stretcher was conceived to hold the partially-inflated balloon above the ground and away from any potential danger. The structure was fastened onto the transportation system of the Mk. 1 at the launch site, which was a rented trailer from U-Haul. A CAD rendering of Talos Mk. 1 can be seen in Figure 6.

The materials used for this first prototype included 3D printed polylactic acid (PLA), ultra-high molecular weight polyethylene (UHMWPE), and polyvinyl chloride (PVC) tubing. These materials were selected because they were cheap, easy to obtain, and could be used for a wide variety of applications within the design.

A full-scale launch test of Talos Mk. 1 took place on June 28, 2018, in Lucerne Valley, California. The launch attempt failed due to poor material choices, oversights in launch procedure, lack of failure-mode contingency planning, and unusually high wind speeds. Multiple components failed, including the 3D printed adapters that allowed the motors to drive the sprockets, rendering the actuating stabilization system inoperable. The balloon ended up tearing after high winds continuously dragged it against wing nuts which were exposed on the structure of Talos. Figure 7 shows this failure.

The failure was necessary in order to expose both critical flaws in the launcher's design. The group learned a great deal from the failure, particularly the importance of unit testing individual subsystems and documenting plans for all possible contingencies.

Talos Mk. 2—After the first iteration (Talos Mk. 1) failed, the group placed a larger emphasis on small-scale prototyping and numerical analysis to prove that a given design could function adequately in the target environment.

Figure 7. Talos Mk. 1 launch failure

Small-scale prototypes were constructed from cheap, expendable materials for testing specific point designs. Different point designs targeted different aspects of the launch process. For example, the design needed a mechanism to protect the balloon both before and after neutral buoyancy, and to allow a smooth transition between the two states. The most promising solution from small-scale prototyping was selected for further development.

As a result of the change in the design process from Mk. 1 to Mk. 2, the structure of the second iteration was completely redesigned. Instead of using the structure to keep the balloon static during inflation, the second iteration was designed to allow the balloon to move relatively freely while keeping it away from any danger and reducing the stresses on its neck. This was done by suspending the neck of the balloon up in the air, allowing the balloon to swing gently without harming itself or interrupting inflation. The structure consisted of a vertical "mast" to hold the balloon above the ground and a horizontal "boom" on top of the mast to hold the balloon away from the mast. The boom could also rotate about the vertical axis, allowing the balloon to move with the wind in order to reduce the impulse experienced by the balloon due to a sudden change in wind direction. This mechanism can be seen in Figure 8. As the image shows, at 3.05 m (10 ft) tall, the mast of the Mk. 2 structure was not tall enough to completely suspend the balloon above the ground, and so an operator was required to hold the excess balloon hanging down before inflation.

The material used for both the boom and mast was aluminum 6061 T-slot extrusion ordered in various sizes. This material was chosen because it was much stronger than the materials used for the Mk. 1, and it was versatile in that it could be used for a wide variety of applications within the design. The mast was comprised of a single, 3.05 m (10 ft) long section with a side length of 8 cm (3.15 in). The boom was a single 1.83 m (6 ft) long section with side length of 8 cm (1.56 in). To support the mast from tipping, 60.96 cm (2 ft) angle and base supports were added on all four sides, also made of the aluminum T-slot extrusion. The turntable placed at the top of the mast acts as the connection point between the mast and the boom. Its purpose was to allow the boom to rotate and support the balloon's weight. The turntable allowed the balloon to dictate the motion of the boom so that the wind never forced the balloon into a harmful surface. To further protect the balloon from harmful surfaces, all exposed sharp corners, bare metal, or zip ties on the boom were covered in foam or tape.

Figure 8. Talos Mk. 2 pre-inflation

The Mk. 2 structure was tested during the launch of the Zephyrus VII flight and satisfied its design requirements successfully. After the balloon achieved neutral buoyancy, the operator was able to step away from holding the excess balloon as in Figure 9. From this point on, the balloon inflated smoothly without further human interaction until final lift measurements and release, which were done by hand.

Talos Mk. 3—The major change in structural design between Talos Mk. 2 and Mk. 3 was on the transportation side. The mast of the Mk. 2, being one large piece of aluminum, was quite difficult to tie down to the bed of a pickup truck and transport to the launch site. The boom was transported separately and attached on site. After being assembled on site, the Mk. 2 was then carried out to a flat area and hoisted up by multiple team members for the launch process to begin.

