Climatic High-Altitude Navigator for Optical Signal Measurement (C.H.A.N.-O.S.M.)

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***Abstract* — Wildfires have become a looming threat all over the globe. Our project aims to be a low-cost modular payload capable of being used for wildfire detection, characterization, and prediction. On board, we have a sensor suite, RF communication system, and optical subsystem. Our optical subsystem consists of a spectrometer with +/- 10 nm resolution and a filtered lux meter for detecting unburnt and fully burnt vegetation. With a tested on-ground communication range of over 1000 feet and accurate data with a detailed GUI, our project can be used to relay data to firefighters and meteorologists.**

***Index Terms* — Spectroscopy, Aerospace Testing,, Remote Sensing, Wildfires**

I. Introduction

The wildfire prediction market size was 10 billion dollars in 2024 and is predicted to reach 22.5 billion in 2032. [1] With wildfires becoming more common, there is a need to be able to characterize and predict wildfire movement. Typically, this is done with expensive satellites equipped with high-end instruments using remote sensing. Our project aims to bridge the gap as a low-cost, high-resolution alternative. The payload we designed comes equipped with a suite of sensors and a high-resolution camera for data collection and wildfire monitoring. We plan to test this payload on a high-altitude balloon; however, as our main project is the payload, the future plan is to create a more modular design allowing more cameras, AI/machine learning categorization, as well as other additional instruments. This payload can then be deployed on a drone, high-altitude balloon, blimp, or other means of air transportation to reach over fires. The data collected can be used for early warning systems or be transmitted to firefighters on the ground for live updates. A high-resolution optical system is on board, measuring the spectra of the fire to predict what material is currently being burned. This system also scans the ground and can see if the earth below is currently unburnt, burning, or already burnt.

II. System Overview

A. Atmospheric Subsystem

The core of our project involves reading atmospheric data at different altitudes. We will employ sensors to get the four basic atmospheric conditions of temperature, air pressure, humidity (RH), and wind speed. The measured data will be stored on a local storage device and then transmitted in time intervals to a ground station for a real-time display of data. Additionally, we will attach a camera to the payload for a top-down view of the landscape. To keep the design cheap and straightforward, the camera will not be sending its video feed. This data will be stored on a separate local storage device for viewing after collection.

The sensors chosen must all contain a large temperature operating range due to the large temperature shift between the surface and high altitude. While insulation can mitigate this to some degree, this constraint will affect every system, from the atmospheric subsystem to the telemetry.

B. Telemetry Subsystem

The telemetry subsystem records the position, altitude, direction, and velocity of the payload while in the air. It includes a GPS, altimeter, and IMU. While it is subjected to the same conditions as the atmospheric sensors, the telemetry subsystem is crucial for retrieval of the balloon. A failed recovery means loss of data since it will all be stored locally on the payload. Additionally, the payload consists of many metal, plastic, and semiconductor parts, which pose an environmental risk in the event of not being able to recover the payload.

C. Payload Design

The electronics and optics subsystems will be housed inside a 3D printed and insulated box called the Balloon Payload System (B.P.S.). This housing must be able to reliably house and protect all of the optical components, antennas, parachute, and other systems while being lifted through the atmosphere by the balloon. From liftoff to landing, the payload is designed to handle a variety of environmental concerns.examples of some high impact constraints include high humidity, low temperatures, and the impact upon descent.

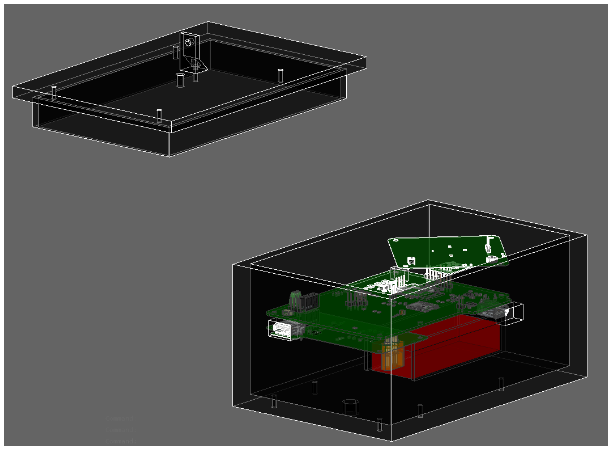

Figure 1: *3D Model of Payload*

D. Radio Frequency (RF) Subsystem

Retrieval of the B.P.S. plays a major role in our design. The RF subsystem requires an antenna and transmitter on the balloon to send information to the base station. The base station utilizes a matching RF module and antenna to receive data packets from the payload to be displayed on the base station's LCD screen.

