# Integration of a Flight Management System and an Unmanned Aerial Vehicle

## Resulting in Improved Safety and Efficiency During Autonomous Flight


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# Abstract

Within aviation, safety is always priority number one. It is the first requirement when any part, assembly, or aircraft is designed. The emerging unmanned aerial vehicle (UAV) industry leaves itself vulnerable to the effects weather conditions can have on flight. While most UAVs are but a fraction of the size of a 737, they are just as prone to turbulence and weather conditions. This vulnerability poses a substantial problem to guaranteeing safe UAV flight. This project proposes a solution to strategically mount sensors on-board a UAV to avoid bias in measurement of wind speed, ambient temperature, pressure, humidity, and the presence of lightning. The data collected from sensors is then gathered onto an on-board Raspberry Pi where a Python script confirms that safe operating conditions have not been violated. If safe operating conditions have been exceeded, a command will be sent to the UAV's flight controller, the Pixhawk 4, changing the flight plan. The suite of sensors and Raspberry Pi make up the key components of the flight management system (FMS) that will increase safety of autonomous UAV flight and provide a way to boost efficiency and performance of UAV flight.

# State of the Industry

While we are not reaching cruising altitude during a trip to the grocery store yet, the aviation and consumer goods industries are progressing to incorporate drones and unmanned aerial vehicles (UAVs) into our daily lives. Since 2010, NASA has been using high-altitude drones to obtain more accurate data of hurricanes and other storms.[2] Amazon created their subsidiary Amazon Prime Air in 2016 to expedite package delivery to under 30 minutes by way of quadcopter drones – and have been refining their system ever since. The nimble and uniquely versatile machines have been coming to the rescue in some less-than-obvious places too.

Ocean Alliance, a not-for-profit organization advocating for conservation and awareness of oceans and whales, turned heads by using DJI drones to collect samples of whales 'blow'.[6] Not being coy, the organization labeled their modified drones SnotBots. Previously teams from Ocean Alliance would carry out costly, dangerous boating expeditions to collect specimen putting themselves and the whales at risk. With the advent of the SnotBot, they are able to reduce risk for themselves and the whales, decrease the cost of their efforts, and collect data faster than ever before.

*A drone collecting 'blow' from a whale*

The list of issues that drone implementation remedies doesn't stop any time soon. Drones and UAVs have played a hand in triggering controlled avalanches, preventing shark attacks, dispensing fertilizer and pesticides, and replacing fireworks at Disney Land as well as the Sydney Opera House.

This swiss army knife of technology and equipment still faces many barriers to becoming as ubiquitous as the gas station on the corner. The biggest and most challenging two are creating reliable, effectual safety standards and regulations. Over the past years, governing authorities have to create solutions to these short comings. In response, private companies, universities, and research groups have taken aim at being the first to produce an option capable of being adopted universally.

## Motivation

Thanks to modern manufacturing processes and advances in computing, drones and UAVs have been proven to be trustworthy in their construction and design. Under manufacturers' standard operating conditions, commercial and hobbyist drones fly without incident every day. Most of these flights take place without the drone ever leaving sight of the pilot who can ensure clear skies and safe conditions. However, as the scope of drone functions expands, so too does the necessity for dependable, autonomous flight.

The largest irritant to safe, autonomous drone flight is inclement weather.

There are hundreds of established weather data collection systems scattered throughout the world. Though, the data captured by these systems is not updated with enough frequency nor with enough localized coverage to be beneficial in improving drone flight safety. As is the case with Amazon Prime Air, a company not afraid to push limits, the maximum flight time is 60 minutes; and in Colorado, that's enough time to experience all four seasons.

Having autonomous drone flight means that the drone must be able to respond to every situation without crashing to the ground. It is paramount that weather conditions immediately surrounding a drone are detected accurately and in a timely manner without pilot input once in flight.

## Problem Statement

A system would be designed to mitigate the risk of drone crashes by ensuring that the duration of each flight is within safe operating weather conditions and change the preplanned flight of the drone appropriately in response to safe operating weather conditions being exceeded.

This system would be retrofitted to drones allowing all forms of weather data to be collected via on-board sensors. These forms would include temperature, pressure, humidity, and wind speed. While each variable may not impact the flight of the drone in a critical manner, each variable has the potential to show weather patterns emerging in real time and enhance or degrade the performance of each drone flight.

