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High-Altitude Ballooning and Payload Design

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Murray State University Honors College

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High-Altitude Ballooning and Payload Design

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High-Altitude Ballooning and Payload Design

Submitted in partial fulfillment
of the requirements
for the Murray State University Honors Diploma

Matthew Smith

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Abstract

The Icarus project began in 2017 where a team performs high-altitude balloon (HAB) launches to conduct atmospheric and payload design research. The project involves sending a data-collecting payload containing recording equipment to high altitudes (~100,000 feet). This paper outlines the Icarus project as well as the efforts to design a payload that will remain stable throughout flight while also protecting the equipment housed within the payload shell. SOLIDWORKS computer-aided design (CAD) software was used to design a unique payload system. The payload parts were manufactured with PLA filament using a Prusa MK4 3D printer. The secondary goal of this thesis is to demonstrate how the project can be applied to high school and undergraduate level engineering and science classes.

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Historical Background

Balloon satellites are devices that contain data recording equipment or experiments that can carry payloads to altitudes as high as 40,000 meters (130,000 feet) by high altitude weather balloons. They can range from under 100 grams to hundreds of pounds. High Altitude Balloons (HAB) have been an inexpensive option to lift payloads to extreme heights allowing for more accessible scientific research. Scientists have utilized balloons for over 200 years to research the atmosphere and other facets of Science, Technology, Engineering, and Mathematics (STEM) including geology, biology, chemistry, etc. These balloons have been made from many kinds of organic and semi-organic materials including rubberized silk, canvas, and animal intestines. The earliest experiment involving balloons was in 1783 when Etienne and Joseph Montgolfier started to experiment with hydrogen-filled paper bags (Pfotzer 199). Later, J. A. C. Charles, a French Professor of Physics, alongside the Robert Brothers, filled a balloon with hydrogen and demonstrated its flight capabilities to a crowd of 300,000 in Paris, France.

In the 1780's, many flights were conducted by attaching animals to balloons to test the environmental conditions. The first use of an unmanned balloon to collect direct numerical data was in 1892 when Hermite and Besancon launched a balloon made of sheep intestines, with a volume of 113 cubic meters (4000 cubic feet). It was filled with coal gas and carried a meteorograph to 16,000 meters (52,500 feet) and provided reliable temperature measurements up to 12,000 meters (40,000 feet) (Pfotzer 207). The advent of the hot-air balloon lent itself to atmospheric study and, later "it offered the possibility to study radiations from outer space" (Pfotzer 206). In 1912, Victor Hess discovered cosmic rays and "using a manned balloon, he found the altitude variation of the radiation" (Nishimura 1). This discovery was followed by decades of radiation research with the help of balloon experiments. Many advancements were also made in the fields of meteorology and atmospheric science by direct result of experiments involving balloons. In the mid-20th century, many manned flights were still taking place up to 23,000 meters (75,000 feet) but several unmanned flights had reached altitudes surpassing 30,000 meters (100,000 feet).

Up until the late 1940's, balloons had been made from organic and semi-organic materials including rubberized silk, canvas, and animal intestines. O. C. Winzen was the chief engineer at a manufacturing company that ran a laboratory dedicated to the research and development of materials for high altitude balloons. After its dissolution, Winzen was able to obtain contracts from the U.S. Navy to develop high altitude balloons. In 1946, he set up an aeronautical research laboratory in Minneapolis, Minnesota, and this "was the birthplace of the plastic balloon" (Pfotzer 230). Then, in 1947, plastics became available that were suitable to be used in balloon construction that could "withstand stresses exerted by heavy payloads" (Pfotzer 225). The first flight involving this new plastic took place on September 25, 1947, where a 32-kilogram payload was carried to a height of 30 kilometers. Alongside these new balloons, innovations in other fields were being fueled by balloon flights. Between the 1940's to the 1960's "extensive studies with nuclear emulsions discovered high-energy phenomena and new particles" (Nishimura 3). Balloon technology is still driving advancements today with stratospheric balloons being a "viable testbed for life support systems and crew escape tests as well as use as a first stage for sounding rockets" (Clark 1). The use of balloons continue to prove invaluable for scientific discovery and innovation, they allow for complicated and intricate experiments to be conducted by anyone with access to a lighter-than-air gas, usually helium, and a high-altitude balloon.

What is High Altitude Ballooning

Modern-day high-altitude ballooning involves a high-altitude balloon (HAB) and a balloon satellite. A balloon satellite is a payload containing data recording equipment, such as but not limited to, cameras, dataloggers, GPS trackers, biological experiments, and atmospheric experiments, etc. HABs are an inexpensive and efficient way of studying the atmosphere. The amount of data that can be recorded is only limited by the equipment available to the research team. Balloon satellites can be a small science project for a high school class or multi thousand-dollar payload with full radio communication capabilities. Payloads often require a “shell” or “housing” that hold and protect the equipment during a flight. Some housings can be as simple as a cardboard box or as complex as a 3D printed shell with metal fasteners.

The goal of a HAB project is to collect various forms of data including temperature, humidity, air-pressure, telemetry, GPS, audio, video, etc. The process of conducting a HAB launch begins with determining what the goal of the launch is, whether that would be testing payload design or collecting data from the atmosphere. Once a team has a clear view of their goal, selecting equipment and materials based on the data that will be collected and the budget available is the next step. Following the construction of a payload, the team will need to determine the target altitude that they want to reach and then purchase a balloon that has a lift capacity large enough to lift the payload to the predetermined altitude. Along with selecting a balloon, a calculation will need to be made based on payload weight and balloon weight to determine how much helium will be needed. To find the amount of helium needed to suspend the payload in air, use the equation [Helium needed] > [weight of balloon, payload, and parachute]/ $28g/ft^3$. This amount will need to be surpassed to lift the balloon to the target altitude. There are many balloon performance calculators online that can aid in these calculations. A parachute will also need to be purchased to keep the descent rate under 6 m/s. There are many parachute shapes that can be chosen, and they all have online calculators to help determine the minimum size that will be needed. One important thing to consider is that all Federal Aviation Administration (FAA) and Federal Communications Commission (FCC) regulations must be followed when conducting HAB launches. A brief Summary of the laws and regulations are:

1. Any on-board cellular (phone) tracking systems must be turned off (Airplane mode enabled) as it leaves the ground.
2. Any individual payload box/package must weigh less than 6 pounds.
3. If a payload package has a weight-to-size ratio of more than 3.0 ounces per square inch it must weigh less than 4 lbs.
    - Calculation = Total payload package weight in ounces divided by the area of its smallest face in inches.
4. Flights with multiple payload packages carried by one balloon must weigh less than 12 pounds in combined total.
5. The string used to suspend the payload package(s) from the balloon must be able to separate/terminate with an impact force of no more than 50 pounds.
6. No person may design or intentionally operate any unmanned free balloon in a manner that creates a hazard to other persons or their property.
7. No person operating any unmanned free balloon may allow an object to be dropped therefrom, if such action creates a hazard to other persons or their property.

After acquiring all equipment and helium and ensuring that all laws will be followed, the team should run flight predictions with the Cambridge University Spaceflight (CUSF) landing predictor or some similar landing prediction software using the payload weight and target altitude values previously determined. This predictor will highlight any landing sites that would be unfavorable to recovery such as military installations, airports and airfields, cities, bodies of water, forests, etc. High winds (>10mph) can also make a HAB launch near impossible and checking the weather forecast will need to be a priority alongside the CUSF landing predictor. Once a day has been found that has favorable weather and a favorable landing site, local air traffic control (ATC) and any relevant airport should be given a twenty-four (24) hour notice and a one (1) hour notice of any HAB launch that is to take place. On the launch date, the team should arrive at the launch site early to begin setup of the payload and filling of the balloon. The balloons are made of a thin latex which is very sensitive to the oils present on human skin which will cause it to break down and result in a premature burst of the balloon. Therefore, the team should wear wither latex or cloth gloves to avoid contaminating the balloon. Once the balloon is filled with the correct amount of helium, it will need to be tied off to prevent the escape of helium but also should be tied in such a way that allows for the main line to be attached to the balloon. See figures 1-4 to visualize the balloon tying process. Note: no gloves are used in these images because the launch team is grabbing the neck of the balloon where the rubber is thickest and not susceptible to extensive material degradation.

Figure 1: Grabbing the balloon firmly after filling with helium

Figure 2: Using elastic bands to secure two spots on the neck of the balloon

Figure 3: Inserting a tie point between both secured spots on the balloon neck and folding it so that the secured spots are touching

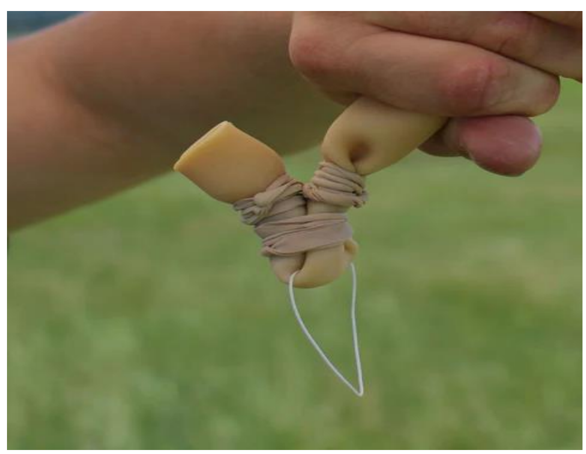

Figure 4: Secure the tie point by using more elastic bands to create a "loop"

Once the balloon has been tied with the elastic bands, it is good practice to secure the tied portion with tape. After the balloon is tied and the payload and parachute are attached, the team should run the CUSF landing predictor with the current time and then release the balloon. The team should clean up the launch site and begin driving towards the expected landing site. Most trackers utilize cellular GPS tracking and will stop transmitting after the payload has surpassed approximately 30,000 feet. This is expected and transmitting will return once the payload has fallen past that 30,000-foot threshold. Once the payload has landed the team should ensure that they do not trespass to retrieve the payload and should make an effort to reach out to any property owner if applicable. Once the payload has been recovered the team can begin data analysis.

Icarus Project

The Icarus project began in April of 2017 when the University of Kentucky's balloon satellite (BalloonSat) team reached out to Trigg County High School to partner with a high school class for a HAB launch. Dr. Suzanne Smith, then Director of NASA Kentucky Space Grant Consortium, provided guidelines that the team would have to follow when constructing a payload. That payload would fly alongside UK's for their May launch in preparation for the 2017 August Solar Eclipse. Figure 5 shows the Icarus 1, a rudimentary payload the team constructed that was designed to hold one GoPro camera and a temperature logger. The payload was attached to the main line by tying one end of paracord string to the main line and the other being weaved through the corner of the payload. The orientation of components was not a top priority, and this was reflected in the video footage captured. The footage was lopsided and shaky. Despite the poor footage quality, this launch was a success and provided the team with valuable data about the overall design of the payload, what needed to be changed to produce more stable footage, and expanded the scope of what could be achieved. Later that year, the team worked with Hopkinsville Community College's BalloonSat director, Sherry McCormack, to launch a new payload, the Icarus 2 for the Solar eclipse on August 21, 2017. Figure 6 shows the Icarus 2 and highlights some of the design changes. In an effort to capture footage that was more stable and easier to view, the payload was tied to be level on the ascent featuring a paracord line on each corner rather than one. Another design change that was made was adding a second camera to the payload that was facing upwards to record the balloon burst. This design proved to be more successful and produced more stable footage (see Appendix for edited eclipse footage recorded from the Icarus 2). However, the footage recorded tended to swing wildly and was not pleasant to watch at times.

During the fall of 2020 and spring of 2021, the focus of the research was establishing a BalloonSat team at Murray State University. The team would then be constructing a functioning payload to launch while improving upon the design of the Icarus 1 and 2. The project's first step

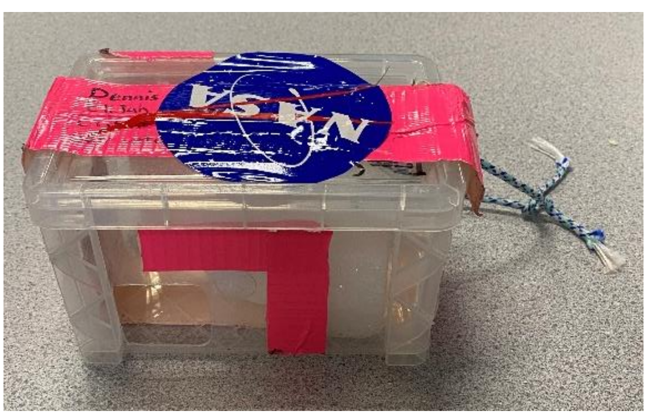

Figure 5: Icarus 1 payload shell without the flight camera or temperature logger, launched May 2017

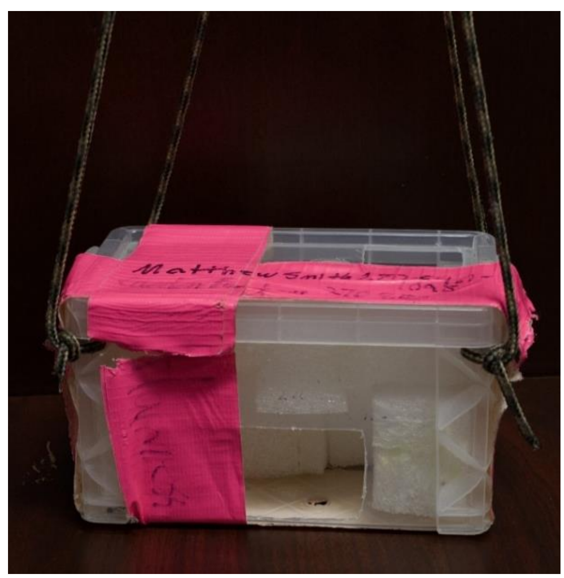

Figure 6: Icarus 2 payload shell without the two flight cameras, launched August 2017

was to reach out to the former BalloonSat directors that had previously worked with the team and ask about best practices for launching payloads and coordinating a BalloonSat team. The team worked with the project advisor, Dr. Rudy Ottway, who provided insight to design features and manufacturing processes that could be utilized when designing new payloads. To control all relevant geometry, the team utilized SOLIDWORKS to design the payload. SOLIDWORKS creates 3D geometry in the form of .SLDPRT (Part) files. They can then be exported to .STL files that can then be uploaded into a 3D printing slicing software. Slicing refers to creating the individual layers that a 3D printer will print when creating the part. The team used the Prusa slicing software to coordinate with Prusa 3D printers. Once the part has been sliced, a .GCODE file will be created. This file is used by the 3D printer allowing it to create the part using a 3D coordinate system. The payload parts were manufactured with PLA filament using a Prusa MK4 3D printer. PLA was chosen because it can withstand the approximately 50° C temperature threshold that a payload could experience during a flight without plasticizing. Considerable time was spent developing prototypes and payload designs and were continuously improved upon until the team settled on the design of the Icarus 9.

Icarus 9

The driving idea behind the design of the Icarus 9 was video stability. After many iterations and prototypes, the Icarus 9 showcased a spherical design with three camera ports. The cameras were oriented to capture up, out, and down to capture these three angles of video footage. Three cameras were used because it would provide the most informative views. The payload also had the main payload line running through the body of the payload. This design change was meant to reduce the swinging that was observed when it was attached parallel to the main line. This solution was selected because it reduces the number of knots that would have to be tied and prevented the out-facing footage from seeing the payload line compared to the footage from the Icarus 1 and 2. SOLIDWORKS was the primary computer-aided design (CAD) software used to design the payload shell. This payload was several times larger than the previous payloads but allowed for experimentation with the internal design and layout of components. This allowed for maximum ease of set-up and construction.

Once the payload was designed, PLA filament was used with the Prusa MK4 3D printer to print the payload. Initially, the payload's top and bottom hemispheres were printed as one large part, but after several printing failures, the payload's hemispheres were cut into four wedges and printed individually, proving more efficient. The main reason that large prints fail is a combination of warping of the material as it cools, software errors, and build plate adhesion. The individual pieces of the Icarus 9 took seven to ten hours to print and were then assembled using epoxy. Once the payload had been assembled and the epoxy allowed to cure, construction of the internal layout began. The internals of the Icarus 9 consisted of three GoPro Hero 4 Silver cameras, one Datalogger STRATO3, and one Cellular GPS tracker supplied by LoneStar Tracking. The data logger was selected because it could record temperature, pressure, humidity, longitude, latitude, speed, altitude, and arrived preloaded with software. The internal support was created by cutting and assembling pieces of structural foam. This structural foam was salvaged from packaging that housed research components during shipping. The assembly of the Icarus 9 can be seen in figures 7-14.

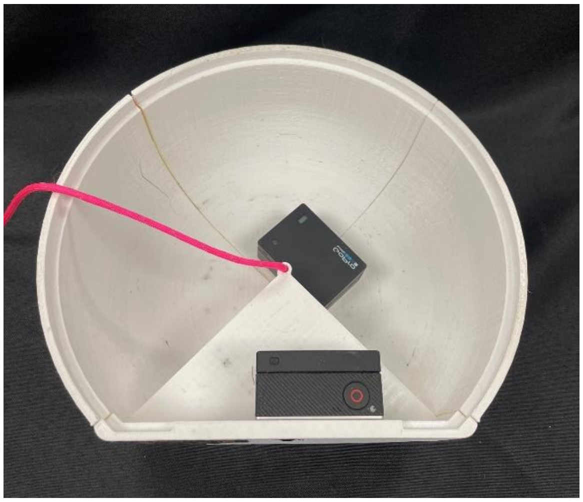

Figure 7: Icarus 9 with the out and down facing GoPros inserted

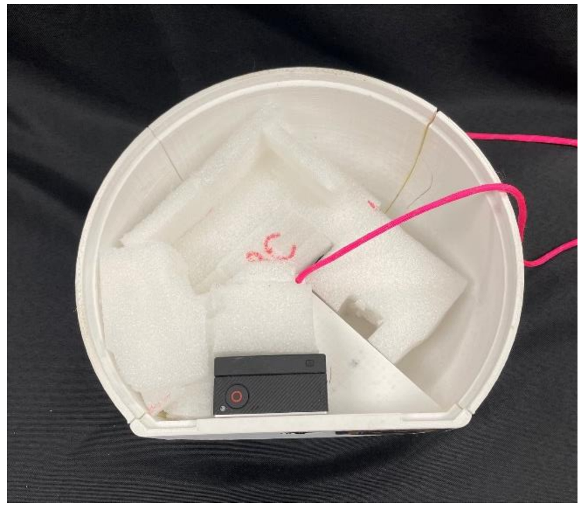

Figure 8: The second step of internal assembly with structural foam creating a mount for the Datalogger STRATO3

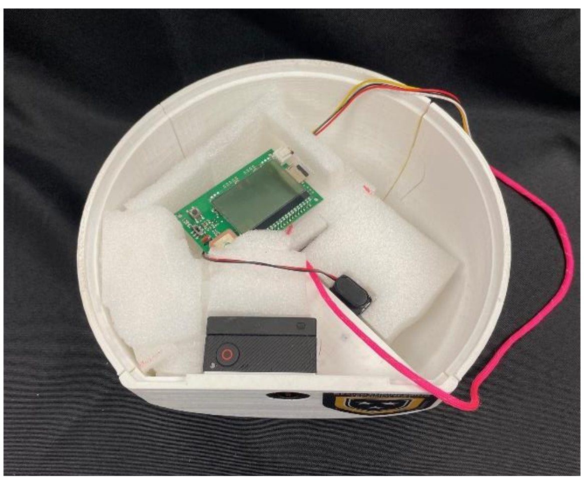

Figure 9: The Datalogger STRATO3 after being mounted inside of the bottom hemisphere

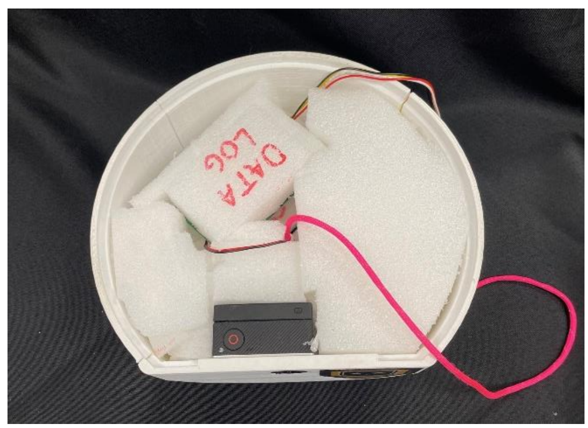

Figure 10: The last piece of structural foam being placed on top of the Datalogger STRATO3 to prevent movement

Figure 11: The Icarus 9 top hemisphere without any components installed

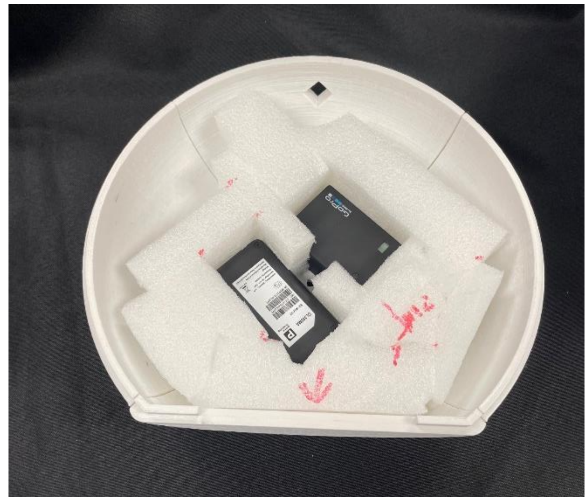

Figure 12: The cellular GPS tracker and the top GoPro installed along with structural foam

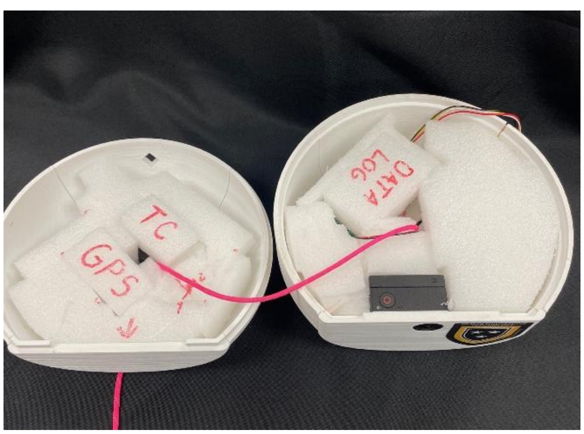

Figure 13: The top and bottom hemispheres with all components and structural foam inserted

Figure 14: The fully assembled Icarus 9 payload

Once the assembly was complete and no changes needed to be made to the layout, the payload was weighed for a final payload weight of 1631 grams. The team began early drop tests throughout the summer and conducted a tethered launch to test camera stability and functionality of the overall payload and its design. The tethered launch consisted of filling a smaller, 36-inch, balloon with enough helium to lift the payload off the ground. The payload was still tethered to the ground using a fishing pole. Photos were taken showing the payload and HAB assembly during flight as well as after a balloon burst with the parachute deployed. These tests proved successful, figure 15 shows the Icarus 9 in flight. After reviewing the footage and data from the tethered test, a launch date was set for November of 2021. The beginning of the fall 2021 semester was used to coordinate with the BalloonSat team to make sure there were no scheduling conflicts between team members. This time was also used to ensure that the project was going to abide by all FAA and FCC regulations.

Launch 11/16/2021

November 16, 2021, was selected as the launch date because the landing predictor showed the payload touching down in an agricultural area 20 minutes east of Clarksville, TN, with few structures and the weather was favorable with wind speed not exceeding 6mph. The launch team arrived to Roy Stewart Stadium at Murray State University at 9am, an hour before the launch was supposed to take place. There were 4 team members total for this launch and each had their own responsibilities ranging from balloon filling to equipment prep. The payload assembly of the Icarus 9 went as planned. All equipment passed initial pre-launch checks and was functioning when the payload was sealed. The payload was attached to the main line with a

Figure 15: The Icarus 9 during the tethered test as seen from a drone

single knot at the bottom of the payload. The payload was only supported by this knot. Attaching the payload and parachute to the balloon was successful and presented no unexpected challenges.

Once all equipment had been attached and the balloon was ready to fly, a final landing prediction was made, and the balloon was released. The GPS tracker started to provide real time updates on location and speed. The team then began cleanup of the launch site, and the recovery team began driving towards the expected landing site. During travel towards the indicated landing site, the GPS tracker began to provide live updates again, 45 minutes earlier than expected. The recovery team adjusted their direction and began to travel towards Dover, TN. The GPS tracker indicated the payload had come to rest in a wooded area off Bumpus Mills Road. Initial attempts to located the payload visually failed and after searching for two days and reviewing flight data, it was hypothesized that the payload must have broken apart and that the search was only for the GPS tracker. This was confirmed in figure 16, where the tracker can be seen resting amongst the tree litter. Attempts were made to search the surrounding area for any other components that could be recovered but were unsuccessful. With only data from the GPS tracker, the team reached the conclusion that somewhere between approximately 50,000 and 60,000 feet, the payload suffered some mechanical failure causing the payload to either break

Figure 16: The Cellular tracker on the ground after the mid-flight break up of the Icarus 9

apart or the knot at the bottom of the payload to loosen, resulting in the payload and its components to begin a freefall. As the payload began to fall, gravitational and centrifugal forces caused the payload to open as the only thing holding it together was duct tape now that the main line was no longer attached. The payload hemispheres and internal components scattered over a large area in west Tennessee. Figure 17 shows the final flight path of the GPS tracker after it had begun its freefall. While the loss of the payload was not the expected and desired outcome, it did lead to more brainstorming and design ideas that would be reflected in successive iterations of the Icarus project.

Icarus 10

Following the failure of the Icarus 9, addressing the problem of keeping the payload in one piece was a top priority. The main goal was that, even in the event of a separation from the main line, the payload would be able to be recovered in its entirety. Several ideas were tested when attempting to address this problem. One design, seen in figure 18, was to have interlocking hemispheres that twisted together. However, it was determined that while the slotting feature

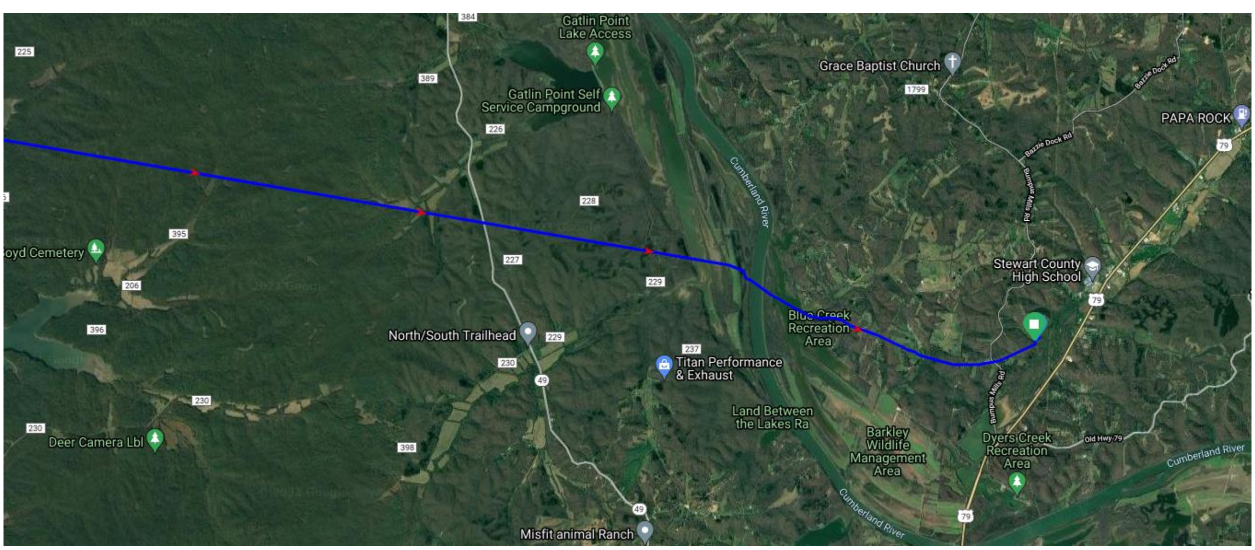

Figure 17: Flight path of the GPS tracker after separating from the Icarus 9

would provide extra internal support to holding the payload together, the existence of the feature caused the 3D prints to become unstable and prone to failure. Another design feature that was evaluated was the addition of tabs seen in figure 19, that could be zip tied together to provide a mechanical fastening, more resilient than duct tape. These two changes were focused on keeping the payload in one piece. The next major design change for the Icarus 10 would be the addition of a bottom plate that would attach to the bottom of the payload and would feature a tie-off point for the main line in contrast to having a single knot at the end. As seen in figure 20, the bottom plate encompassed 75% of the bottom with a wedge removed so that it would not obstruct the camera port as seen in figure 21. The final major change in the design of the Icarus 10 was reducing the overall footprint and weight of the payload. The Icarus 9 weighed 1600 grams and after reducing wall thickness, height, and infill percentage during manufacturing, the Icarus 10 achieved a 23% reduction in weight. The team utilized SOLIDWORKS for all the CAD drafting of the parts and followed the same process when manufacturing, using the Prusa MK4 3D printers. White PLA was used again when manufacturing the payload.

For this payload, 3 GoPro Hero 4 Silver cameras were used for video recording. It also housed the Eagle Flight Computer, which was used to record temperature, pressure, humidity, longitude, latitude, speed, and altitude. The Cellular GPS tracker from LoneStar Tracking was also used in this payload. Due to the similarity in overall shape, the team decided against doing a tethered test and opted to launch the payload as is. A new, 36”, parachute was also purchased for the payload. A comparison between the CAD model and the final payload can be seen in figure 22 and 23.

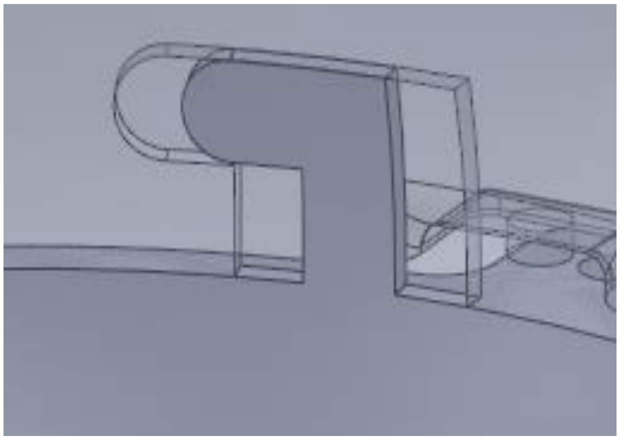

Figure 18: Slotting feature tested on the Icarus 10 seen in SOLIDWORKS

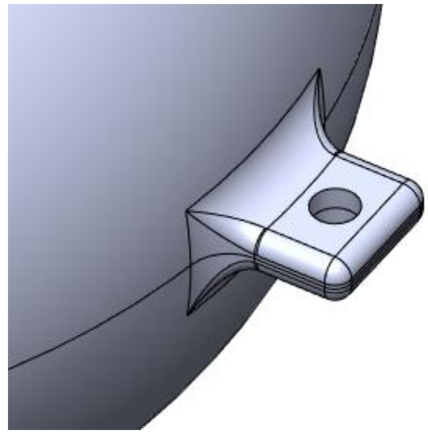

Figure 19: Tab feature tested on the Icarus 10 seen in SOLIDWORKS

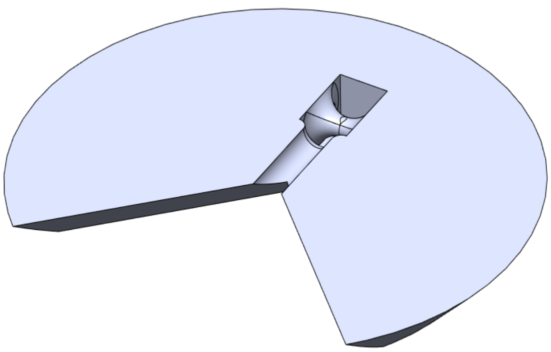

Figure 20: The bottom plate that the main line attached to and was then glued to the bottom of the Icarus 10

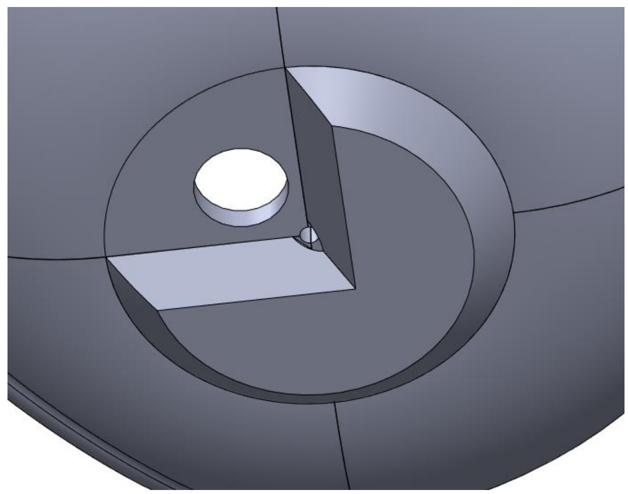

Figure 21: The bottom plate when attached to the bottom hemisphere of the Icarus 10

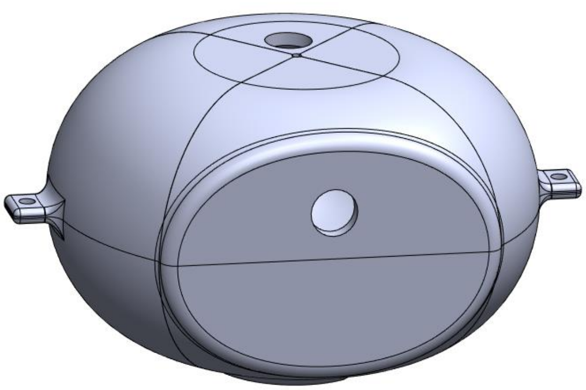

Figure 22: The Icarus 10 CAD model seen in SOLIDWORKS

Figure 23: The finished payload of the Icarus 10 post recovery

Launch 03/02/2024

March 2, 2024, was selected as the launch date for the Icarus 10 because the landing predictor showed the payload touching down in Lewisburg, KY. Lewisburg is a sparsely populated agricultural area with few wooded areas and structures, 20 minutes east of Hopkinsville KY. The weather was favorable with wind speed not exceeding 8mph. The launch team arrived at the Trigg County Recreation Complex at 8:30am, 90 minutes before the launch was supposed to take place. There were 6 team members total for this launch and each had their own responsibilities as they pertained to the launch. Before balloon filling began, the launch team and recovery team were briefed and given preliminary information about the path of the balloon and landing location. The week leading up to the Saturday launch included testing of the cameras, tracking equipment, and various structural tests if the Icarus 10. The launch team started filling the balloon at 9:05 am and continued to prep the equipment for launch.

Once it was confirmed that all cameras and data recording equipment were functioning, the payload was sealed and secured with zip ties. The balloon was filled with 165 cubic feet of helium and attached to the payload. One final landing prediction was calculated, and the entire system was launched at 9:52 am. Cleanup of the site began immediately after. The GPS tracker was behaving as expected and provided data until the tracker lost cellular connection. After cleanup was completed, the recovery team started towards the expected landing site. While enroute, a team member received a call from a farmer who had discovered the payload at the edge of his cattle pasture. All cameras and equipment were functioning upon landing, but the force of the landing caused the payload shell to split apart and spill the components onto the ground. The breaking apart of the payload upon impact was not a concern to the team, as the payload met the requirement of ensuring that all components were in one location. The data recovered from the payload gave many insights about atmospheric data such as temperature changes, airspeed, and changes that need to be made to the design of the payload. It was determined that the payload reached a maximum altitude of approximately 97,000 feet. A maximum temperature reading of 54°C and minimum of -38°C. The footage captured also gave great insights as to the stability of the payload by showing that it maintained level flight throughout the course of the transit. The payload also did not exhibit the rapid and uncontrolled spinning seen on the Icarus 1 and 2. Figure 24 shows the final flight path of the Icarus 10 and figure 25 shows the payload after it hit the ground and split apart. See the appendix for a QR code that links to the edited footage from the Icarus 10 flight.

Icarus 11

Following the success of the Icarus 10, the design of the Icarus 11 was very similar to that of its predecessor but attempted to reduce the overall weight and volume of the payload. By reducing weight, the required helium to lift the payload to the desired altitude decreases. There

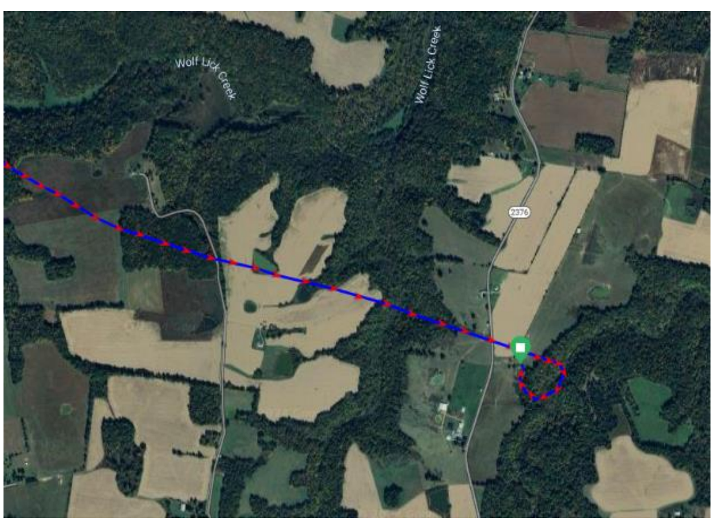

Figure 24: Final flight path of the Icarus 10 as it landed in Lewisburg, KY

Figure 25: The debris of the broken Icarus 10 payload after landing

was also extra effort in making the payload more stable. By arranging the components to be closer to the payload's center of mass, the payload would not swing as much during transit. The major changes that were made involved the bottom plate that secured to the payload, the front face of the payload, and the overall volume. Figure 26 shows the bottom plate featuring pegs that would create interference fits with the housing walls. This was changed so that the payload was more likely to stay intact upon landing due to the distribution of the impact force. The front face of the payload was made to encompass the whole wall instead of being split between the two hemispheres. This was done to avoid having the camera hole and shelf split across both hemispheres. Figure 27 shows how the bottom component absorbed the majority of the top portion of the front face. The last design change made to the Icarus 11 was the removal of two 2" wedges to reduce the internal volume and overall material requirement. Figure 28 shows the updated design of the Icarus 11 with the wedges removed. The team utilized SOLIDWORKS for all the CAD drafting of the new parts and followed the same process when manufacturing, using the Prusa MK4 3D printers. White PLA was used again when manufacturing the Icarus 11. The components used for the launch were reused from the previous payload.

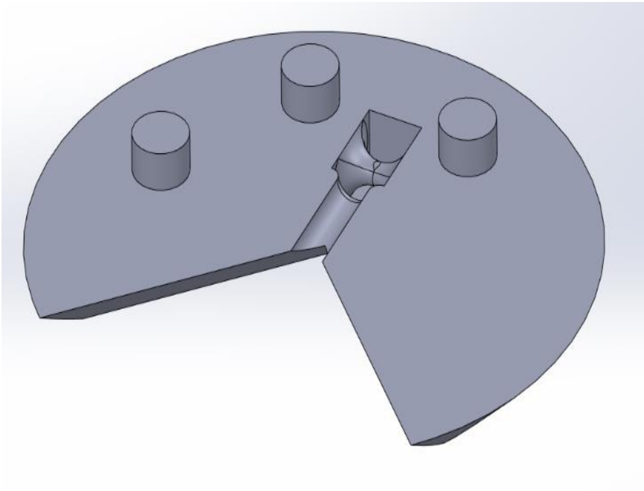

Figure 26: The redesigned bottom plate for the Icarus 11 as showed in SOLIDWORKS

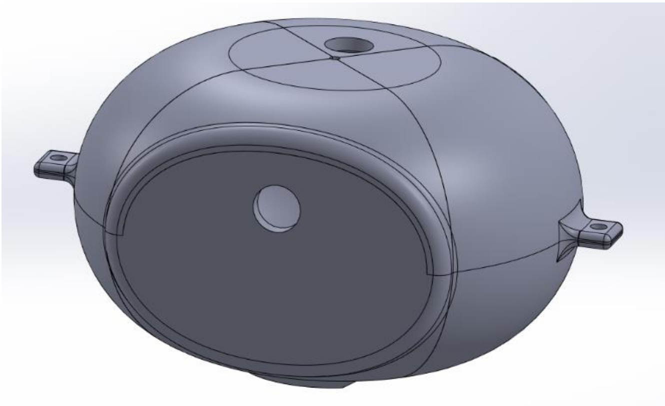

Figure 27: The updated front face which allows for the unification of the camera port and shelf

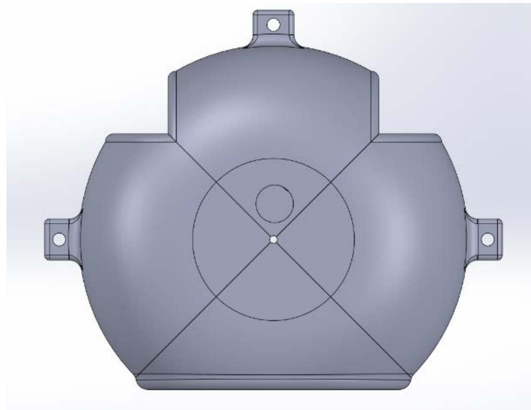

Figure 28: The updated payload shell of the Icarus 11 with the wedges removed

That includes 3 GoPro Hero 4 Silver cameras, the Eagle Flight Computer, and the Cellular GPS tracker from LoneStar Tracking, Due to the similarity in shape, much of the internal support was reused and only needed minor adjustments. The previous, 36", parachute was also used for this payload.

Launch 04/08/2024 Solar Eclipse

The launch date for April 8, 2024, was selected years in advance due the total solar eclipse. After reaching out to several individuals, the team selected Benton, IL as the point of launch due to its location on the path of totality. A total solar eclipse occurs when the moon passes between the Earth and the sun, blocking out the sun's light completely. During a total solar eclipse, the sky darkens dramatically, and observers within the path of totality can see the sun's corona, the sun's outer atmosphere. The goal of this HAB launch was to record the shadow of the moon as it passes across the surface of the Earth. The launch team arrived at the launch site several hours early in an effort to avoid heavy traffic. Another reason for the exceptionally early arrival was to ensure that the payload could be launched one hour prior to totality so that the payload would be at 90,000 feet or higher when totality began. The launch team began filling the balloon at 12:15 pm and began preparing the equipment for launch.

After confirming all equipment was functioning and recording, the payload was closed and sealed in the same manner as the Icarus 9. The balloon was filled with 175 cubic feet of helium and the payload was attached at 12:57 pm. The entire system was launched at 1:05 pm and site cleanup began. The GPS tracker was working and updating its location as expected and provided telemetry data until the tracker lost cellular connection. After viewing the eclipse totality, the recovery team began heading towards the expected landing site. Immediately after leaving Benton, the GPS tracker began updating its location. This was unexpected and indicated a premature burst of the balloon. The data received showed that the payload had been on the ground since 2:19 pm, 17 minutes after totality, 45 minutes earlier than expected. The recovery team rerouted towards the newly indicated landing site to begin recovery. After arriving at the expected landing site, visual confirmation of the payload failed. After scanning for several minutes, the recovery team found the tracker embedded in the mud. Figure 29 shows the tracker

Figure 29: The GPS tracker sticking out of the mud after the midflight structural failure

in the mud after it impacted the ground at an estimated 130 mph. The leading theory is that the Icarus 11 experienced a similar mechanical failure as the Icarus 9 and broke apart midflight. The breakups occurred during the same period of flight at roughly the same altitude of approximately 50,000 – 60,000 feet.

Moving Forward

After the launch of the Icarus 11, there are currently no plans to continue the BalloonSat team or HAB research. If a new Murray State team were to revisit the Icarus project in the future, they would need to learn from the previous launches. The current team developed a procedure sheet that contains helpful information and outlines the project from brainstorming and material selection to recovery and data analysis. A QR code linking to the procedure sheet can be found in the appendix. This new team should explore new designs for payloads and satellite operation. Another thing that would be beneficial to a BalloonSat team would be more interdisciplinary collaboration. Working with students in engineering, earth and atmospheric science, and computer science would allow for more complete solutions to problems and unique approaches to challenges that a BalloonSat team might face. The most important thing for this team to know going forward would be that setbacks are common, but they allow for new growth. Setbacks can also help a team explore design techniques that they otherwise wouldn't have considered.

If there were plans to continue the research, the Icarus 12 would feature many design changes. The main design change would be to address the expected midflight payload shell failure. This issue would be solved by changing the hemispheres to be individual, solid, pieces. Currently the hemispheres are split into 4 even wedges to aid in 3D printing by reducing the part size and print failure rates. 3D prints fail for a variety of reasons including warping, build plate adhesion, and structural deficits. Warping is the most significant contributor to print failures, and this is due to the difference between the temperature of the part and the temperature of the ambient air. One way to reduce warping is to include a shroud that surrounds the part while it is printing. This shroud traps heat and reduces the overall difference between the temperature of the part and surrounding air. Another design change that can be implemented is reducing the overall size of the payload. Since the hemispheres will be printed as whole pieces, it would be prudent to make the pieces small enough to fit on a 7in x 7in build plate. This would allow the payload to be printed on most mid-sized 3D printers making it accessible to most educational institutions. The CAD files for the Icarus 9, Icarus 10, and Icarus 11 can all be found in the appendix along with all other materials mentioned in this thesis. This Icarus project has been both rewarding and trying at times but taught many important lessons in perseverance, collaboration, and adapting to new situations quickly. The amount to learn from a BalloonSat project is great and is highly recommended to increase one's ability in engineering design and intrapersonal skills.

Figure 30: The payload shells (from left to right) of the Icarus 1, Icarus 2, Icarus 9, Icarus 10, and Icarus 11

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Appendix

QR code linking to the *NASA Balloon GoPro Launch - Solar Eclipse 8-21-2017* video. It is the final edited footage from the 2017 solar eclipse.

QR code linking to the *Scholars Week High Altitude Ballooning and Payload Design* video. It is the final edited footage from the March 2nd, 2024, HAB launch.

QR code linking to a Google Drive folder that contains the CAD files for the Icarus 9, Icarus 10, Icarus 11, and also the procedure sheet for launching a HAB satellite.