AVIS IMPAR
AUVSI SUAS at Virginia Tech

2018 AUVSI SUAS Technical Design Paper - Virginia Tech

Abstract

This technical paper presents the design, development, and testing of our UAS for the 2018 AUVSI SUAS competition. As a first year design team at Virginia Tech, Avis Impar's initial primary objective was to design and develop a reliable unmanned aerial system (UAS) capable of completing waypoint navigation and air delivery with full autonomy and high degrees of accuracy. Mission tasks such as obstacle avoidance and object, detection, classification, localization (ODCL) were classified as secondary objectives for the team. Through a collective effort of 25 undergraduate students majoring in the fields of Mechanical Engineering, Electrical Engineering, Computer Science, Computer Engineering, Aerospace Engineering, Material Science and Engineering, and General Engineering. Avis Impar is proud to present Trochilidae - a custom octocopter featuring an onboard imaging system, high accuracy waypoint navigation, precise air delivery, and fully autonomous flight. Simulations and component analyses were performed to safely test all individual aspects before their implementation on Trochilidae. Throughout development, Avis Impar emphasized the importance of testing, safety, and reliability to ensure that all devices on Trochilidae are ready for flight.

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1. Systems Engineering Approach

1.1. Mission Requirement Analysis

Trochilidae was designed and developed for optimal performance in the search and rescue mission at the 2018 AUVSI SUAS competition. The UAS can perform autonomous flight, air delivery, image capture, manual object detection and classification, and obstacle avoidance. **Table 1** describes each mission task and what is necessitated by the UAS to complete each requirement.

Table 1: *Mission Requirement Analysis*

Mission Task	Description	Team and System Requirements
Timeline (10%)	● Complete the mission in the shortest amount of time (80%) ● Complete the mission without the need of a timeout (20%)	● UAS capable of high speeds, precise maneuverability, and long range flight ● Full mission testing to ensure reliability of the UAS
Autonomous Flight (30%)	● Capture waypoints with high accuracy and precision (60%) ● Fly autonomously with minimal manual intervention (40%)	● UAS capable of navigating all waypoints accurately ● Telemetry data sent to the interoperability system at a minimum rate of 1Hz
Obstacle Avoidance (20%)	● Avoid stationary obstacles (50%) ● Avoid moving obstacles (50%) ● Remain in bounds during avoidance	● An algorithm that predicts collisions and updates the UAV's flight path in real time, while ensuring the path remains within the boundaries
Object Detection Classification Localization (20%)	● Classify object shape, shape color, alphanumeric, alphanumeric color, and alphanumeric orientation (20%) ● Provide the GPS location of a object (30%) ● Provide all object information autonomously (20%) ● Submit object data within first flight (30%)	● UAS capable of manual and autonomous object detection, classification, and localization ● Imaging system capable of capturing pictures at high speeds and some vibration ● An algorithm that can localize objects and objects by using telemetry data from the autopilot system ● Frequency that relays all images to the Ground Control Station (GCS) and Interop
Air Delivery (10%)	● Deliver an 8 oz water bottle to the drop location - ensuring an explosion (100%)	● An air delivery mechanism that accurately drops an 8 oz water bottle
Operational Excellence (10%)	● Conduct professional behavior and communication between team members ● Be attentive to safety at all times	● Gracious and professional attitude. ● Attend competition well prepared and confident in the craft and mission

After launching an in-depth analysis of the mission elements and the systems needed to successfully complete each task, the team assessed the aspects of the mission by their ease of implementation and effect on mission score. In order to maximize points and allow for the completion of other mission elements, the team is required to create an UAV that is capable of *Autonomous Flight*. This requires an airframe and autopilot combination that can takeoff, accurately navigate waypoints, and land without human assistance. The *Obstacle*

Avoidance task requires an algorithm that is capable of detecting obstacles, computing the best avoidance path, and readjusting the UAV's flight path in real time. The UAV itself must also be highly maneuverable and responsive to any sudden changes in its flight path. The *Object Detection, Classification, Localization* task requires the UAV to carry a high resolution camera with a directable field of view (FOV). In order to submit the data autonomously and within the first flight, a data link must be established between the UAV, Ground Control Station, and Interoperability Server. The *Air Delivery* task requires a craft that is able to carry and deliver a payload reliably and accurately. Lastly, the *Timeline* and *Operational Excellence* tasks require the team to practice full missions prior to the competition date in order to ensure an efficient and timely mission demonstration. In order to achieve all the requirements set forth, the team knew that weight reduction and flight efficiency were key factors in the design process.