A mixture of sensor data and drone pilot experience would be used to set threshold limits for safe flight operations. Carrying out drone flights under threshold values would effectively eliminate the risk of drone crashes due to weather related circumstances, increasing the safety and practicality of regular drone flight. However, accurately sensing the weather conditions a drone is experiencing is not enough.

If during flight the sensors record values above set threshold limits, the system should disrupt the pre-planned, autonomous flight plan and redirect the drone's flight appropriately. The decision and command to reroute the flight of the drone would come solely from the system on-board the drone, with the discretion of the pilot on the ground to obtain manual flight control at any point.

To minimize the impact on flight performance, this system would need to be designed such that weight and space required on the drone frame are balanced with redundancy and ruggedness. This system should be adaptable to any drone frame with only small changes to the original design.

# Solution

## Basic Drone Configuration

To begin, a hobbyist drone was to be built which could fly in inclement weather conditions comfortably and provide sufficient room to mount components and the flight management system (FMS). The Tarot 650 Sport Quadcopter fit the bill for its power and numerous mounting options. Equipped with Tarot 4114 high power brushless motors and Tarot 1555 high efficiency folding propellers, this combination of motors and propellers can create a total of 5.0kg of thrust at 50% throttle. The frame is held together by two large, flat plates perfect for mounting components and having easy access to components.

*Tarot 650 Sport Drone Frame*

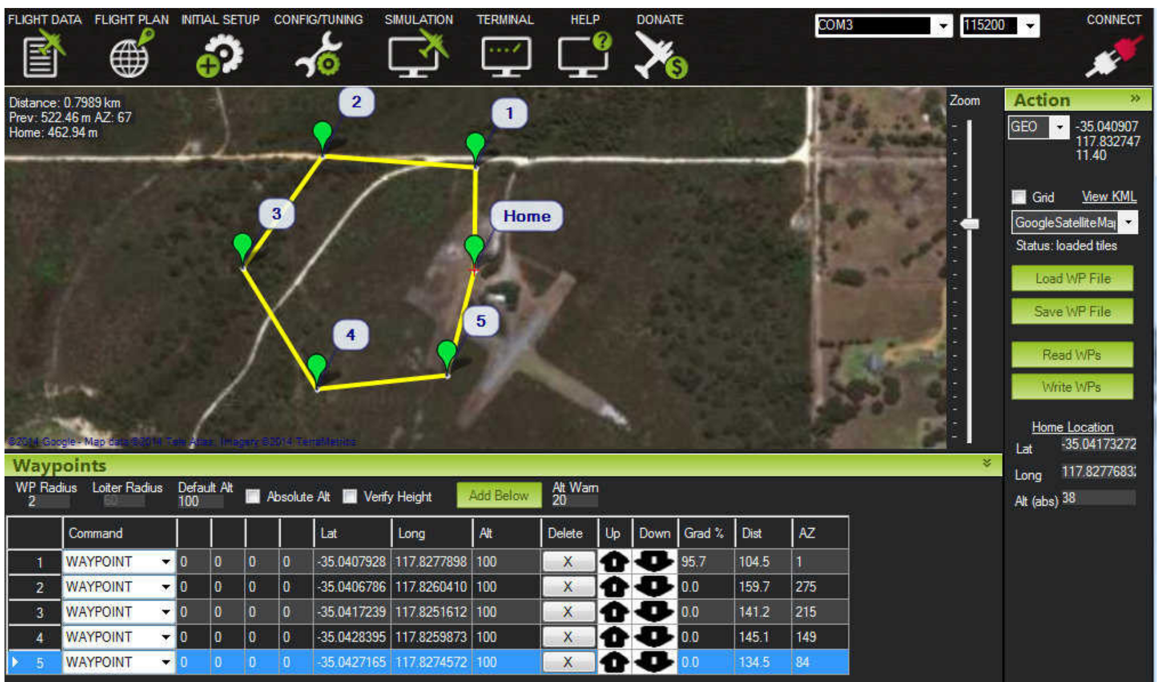

*Tarot 4114 Brushless Motor*

ArduPilot, a full-featured and reliable open source autopilot software, was chosen to be the software running on the drone. It is the most tested and proven autopilot software on the market and used by our client, Boeing, for testing.[1] ArduPilot provides all of the groundwork to have the drone perform autonomous flight with basic input to its ground station computer companion application Mission Planner. However, ArduPilot software also allows for a pilot using a transmitter on the ground to take manual control over the flight at any time. A key feature in increasing the safety of drone flight.

ArduPilot was uploaded to the Pixhawk 4 flight controller which sits on-board the drone and acts as the 'computer-pilot'. After the drone is given the launch command, the Pixhawk 4 controls all aspects of the drone's flight. The Pixhawk 4 interprets and carries out flight commands that control the position of the drone, collects data from the Global Positioning System (GPS) and integrated sensors during flight, and it is where the flight plan is stored and uploaded.


*Pixhawk 4*
*Flight Controller*

Flight plans are created in the ArduPilot computer companion application Mission Planner. Flight details such as waypoints, altitude, and other more complex flight options can be mapped out in the application.[5] Once all flight details are documented in Mission Planner, the flight plan is sent to the Pixhawk 4 wirelessly via telemetry link. After the flan plan has been received by the Pixhawk 4, the drone can be primed, armed, and given the command to carry out the flight plan.




*A snapshot of the Mission Planner interface*

These pieces of equipment and software comprise the bare-bones elements of a hobbyist drone. They allow the drone to fly in either autonomous or manual mode and let hobbyists take to the skies. This baseline set up was used as a benchmark to identify scenarios that drones of similar caliber might experience during flight.

## Flight Scenarios

Potential flight scenarios range from normal flight procedure to emergency action required. The potential flight scenario tree (see appendix) includes scenarios that wouldn't occur as a result of extreme weather; but, as the intent of this project is to increase drone safety, they have been included in the potential flight scenario tree. There are three main outcomes of drone flight:

1. The drone lands at its preplanned destination

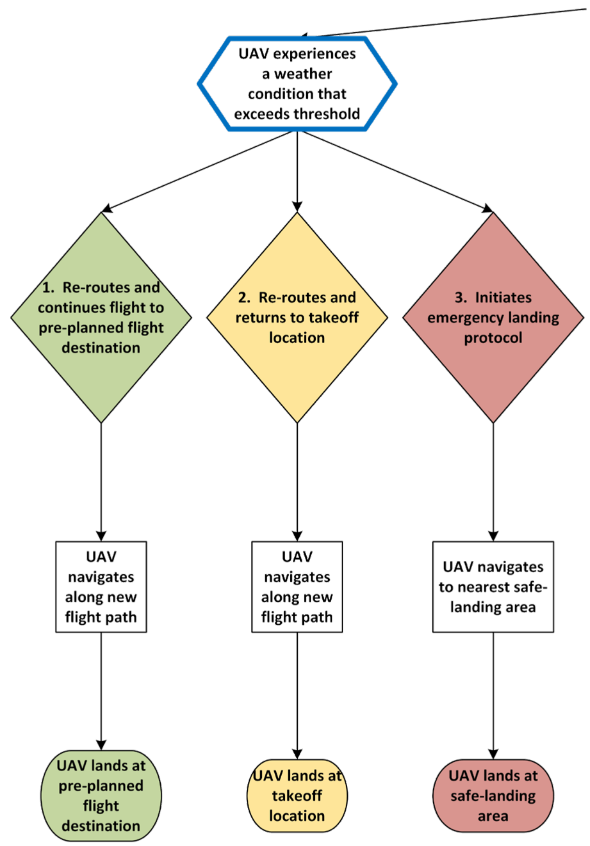
2. The drone experiences an issue in-flight and the FMS commands the drone to return to the launch location

3. The drone experiences a problem in-flight and the FMS enacts the emergency action protocol

In the first outcome, the drone most likely experiences no issues during the course of the flight. Though, the FMS could detect a breach of threshold such as temperature or pressure, be determined non-critical, and continue its original flight plan. As well, the FMS could detect data values above threshold limits, determine them erroneous, and continue its original flight plan.

The second outcome is the focus of this project: the FMS detects values above threshold limits, verifies that they are not erroneous, and sends a flight command to the Pixhawk 4 to return to the launch location. This outcome would come as a result of a critical weather threshold being broken such as wind, humidity, or extreme temperature.

Unfortunately, the third outcome would mean that the drone has lost all flight stability and is free falling to the ground. This outcome is exactly what the FMS aims to mitigate; but, it is accepted as a potential flight scenario outcome.




*Flight scenario outcomes once the drone is in flight and experiences a weather condition that exceeds a threshold*

As insurance, the project team mounted a parachute to the drone frame set to launch at a 45° angle to the rear of the drone. The parachute will engage approximately one second after being deployed and minimize the impact of the drone landing on the ground. The drone pilot is required to manually activate the deployment of the parachute via the transmitter switch. While it is possible to deploy the parachute automatically, creating a solution to prevent unnecessary parachute deployments is outside of the scope of this project.

## Weather Variables and Sensors

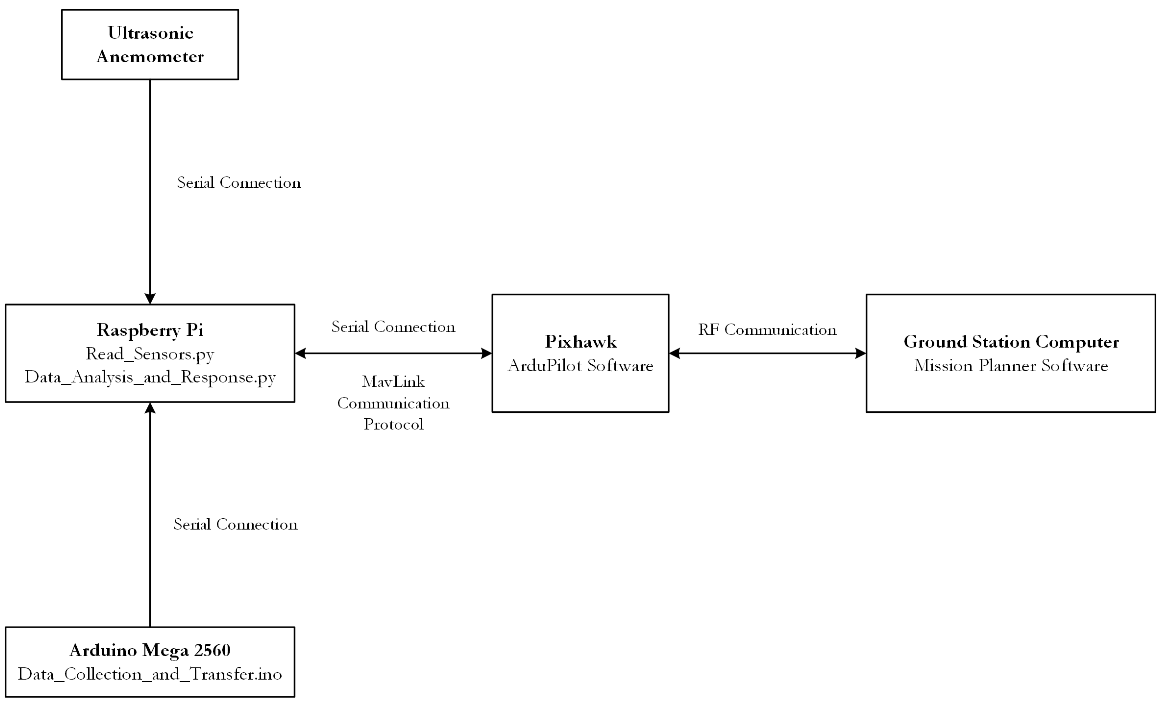
Zeroing in on weather and FMS related scenarios, the project team chose weather variables that could be sensed on-board the drone: temperature, humidity, pressure, the presence of lightning, and wind speed. Incidentally, these represent almost every weather variable that meteorologists use to predict weather daily. When it comes to improving the safety of drone flight, these variables are interpreted and will affect drone flight both directly and indirectly. Each weather variable, the sensor used to detect it (including redundant sensors), and it's determination as direct or indirect effect on drone flight are shown in the table below.

| Weather Variable | Sensors to Detect Variable | Effects on Flight |
|---|---|---|
| Temperature | 1. TMP117 Temperature Sensor<br>2. Bosch BME280 Combo Sensor<br>3. Ultrasonic Anemometer | By in large temperature is a direct impact weather variable. However, if the ambient temperature exceeds the safe operating limits of the drone or FMS components, it can directly impact the drone flight. |
| Humidity | 1. HIH-4030 Humidity Sensor<br>2. Bosch BME280 Combo Sensor<br>3. Ultrasonic Anemometer | A humidity level less than 100% would have an indirect impact on flight. In association it can change the dew point, which would affect flight performance and potentially flight stability. A humidity level equal to 100% would have a direct impact on the flight and hardware on-board the drone. |
| Pressure | 1. Bosch BME 280 Combo Sensor<br>2. Ultrasonic Anemometer<br>3. Pixhawk 4 | Pressure has an indirect impact on drone flight performance by affecting the dew point. |
| Presence of Lightning | 1. AS3935 Lightning Sensor | The presence of lightning has a direct impact on safe drone flight. If lightning were to strike the drone, or strike near the drone, the effects would likely render the drone's functions useless. |

| Weather Variable | Sensors to Detect Variable | Effects on Flight |
|---|---|---|
| Wind Speed | 1. Ultrasonic Anemometer | Wind directly impacts drone flight. Wind decreases the stability of the drone's flight, can decrease flight duration and efficiency, and has the potential to carry debris into the drone. |

## Data Collection and Analysis

All the data from these sensors must be collected and analyzed. At the heart of the FMS lies a Raspberry Pi where the Data Analysis and Response (DAR) script is located. This script is started manually from the ground station computer before a flight is conducted. Once running, the script has three main functions.




*A diagram showing the data flow and signal methods between components of the FMS*

The first function of the DAR script is to collect and organize incoming data from all the sensors within the FMS. In order to do this the Raspberry Pi must communicate with three different devices.

1. An Arduino Mega 2560 (where data from the TMP117 Temperature Sensor, Bosch BME280 Combo Sensor, HIH-4030 Humidity Sensor, and AS3935 Lightning Sensor is first processed) via serial communication to collect sensor data

2. The Ultrasonic Anemometer via serial communication to collect sensor data

3. The Pixhawk 4 via MAVLink communication protocol to collect information such as latitude and longitude, heading, ground speed, altitude, and battery life.

All sensor and Pixhawk 4 data is parsed within the script as well as saved to a .CSV file for post-flight analysis.

The second function of the DAR script is to analyze sensor data live and compare it to predefined weather thresholds. In order to do this, data is averaged in two different ways:

1. Due to there being multiple temperature, pressure, and humidity sensors within the FMS, all separate sensor values are averaged with each other. If sensor values differ from each other more than a certain amount, the disparity is flagged, and the DAR script only refers to the most reliable sensor in order to ensure data is accurate.

2. Data is also time averaged over an amount of time longer than the sampling period in order to flatten out any spikes in readings. If no weather thresholds are reached then the flight will continue as normal until the UAV reaches its intended destination. If a weather threshold is reached the script will move onto its third and final essential function.

The third function of the DAR script is to alter the UAV's flight plan if sensor readings pass the defined weather threshold. To do this, flight commands are sent to the Pixhawk from the Raspberry Pi via the aforementioned MAVLink communication protocol. The DAR script can send a number of commands depending on the amount by which the threshold has been broken. The potential responses are listed below from least to most severe response:

1. Change the flight plan slightly but continue the flight to the intended destination

2. Command the UAV to land in a predefined safe area, which could be the initial launch site

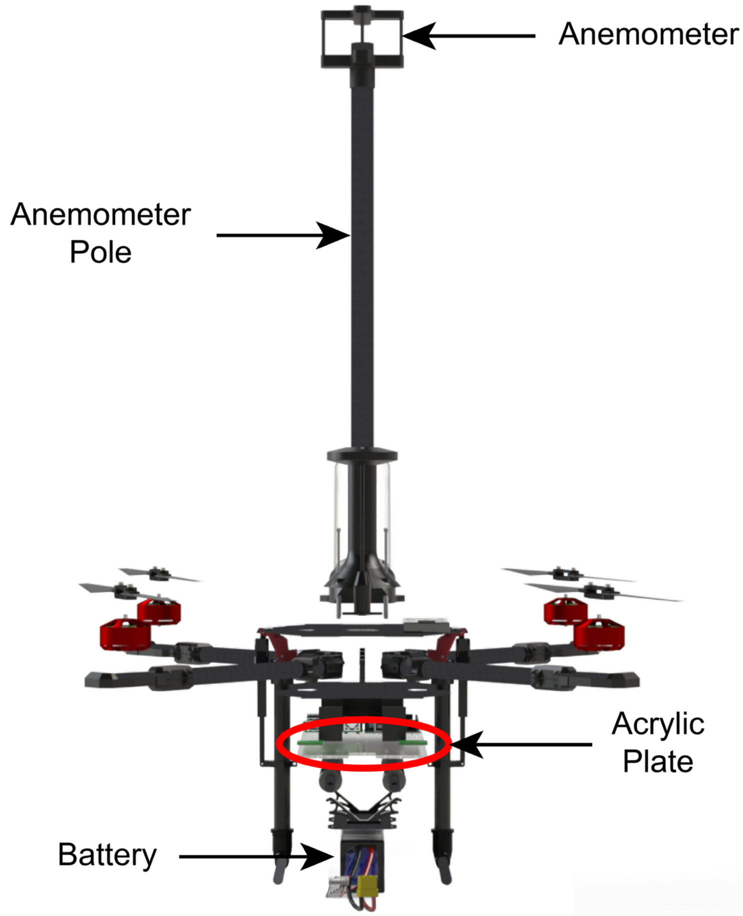
3. Stop the current flight plan and perform an immediate landing at the location where the threshold was broken

4. Immediately stop power to all motors and initiate the emergency response protocol, letting the safety parachute deploy and ensuring the UAV reaches the ground safely

Once the drone has landed the DAR script will record the landing location and will save all flight data to a .CSV file before ending.

## Component Placement

This flight management system would all be for not if the flight performance and capabilities of the drone were hindered after mounting them on-board. The sensor suite was mounted on the drone with consideration of the potential bias that the propeller wash could create and minimizing the shift of center of gravity to preserve flight stability.



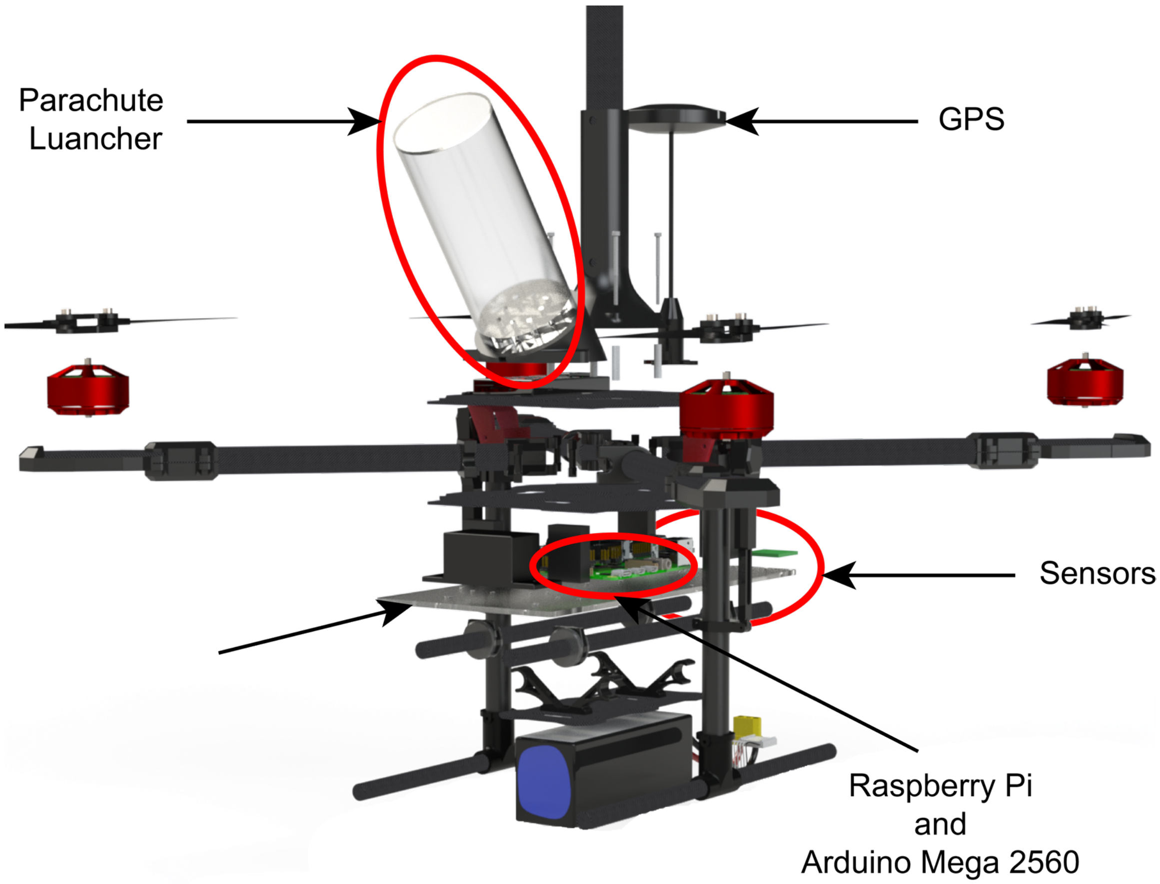

*An exploded view of the UAV and FMS assembly*

The ultrasonic anemometer was placed atop a 20-inch carbon fiber pole in the middle of the drone frame's top plate. This height above the plane of the propellers was recommended by the ultrasonic anemometer's manufacturer and proven during testing to show no bias in the sensor data. A mount to connect the top plate of the drone frame and the anemometer pole was created in SolidWorks and 3D printed using the Markforged printer with its proprietary Onyx material.

*The anemometer pole mount*

*The acrylic plate where the Raspberry Pi, Arduino Mega 2560, and sensors mount*

The remaining sensors, in addition to the Raspberry Pi and Arduino Mega 2560, were mounted to an acrylic plate between the drone battery and the bottom plate of the drone frame. This placement of the remaining sensors showed the least impact on sensor data as they are partially sheltered from the downwash of the propellers by the top and bottom plates of the drone frame. With all the components of the FMS mounted to the drone frame, the FMS became operational.




*A close-up view of the UAV and FMS assembly*

## Flight Testing

During outdoor flight testing, the sensor data continued to show no bias and accurately detected weather conditions when compared to the National Weather Service reports of the flight area. Even when subject to moderate, constant winds, the drone and FMS withstood the agitation and performed many flight tests without issue under autonomous and manual control. The same can be said for flight tests in which the outdoor ambient temperature was near freezing, when clouds and overcast skies were present, and when there were warmer and dryer flight conditions.

The Pixhawk 4 has successfully received and enacted flight commands sent by the Raspberry Pi during flight. The functionality has been confirmed for the UAV to first return to the launch site then land as well as landing at the UAV's location at the time of the threshold being broken. The deployment of the parachute is tested and working properly.

Currently the project team is in the process of collecting as much outdoor data as possible to refine the weather thresholds within the DAR script. The current weather thresholds have been derived from manufacturer recommended safe operating conditions, input from experienced drone pilots, and UAV forums online. These initial weather thresholds are being confirmed and supported by outdoor flight test data.

# Conclusion

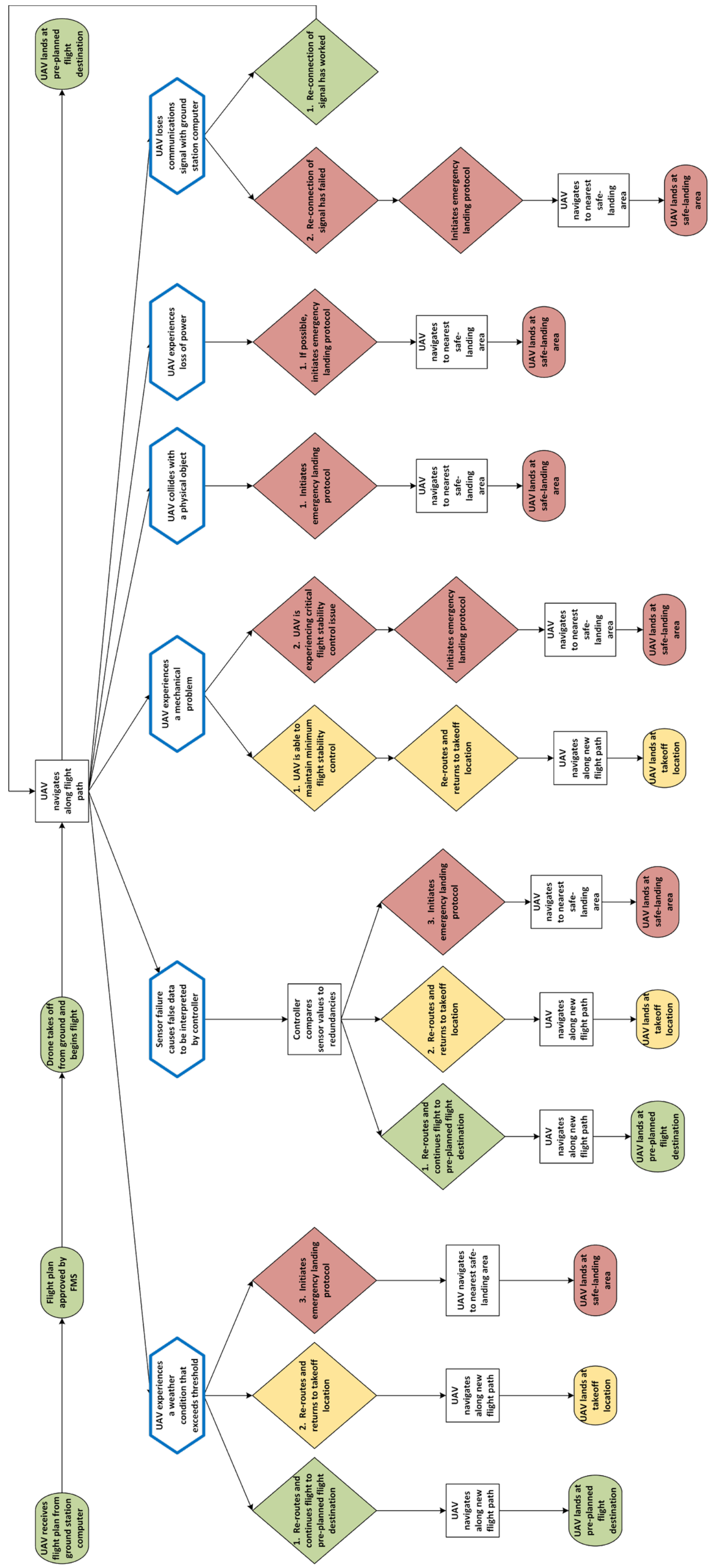
All components of the flight management system are mounted to the UAV frame and working properly. The sensor suite is able to accurately and precisely detect weather conditions immediately surrounding the drone and show no bias in the collected data. The Data Analysis and Response script is able to analyze the sensor data and send an appropriate flight command to the Pixhawk 4 if necessary. Although the FMS is up and running, the DAR script is still undergoing refinement to see if other methods of determining if weather threshold values have been surpassed are more consistent and or precise.

The FMS has the ability to be installed on most any drone with minimal modifications needed to the anemometer pole mount and acrylic plate's mounts; and there's no reason to wait. As it stands, the safety of UAV flight is compromised and vulnerable to the influence of weather conditions. Having UAVs falling out of the sky is completely avoidable. Flight safety is greatly improved while the FMS is continuously analyzing weather conditions surrounding the UAV, ready to react if safe flight operating conditions are breached.

Beyond safety, the FMS can also increase the efficiency of UAV flight. Moisture in the air can impact propeller performance, extreme ambient temperatures can drain batteries faster than normal, and anything other than no wind will push UAVs to work harder than needed. By collecting weather data and making appropriate changes to flight plans, the range of a UAV's flight can be extended. These longer flights mean delivery companies would have even more reason to incorporate UAVs into their fleet and shrink delivery times. However, as the abilities of drones expand to include performing roof inspections[4] and population control of invasive animals[3], so too does the need for controlled, safe drone flight expand.

# Appendix

## Flight Scenario Tree



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