The Mk. 3 had a much more transportable design. The mast was now three pieces instead of one, each 1.22 m (4 ft) long and attached with hinges. The boom was also split into three pieces and hinged at the joints. As a result, the mast was .61 m (2 ft) taller than the Mk. 2 mast, giving more clearance to the hanging uninflated balloon, and the entire system folded down and could be transported in a U-Haul trailer. A CAD rendering of the folded Talos Mk. 3 structure can be seen in Figure 10. Upon arrival at the launch site, the Mk. 3 was unfolded by a single operator, and aluminum plates were slid over the hinge joints and tightened by hand into the T-slots with bolts. It took two operators to then raise the mast to the vertical position, as a result of it being too heavy for one operator to raise.

Figure 9. Talos Mk. 2 going through phases of inflation

Figure 10. Talos Mk. 3 folded for transport

Figure 11. CAD rendering of Talos Mk. 4 in transport mode

Small improvements were made to the launcher mechanism in an attempt to reduce the amount of people required to perform the launch. The height of the mast, for example, was increased to remove the person standing below the boom holding the uninflated balloon for the first part of inflation. The vinyl helium tube was routed through a spring just under the balloon's neck to keep it from folding/pinching in on itself as the balloon moved with the wind (seen in Figure 16).

Talos Mk. 4—The fourth, and most recent, iteration of Talos is the most successful design to date. Talos Mk. 4 was tested via a tethered balloon launch at JPL in mid-September of 2018 and was deemed a success after a single person was able to set up the entire mechanism in under 15 minutes and launch a tethered balloon in under one hour.

The main concerns with Mk. 3 had to do with the setup requiring more than one person (it was too heavy for an individual to hoist alone) and the transportability of the system. While Talos Mk. 3 was able to be transported effectively in a U-Haul trailer, it took up the majority of the floor space of the trailer.

The goal for Talos Mk. 4 was to keep the systems that worked well in Mk. 2, and Mk. 3, while making sure one person could easily set it up from transport mode to launch mode in under 15 minutes, with the added secondary goal of creating a smaller footprint than Talos Mk. 3.

Talos Mk. 4's mast telescoped upward in three parts allowing a single user the mechanical advantage of a rope and pulley system to lift the mast to its full height. Each tier of the telescoping mast is 1.8 m (6 ft) tall, with 0.3 m (1 ft) of overlap between tiers when fully erected. The result is a system that is 1.8 m (6 ft) tall, with a ground footprint of only 0.6 x 0.6 m (2 x 2 ft) when fully stowed in transport mode (shown in Figures 11 and 12), and 5.2 m (17 ft) tall when in launch mode (shown in Figures 13 and 14).

External Environmental Sensor Suite and Controls

The duration and path of a balloon flight depend on the initial conditions at launch namely balloon lift, payload weight, and weather conditions. While weather conditions cannot be controlled and payload weight is predetermined, the balloon lift is variable and must be regulated precisely in order for a flight path to match predictions. The environmental sensor suite and controls system consists of:

- A solenoid valve and a relay shield for starting and stopping helium flow
- A barometer, IMU, and anemometer for obtaining ambient weather conditions

Figure 12. Talos Mk. 4 in transport mode

Figure 13. CAD rendering of Talos Mk. 4 in launch mode

Figure 14. Paracord pulley configuration on Talos Mk. 4 (rotating boom not pictured)

- A strain gauge load cell for measuring balloon lift, and nichrome wire cutter for cutting the lift measuring linkage before launch
- A Real Time Clock (RTC) and Arduino Mega microcontroller
- Lithium polymer batteries and voltage converters to power all onboard systems

Talos Mk. 1—For Mk. 1, the external environmental sensor suite and controls were housed in laser-cut plywood box placed on top of a table near the Mk. 1 autolauncher. It used a set of four 10 kg-rated load cells attached to the neck of the balloon to measure lift. No data for this configuration was collected, because the launcher failed before accurate lift measurements could be made. Though this iteration had a functional anemometer, it was placed too low to the ground to obtain an accurate wind measurement. This iteration did not utilize a nichrome wire cutter or a solenoid valve to control helium flow.

Talos Mk. 2—Mk. 2's sensor suite and controls were housed in the same plywood box placed much farther away from the autolauncher (8 m). This iteration was the first that implemented the solenoid valve as a way to control helium flow. If the balloon's neck twisted during inflation, the pressure build-up resulting from the blocked flow could cause a perforation in the neck of the balloon. For this reason, it was necessary to include the ability to completely stop flow if necessary (electronically, instead of manually via the helium regulator). Instead of using a strain gauge, lift measurements were taken manually using a commercial luggage scale.