1.2. Design Rationale

As a first year team, Avis Impar chose to focus its primary efforts upon designing an UAS that is capable of achieving fully autonomous flight, successful air delivery, and high-resolution image capture. Additional mission tasks such as *Object Detection, Classification, Localization* and *Obstacle Avoidance* will be attempted during the mission demonstration, but Trochilidae will not be capable of achieving maximum score in these areas. The following design decisions, as shown in **Figure 1**, are ordered in terms of their importance to a successful mission.

Figure 1: *Decision Flowchart*

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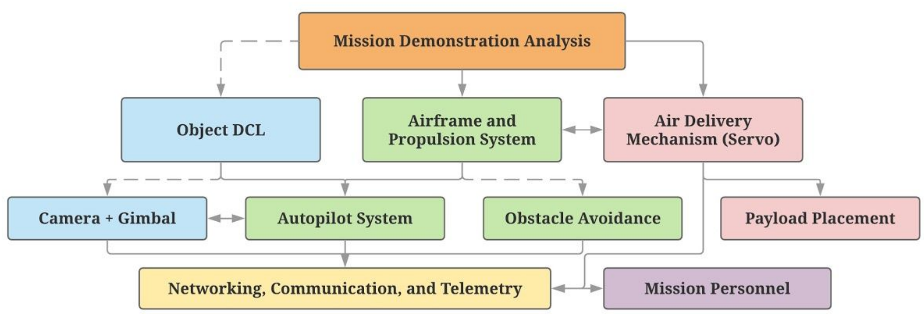


Solid Lines Indicate Tasks of Higher Importance

1.2.1 Airframe and Propulsion System

The first decision focused on creating an airframe design. Using the mission requirement analysis conducted in **Table 1**, Avis Impar created a list of requirements for the UAS. **Table 2** describes the strengths and weaknesses of each aerial platform when tasked with the requirements set forth by the team. Through the aerial platform analysis, Avis Impar found that a multirotor would provide the team with a UAS that is capable of fully autonomous flight with superior airdrop and waypoint accuracy. Thus, Avis Impar decided upon designing a multirotor for the 2018 AUVSI SUAS competition. Designing a propulsion system for Trochilidae was the second most important design decision. After deciding upon the aerial platform, the team researched several multirotor platforms ranging from tricopters to octocopters. Avis Impar found that a large octocopter platform maintained all the benefits of a multirotor platform, while also providing the craft with the minimum required flight range and propulsion redundancies. In order to achieve optimal efficiency, the team decided upon using low kV motors paired with high diameter propellers. This propulsion system must

Table 2: *Aerial Platform Comparison**

Elements	F-W	M	H
Flight Time/Range	1	3	2
Maneuverability	3	1	2
Payload	3	1	2
Speed	1	2	3
Affordability	1	3	2
Landing/Takeoff	3	1	2
Average Rating ≅	2.0	1.8	2.2

**F-W = Fixed-Wing / M = Multirotor / H = Helicopter* also be capable of providing the craft with a minimum thrust to weight ratio of 2.5:1.

1.2.2 Autopilot System and Obstacle Avoidance

The third design decision was the choice of an autopilot system. Avis Impar chose the Pixhawk 2.1 autopilot because of its open source firmware and internal sensor redundancy. Paired with Mission Planner and Arducopter, the Pixhawk 2.1 would allow Trochilidae to reliably perform takeoff, landing, waypoint navigation, obstacle avoidance, and air delivery with full autonomy and high accuracy. Mission Planner is also open source, which gives Avis Impar the ability to create modifications that aid Trochilidae during *Obstacle Avoidance*. The main benefit of Mission Planner is its ability to receive additional waypoints from an external script and push them to the UAV in real time.