The communication method is chosen based on the balance of bit rate versus range. Bluetooth, a common method, can send large amounts of data but only operates at short ranges. The payload only sends telemetry and atmospheric data, which is a small data stream, therefore, a long-range method was chosen to maximize our retrieval chances.

E. Optics

The first optical subsystem consists of a spectrometer composed of a slit, three lenses, a diffraction grating, and a CMOS detector. The light enters through a wide angle collecting lens into the 1mm-wide slit, into the collimating lens and onto the reflective diffraction grating. The diffracted wavelengths then pass through a focusing lens and focus on the detector (see Figure 3 for a visualization). Since sunlight is the source of light in this project, the range of potential wavelengths that can be produced is nearly limitless. The compounds we need to detect peak in the visible to NIR range.

To take budget and general feasibility into account, the team decided to utilize a COTS Raspberry Pi camera detector. This component will be able to interface with the lens system designed by the team as well as the electronic components needed to convert the optical signal to a quantifiable spectrum. The camera detector will be connected to a physical Raspberry Pi module to process the data and provide the proper conversion.

The second optical subsystem serves the purpose of detecting green, unburnt vegetation on the ground below from the balloon above. A bandpass filter was installed over a highly sensitive photodiode module that interfaced directly with the Raspberry Pi. A Python script was utilized to plot the last 60 seconds of live data on a graph that measured the lux detected. Since the green bandpass filter was over the diode, only the reflected wavelengths of chlorophyll A and B would pass, indicating green and unburnt vegetation.

In theory, for the spectrometer, the sunlight will reflect off the ground and into the lens system to be diffracted into multiple wavelengths. If a specific wavelength is missing, it was absorbed by something on the ground or in the outside air. The sun spectrum produced from this setup will have drops in transmissivity, indicating the presence of compounds and chemicals such as sodium or potassium, and potentially a post-burn carbon absorption graph that peaks in the ultraviolet region and decreases exponentially into the infrared region.

Since the detector portion will not be limited to only a handful of wavelengths, we expect to detect multiple chemicals and compounds simultaneously. The CMOS, however, is limited by the range of wavelengths it can absorb, roughly between 400 nm and 800 nm. Any wavelengths beyond the NIR or NUV regions will be more difficult to collect due to their required detectors' exponential increase in price margin.

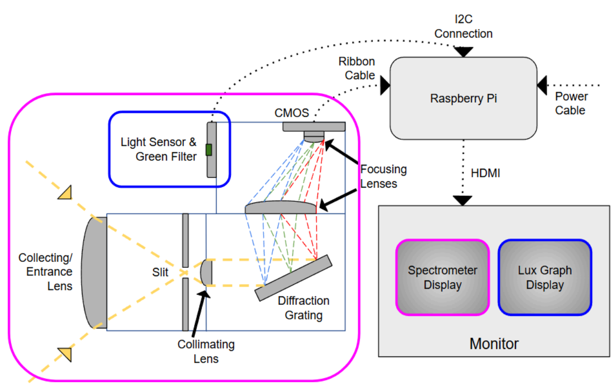

Figure 3: *Optics Hardware Diagram. Source: Authors*

To limit system contamination and reduce background signal (light) noise, the spectrometer will be fully enclosed and darkened. To detect compounds in vegetation, the sunlight will shine down and reflect off the compounds on the ground and into the lens system to be diffracted into multiple wavelengths. Once interfaced onto the detector, the pixel values will be used to see the presence of various colors, or lack thereof. This setup will provide insight into the change in chemical composition in varying regions at the different altitudes of the balloon's position, particularly if a densely forested region is live and vibrant (using the lux meter), if it is burning, or if it has already burned (both using the spectrometer). The goal and objective for this project is to provide general data and insight to aid local authorities of wildfires. The spectrometer and detector setup will merely detect the presence of compounds, not the exact concentration, density, or numerical count.

The general layout of the spectrometer is an unfolded Czerny Turner. The detector in this system will be a Raspberry Pi camera connected to a Raspberry Pi module, so the resolution will be admittedly low due to time, budget, and physical space constraints on the payload, but the mere presence of the compounds – or lack thereof – should be resolvable. The two subsystems in their entirety can be found in Figure 3.

F. Power

A power system determines successful retrieval of the B.P.S. It must remain active for as long as telemetry is needed. An operational time of three hours is sufficient for a launch, landing, and retrieval. The power system takes unregulated DC battery voltage and delivers stable power to its peripherals. The battery will hold a roughly 7V signal to be stepped down via voltage regulators and sent to a series of power buses. There will be a 5V and 3.3V bus.

III. System Components

A. Microcontroller (MCU)

The microcontroller serves as the backbone of the B.P.S. Therefore, this component must be chosen with great attention to several key parameters that ensure a successful mission. These parameters are: processing capabilities, power consumption, flash memory and RAM capacity, peripheral connections variety, programmability, and solderability. The ESP32 was chosen for four major reasons: onboard flash, programmability, solderability, and low power consumption.

Although the i.MX RT1062 and the STM32F446 beat the ESP32 in several other categories; the solderability and programmability of the ESP32 weigh much heavier on the final decision than performance and peripheral numbers. The ESP32 also boasts the largest on-board flash size, almost eight times larger than the STM32F446. Additionally it has the second-highest Coremark score, the second largest on-board RAM bank, and the second lowest price,

In summary, the ESP32 is the best choice for our brand new design, as it not only supplies sufficient computing power to handle all our sensors but it is also straightforward to program, is easy to solder, and has a large pool of peer-to-peer support. The specific ESP32 model chosen was the ESP32-WROOM-32D. This is one of the most powerful ESP32 models, it sports dual cores, 520 kB of RAM, a maximum clock speed of 240 MHz, and all the peripherals. This model also offers up to 16 MB of RAM, we opted for 4 MB as this was more than enough for our application.

B. Temperature Sensor

The temperature sensor needs to focus on having the most stable operating range. It needs to be able to read as hot as 65℃ when near wildfires and go as low as -40℃ for high altitudes. While this is the expected range, choosing a balloon for very high altitudes can bring payload up to 100,000ft, with temperatures as low as 100℃. Temperature is also affected by other factors such as humidity and wind speed, so a sensor that is resistant to these changes is also considered. Initially, an RTD-based sensor was chosen. However, a similar performance was be achieved by using a semiconductor based sensor called the HTU21: a 2-in-1 package component that will also measure humidity.

C. Humidity Sensor

The humidity sensor also has two major challenges. During the flight of the payload, the sensor needs to focus on a low limit of detection since air gets thinner at high altitudes. A high responsivity is needed as clouds are concentrated areas of high humidity; the payload must be able to read this saturation and recover from this quickly. If not, the sensor will give false readings of humidity and bias the sensor higher than the true value. As mentioned in section A, the HTU21D was ultimately chosen. The HTU 31 was an overall better option, but the company charged for the SPICE model, so the HTU21D was ultimately used.

D. Air Pressure Sensor

As altitude increases, air pressure decreases. Even on the ground, the air pressure does not exceed any abnormal limits that any modern-day air pressure sensor can handle. The main focus is on picking a barometer that is as sensitive and has as low a limit of detection as possible. While this is our biggest focus, it is not crucial as even low end sensors would not affect the system to a large degree. The two main technologies are mechanical aneroid barometers and electrical capacitive ones. The final decision was to go with the electrical MS580301BA03-00 as it is much more resistant to drifting due to temperature, which will impact the system to a large degree at high altitudes.

E. Anemometer

For the anemometer, five different technologies were compared: cup, vane, sonic, LiDAR, and hotwire. The two major non-cost factors are size and upper limit resolution/accuracy. Vane and Cup anemometers are very similar, but cup anemometers are sold in more ECE-friendly packages, such as a reed switch, while vanes are often standalone products. LiDAR and sonic are both significantly superior technologies when it comes to performance, with LiDAR being the best choice. While the sonic anemometer is slightly more accurate, the LiDAR is the least temperature-sensitive component and will stay accurate at high speeds the best. Ultimately, the cup anemometer was chosen. The Cup anemometer can go as low as $20 or as high as $400 for a high-end version. LiDAR begins at 300 on the cheap end. Many things can cause the payload to be either lost or destroyed. Using a cheap cup anemometer, which still gives a competitive performance to the other options, will make the payload more affordable. The visual of the moving cups is also likely to be a more attractive visual for a consumer, than using a LiDAR module.

F. GNSS Module

For the GNSS module, we compared four different products, all from the same manufacturer (Ublox). This was because there is very little variety when it comes to GNSS modules. We compared the MAX-M10S, NEO-F10N, ZED-F9P, and SAM-M8Q. The SAM-M8Q was chosen for its highest velocity accuracy, I2C support, and antenna-on-chip design.

G. Inertial Measurement Unit

We initially compared MEMS and FOG technologies. The MEMS topology was used due to its smaller weight. We compared three different models: The TDK Invensense ICM20948, the CEVA BNO086, and the ST ISM330DHCX. We chose the ISM330DHCX as it had the lowest gyro drift over temperature, the lowest accelerometer drift over temperature, and the highest accelerometer update rate.

H. Altimeter

We compared barometric, GPS, radar, and laser altimeter technologies. We ultimately decided on using a barometric altimeter, as it is easily implemented into our project. It is also accurate up to a high range as it doesn't interfere with any government regulations, nor is it affected by cloud coverage. We will be carrying a GPS system for tracking purposes, which can implement altitude calculations. This will be our main source of altitude measurements; however, if GPS is unavailable or unable to operate past a certain altitude, this barometric altimeter will be implemented for redundancy. The reason 2 barometers are used as opposed to 1 is for the simplicity of the calibrations. Companies calibrate either for air pressure or altitude.

I. Radio Module

The Radio Module is an essential part of being able to communicate, control, transmit, and receive data. Our radio module on the payload will be "transmit only." Meanwhile, our radio module on the ground will be "receive only." This is because the payload will serve as the active system, collecting and storing data. This data, telemetry, and information will then be transmitted and received by the ground station which will be utilizing the same radio module as the payload.

LoRa - LoRa is an open user transmission module. LoRa is known for its long range and highly accurate bidirectional capabilities. [2] Users can pick up LoRa signals and upload them to an open database for the public to see. LoRa is popular in Europe but does not have a lot of users in the United States. Operating at 433 MHz or 915 MHz, LoRa transmitters are very accessible for purchase. This will make procurement and implementation on the easier side.

There are a plethora of inexpensive LoRa modules with widespread community support.. We chose to incorporate the SX1276 as our radio module; this chip uses the LoRa network at 915 MHz. We chose this specific chip and settings based on the availability of hardware, performance output, as well as ease of implementation.

IV. System Protocols & Standards

A. PCB Design Standards

Given that this project is taking place within the borders of the United States of America, it must adhere to American National Standards Institute (ANSI) standards. For PCB design, ANSI has adopted the standard set forth by the Institute of Printed Circuits (IPC), specifically IPC-2221. This standard is designed to be a generic, wide-coverage guideline for PCB design. The objective of the IPC-2221 standard (and IPC as a whole) is to universalize reliable, manufacturable, and safe printed circuit boards across all manufacturers [3].

Although it is a given that the team's design will be governed by the IPC-2221 standard, there are additional IPC standards that may apply as well. For example, IPC-4101 will apply, as it defines what materials should be used for the physical construction of the PCB board, such as laminate. IPC-2152 will also apply, as it governs the thickness of copper traces based on the amount of current it will carry. IPC-4761 will apply as it covers proper via protection methods. Our circuit boards will be relatively dense with components, so vias will be a necessity. IPC-A-600 will apply as it presents the standards by which a PCB should be accepted or rejected. In addition, it defines the three classes of circuit board assemblies, our PCBs will fall within one of these classes.

IPC-A-600 defines three different classes for PCB products: Class 1 is for more generic products that have a short lifespan and limited use cases. Class 2 is for products that typically are part of a larger system and have to perform in an on-demand environment, such as a graphics card in a PC, an embedded system on a smart TV, or an infotainment system in an automobile. Class 2 products must be able to perform for an extended period of time compared to Class 1 products. Class 3 products are held to very strict PCB manufacturing tolerances and must reach heightened reliability targets. Class 3 specifies a plating thickness for the PCB top and bottom layers and through-hole vias, it also specifies the overall cleanliness of the assembly and teardrop profiles for trace to via connections [4].

The goal for this project is to meet Class 2 criteria. Given that we don't have the facilities to tightly control PCB cleanliness during assembly, we also do not have control over PCB plating thickness, which falls under our fabrication provider, JLCPCB. JLCPCB has its own set of standards, which we are bound to as their customer.

Ultimately, these constraints will govern our PCB design [5]. While we will strive to meet IPC Class 2 standards, those standards are not openly available and must be purchased for a significant price from IPC. In addition to this, we cannot control every aspect of our board's production. Given that this is an experimental project, using JLCPCB to affordably produce our PCBs is the best option for us. If this project becomes a viable product, it is understood that we will invest in IPC documentation and locate a fabrication house that can meet their standards.

B. Lens Manufacturing Standards

The optics portion of the project must follow the national standards established by the international standards put forth by the International Organization for Standardization (ISO) and military specifications that trickled down into what optics requirements look like today. Within both versions of constraints, the primary focus is on the initial design of the lenses and other optical elements rather than the assembly of the system itself. Since the lenses, diffraction grating, and detector for this project will be commercial off-the-shelf (COTS) products then these standards must be implemented by the manufacturers themselves.

C. Diffraction Grating Manufacturing Standards

Diffraction grating manufacturing standards are largely around the ISO specifications compared to the fabricating of lenses which often referenced a variety of different sources for standards. ISO manufacturing standards for diffraction gratings primarily focus on quality management and ensuring that products meet stringent requirements. ISO 9001:2015 is the most relevant standard, which provides a framework for quality management systems. This standard emphasizes customer satisfaction, continuous improvement, and the application of a systematic approach to manage processes.

D. Radio Communication Standards

Our payload will be equipped with the ability to transmit live data over the air using our RF subsystem. We will be using LoRa as the communication protocol. LoRa stands for "Long Range" and it is designed to be used by amateur radio enthusiasts. LoRa is known for its ability to have operators; these operators deploy antennas operating on the specific LoRa frequency, in our case, 915 MHz. In Europe, the dedicated LoRa frequency is 868 MHz. In Asia, the frequency is either 433 MHz or 920 - 923 MHz, depending on the country. LoRa is separated into three classes of devices: Class A are devices that are always transmitting and receiving, Class B are devices that transmit and receive in windows of time, and Class C are receive-only devices.

The FCC regulations we are looking at are for LoRa devices based in the operating frequency bands of 902 - 928 MHz. For devices in this band the requirements of transmitters can be found in section 15.247 [2].

V. Software Design

A. Overview

The high-altitude balloon requires a series of software designs to achieve proper and reliable functionality among the different sections that make up the entirety of this project. For proper and reliable functionality, the High-Altitude Balloon project will be separated into two different sections. One section will be dedicated to the payload, which is going to be in the sky, and the other section will be dedicated to the base station, which is going to be on the ground. In addition to that, each section can be separated into subsystems to ensure proper and reliable software design, making sure each component is being used as intended.

The first section can be defined as the payload, where the MCU and all of the atmospheric and telemetry peripherals will be located to collect data along the trajectory of the flight to later communicate with the MCU, which processes the data from each atmospheric and telemetry peripheral and later store them into the SD card. In addition to reading and storing the data, the software should also be designed so it can identify whether the data is telemetry or not, being that telemetry data needs to be transmitted to the base station to be able locate the payload in real time to track its path and successfully recover the payload once it lands back. It is important to mention that although a camera is also being used to record the trajectory of the flight, a software design to implement this component is not required, being that the camera is set to record manually before launching the High-Altitude Balloon, in addition of having an independent SD card dedicated to store all footage recorded along the flight.

The second section can be defined as the base station, where the computer and communication peripherals will be located to receive data from the payload during its flight and process the data stored in the SD card once the payload is recovered. The base station software design can be split into two different subsections, one for the communication and one for the GUI implementation. For communication, the base station software is designed so it guarantees reliable real-time communication with the payload to receive essential telemetry data such as location or altitude that will ease the process of tracking the balloon during its flight and once it lands back.

Finally, for the GUI implementation, the base station software is designed to provide a fully customized user interface where all the data acquired during the flight, stored in the SD card, can be visualized and analyzed in multiple ways and settings, providing plots, maps, tables, and any additional analysis relevant to this topic. It is important to mention that although a communication software design is mentioned, in reality, open-source software will be used and integrated into the GUI.

B. Payload Software Design

The first section that compose this software design section, as mentioned above, is going to be the payload software, and along the most important tasks there is MCU and peripheral communication, proper data formatting and separation, convenient for data processing on the base station once the payload lands back, and periodic real-time communication with the base station for tracking purposes. A more detailed explanation will be provided to describe the design of the payload software.

C. Base Station Software Design

The second section that composes this software design section, as mentioned previously, is going to be the base station software, and along the most important tasks that need to be performed, there is constant and live communication with the payload, and post-recovery data processing, which will be integrated with a graphical user interface. Figure 1 shows the overall software design structure for both subsections of this base station section, showing in detail how the base station receiver is going to communicate with the payload and how the GUI is going to be used by users to display and analyze all data collected. A more detailed explanation will be provided to describe the design for each of the base station software subsections.

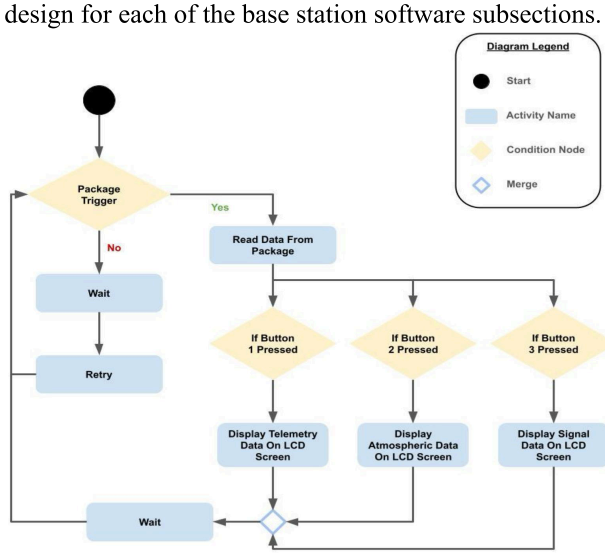

Figure 1

D. GUI and Data Processing Software Design

The last software design section for this project is the Graphical User Interface (GUI), which will be responsible for displaying all the collected data to the users. To achieve a professional and custom design for the GUI, multiple libraries to allow customization were added such as tkinter and customtkinter, which in addition of providing all the customization tools needed, it also has different online resources and examples that can be used to have a more clear idea of how to work with said libraries. As it can be seen in Figure 1, the logic that this GUI follows is very simple, as it starts in a windowed screen with two buttons to either plot data or exit the program. If the plot data button is pressed, then the program runs a separate full-windowed screen where all data can be plotted as long as the data is available in the selected CSV file. To select CSV files, the user only needs to press the green "Select CSV File" button, which is linked to a function that triggers a file dialog which asks the user specifically to browse and select a CSV file, practically the CSV file will be selected from the payload SD card to ensure the program reads the data properly. Once a CSV file is selected, users can start pressing different buttons to display and see the different data collected using data plotting and analysis libraries such as matplotlib and pandas. Finally, once the user wants to exit the GUI, the red "Exit" button can be pressed, which will trigger a built-in function from customtkinter that will make the app stop running and close it.

VI. Hardware Design

A. MCU Board

The MCU board houses the ESP32, Ebyte E19 LoRA module, altimeter, IMU, pressure sensor, SD card slot, and temperature/humidity sensor. The MCU board is the most critical component of the Balloon Payload System. The board itself consists of 4 layers. Layers 1 and 4 are signal layers containing ground pours, layer 2 is the power layer, and layer 3 is the ground layer. This board also provides additional components for the JTAG and I2C pull up resistors, as well 0 Ohm resistors and LEDS allowing isolation of each subsystem to allow for troubleshooting.

B. Power Board

The power board houses the 5V and 3.3V buck converters and the battery charge monitor. The power board supplies power to the MCU and GNSS. Each rail supplies approximately 1.5A. The monitor tracks the LiPo batteries and voltage and sends this via I2C to the user. To protect from overvoltage and overcurrent, each rail has PTC resettable fuses along with zener diodes to clamp down the output in the case of any shorts

C. GNSS Board

The GNSS board houses the Ublox SAM-M8Q GNSS module/antenna. The GNSS board was designed to provide the SAM-M8Q with an ample ground plane for its onboard patch antenna to function properly. The GNSS board communicates with the MCU board over I2C with a JST SH connection.

D. IMU Board

The IMU board houses the ISM330DHCXTR IMU. The 2 layer board consists of a single layer and a ground pour layer with stitching vias to ensure a low impedance, low noise connection. The IMU board communicates with the MCU board through I2C, with a standard 4-pin header connecting to the board.

VII. Testing

Two different types of testing were conducted, components and systems. The component testing involved a manual verification of each sensor with a reference. For temperature and humidity, the UCF Research 1 building contained multiple sensors and was used as the standard. For wind speed, a separate anemometer borrowed from the mechanical engineering department was used for verification. Air Pressure was verified using multiple weather programs. Telemetry accuracy was tested by using Google Images and moving around the UCF campus.

The system's testing was repeated 3 times. The first time was in the form of breakout components, while the second and third time was performed using the four PCB boards inside the payload.

All sensors were verified in the field using either google maps after data was processed, or using the current weather conditions from weather programs. While the first testing initially produced out of specification results, the issues were addressed and fixed by the end of the first round of testing. The second and third round of testing was successful with no issues.

VIII. Conclusion

The C.H.A.N. - O.S.M. system was developed out of the interest in expanding the aeronautics field that is extremely prevalent in Central Florida. Beginning with an interest stemming from previous experience with clubs such as Knights Experimental Rocketry (KXR) and Knights Satellite Club (KSC), a search for a unique application for a weather balloon began. The purpose of the payload is to collect information in the atmosphere around possible wildfire locations. There are detection systems utilized in satellites for wildfire tracking and characterization, but they come with drawbacks. Firstly, it requires satellite access, which is not always available in other countries. Secondly, these satellites are only over the target area of interest during a certain window of their orbit. Lastly, cloud cover can obscure the land from view. This payload system can address these challenges at a significantly cheaper cost than a satellite.

This report details the goal, planning, research, implementation, and testing of the C.H.A.N.-O.S.M. Each student listed on the cover page has dedicated much of their expertise and has made every effort to expand their skill set to meet the unique challenges and requirements of this system. The opportunity to take on this project has led to sponsorship and networking with the Athletics Department on ways to use a balloon for advertising the UCF Space Game next November. These experiences will undoubtedly lead to the advancement of our capabilities as engineers moving into Senior Design 2 and, eventually, our careers and graduate studies.

Acknowledgements

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References

[1] Wildfire Protection System Market Size, Share & Outlook to 2032 (n.d.). Retrieved from https://www.businessresearchinsights.com/market-reports/wildfire-protection-system-market-118395#:~:text=WILDFIRE%20PROTECTION%20SYSTEM%20MARKET%20OVERVIEW,12.6%25%20during%20the%20forecast%20period

[2] Lora Alliance, "What Is LoRaWAN® Specification," *LoRa Alliance®*, 2023. https://lora-alliance.org/about-lorawan/

[3] Z. Peterson, "IPC Classes and Complying with IPC Standards for PCB Design," *Altium*, Jul. 01, 2024. https://resources.altium.com/p/complying-with-ipc-standards-for-pcb-design

[4] "Working with PCB Design Standards," Mar. 19, 2021. https://resources.pcb.cadence.com/blog/2021-working-with-pcb-design-standards

[5] "PCB Manufacturing & Assembly Capabilities - JLCPCB." https://jlcpcb.com/capabilities/pcb-capabilities