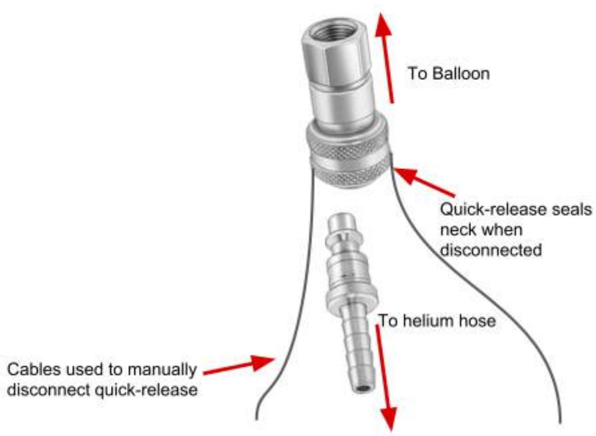

Figure 15. Diagram of quick release mechanism inserted into the neck of the balloon

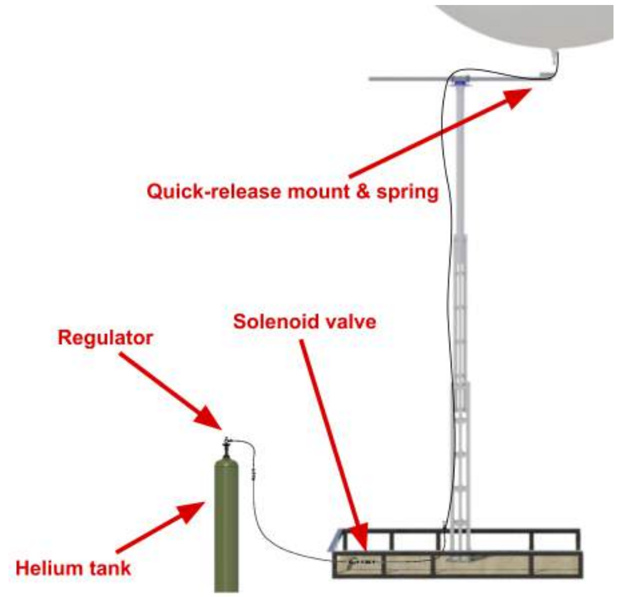

Figure 16. CAD rendering showing the pressure system used in Talos Mk. 4

Talos Mk. 3—For Mk. 3, the sensor suite and controls were moved to a new plywood box at the base of the structure, attached to the support rails. Since the box stayed attached to the structure during transport, the bottom of the box was lined with vibration-insulating foam in order to protect the electronics within from being damaged. Lift was measured from one 20 kg-rated load cell (the same kind of device used for Mk. 1) mounted to the boom and connected to a line in tension from the balloon. The strain gauge is calibrated on the boom using known masses. This calibration was accurate to 0.1 kg (.2 lbs) when tested in the lab, but did not perform as expected during flight testing. During the flight test, the load cell reported lifts higher than the actual lift of the balloon. These measurements were compared to those taken manually with a luggage scale (similarly to how measurements were taken during the Mk. 2 test), which were more reliable. The anemometer was unavailable at this time. Mk. 3 also used a nichrome cutter to command the release of the balloon by cutting through the helium tubing and anchor line at the balloon's neck.

Talos Mk. 4—Talos Mk. 4 utilized the same devices and configuration as was used in Mk. 3. All devices, except for the load cell, were simply transferred to the new telescoping structure. During the Talos Mk. 4 tethered balloon test, a luggage scale was used to measure lift due to lack of time needed to correctly calibrate the load cells.

Pressure Systems

The pressure system is the unbroken line allowing the flow of helium from tank to balloon. The pressure out of the tank is controlled by a regulator. The helium flows through a vinyl tube to a solenoid valve controlled by the electronics bay discussed in the previous section. When the solenoid valve is open, the helium continues to the balloon.

Talos Mk. 1—The pressure system for the Talos Mk. 1 design was fairly typical of a regular HAB launch. The major changes were the implementations of a quick release mechanism that was permanently inserted into the neck of the balloon prior to launch (seen in Figre 15), and the addition of the flow gauge and solenoid valve in the helium flow line. Neither systems were used during the field test however, because of the failure of the structure to stabilize the balloon.