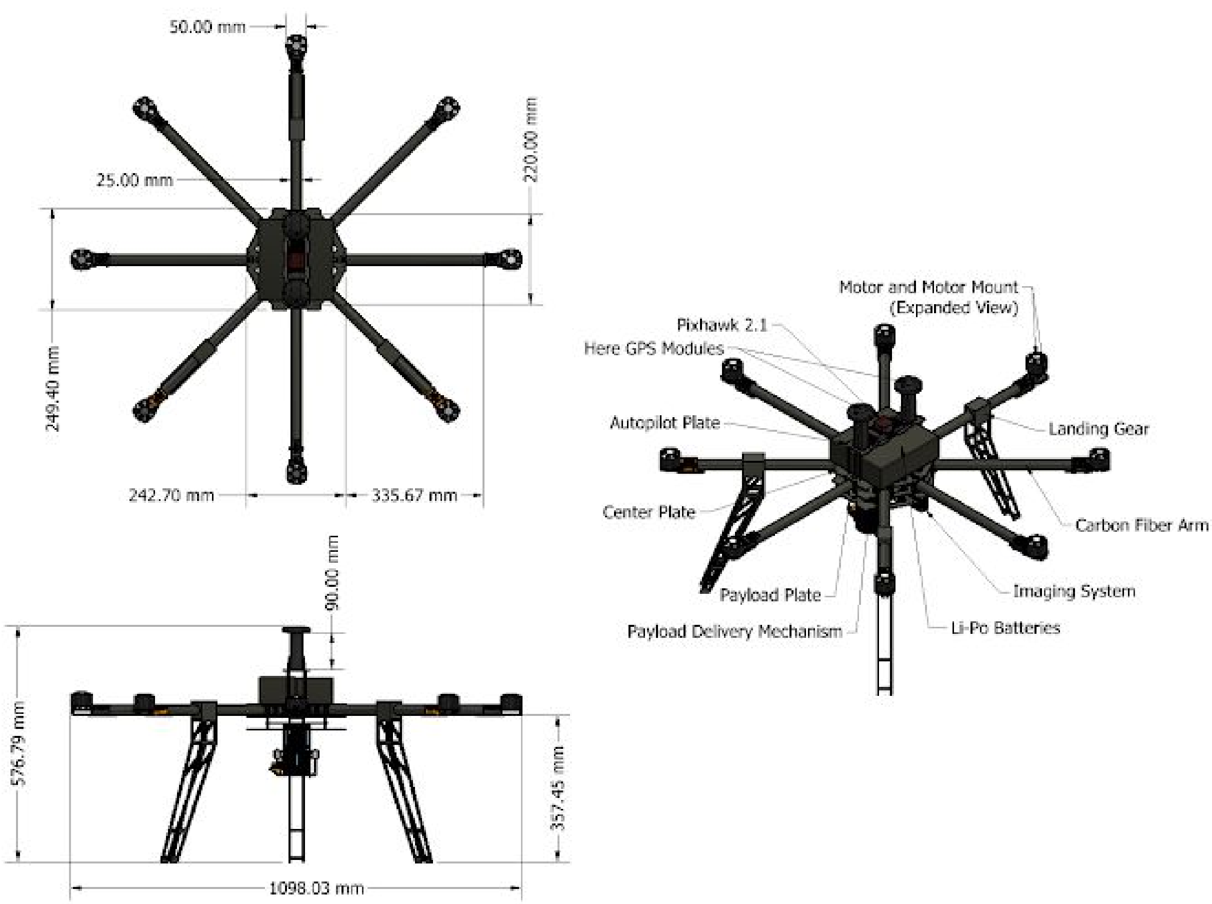
1.2.3 Air Delivery

Considered fourth, air delivery required a hold and release mechanism that interacts with Mission Planner through the Pixhawk 2.1's auxiliary ports. In the event of a system power failure, the mechanism must also be able to keep the payload so that it is not released outside of the drop point. This mechanism would also need to be placed near the craft's center of gravity so that Trochilidae's stability is not adversely affected by the payload release.

1.2.4 Imaging System and Object Detection, Classification, Localization

Avis Impar's final design decision was to decide upon the imaging system for Trochilidae. The Firefly 8s action camera was chosen due to its wide FOV, small footprint, light weight, high resolution, and low cost. A gimbal was also deemed advantageous to minimize motion blur and equip Trochilidae with the ability to direct the camera's FOV towards the off-axis target.

Figure 2: *Craft Design and Dimensions*



2. Systems Design

2.1. Aircraft

Trochilidae was designed using a modified version of the Tarot Iron Man 1000 octocopter frame. The base airframe - consisting of eight arms, four center plates, and three landing legs - is composed primarily of carbon fiber to maximize strength while minimizing weight. To maximize modularity, each center plate is has been designated with its own responsibilities. From top to bottom, the sections are referred to as the following: avionics plate, propulsion plate, electronics plate, and payload bay. In order to reduce the effects of the craft vibration, all sensor based components are connected via a foam separation from their respective plate. In order to be removed from the magnetic field of the batteries, the GPS modules have been placed three inches above the avionics plate. Thus, allowing for a accurate compass measurements during flight. As for the layout of the propulsion system, an octocopter + formation was chosen for its increased flight stability and maneuverability at high speeds. Additionally, in order to ensure high stability, battery placement was calculated to keep the center of mass in the same plane as the propulsion system. To reduce drag and wind effects on Trochilidae, the arms and landing gear of the frame were shortened to minimize cross-sectional area in all axes. Specific properties and dimensions of Trochilidae can be found in **Figure 2** and **Table 3**.

Table 3: *Craft Specifications*

Length (mm)	1098.03
Width (mm)	1098.03
Height (mm)	576.79
Weight (kg)	10.83
Max Flight Time (min)	40.00
Max Speed (knots)	29.87
Max Flight Range (km)	11.43
Max Climb Rate (knots)	23.52
MTOW (kg)	22.50
Operational Range (km)	3.50
Thrust to Weight Ratio	2.8 : 1
Max Tilt Angle (°)	66*

**Software Restricted to 45°*

After deciding upon the frame and the size constraints it created, the team prioritized designing a powerful, yet efficient, propulsion system. In order to reach optimal efficiency, the propulsion system was designed using low kV motors paired with large propellers. After researching the many available motor choices, the team decided upon using Tiger MN4120 400kV motors running off of a 6s, 25.2V, Lithium Polymer (Li-Po) battery. As for the speed controllers, KDEXF-UAS55 ESCs were chosen for their 600Hz refresh rate and regenerative braking capabilities. Coupled with high pitch propellers and Tiger MN4120 400kV motors, the ESCs provide a near instantaneous response and high efficiency in flight. In order to pair this power system with the best propeller type, the team conducted a mathematical and physical analysis of the relation between propeller characteristics and specific thrust efficiency. Prior to any data collection, mathematical calculations were conducted to observe the effects of propeller diameter, pitch, and material. These calculations were based on the McCormick method - assuming no resistance or magnetic interference - and were verified using the performance data provided by the suppliers. After performing a statistical analysis on the data provided by the mathematical analysis, the team found that two different propellers - Tarot 1575 and Xaor 1660 Carbon propeller - provided similar results of optimal efficiency. In order to decide upon the final propeller choice, both propellers were then acquired and physically tested in the lab. Through the use of a Turnigy Power Systems Propeller Tester, the team was able to collect the specific thrust and power data from each combination.

After conducting a statistical analysis on the data provided by the bench tests, the team deemed the 1660 Carbon propellers were the superior choice. Though the data illustrated their increased current usage at a throttle of 43% or less, the 1660 Carbon propellers allow for a greater stability when flying at speeds of 6 knots or more. This is due to the propeller's comparatively low pitch, which allows the craft to fly with lower vibrations - increasing stability in flight. After finalizing the propulsion system, the team set forth to optimize the battery capacity of the octocopter.

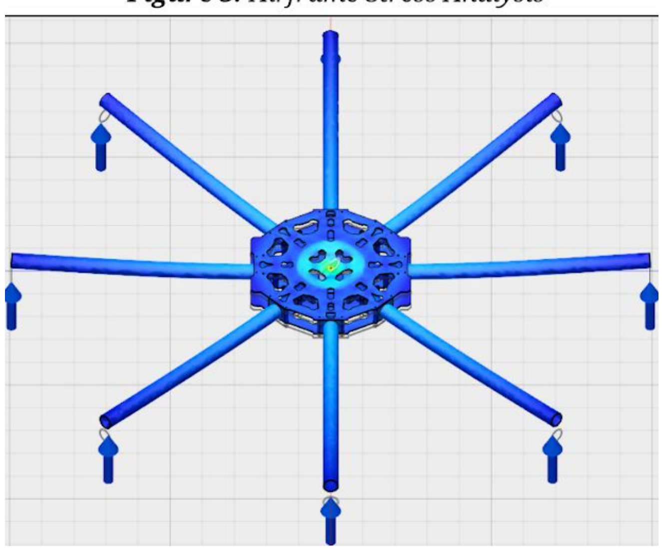
By conducting a craft weight analysis, without the inclusion of battery weight, we were able to calculate the approximate battery capacity needed to guarantee a minimum flight range of 6 kilometers. This was done by optimizing a function of flight range and capacity, while keeping in mind our required minimum thrust to weight ratio of 2.5:1. The additional weight of the theoretical battery was calculated using the average energy density of commercially produced 25.2V Li-Po batteries. After optimizing the function, we found that the ideal battery capacity of our craft would be approximately 47 Ah. This provided our craft with a theoretical range of 11.75 kilometers and a thrust to weight ratio of 2.75:1. However, due to product and budget constraints, the team was limited in its selection and finalized their decision upon dual 22 Ah 6s Li-Po batteries. Which, when wired in a parallel configuration, supply the craft with a 25.2V 44Ah power source. Using this battery capacity, Trochilidae is able to achieve the flight characteristics shown in **Table 3**. By utilizing two batteries, instead of one, Avis Impar is able to provide power to the Pixhawk 2.1 and power distribution board through two separate connections. This allows Trochilidae to have internal power redundancy and gives it the ability to fly in case of a singular power failure. Further specifications of the electrical system on Trochilidae can be seen on **Table 4.**

Table 4: *Electrical System*

Electrical System Components		Electrical System Characteristics	
Motor	T-Motor MN4120 400kv	Max Amp Draw (A)	360
Propeller (in)	Xoar 16x6.0 Carbon Fiber	Hover Amp Draw (A)	62.3
ESC (A)	KDEXF-UAS55+	Voltage Range (V)	20.4 - 25.2
Total Li-Po Battery Capacity (Ah)	44 (Dual 22 in Parallel)	Power Distribution Board Maximum Amperage (A)	360 Continuous 400 Burst

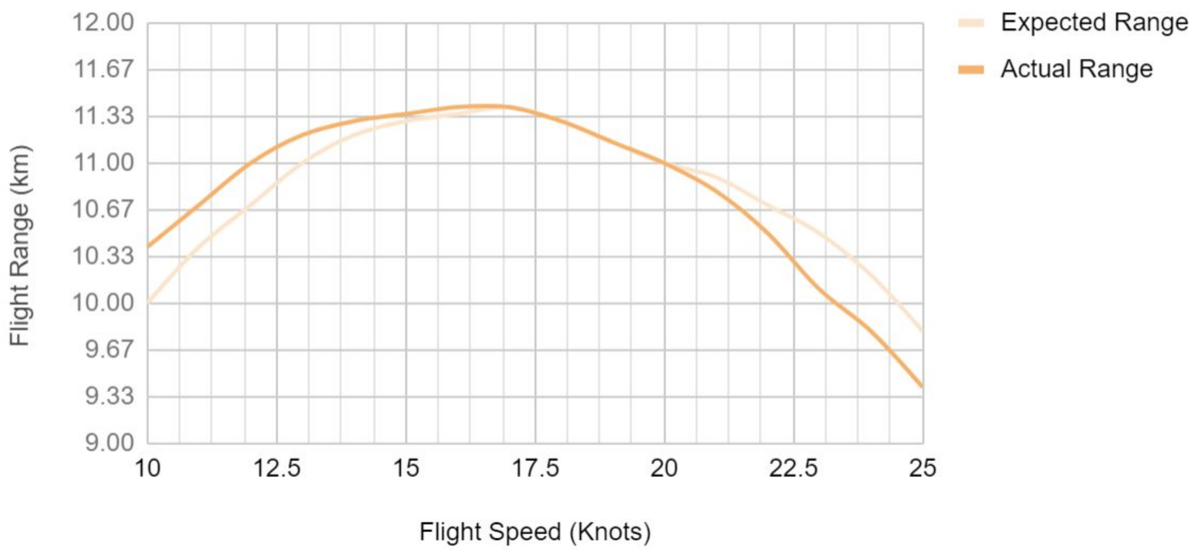
Before constructing and flying the craft, Avis Impar chose to evaluate the strength and reliability of the airframe in several scenarios. Using AutoDesk Fusion 360, the team was able to conduct multiple simulations and analyses that lead to the development of the craft. These simulations were carried out using the several study types allowed for by AutoDesk Fusion 360. An exaggerated view of the stress analysis shown in **Figure 3** depicts the loads placed upon the airframe when Trochilidae is flying at full throttle and is at competition weight. As shown in the analysis, the frame endures very minimal stress at all critical points of the airframe - allowing for a safety factor of 4.1:1. The team also conducted thermal tests upon all PLA based components, such as the payload mechanism, to ensure their reliability when exposed to high temperatures.

Figure 3: *Airframe Stress Analysis*



To optimize the airspeed of the craft in flight, the team conducted simulations and calculations on how different speeds affected the flight range and drag encountered by the craft. During these calculations, the craft was limited to a maximum tilt angle of 45° - thus allowing for a 21° emergency overhead. After conducting several simulations, the team found that optimum airspeed of the craft was 16.94 knots. To ensure this was accurate, the team collected real-time data of Trochilidae's flight time and range at speeds between 10-25 knots. During these tests, the data collected was less than 5% off of the simulated results - thus the cruising airspeed of Trochilidae was considered to be 16.5 knots. At this speed, Trochilidae endured minimal stress upon its frame and was able to travel the maximum amount of distance. Specific results from the simulations and flight testing can be found in **Figure 4**.

Figure 4: Range Testing and Results



2.2. Autopilot

In order to select the optimal autopilot system, the team analyzed all available options prior to the development of Trochilidae. A thorough research period ended with the collection of five different autopilot choices: Pixhawk 1.0, Pixhawk 2.1, Pixhawk 3.0, NAVIO2, and DJI NAZA-M V2. All autopilots were chosen for their stock ability to provide Trochilidae with a fully autonomous takeoff, flight, and landing. To narrow down the alternatives, each option was ranked based on the requirements shown below.

- **Manual Override** - The pilot must maintain the ability to gain full manual control of Trochilidae at any time.
- **External Sensor Integration** - The autopilot system must allow for the addition of external sensors - such as GPS, LiDar, AHRS, and compass.
- **Internal Sensors** - Along with its ability to communicate with external sensors, the autopilot system must also have an IMU. Internal sensor redundancy was also heavily favored.
- **Customizability** - The autopilot system must be open source and allow for external software manipulation - thus allowing for the completion of tasks like ODCL and obstacle avoidance.
- **Affordability and Reliability** - The autopilot system must be a cost effective option - while also providing the team with reliable autonomous flight.
- **Mass and Footprint** - The autopilot system, along with all external sensors, must weigh less than 300g and have a minimal footprint.

After comparing each system, the team observed that the Pixhawk 2.1 autopilot system consistently ranked higher than the others. With an economical price of $198.00, the Pixhawk 2.1 was able to fulfill every requirement above, and provided other benefits such as internal heating. Consisting of three accelerometers, gyroscopes, and magnetometers, the Pixhawk 2.1 also includes internal sensor redundancy. In order to maintain precise and accurate location data, two Here GPS modules are connected to the Pixhawk 2.1. This allows Trochilidae to perform reliable waypoint navigation within a radius of 3’. Along with the internal sensor redundancy of the Pixhawk 2.1, the dual GPS modules outfit Trochilidae with a fully redundant autopilot system. A full diagram of Trochilidae’s autopilot system can be seen in **Figure 5**.

In terms of autopilot software, the team runs Arducopter 3.5 on the Pixhawk 2.1. It was chosen due to its open-source nature, ability to communicate with a Ground Control Station, and pre-built functions for autonomous flight. Communication with the primary Ground Control Station running Mission Planner gives Trochilidae the ability to perform reliable waypoint navigation and air delivery, without the need for external software manipulation. Arducopter is also capable of performing stable autonomous takeoffs and landings - maximizing the amount of points received for autonomous flight. The mapping feature pre-built into Mission Planner allows the team to create a flight path that is best optimized for Trochilidae. This allows Trochilidae to quickly cover all portions of search area, while also consuming the least amount of power. At all times throughout the flight, the team is also able to directly observe the exact battery level, power consumption, location, and other aspects of the craft through Mission Planner. When paired with a slight modified version of MavProxy, the Ground Control Station is able to forward this data to the interoperability server in the formats specified by the rules. This link provides a communication pipeline between GCS and the interoperability server - allowing for the completion of obstacle avoidance and telemetry upload. By stress testing the platform, the team was also able to observe Mission Planner's protocol behind loss of communication between the GCS and UAS. The team found that Mission Planner was able to achieve all requirements set for by the competition rules and provided backup options in case of failure. These options allow for the optimization of Trochilidae's communication - allowing it to have a large and safe operational range. A visual representation of the GCS during a simulated flight is shown in **Figure 6**.

Figure 5: *Autopilot System Diagram*

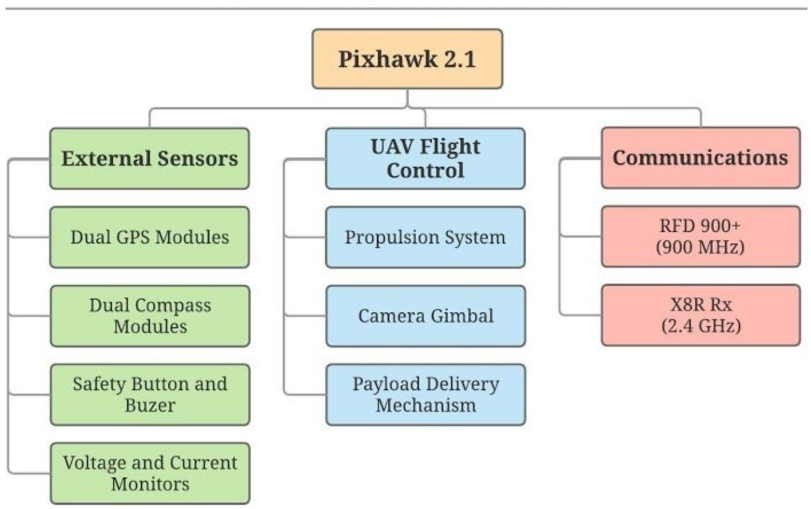
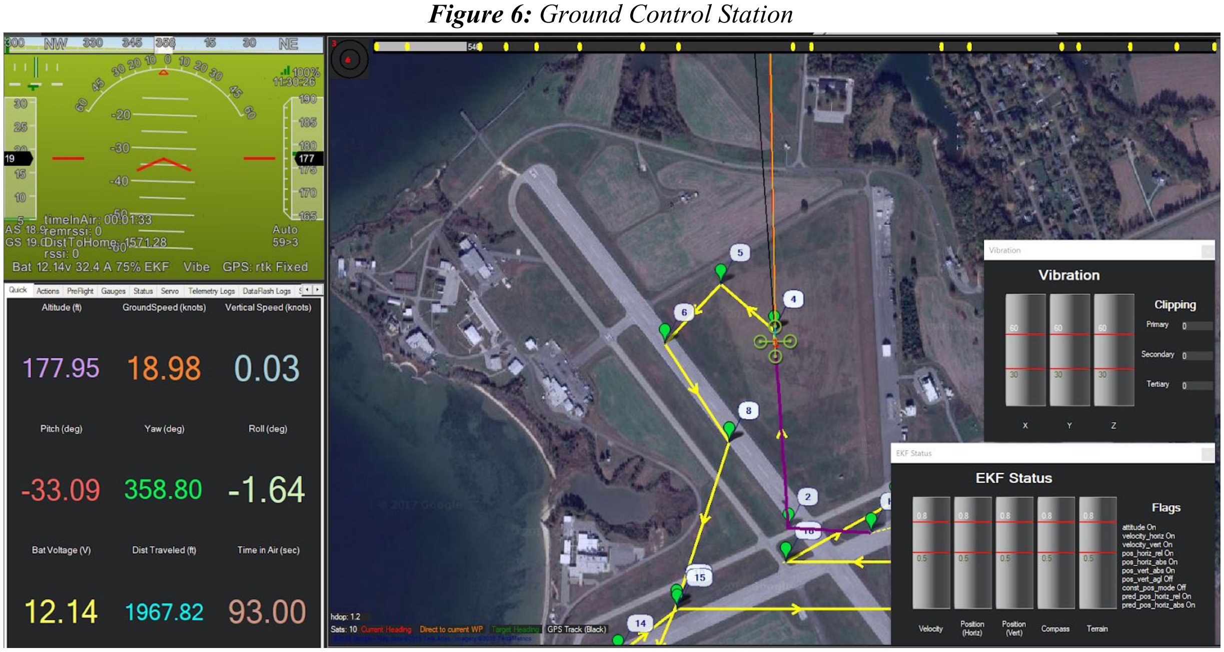


Figure 6: *Ground Control Station*

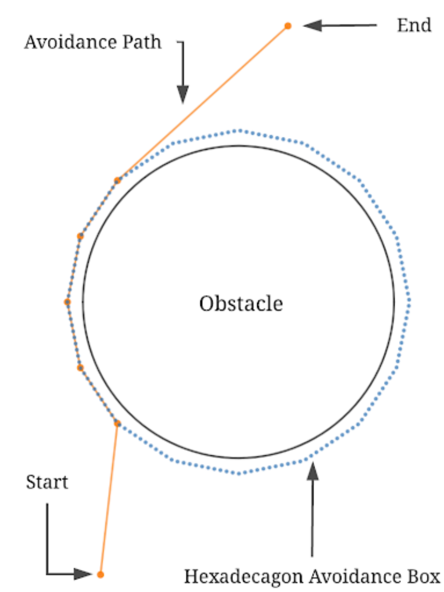


2.3. Obstacle Avoidance

In order to successfully complete the *Obstacle Avoidance* task, Avis Impar developed a custom Obstacle Avoidance Algorithm (OAA) that has been tuned to work with Trochilidae. Through MavProxy, the OAA is able to autonomously calculate efficient avoidance paths and update Trochilidae's flight path at a rate of 1 Hz. This allows Trochilidae to dynamically change its path in order to avoid moving obstacles. The GCS and remote transmitter has also been equipped with an OAA failsafe. This is to ensure that avoiding the obstacle would not cause Trochilidae to exit the flight boundary or cause harm to other individuals. Due to Trochilidae's ability to instantaneously change direction and altitude, the OAA is able to avoid all obstacles with minimal deviation from its initial path.

As aforementioned, