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A High-Altitude Balloon Camera Stabilization System to Capture the Shadow of the Moon Cast on the Earth during 2024 Solar Eclipse

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Abstract

On April 8th of 2024, a total solar eclipse occurred, and the path of totality crossed North America, including parts of Indiana. A high-altitude weather balloon (HAB) with a camera stabilization system attached was launched into the atmosphere to capture footage of the shadow of the Moon cast on the Earth during the progression of the total solar eclipse. High altitude balloons have been used to view eclipses and their shadows from the atmosphere but have had many challenges when it comes to stabilizing the payloads so that a clear image or video can be taken. This team re-designed a camera stabilization system considering results from a previous USI research project and a comprehensive literature review. This report presents the design of a camera stabilization system, including a description of its main components consisting of a magnetometer, an accelerometer and gyroscope, two Arduinos, and a GoPro camera. Additionally, the team conducted tests and SolidWorks simulations to support design changes to the system. The final design presented in Section 4 shows how the sensors and Arduinos work together to control the stepper motor to counteract the spin of the camera stabilization system pod induced by the ascent of the HAB and the attached experimental pods. The results from the HAB launch and flight are shown in Section 6.

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1. Introduction

Within this section, the project objective and deliverables are discussed. The objective outlines the team's overall goal for the project. The deliverables outline what the USI 2024 Design team intended to achieve during the Senior Design term.

1.1 Objective

The objective of this project is to:

Analyze and re-design a camera stabilization system to attach to a high-altitude balloon to capture images and videos of the shadow of the Moon cast on Earth during the April 8th, 2024, total solar eclipse.

1.2 Deliverables

- Results of complete engineering testing and simulations of the camera stabilization system
    - Cantilever beam tests of connecting bar between the stepper motor and GoPro camera made of PLA.
    - SolidWorks simulations for the connecting bar between the stepper motor and the GoPro camera made of 6061 Aluminum.
    - SolidWorks simulation for the Plate between motor and turntable made of 6061 Aluminum.
- Final product of the camera stabilization system
- A detailed Senior design presentation, report, and poster

2. Background

High altitude weather balloons have been launched into the atmosphere since 1932 [1]. They have been used to view eclipses and their shadows; in addition to, studying atmospheric conditions such as temperature, humidity, chemical composition, and wind patterns. But, high-altitude ballooning systems (HABS) have had many challenges capturing clear footage while in flight [2]. In Figure 1, is a diagram of the key components of a HABS. Typically, this system begins with a weather balloon, a parachute directly below the balloon, a GPS system, and experimental pods further below. The parachute slows the descent of the experimental pods underneath once the weather balloon bursts. Additionally, the GPS system (Iridium Satellite Tracking Pod) is attached to assist in locating the remaining pods as they descend to Earth. The experimental pods specific to the April 8th, 2024, launch include: 1) a 360-degree camera pod to capture images of the launch and flight, 2) a camera stabilization system pod with a GoPro camera pointing towards the Earth to capture the Moon's shadow cast on the Earth.

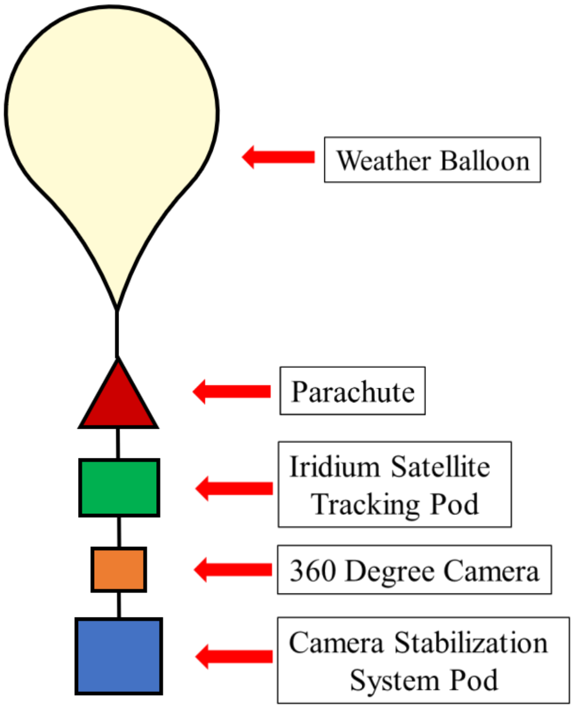


Figure 1.High Altitude Balloon System Key Concepts

2.1 Motivation

The motivation for designing a camera stabilization system was to gain a deeper insight into engineering systems. The team used previous projects associated with camera stabilization systems and high-altitude ballooning to re-design a camera stabilization system. The purpose of this project is to re-design and test a camera stabilization system to capture footage of shadows of the Moon cast on the Earth during the April 8th, 2024 solar eclipse. An example of this is shown in Figure 2 below.

Figure 2. Image of Shadow Cast on Earth from Moon [3]

Although there was not a specific need of re-designing a camera stabilization system and launching a HABS, there are many benefits to researching and executing the designated objectives. HABS launches offer the opportunity to explore different layers of the atmosphere while collecting data using sensors, such as pressure and temperature [3]. Because weather balloons typically ascend into the stratosphere, beyond the clouds within the troposphere, as shown in Figure 3 below, there is a greater chance of capturing clearer footage of the Moon's shadow cast on the Earth. Additionally, with a camera stabilization system, images captured during balloon ascent are valuable to researchers because they provide information about the sun's effect on temperature in the atmosphere [4]. This 2024 eclipse was the last one with its path of totality visible from the contiguous United States until 2044 making this project time-critical and unique [5].

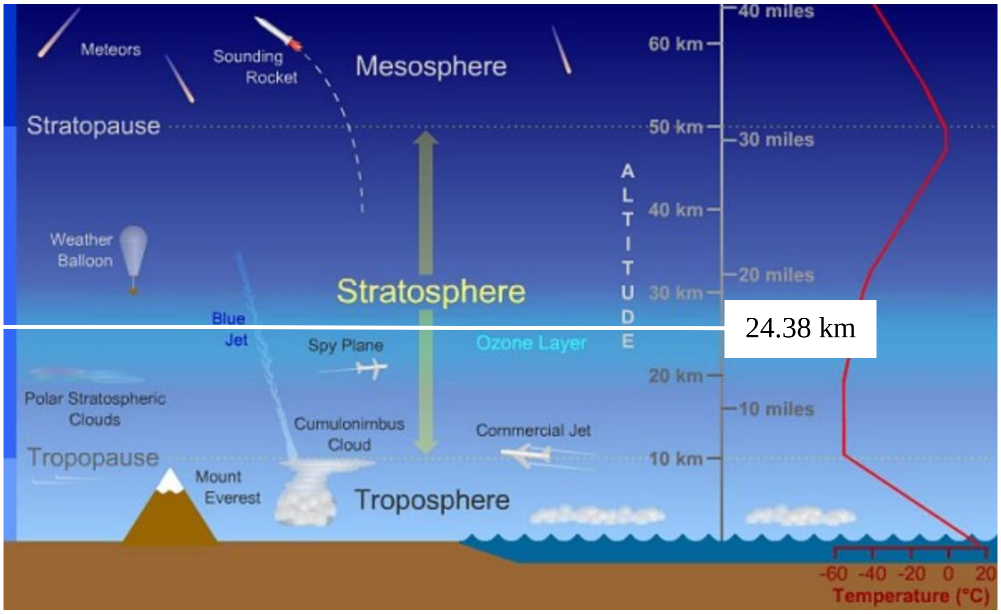


Figure 3. Visual of the average altitude a high-altitude balloon reaches in comparison to other objects in the atmosphere. [6]

In addition to the scientific benefits, the solar eclipse is only visible in specific cities, making it a great opportunity to capture total darkness from at least 80,000 feet (about 24.38 km). The eclipse was visible in the section highlighted in yellow on the map displayed below in Figure 4 and Figure 5 [7]. By integrating a camera stabilization system with a GoPro camera into an experimental pod attached to the HAB, the camera captured footage during the flight.

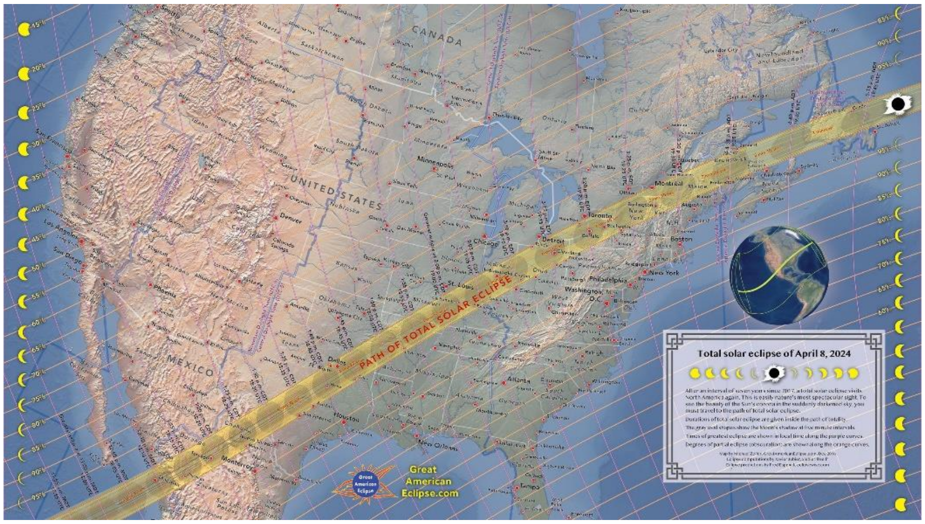


Figure 4. Path of Totality across North America during April 8th, 2024 Solar Eclipse.[7]

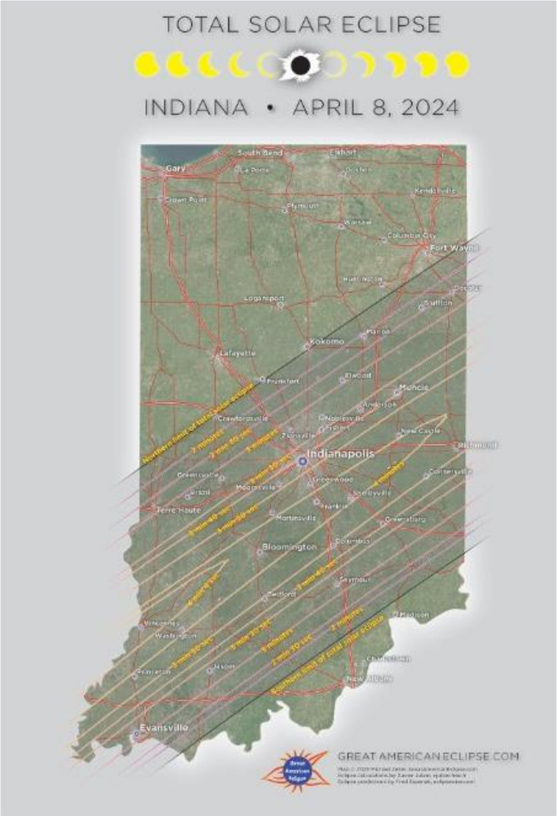


Figure 5. Path of Totality across Indiana during April 8th, 2024 Solar Eclipse [7]

2.2 Near Space Education

The design team partnered with NearSpace Education (NSE) to learn more about ballooning before the solar eclipse. NSE is a program in which its goal is to "provide every student with the opportunity to access space" [8]. They provide training and educational programs as well as monetary and equipment grants to support their mission and core values: inspire, equip, impact.

A training session was held at NearSpace Education in Upland, IN on March 16, 2024. NSE invited all its partnering teams, and the instructor demonstrated how to prepare and launch a HAB. The preparation included filling a 1500 g weather balloon with hydrogen or helium and attaching the experimental pods with tethers in the correct order. An additional 200 g HAB was filled and attached inside the parachute to ensure it deployed properly. The training session was very beneficial and allowed the teams to practice using the equipment that NSE provided. This equipment included two pods to attach to the 1500 g HAB including a 360-degree camera pod and an Iridium Satellite Tracking pod. In addition to the pods, NSE provided a backup GPS and data collection system, extra balloons, a parachute, payload tethers, and balloon filler hose. This training gave good insight into what to expect when launching a HAB and allowed the teams to troubleshoot with ballooning experts.

2.3 Similar Projects

The design project covered various aspects, including the examination of the HABS components, functionality, as well as the motivations and partnerships involved. The primary focus was designing the camera stabilization system. This was done with the consideration of similar projects, standards, and specific requirements. The camera stabilization system was the final pod attached to the HABS, closest to the ground.

2.3.1 Review 1- University of British Columbia

A group of students at the University of British Columbia designed and tested a camera stabilization system intended to be attached to a HAB which is shown below in Figure 6. The purpose of this camera stabilization system was to capture smooth video of the stars and other bodies in the atmosphere by controlling the camera movement in the horizontal and vertical planes using two servo motors. Their system was never flight tested due to not meeting the required rotational speed of 0.05 deg/sec or less necessary to stabilize the video during flight. The main instruments used in their design were a digital gyroscope, two servo motors, and an Arduino [9].

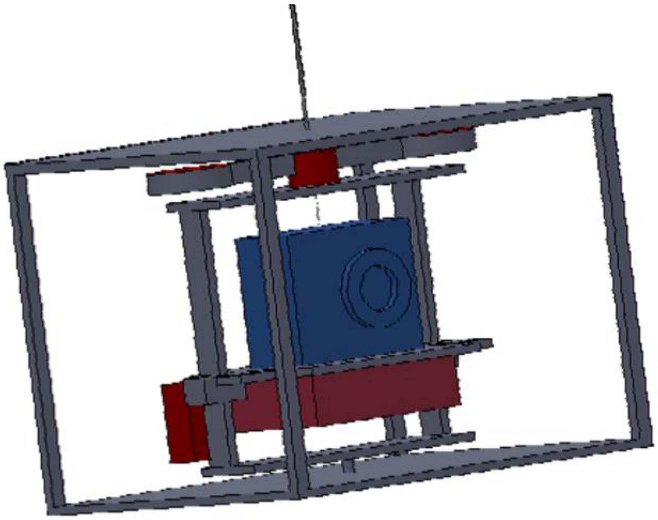


Figure 6. University of British Columbia Design [9]

2.3.2 Review 2- University of Alabama in Huntsville

A team of students at the University of Alabama- Huntsville designed a High-Altitude Visual Orientation Control (HAVOC) platform, shown in Figure 7, with the intention of capturing stable video footage [11]. HAVOC was designed to be easy to use for students. It includes a mechanical subsystem that creates torque using rotational drag on the payload. Another subsystem controls solenoid valves to release gas from the balloon. Lastly, the control system includes sensors used to collect data, such as temperature and pressure. The control system of HAVOC can reduce the angular velocity based on the altitude of the balloon and continuously face any direction. The University of Alabama-Huntsville team launched their balloon in 2021, and they planned to launch it again for the 2024 solar eclipse using a similar payload stabilization with the addition of a camera attached [11].

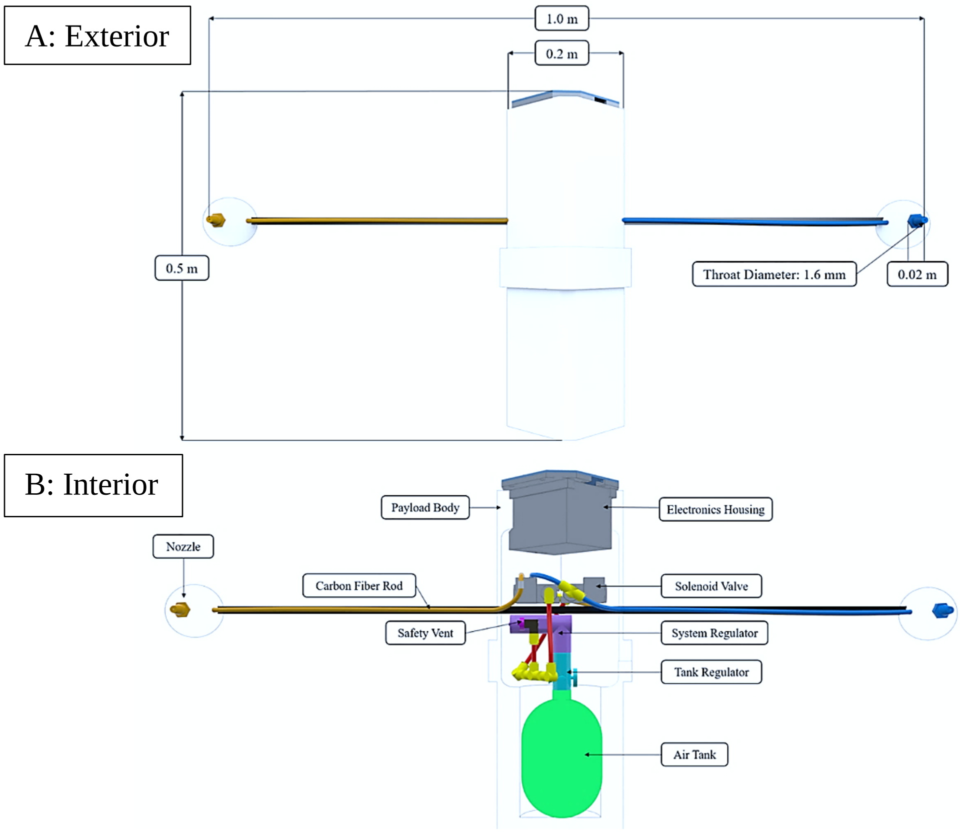


Figure 7.University of Alabama Huntsville HAVOC Device with A) showing the exterior and B) showing the internal components. [11]

2.3.3 Wilbur Wright College

A group of students from Wilbur Wright College in Chicago, IL designed a Controlled Heading Automation Device (CHAD) system pod. The CHAD system is shown in Figure 8 [2]. It can orient a camera mounted below the CHAD about its vertical axis. The students used a stepper motor controlled by an Attitude and Heading Reference System (AHRS) consisting of a magnetometer, an accelerometer and gyroscope, two Arduinos, and a motor controller to orient the camera based on the magnetic field of the Earth.

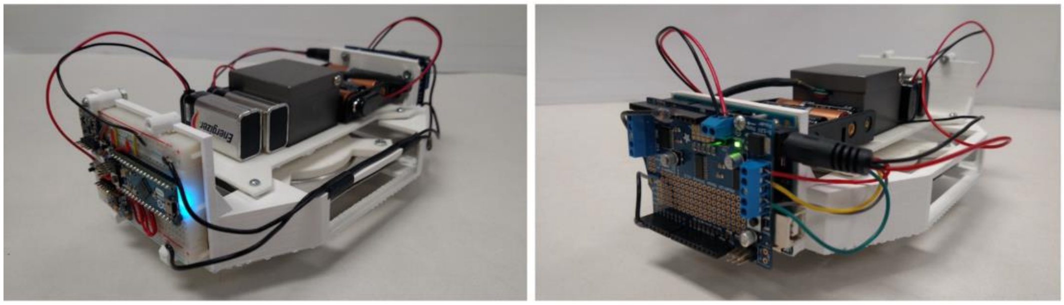


Figure 8. CHAD Orientation and Electronic Setup [2]

Additional components necessary to complete the system include 3-D printed parts such as a connecting bar, shown in Figure 9, between the CHAD and the GoPro camera and a case to hold the electronics in place inside the pod. The Wilbur Wright team did not account for the wind or the extreme low temperatures which caused the gyroscope and accelerometer to not give accurate gravitational measurements [2].

Figure 9. Connecting Bar Between the Camera and the CHAD

In 2016, a group of University of Southern Indiana students launched a high-altitude balloon with an attached camera stabilization system using the same CHAD design as Wilbur Wright. However, the GoPro Camera broke off during flight and was never retrieved. The connecting bar between the motor and where the GoPro camera was initially attached broke off upon landing [10]. The USI team was unable to view the video captured during the flight or analyze the responsiveness of the CHAD system during flight.

2.4 High-Altitude Balloon Standards and Requirements

According to the Federal Aviation Administration (FAA), a weather balloon may carry multiple experimental pods that weigh up to 12 pounds, but one pod may not exceed 6 pounds [16]. The 2024 Senior design team had to ensure that the camera stabilization system did not pose any risk to public health or safety during operations or in case of any failure. Factors such as the materials used, and potential hazards during launch, flight, and recovery were considered.

2.5 Requirements

The high altitude-balloon shall:

Float up to approximately 80000 ft (about 24.38 km) before popping.
Be recoverable using the attached GPS.
Descend the experimental pods to the ground after the parachute deploys.
Carry payloads that weigh less than 12 pounds total. (FAA)

The camera stabilization system shall:

Capture footage of the Moon’s shadow cast on the Earth during the solar eclipse.
Resist unexpected forces between 94-445 Newtons (N) (30.12 – 99.8 pounds (lbs.))
Withstand temperatures between –40°C - 30°C.
Weight less than 6 pounds. (FAA)

3. **Concept Selection**

Based on the research conducted for a camera stabilization system, three concepts were analyzed and considered. The concepts are described in the following sections as well as the reasons for not pursuing each.

3.1 Concept 1 – Gimbal Inspired Design

The gimbal inspired design shown below in Figure 10 allows the camera, represented as a green box, to be controlled by the stepper motors in the X and Z axis. On the left side, a magnetometer, an accelerometer and gyroscope, and an Arduino Micro work together to create an attitude and heading reference system (AHRS). The magnetometer provides a reference for determining the systems orientation relative to the Earth's magnetic field.

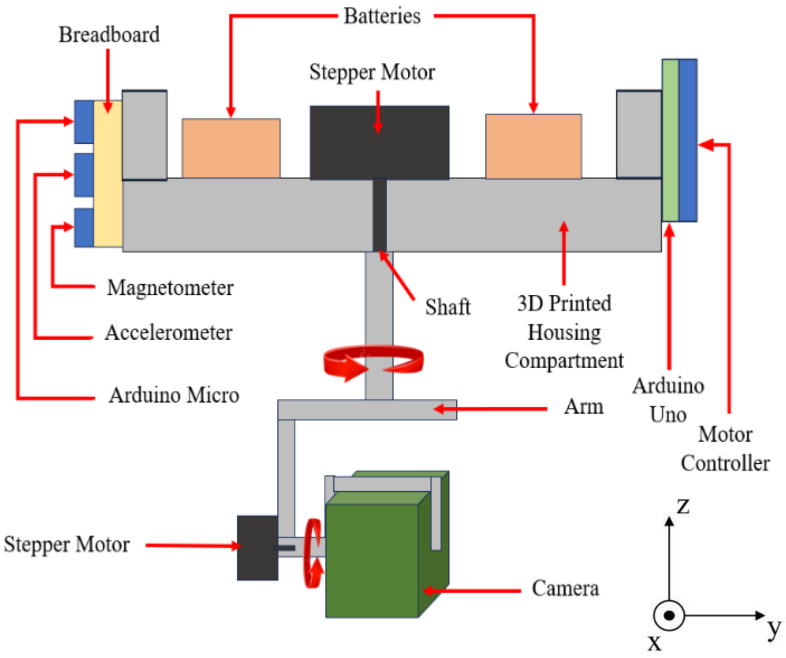


Figure 10. Gimbal Concept Design

The camera's orientation is set before launch and as the balloon begins to rotate during ascent, the AHRS will measure the orientation of the camera relative to the Earth's magnetic field. The orientation measured by the magnetometer is sent to the Arduino Uno on the right side which processes the data to tell the motor controller how many steps the motor needs to rotate back to its original orientation. This concept was not pursued because two stepper motors were needed to operate. Each stepper motor creates its own magnetic field that would likely interfere with the magnetometer and data accuracy. Additionally, using two motors required more involved coding that was beyond the knowledge of the team.

3.2 Concept 2- Cold Gas Thrusters

The HAVOC system shown below in Figure 11 was designed by students at the University of Alabama-Huntsville. The system uses cold-gas thrusters to actively control the orientation of the payload in High Altitude Balloons [11]. It uses valves that can direct the flow of pressurized gas into two sets of nozzles that will generate torque in a counteractive direction to the wind and other forces experienced by the balloon and attached payloads during flight. This concept was not pursued because the University of Alabama-Huntsville team's design did not yet include a camera, the attached camera in Figure 11 was added by the USI team as a possibility for the 2024 solar eclipse. Additionally, as the HABS ascends the temperature and pressure will be different within the nozzles causing other complications.

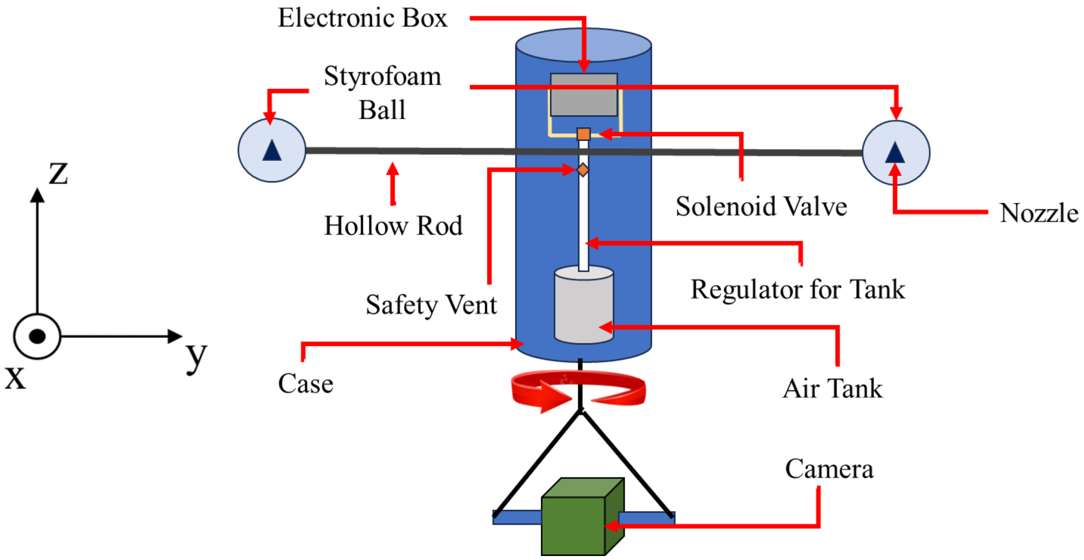


Figure 11. HAVOC System Concept Design

3.3 Concept 3- Gyroscope Inspired System

The concept of the gyroscope shown below in Figure 12, uses a similar sensor configuration to the gimbal described in concept 1. The gyroscope inspired system stemmed from the University of British Columbia but was modified by the USI 2024 Senior Design Team [9]. It uses an accelerometer and a magnetometer to orientate itself to counteract movements in the x, y, and z axes. Counteracting rotation in three directions would require three stepper motors, three Arduino Uno's, and three motor controllers. Additionally, according to the University of British Columbia's design, a light-weight reinforcement system would need to be added. This concept would require multiple design trials to perform adequately, due to lack of knowledge, lack of past similar project reports, and an accelerated timeline, this concept was not pursued.

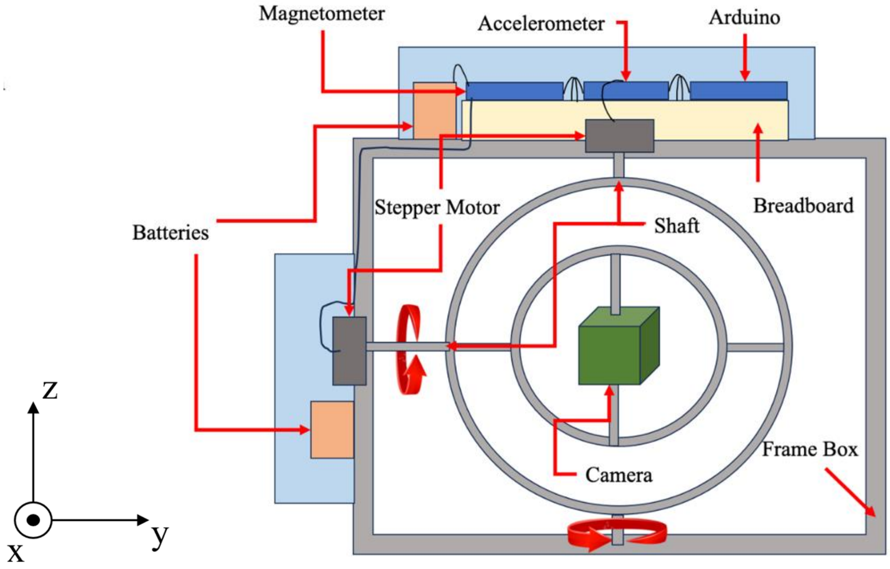


Figure 12. Gyroscope Concept Design

3.4 Justification of Chosen Design

The chosen design for the project can be seen below in Figure 13. The team selected a concept similar to the gimbal inspired design shown in concept 1. The motor that controlled rotation in the Y axis was removed which allowed the team to simplify the design to accommodate an accelerated timeline. The design concept was based on the system created by Wilbur Wright College with a few changes including the 1) material used to manufacture the bar and camera holder and 2) the motor. Concept 2 was not pursued due to the complex design that required more background knowledge. Concept 3 was not pursued due to the intricate manufacturing required for the design.

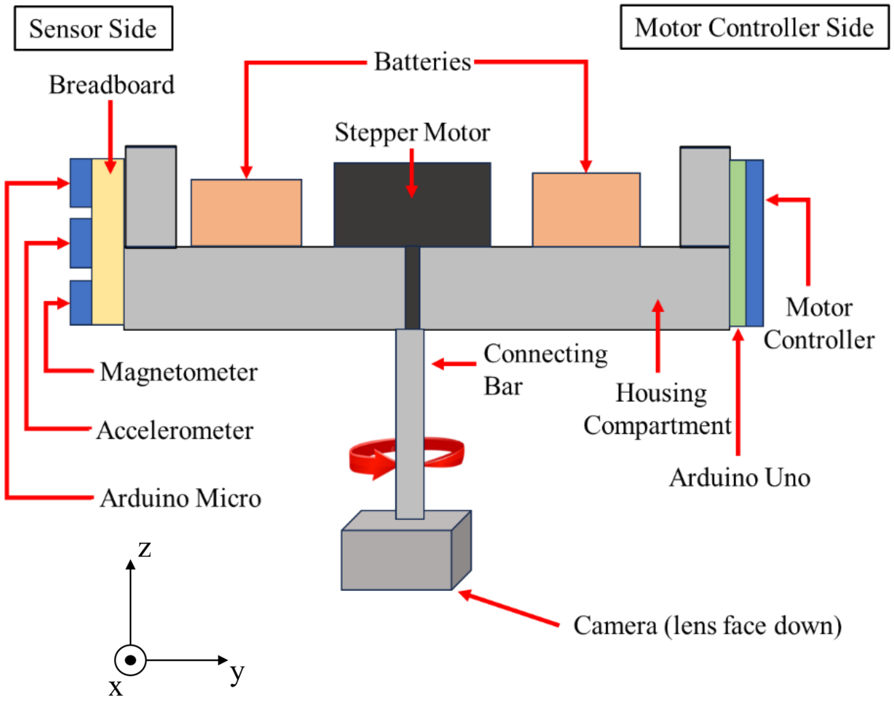


Figure 13. Mechanical Block Diagram for Modified Design

4. Final Design and Analysis

The 2024 Senior design team selected the camera stabilization system originally created by Wilbur Wright College, to re-design for a HABS launch on April 8, 2024. Specific design choices were considered from the results of the HABS launch conducted by a previous USI team, who used this camera stabilization system in 2016. The 2016 USI team built and attached the stabilization system designed by Wilbur Wright to their HABS but encountered several concerns with the design during and after the flight. The primary concern was the connecting bar between the camera and the motor that is controlled by the system. Another issue was the method by which the camera was suspended from the connecting bar. Additionally, the electronic system required an inspection.

4.1 Connecting Bar and Camera Holder Design

During the previous USI team's balloon descent in 2016, the connecting clips that were holding the GoPro camera in place broke. This was caused because when the balloon pops, the payloads thrash around until the parachute deploys. The connecting clips can be seen circled in red in Figure 14A. Also, the connecting bar that connected the GoPro Camera to the system broke during landing. The breaking point of the connecting bar can be seen circled in red in

Figure 14B. These are the main components the 2024 USI senior design team decided to redesign. Cantilever beam test and SolidWorks simulations were conducted to support the design changes made to the connecting bar and camera holder.

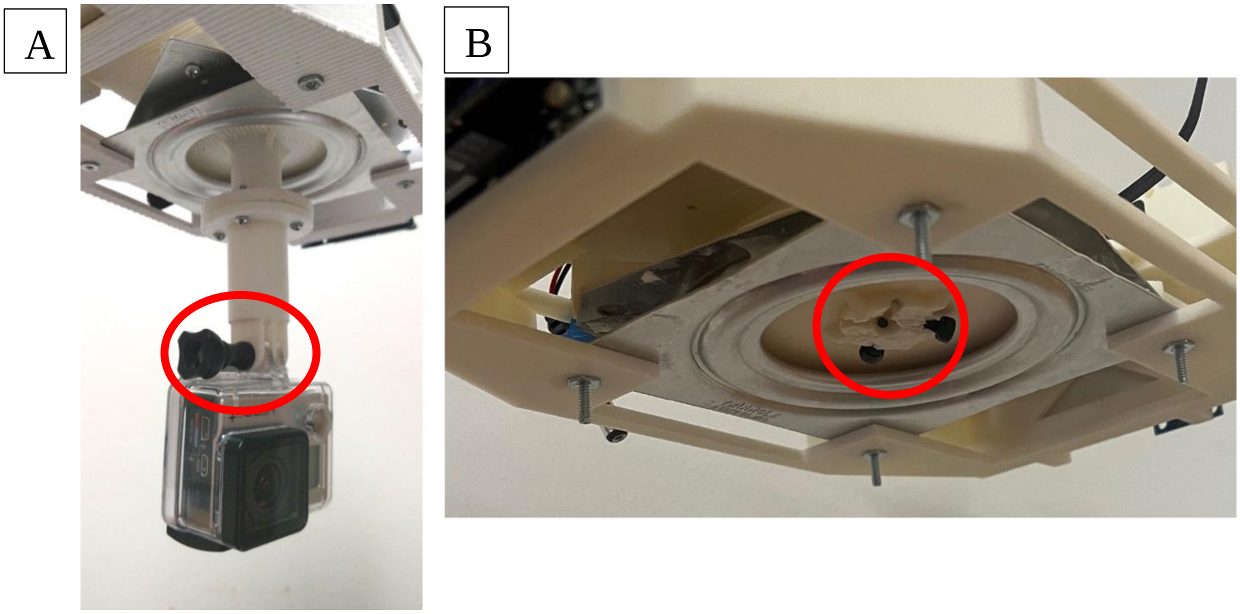


Figure 14. A) Connecting Bar between Camera and Motor with the Connecting Clips Circled in Red B) Breaking Point of Connecting Bar Circled in Red

4.1.1 Connecting Bar Testing and Simulation

The previous USI team's design used PLA as the main material for the framework of the system. Since the main component connecting the GoPro camera to the system failed, the 2024 design team performed three cantilever beam tests on the connecting bar made from PLA to evaluate if it would still be a viable option. A fillet was added at the breaking point of the bar to see if this could decrease the stress concentration at the connection.

The team first tested the initial connecting bar design shown in Figure 14.A that the previous team used. Secondly, they tested the bar after adding a fillet to the connection point where the break occurred. Lastly, dry ice was used to cool the piece, so that atmospheric conditions could be simulated. The results for each test are shown in Figure 15. The gray line indicates the bar that was cooled to simulate atmospheric temperatures was only able to experience around 94 Newtons (N) of force before breaking. The orange line represents the bar without a fillet and the blue line represents the bar with a fillet. The bar with a fillet was able to withstand 155 N while the non-fillet was only able to withstand a 134 N force before breaking. Although there is a 21 N difference after the fillet was added, this only translates to around a 5-pound force difference.

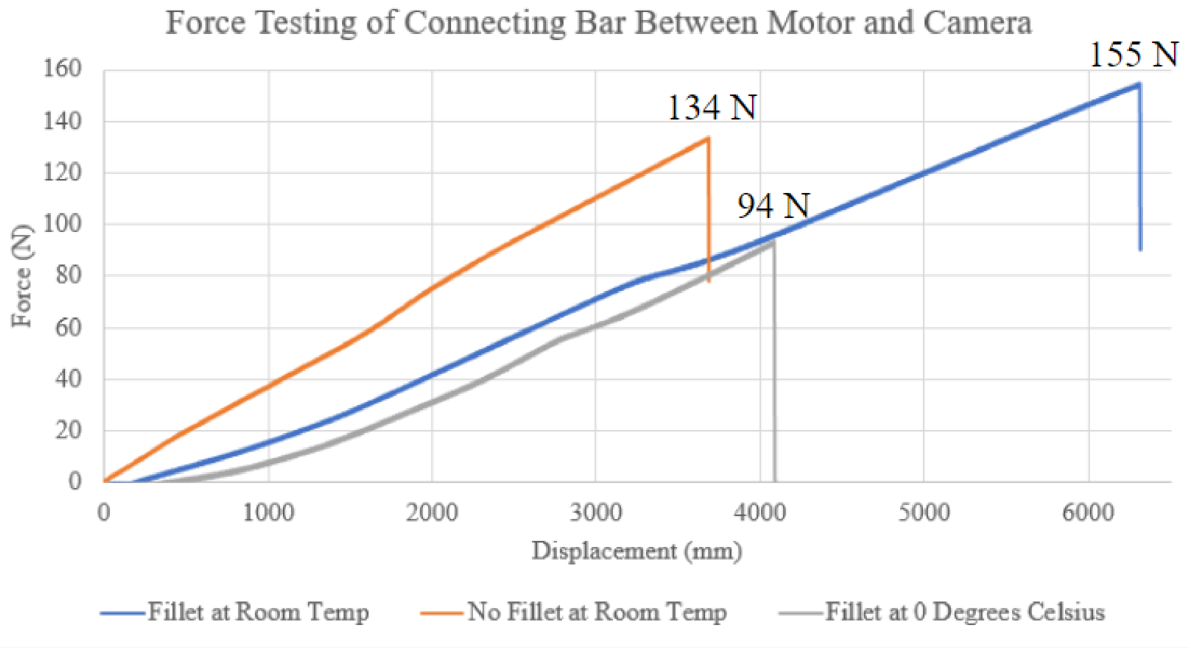


Figure 15. Force Testing on Connecting Bar Between Motor and Camera

Based on these results, the 2024 USI team concluded a different material for the bar would be necessary. Once the balloon pops the system will begin to swing around causing the bar to experience large amounts of force. In order to ensure that the bar would remain intact so that the footage can be obtained from the camera, the connecting bar must be redesigned.

4.1.2 Material Selection for Connecting Bar Between Motor and Camera

3D printable materials were investigated due to their easy manufacturability. When looking into different filaments, ones that would work in temperatures as low as -60 degrees Celsius, were outside the team's budget. Other lightweight materials were investigated, and the new chosen material was Aluminum 6061. Aluminum has desirable properties such as the retention of ductility at low temperatures [17]. A hollow connecting bar as shown in Figure 16 was simulated to ensure that it could withstand a higher force than the previous design. A hollow rod was chosen so that weight could be conserved for the payload.

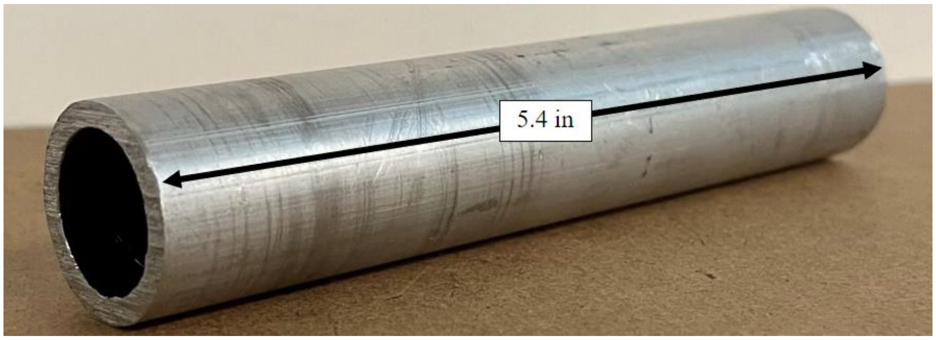


Figure 16. Hollow Connecting Bar

The simulation shown in Figure 17 was estimated as a cantilever beam test with one end being fixed. A force three times the amount that the previous design in PLA could withstand, when cooled to 0 degrees Celsius, was applied. The max stress that the connecting bar experienced is significantly below the yield strength which helps to support the material change.

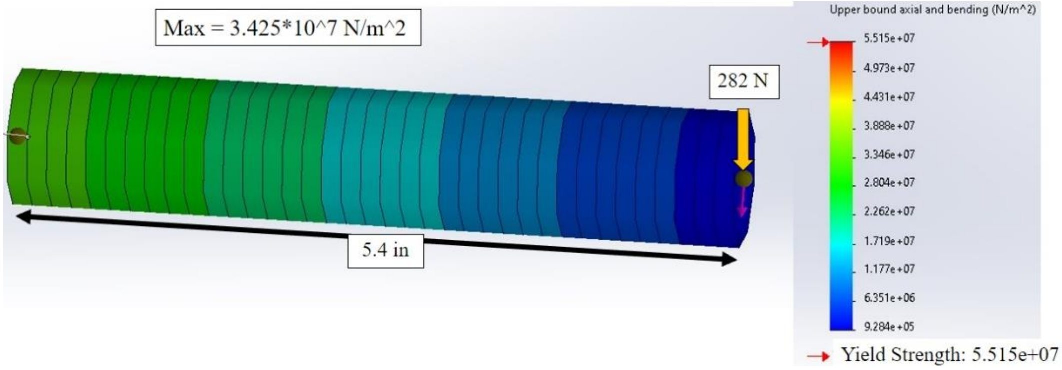


Figure 17. Cantilever Beam Simulation of Hollow Connecting Bar Between Camera and Plate. This figure shows that with an applied load of 282N, the bar will not break.

4.1.3 Material Selection for Plate Between Motor and Turntable

The next piece simulated was the plate between the motor and turntable outlined in red below in Figure 18. This piece was redesigned from aluminum so that the connecting bar could be directly welded to the plate. A simulation was done to ensure that the plate would not break or sink into the hole in the turntable, causing it to lock up.

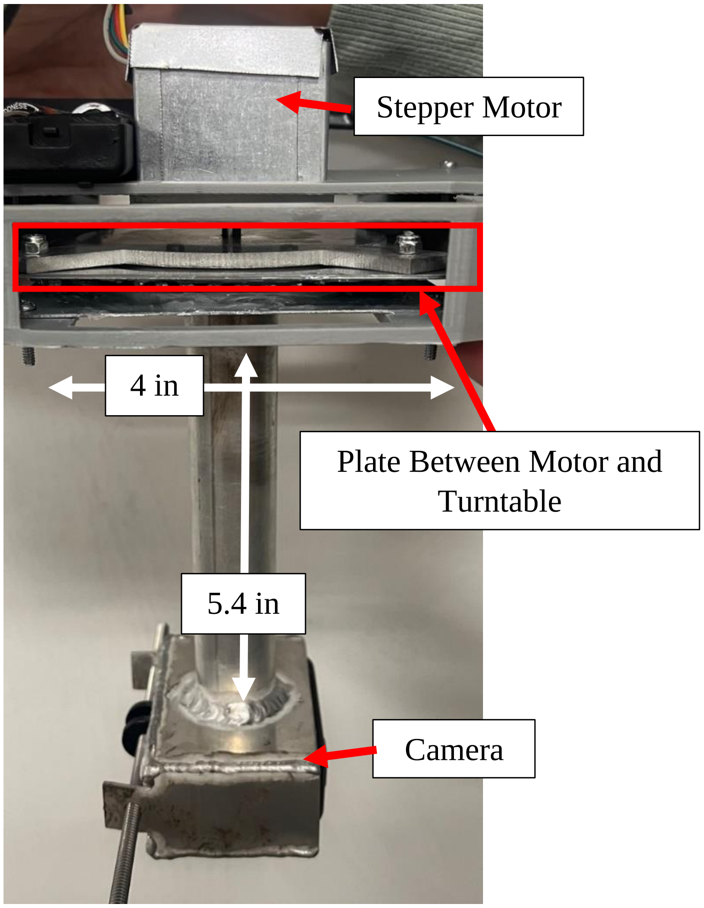


Figure 18. Plate between Motor and Connecting Bar Outlined in Red

The results for the simulation of this piece can be seen below in Figure 19. A 1/16” and a 1/8” thick plate was simulated. The 4.5 N load is about two times the weight of the camera and the holder that will be at the end of the connecting bar. The results show that neither will surpass the yield strength, but the team decided to continue with the 1/8” plate.

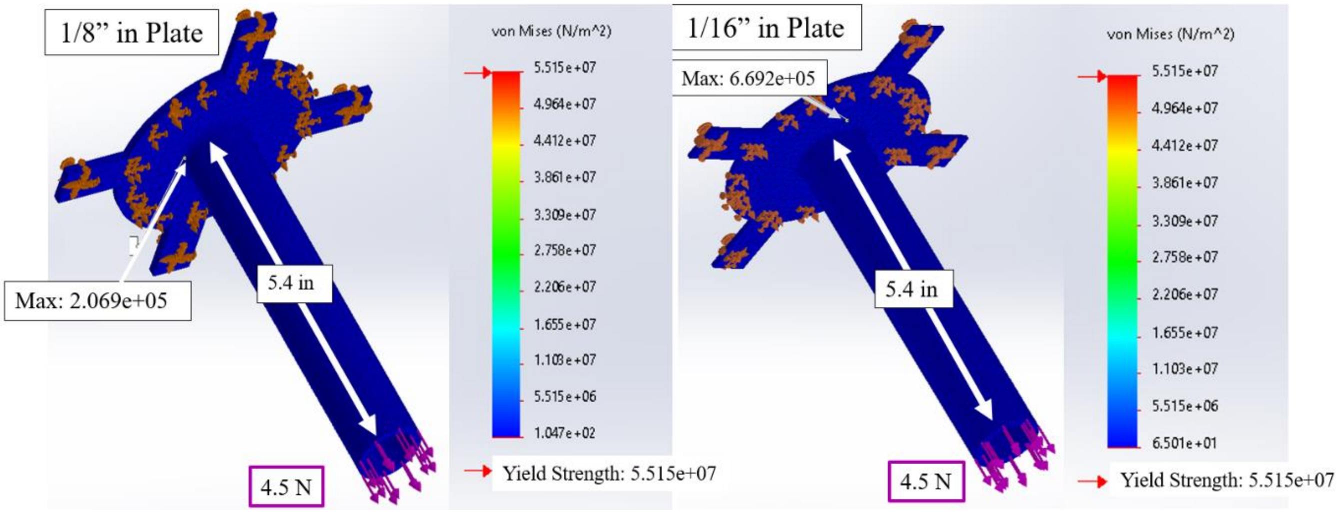
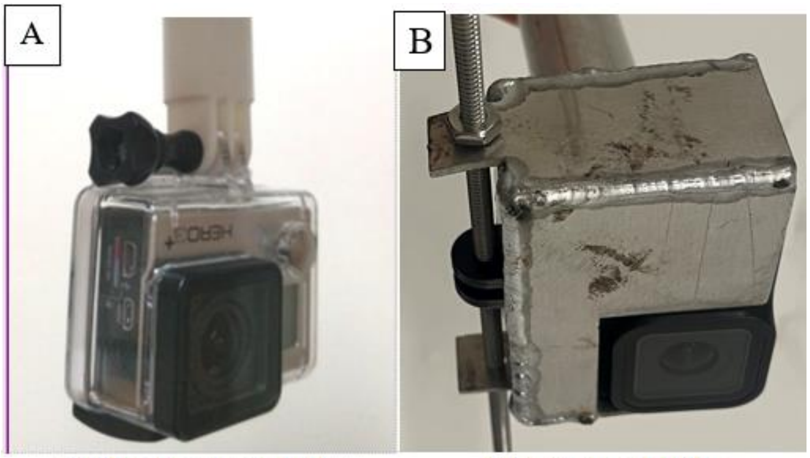


Figure 19. A) 1/8” Plate and B) 1/16” Plate Between Motor and Turntable Design

While the 1/16” plate does not hit the yield strength, the team also had to consider the motor shaft that goes through the plate and into the hollow rod. With the connecting bar being welded to the plate, the heat from the weld would conduct quicker through the thinner plate and potentially conduct up the shaft and damage the stepper motor.

4.1.4 Material Selection and Design for Camera Holder

The final piece tested was the new GoPro camera holder. The 2024 team decided to re-design the camera holder because the camera was facing down rather than tilted like the previous USI project. It was decided that the GoPro camera would be better supported if it was surrounded by an aluminum case. The previous design consisting of two clips that came out of the GoPro that were held into the clips on the bar by a single set pin, can be seen in Figure 20A. The re-design, consisting of a full case and the GoPro Camera being held in by the threaded rod, can be seen in Figure 20B.



Previous Camera Holder New Camera Holder

Figure 20. A) Previous vs B) New Camera Holder Design [2]

As mentioned previously, when the balloon pops, the payloads will begin to swing with large amounts of force until the parachute fully opens and stabilizes. It is difficult to measure how much force the remaining pods will experience during this time. Due to this, a test was conducted to see how much force the threaded rod could withstand before failure resulting in the possibility of the GoPro camera slipping out of the case. The simulation can be seen below in Figure 21. If the threaded rod does break and the camera falls out of the case, then it is known that the holder experienced a force greater than 750 N.

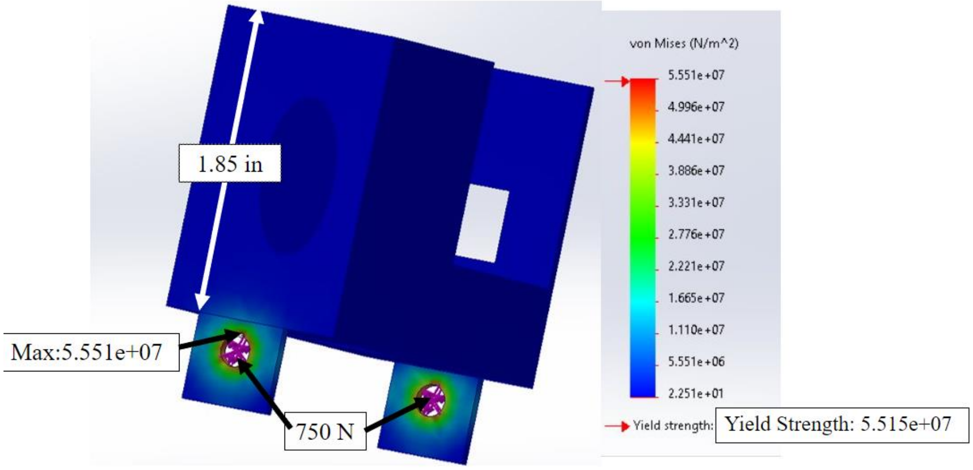


Figure 21. Camera Holder Simulation

4.2 Electronic System

For the electrical design, a system capable of responding to spinning movement of HAB during flight is needed. The system provided by Wilbur Wright College gives the opportunity to understand how to build the electrical design. It also allows for changes based on their results. The first section has two sensors, including an accelerometer, an Arduino microcontroller, and a magnetometer. This design, detailed in a report from Wilbur Wright College, uses the magnetometer to measure the direction of magnetic fields, shown in the top left of Figure 22. Serving as the compass component in the camera heading system, the magnetometer accurately determines the camera's heading relative to magnetic north by measuring the Earth’s magnetic field. This information ensures precise orientation of the camera. The accelerometer on the bottom left of Figure 22 complement the functionality of the magnetometer by detecting changes in the camera’s velocity and acceleration along different axes. This data enables determination of whether the camera is in motion or stationery. Additionally, the accelerometer data is utilized to correct for unwanted movements or vibrations. By combining data from both the magnetometer and accelerometer, sensor fusion algorithms provide a more accurate and robust orientation to the system. The Arduino microcontroller in the middle of Figure 22 serves as the processing unit for handling sensor data from the magnetometer and accelerometer. Acting as an interface between the camera sensor system and external components, it facilitates communication and analysis of the raw data being received.

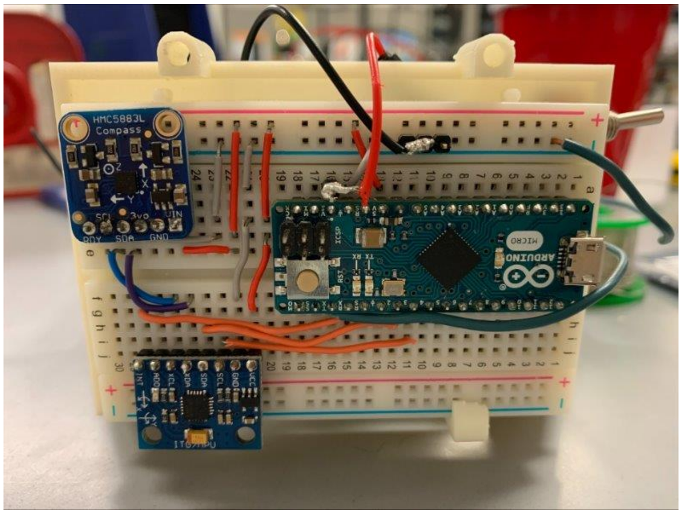


Figure 22. Sensor Side

Given the predetermined sensor choice given by Wilbur Wright college, the immediate task is to set up a method to move a motor that will counteract the balloon's spinning motion, enabling the camera to capture high-quality footage. Positioned behind the motor controller as shown in Figure 23, the Arduino Uno assumes an important role in this configuration. Processing data from the Arduino Micro, the Arduino Uno interfaces with a motor controller, illustrated in Figure 23, to control the movement of the camera's adjusting motor along the Z-axis. This facilitates the execution of commands based on sensor inputs, ensuring precise control over the camera's positioning.

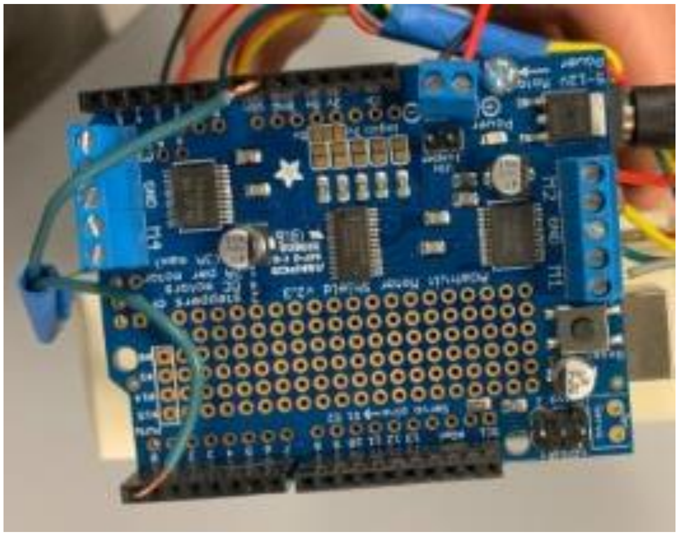


Figure 23. Motor Controller Side

The Arduino Uno serves as a platform for serial communication with the Arduino Micro, establishing coordination between the components. Meanwhile, the motor controller provides the circuits and software interface necessary to drive the stepper motor, allowing for control of its movements in steps and direction.

Motor controllers, particularly those designed for stepper motors like the Adafruit Motor Shield used in the code, offer simplified control interfaces for stepper motor operation. This integration shows ease of use and lays the groundwork for potential future expansions within the electronic system. The functional block diagram of the system is shown in Appendix F. In essence, the combined functionality of the Arduino Uno and the motor controller facilitates control and efficient operation of the camera's movement, ensuring video capture and providing a foundation for potential enhancements to the electronic system.

4.2.1 Flow of Electronic Components.

To gain an understanding of how this system operates internally, particularly concerning it signaling aspects, a flow system was developed. This flow diagram was created to explain the functioning of the system. The information for creating this diagram was extracted from the code developed by the Wilbur Wright College team.

Starting on the sensor side, the system first initializes communication and verifies the functionality of sensors and data configuration. Subsequently, the digital processor within the Arduino microcontroller enters a loop to establish its readiness. The accelerometer then computes data for the roll (y-axis) and yaw (z-axis). Following this, the magnetometer undergoes calibration within the code and provides vectors for all three axes relative to the magnetic field. These processed data are then transmitted to the Arduino UNO via a single serial point established by the Arduino microcontroller. The system then loops to prepare for processing the next set of data. The flow diagram illustrating this process is in Appendix F.

On the motor controller side, the motor shield begins with serial communication with the Arduino microcontroller. It then proceeds to set the maximum speed and acceleration for the stepper motor based on the code, configuring it to a speed of 5000 steps per second and an acceleration of 200 per second. Next the motor shield proceeds to initialize the desired heading and set the starting position. This starting position is determined by incoming data. Essentially, upon power-up, the system sets its initial position at the point it was at when it started, facilitating subsequent movements both forward and backward from that precise location.

As the system rotates, additional serial data instructs the stepper motor to return to its original position. This process is integrated into a loop that continuously monitors the serial data, reads it, and performs necessary conversions. Next, the Arduino Uno calculates the required movement for the stepper motor and sends the serial data to the motor controller. Moreover, the loop is designed to adjust the movement if it exceeds half rotations for the motor. Finally, the process concludes with the stepper motor executing the appropriate number of steps based on the received data, required movement, and half rotation considerations. The flow diagram illustrating this process is in Appendix F [2].

4.2.2 Inertial Measurement Unit (IMU) Consideration

The camera stabilization system uses an accelerometer and magnetometer that sends the processed data of the magnetic field and the acceleration of the roll (Y-axis), pitch (X- axis), and yaw (Z-axis) to the Arduino UNO. However, there is a sensor that combines a magnetometer and accelerometer + gyroscope in a single sensor [14]. This sensor is called SparkFun 9Dof Inertial Measurement Unit (IMU) as seen in Figure 24 below. It incorporates a 3-axis gyroscope, a 3-axis accelerometer, a 3-axis compass, and a Digital Motion Processor. IMUs can perform sensor fusion algorithms to combine data from multiple sensors, such as accelerometers and gyroscopes, to improve accuracy and reliability in estimating orientation, motion, and position. IMUs can offer improved performance in terms of accuracy and responsiveness [14]. The point of using this device is to facilitate the coding of the Arduino micro by only connecting to one sensor, rather than two. This allows for less wiring on a breadboard and can help avoid any unwiring while the system is in flight.

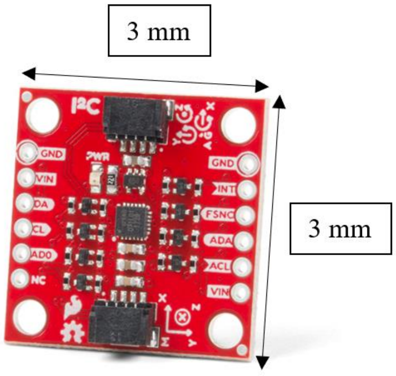


Figure 24. SparkFun 9DoF IMU [15].

The IMU was tested with an Arduino Uno board. The IMU chip was working and giving the data from the roll, pitch, and yaw. Also, it was giving the information from the magnetometer. Since the system is working, it was time to check if it worked with the Arduino micro. As testing was conducted, some limitations were found. including that the integration of multiple sensors can be computationally intensive when processing this data. An Arduino Micro has limited processing power and memory, which limited its ability to execute the algorithms efficiently [15]. An IMU requires high-speed data acquisition and real-time processing. Arduino microcontrollers have constraints regarding achieving real-time performance due to factors such as interrupt handling, multitasking, and clock speed [15]. Some advanced IMUs offer features such as built-in sensor fusion algorithms, onboard calibration, or digital filtering [14]. Arduino microcontrollers could not fully utilize these advanced features due to software constraints.

5. **High-Altitude Balloon Launch**

This section discusses the aspects of a HABS launch, including the concept of operations followed on launch day, the launch site and why it was chosen, the equipment needed to successfully launch a HABS, and the flight logistics. The flight logistics include the amount of helium needed for launch based on the weight of the balloon and the attached payloads and the predicted flight trajectory given for April 8, 2024.

5.1 Concept of Operations

There are seven key procedures for launching a high-altitude ballooning system. First, you must select and travel to an appropriate launch site. This includes having a large open space away from trees and other obstacles. If launching from a private space, you much obtain permission from the owner. Next, the balloon must be filled with helium and the experimental pods and parachute attached in correct order: balloon, parachute, then experimental pods. Once filled, the balloon is released and ascends into the atmosphere. During step 3, the balloon continues to ascend, increasing in size due to the lower atmospheric pressure at higher elevations. The experimental pods continue to collect data during the ascent. In step 4, the balloon is stretched to its maximum capacity and finally bursts. After popping, the parachute is released and the remaining pods slowly descend back to Earth, illustrated in step 5. Throughout the process, the ascent and descent of the system is tracked via GPS, leading to step 6: recovery. Once recovered, the team can collect the remaining pods and return home for analysis: step 7. This process is illustrated in Figure 25 below.

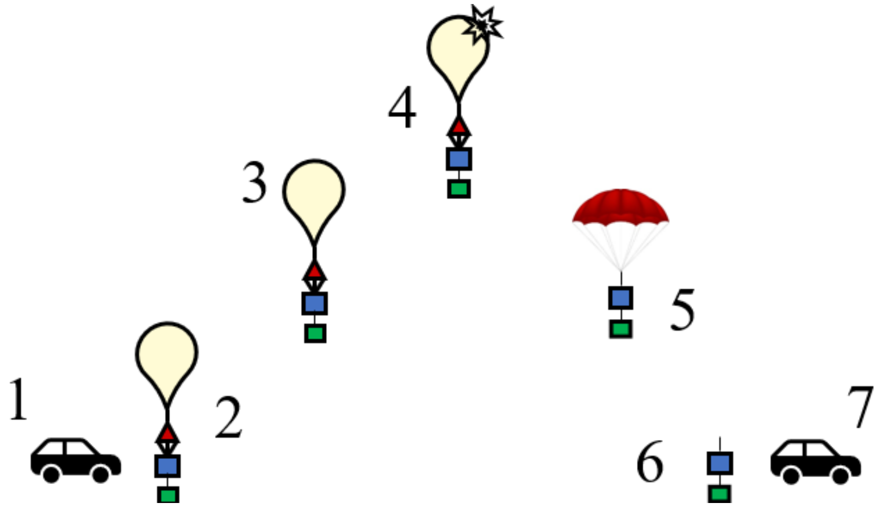


Figure 25. Concept of Operations for Launching a High-Altitude Balloon

5.2 Launch Site

Selecting an appropriate launch site is a crucial step in launching a HABS. The site much be a large open space, free from obstacles such as trees or buildings. The team chose to launch from Linton-Stockton High School for several different reasons. The first reason is that the school has a football field with plenty of space to prepare for and launch the HABS. Second, Linton, IN was in the center of the path of totality. This increased the likelihood that regardless of the wind patterns the balloon would remain in the path of totality to capture video before the balloon bursts and falls to the ground. Lastly, a team from Linton-Stockton also launched a high-altitude balloon on April 8th and due to the USI team's lack of ballooning experience, they decided to launch with a team with more experience in case of any issues that could arise during the flight preparation or launch.

5.3 Equipment Needed for HABS Launch

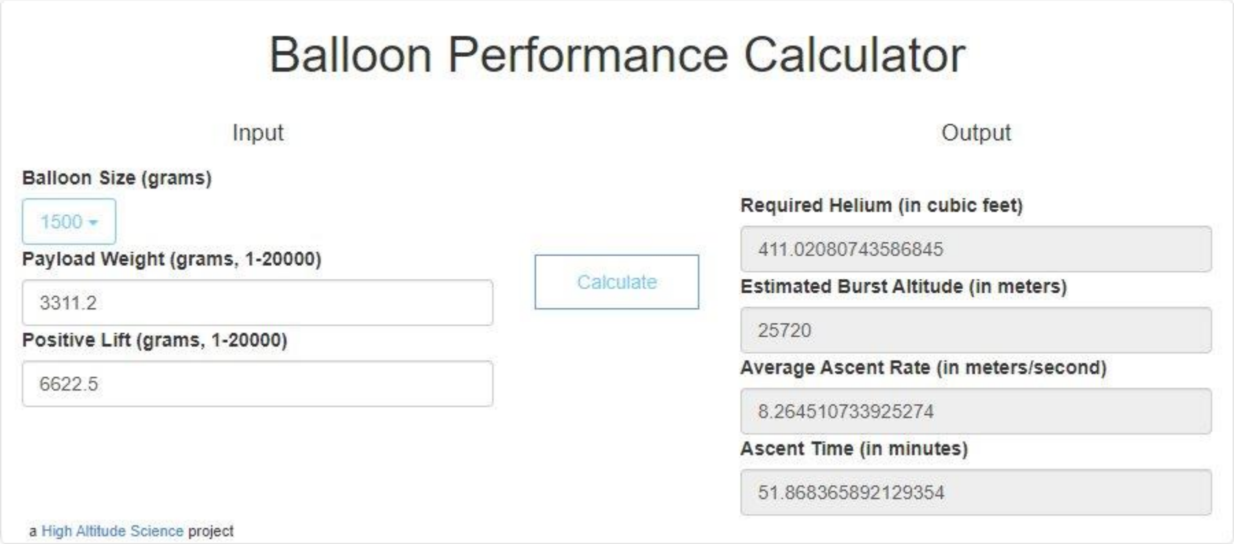
The equipment needed for HABS Launch includes:

Table 1. Equipment Needed for HABS Launch

1500 g HAB	Helium Tank(s)	Camera Stabilization System
360 Degree Camera Pod	Parachute	200 g HAB
GPS Pod	Gloves	Tethers
Luggage Scale	Tarps	Electrical and Duct Tape
Tools (scissors, tape measure, screwdriver)	Helium Regulator and Fill Hose	Zip Ties
Backup Batteries	First Aid Kit	Steel Plates

5.4 Flight Logistics

According to an online balloon performance calculator shown in Figure 26, 411 cubic feet of helium was needed to launch a 1500-gram balloon with attached payloads weighing 7.3 lbs [12]. This calculation factors in the weight of the payload and the positive lift, which is the payload weight times two, that allows the balloon to ascend into the atmosphere. With those inputs the calculator calculated the required helium, the estimated burst altitude, and the average ascent rate and time. The calculated ascent rate was needed to predict the flight trajectory as shown in Figure 27.



Balloon Performance Calculator

Input

Balloon Size (grams): 1500

Payload Weight (grams, 1-20000): 3311.2

Positive Lift (grams, 1-20000): 6622.5

Output

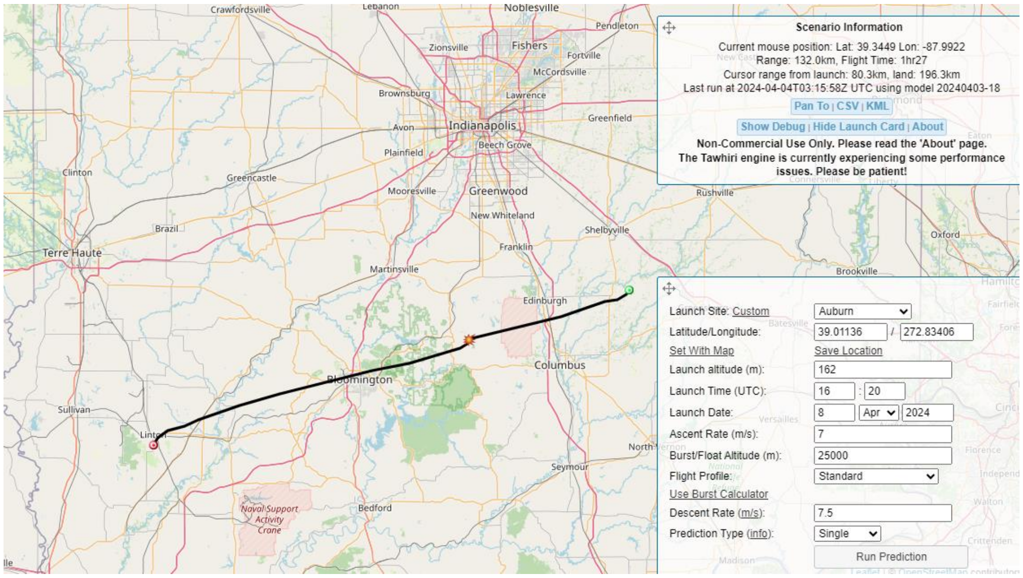
Required Helium (in cubic feet): 411.02080743586845

Estimated Burst Altitude (in meters): 25720

Average Ascent Rate (in meters/second): 8.264510733925274

Ascent Time (in minutes): 51.868365892129354

Figure 26. High-Altitude Balloon Calculation [12]



Scenario Information

Current mouse position: Lat: 39.3449 Lon: -87.9922

Range: 132.0km, Flight Time: 1hr27

Cursor range from launch: 80.3km, land: 196.3km

Last run at 2024-04-04T03:15:58Z UTC using model 20240403-18

Non-Commercial Use Only. Please read the 'About' page.

The Tawhiri engine is currently experiencing some performance issues. Please be patient!

Launch Site: Custom: Auburn

Latitude/Longitude: 39.01136 / 272.83406

Launch altitude (m): 162

Launch Time (UTC): 16 : 20

Launch Date: 8 Apr 2024

Ascent Rate (m/s): 7

Burst/Float Altitude (m): 25000

Flight Profile: Standard

Descent Rate (m/s): 7.5

Prediction Type (info): Single

Figure 27. High-Altitude Balloon Predicted Flight Trajectory for April 8, 2024 [13].

6. **Flight Results**

On April 8, 2024, HAB-28, the 28th balloon that has been launched by a USI team, was launched from Linton-Stockton High School. Balloon and flight prep work was done on Linton's football field. The balloon was filled starting at 1:45 pm EST and was released at 2:20 pm EST, approximately 45 minutes before totality. Based on the altitude sensor in the Iridium Satellite Tracking sensor, the balloon reached an altitude of 93,263 ft (28426 m) before bursting and it landed in a corn field in Liberty, Indiana. The duration of flight was approximately 1 hour and 47 minutes, and the flight trajectory is highlighted in green shown in Figure 28 below.

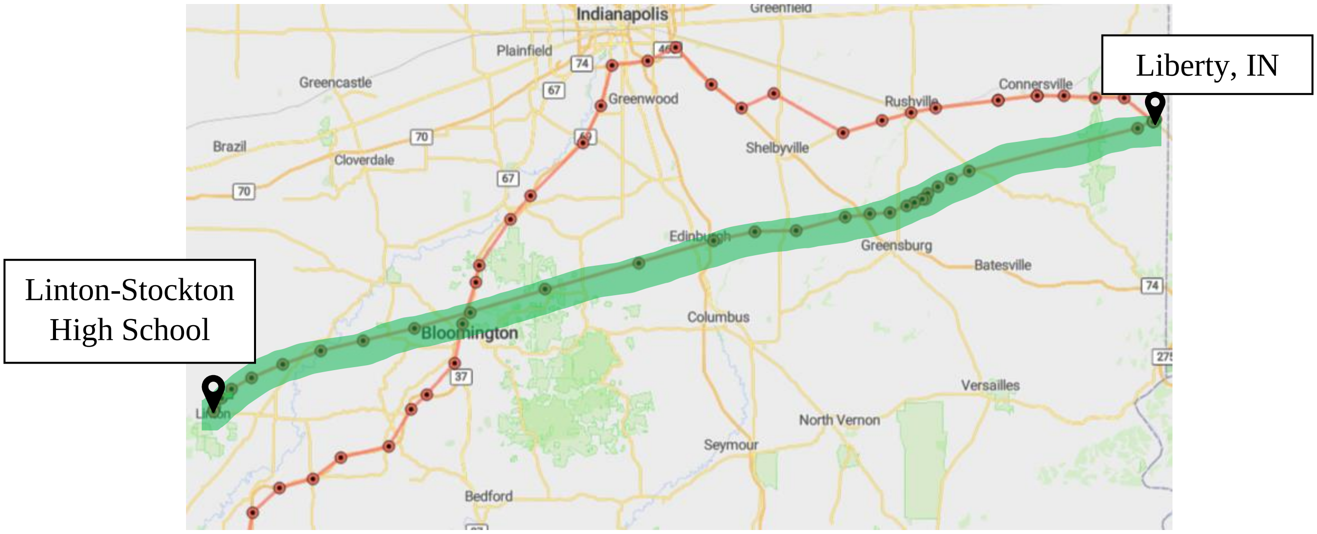


Figure 28. The Flight Trajectory of HAB-28 on April 8, 2024, is highlighted in green.

Upon landing the connecting bar broke free from the CHAD system as shown in Figure 29 A. The broken connecting bar and the broken tack welds on the plate can be seen in Figure 29 C and D. After observing the simulations done to confirm the new design it was noticed that the actual connecting bar was not welded all the way around the bar. It was held in place by two tac welds as circled in red in Figure 29 B. This shows that the simulation was not an accurate representation of the part. The camera holder was still intact.

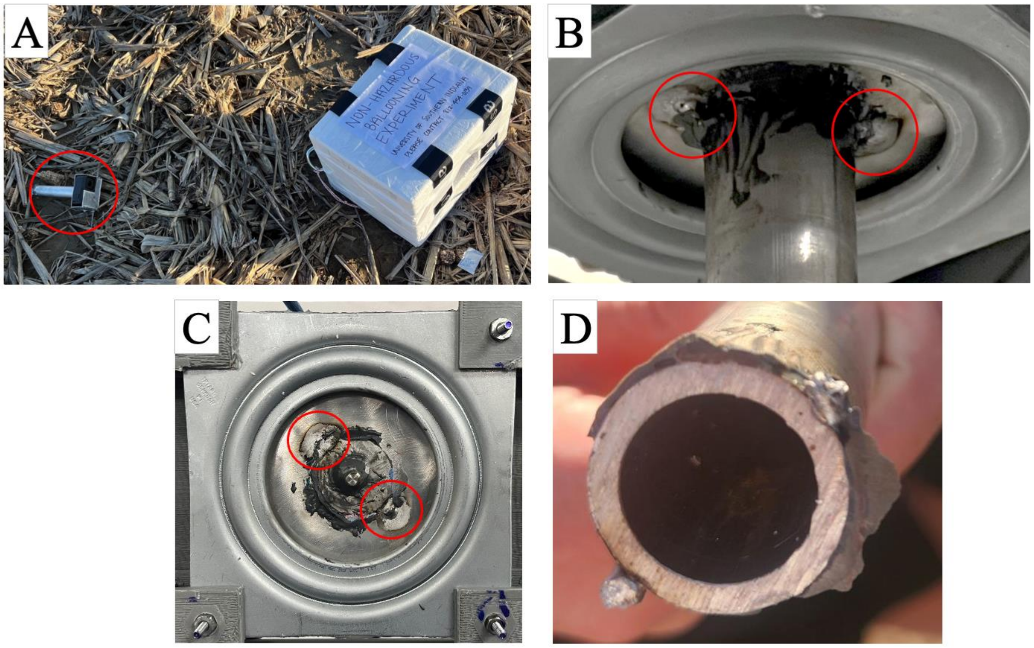


Figure 29. A) Circled in red is the broken connecting bar found at the landing site. B) Shows the original tac weld connection C) Circled in red are the two broken tack welds on the plate. D) Shows the broken off connecting bar with the remaining portion of the tac weld

7. Lessons Learned

One lesson learned is that the use of tack welds and JB Weld was not a sufficient way to adhere the connecting bar to the connecting plate. So, these two did not accurately reflect the simulations explained in Section 4. The two tack welds were not enough to withstand the force that the connecting bar experienced during landing, which caused it to break. An alternative form of connection could be using a keyway shaft. An example of a key and keyway can be seen in Figure 30. The key seat would be in the motor shaft and the key would be inset inside the connecting plate. This would eliminate the need for welding and potentially damaging the system. So, it can facilitate the assembly of the connecting bar and the connecting plate, both of which can be fully welded.

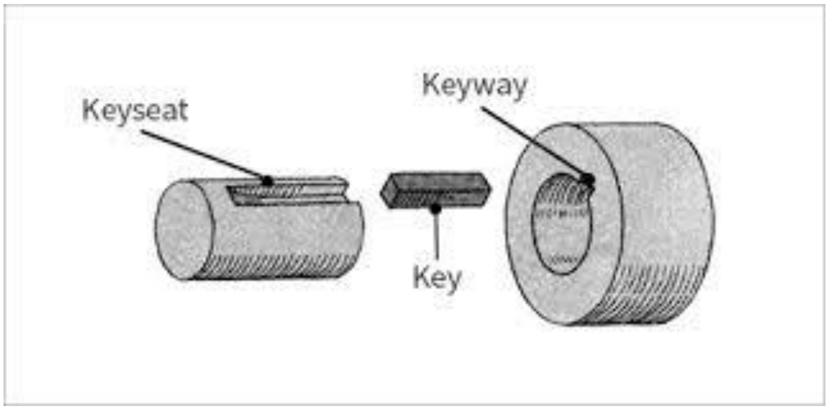


Figure 30. Key and Keyway for Motor Shaft

Another lesson learned is that the assembly process should be developed and documented before building. The 2024 team struggled with the assembly of the system and had to repeatedly take apart and rebuild the system. A future team could develop an assembly process before building to increase efficiency and reduce time wasted.

While the system did respond to counteract the movements of the high-altitude balloon, it was slow. A future team could investigate the processing speed of the Arduinos and the motor response time to enhance the system's effectiveness against the rotations of the HABS. An electronic system with a wider data processing range would allow for a more responsive system and consequently, more stabilized camera footage. As the balloon ascended around the jet stream, it started spinning more rapidly, causing the system to fall behind. This resulted in unstable and blurry footage being captured.

An additional lesson learned is that the digital luggage scale used to measure the amount of upward lift of the weather balloon experienced complications providing accurate readings. The use of an analog luggage scale would provide a quicker and more accurate reading while in the time-critical phase of filling up the weather balloon.

Also, the camera’s battery life expired before totality occurred, preventing the 2024 team from capturing the desired image. Research will be necessary to find a new camera with an extended battery life and higher resolution. Ideally, the camera's battery should last between 2 to 4 hours.

8. **Disposal Plan**

The camera stabilization system and other related equipment is going to be stored in the engineering closet in the BEC so if a future senior design group chooses to pursue a similar project, they can use the system for reference. If the system were to be disposed of, the disposal plan of the components is shown in Table 2 below.

Table 2. Disposal Plan for Project

Component:	If in working condition:	If obsolete:	Recycle As:
Arduino Micro	Re-use within department	Recycle	Electronics
Arduino Uno	Re-use within department	Recycle	Electronics
Motor Controller	Re-use within department	Recycle	Electronics
Magnetometer	Re-use within department	Recycle	Electronics
Accelerometer + gyroscope	Re-use within department	Recycle	Electronics
Connecting Bar	Sell for scrap	Recycle	Metal
Stepper Motor	Re-use within department	Recycle	Electronics
Batteries	Re-use within department	Recycle	Electronics
Aluminum Turntable	Re-use within department	Recycle	Metal
Battery Pack	Re-use within department	Recycle	Electronics
Breadboard	Re-use within department	Recycle	Electronics
GoPro Camera	Re-use within department	Recycle	Electronics
Battery Case	Re-use within department	Recycle	Electronics
Aluminum Camera Case	Re-use within department	Recycle	Metal
Stepper Motor Shield	Re-use within department	Recycle	Electronics

9. Conclusion

From the re-design of the system and the results of the HABS launch, there were several conclusions made by the 2024 High-Altitude Balloon Camera Stabilization Design Team. First, the system did operate as expected, but the motor did not respond quick enough to counteract the motion of the pods due to the high ascent rate of the HABS that causes the pods to thrash erratically. The video captured during ascent supports this conclusion. Secondly, the GoPro camera did capture footage, but the battery life expired after 32 minutes. Battery life was predicted to last about 56 minutes; however, the low temperatures of the upper atmosphere may have drained the battery quicker than expected. Additionally, the combination of the tac weld and JB Weld to attach the connecting bar to the 1/8” connecting plate on top of the turntable was not sufficient to withstand the forces of landing. This is supported by the images shown in Figure 29, which indicate the connecting bar disconnected from the CHAD upon landing. This could be fixed by using more sufficient welding techniques or assembly methods and validating simulations through testing. Lastly, unfamiliarity with the digital luggage scale and the connections between the helium regulator and the weather balloon could have been mitigated with a practice launch. Due to these unfamiliarities, it is possible that the weather balloon was over-filled, causing the HABS to travel further than predicted. The result of which was a 7-hour recovery trip and a very long day. Overall, the Senior Design Project resulted in many successes and failures, and ultimately several lessons learned for a future design team to build from.

References

[1] "Pressurized Balloons." *Pioneers of Flight*, pioneersofflight.si.edu. Accessed 7 Feb. 2024.

[2] Kruger, Andrew, et al. 2017, pp. 1–10, *Active Heading Control Platform for Instruments Flown on High Altitude Balloons*.

[3] Norris, Peggy. "Solar Eclipse Balloon Project." *Sanford Underground Research Facility*, 28 Aug. 2017, sanfordlab.org.

[4] "Science from the Ground." *NASA*, NASA, eclipse2017.nasa.gov/science-ground. Accessed 7 Feb. 2024.

[5] "What to Expect - NASA Science." *NASA*, NASA, science.nasa.gov. Accessed 7 Feb. 2024.

[6] Russell, Randy. "The Stratosphere." *The Stratosphere - Windows to the Universe*, 30 Mar. 2009, www.windows2universe.org.

[7] Zeiler, Michael. "Total Solar Eclipse 2024 Indiana." *Great American Eclipse*, www.greatamericaneclipse.com. Accessed 2 Apr. 2024.

[8] "Our Mission." *NearSpace Education*, www.nearspaceeducation.org. Accessed 2 Apr. 2024.

[9] Wasilenko, Lee. 2011, pp. 2–39, *High Altitude Balloon with Stabilized Camera System*.

[10] https://docs.google.com/presentation/d/12n3zkxiX8Cp8eVVQj74zeSX1mk15h73_/edit#slide=id.p2.

[11] Stark, Jaiden, et al. "A platform for active stabilization of high-altitude balloon payloads." *Bulletin of the American Meteorological Society*, vol. 104, no. 6, 2023, https://doi.org.

[12] "Balloon Performance Calculator." *Balloon Performance Calculator*, tools.highaltitudescience.com/. Accessed 2 Apr. 2024.

[13] *CUSF / SondeHub Predictor*, predict.sondehub.org/. Accessed 2 Apr. 2024.

[14] *Sparkfun*, cdn.sparkfun.com/assets/7/f/e/c/d/DS-000189-ICM-20948-v1.3.pdf. Accessed 2 Apr. 2024.

[15] “Arduino Micro.” *Arduino Online Shop*, store-usa.arduino.cc/products/arduino-micro. Accessed 2 Apr. 2024.

[16] “Unmanned Free Balloons.” FAA, www.faa.gov Accessed 24 Apr. 2024.

[17] Admin. “Cold Temperature Advantages of Aluminum - Minalex Extrusions.” *Minalex*, 27 Nov. 2023, www.minalex.com/2023/10/09/extruding-with-aluminum-the-cold-hard-facts/.

Appendix A- Budget

Table 3. Project Budget

Quantity	Item	Cost
1	1500-gram Balloons	115.00
1	6ft High Altitude Balloon Parachute	60.50
1	Creality 3D Printer Filament	30.00
1	HMC5883L 3-axis Magnetometer	5.99
1	Half Size Breadboard	6.95
1	MPU6050 Accelerometer	6.49
1	Adafruit Motor Shield V2.3	24.00
1	Sparkfun IMU 9 DF	18.50
1	Stepper Motor	10.99
1	Arduino Micro	23.99
1	Arduino Uno	27.60
1	9 V Battery Holder (without switch)	8.99
1	AA Battery Holder	6.99
1	3a250vac 6a125vac switch	8.00
1	6061 Aluminum Rod 1" diameter	20.00
1	5052 Aluminum Sheet (12 x 12 x 1/64")	20.00
1	Electrical Wires	9.99
1	Anti-fog spray	10.00
1	Boxes Fast Small Business Packaging, Shipping Box 9 1/2 x 9 1/2 x 7	66.00
1	Super Lube-21030 Synthetic Multi-Purpose Grease, 3 Oz.	10.67
1	Lazy Susan Bearings, 4", 5/16" Thick, Capacity 300 lbs.	5.49
1	PET Plastic Sheets	20.00
1	Kite String	8.50
1	Iridium tracking device- Eyepod	250.00
	Total	774.64

Appendix B- Timeline

Table 4. Spring 2024 Schedule ME 491

Spring 2024 Schedule ME 491	
Task	Date
Team Weekly Meetings	Wed 12-2 pm and Thr 10:30-12pm
Advisor Meetings	Thr 9:30-10:30
Arrange weekly meetings with Senior Design Faculty Adviser	1/8/2024
Budget Revision	1/10/2024
Revise schedule and start outlining report/work on budget request	1/11/2024
Start 3D printing parts for prototype	1/15/2024
Design Decisions about camera case	1/18/2024
Order Items necessary for project	1/22/2024
Decisions about the rod	1/25/2024
Finalizing camera case design	1/29/2024
Water Jet training	2/1/2024
Water Jet training	2/5/2024
USI Endeavor Grant Proposal Due	2/9/2024
Cut Aluminum pieces using Water Jet	2/15/2024
Checking on items in the basement	2/19/2024
Work on the electronics	2/21/2024
Work on the electronics	2/26/2024
Work on the electronics	2/28/2024
HAB Balloon Training with NearSpace Education	3/16/2024
Build Camera Stabilization System Pod	3/24/2024
Design Presentation Review	3/28/2024
Team Review of Draft Report	4/3/2024
Draft Report Due to Adviser	4/5/2024
Solar Eclipse- HABS Launch	4/8/2024
Senior Design Presentation	4/19/2024
Senior Design Poster Session	4/25/2024
Final Report, Due to Advisor, Shared Drive	4/26/2024
Final Report Submitted to SOAR	5/3/2024

Appendix C- Mass Table

Table 5. Mass Table

Camera Stabilization System Weight Table		
Quantity	Item	Weight (lbs)
1	Magnetometer	0.006
1	1/2 Breadboard	0.082
1	Accelerometer	0.004
1	Stepper Motor	0.615
1	Arduino Micro	0.012
1	Arduino Uno	0.060
1	Motor Controller	0.050
1	GoPro Camera	0.274
1	Aluminum Camera case	0.110
1	Aluminum Threaded rod	0.032
1	Aluminum Connecting Bar (motor → camera)	0.178
1	Main Housing Compartment	0.212
1	Connecting plate (motor → turntable)	0.122
1	Aluminum Turntable	0.338
4	AA battery	0.200
1	AA battery holder	0.032
2	9 V Battery	0.196
2	9 V Battery holder	0.044
1	Styrofoam box	0.616
1	Powerbank	0.742
1	1/2" Plywood (9" x 5.8")	0.500
	TOTAL	4.425

Table 6. Weight of Individual Pods

Pod	Weight (lbs)
Camera Stabilization System	4.425
Iridium Satellite Tacking Pod + 360 Degree Camera	2.500
Parachute	0.375
TOTAL OF ALL PODS	7.3

Appendix D- System Hierarchy

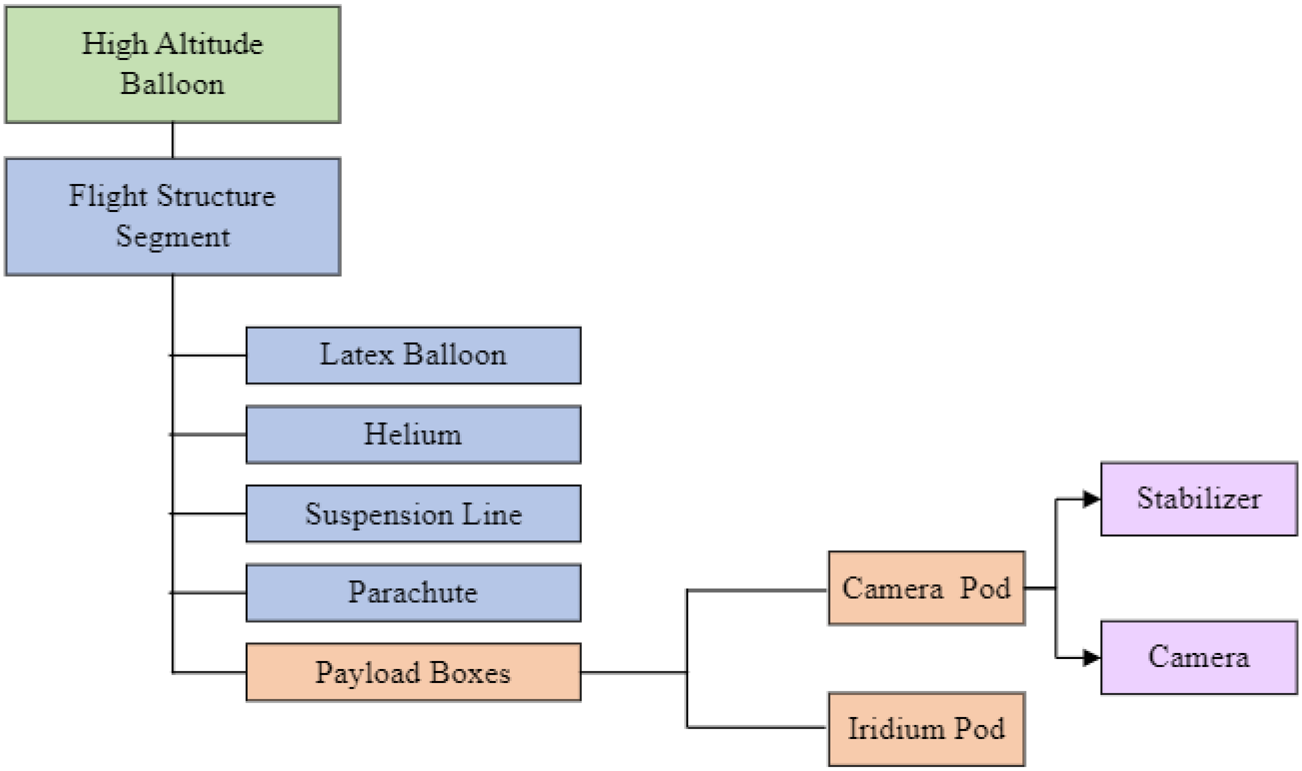


Figure 31. Overall Balloon Hierarchy

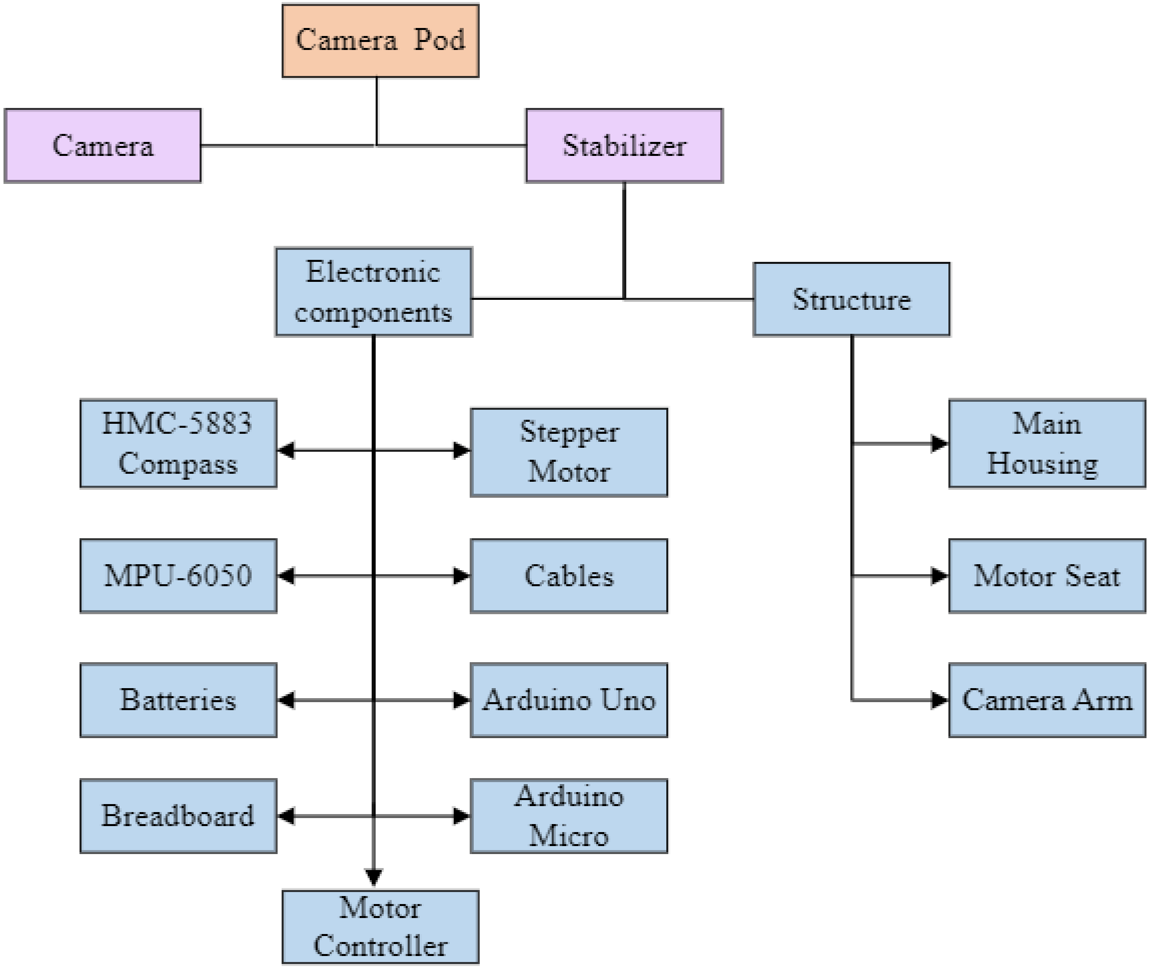


Figure 32. Camera Pod Hierarchy

Appendix E- Flow Diagram of Electronic System

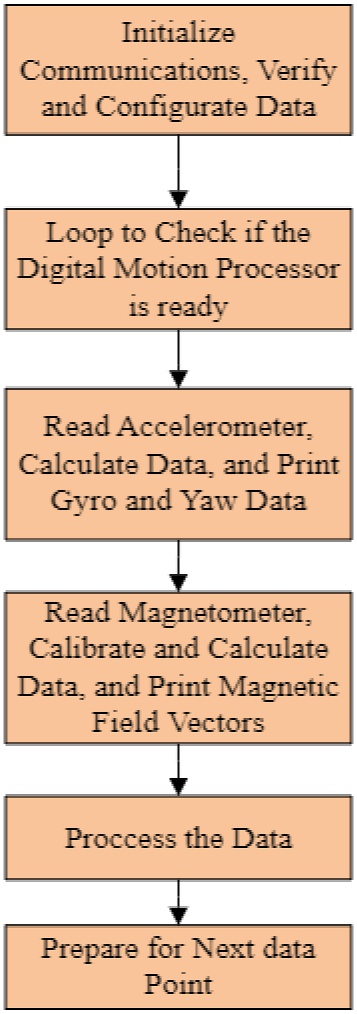


Figure 33 Flow Diagram of Sensors

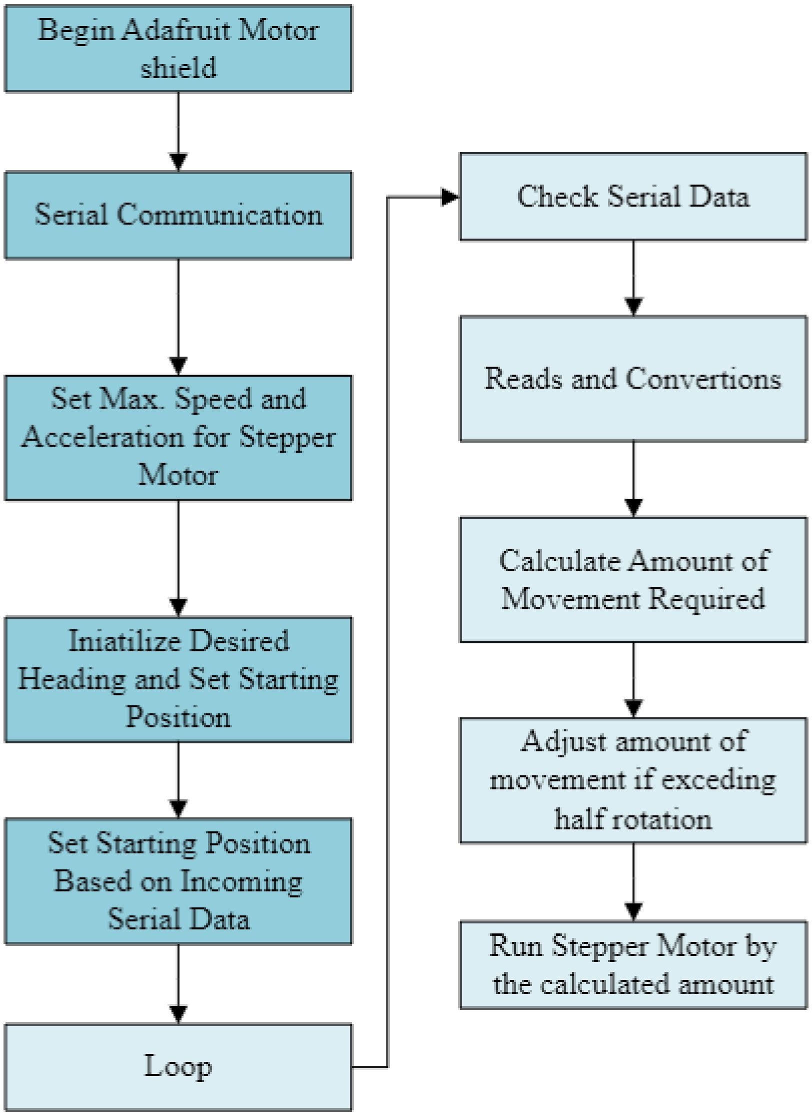


Figure 34. Flow Diagram for Motor Controller

Appendix F- Functional Block Diagram

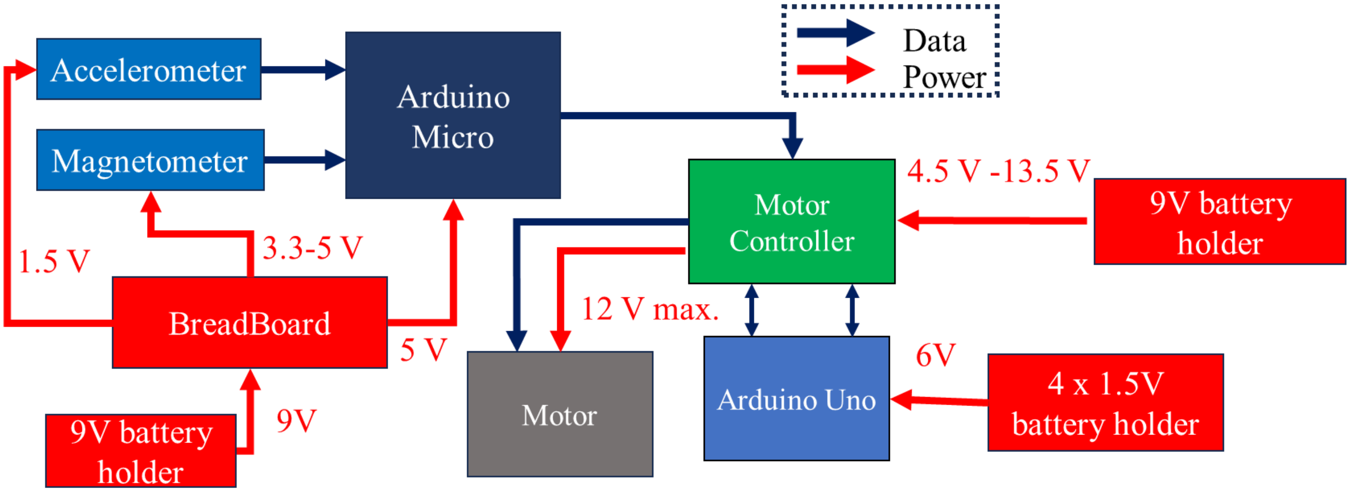


Figure 35. Functional Block Diagram

Appendix G- ABET Outcome 2, Design Factor Considerations

ABET Outcome 2 states "*An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors*."

Table 7. Design factors Considered.

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	Section 2.4, Page 9.
Global	Section 2.4, Page 9.
Cultural	N/A due to the camera stabilization system having no cultural impacts
Social	Section 2.2, Page 5
Environmental	Section 8. Page 30.
Reference for Standards	Section 2.4, Page 9.