Talos Mk. 2—Talos Mk. 2 had a very similar pressure system design as Talos Mk. 1, but used longer pressure tubing to allow more freedom as the boom would twist, a larger diameter pressure tubing to increase flow rate, and more quick release connections that were attached on Talos itself for ease of pressure system assembly on-site. Talos Mk. 2 utilized the in-neck quick release mechanism as well, and during the launch of Zephyrus VII it proved to be a significant time-saving improvement. Including the quick release added about 100 grams of mass to the payload, while saving nearly 10 minutes in manual labor. Instead of tying the balloon off, sealing the neck, and attaching the payload in the traditional fashion just before liftoff, the quick release mechanism required only a single pull from an attached string to safely release the balloon from Talos and let the payload rise freely. There is no need to tie off the balloon's neck to prevent helium from escaping, since the quick release acts as a back-flow prevention valve when the two halves of the quick release are separated.

Talos Mk. 3—After the success of the Mk. 2 design, the pressure systems were nearly unchanged for Talos Mk. 3, besides the implementation of two more quick release points along the structure to help quickly transition from transport mode to launch mode.

Talos Mk. 4—The pressure systems in Talos Mk. 4 were identical to those in Mk. 3 and will now be implemented in every future launch. The Talos Mk. 4 pressure system can be seen in Figure 16.

Transportation

Talos Mk. 1—Talos Mk. 1 proved unwieldy and inconvenient to transport. When transporting from lab to the field, the entire device was deconstructed down to the individual pole-rail apparatuses and laid in the back of a standard 1.8 m (6 ft) U-Haul trailer. Upon reaching the desired launch location, substantial manpower was required to unpack and set up the rails and their PVC piping supports. Likewise, packing up Talos Mk. 1 after the field test was laborious.

Talos Mk. 2—While Talos Mk. 2 proved to be much more portable than its predecessor, this design did not fulfill the project requirement of being able to be set up by one person in under 15 minutes.

Mk. 2 was also transported via U-Haul trailer, fully assembled apart from the boom being detached from the mast. Upon reaching the launch location, 4 bolts had to be screwed in, attaching the turntable with the boom mounted onto the top of the mast. Next, Mk. 2 required that the main mast be stood upright. Given the awkward shape and large mass of the structure, this task required three people to raise the structure to its vertical launch orientation. After this, sandbags were placed on the base to ensure absolute stability when the balloon would be fully inflated and swaying on the boom in the wind.

Talos Mk. 3—Mk. 3 focused on iterating on Mk. 2's design to make it more transportable. With the hinges in the mast and boom, the launcher was able to be operated directly in the bed of the trailer it was transported in. In its folded position, it was placed upright on its base. In order to go from transport mode to launch mode at the launch site, it was a matter of unfolding and securing the hinge supports. Due to the weight of the structure, this task was not safe for just one person to accomplish alone. However, it proved to be a substantial improvement over Mk. 2 in terms of using two people to simply raise the mast to the vertical position on a hinged system, then locking the final bottom hinge with bolts.

Talos Mk. 4—The transportation of Mk. 4 was simplified dramatically over the previous iterations one person was able to put Talos in a vehicle for transportation from the location it was constructed at JPL to its test location on the other side of JPL. It is important to note that this version of Mk. 4 was intended to be permanently mounted to a open-top flatbed trailer for both transportation and operation (allowing mobile operation if needed), but the trailer was not modifiable at the time of testing. Therefore, this version of Mk. 4 was modified to use wide legs as its base (similar to Mk. 2).

4. Conclusions

The Innovation to Flight student team successfully developed a versatile, robust, and reusable high-altitude balloon launch system. The Zephyrus flight payload leveraged commercial hardware, custom software to reliably transmit telemetry to ground operators, and a modular design, allowing it to service a broad range of payloads. The Talos autolauncher system was developed with a deep understanding of the inflation problem. Experience from many manual launches was employed to develop a user-friendly system to streamline the launch process. The successes of Talos show that it is possible to reduce the amount of time and manpower required to launch a high-altitude balloon to just one person taking 15 minutes to set up Talos Mk. 4. While the time frame of the project (10 weeks) proved challenging, a platform has been developed for future work. In its current state, Talos is still a work in progress and cannot yet accurately measure lift or self-deploy. Future iterations of Talos will address these issues and incorporate a lighter structure to increase portability.

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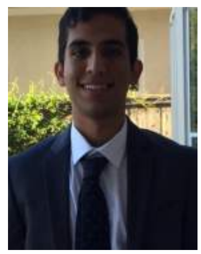

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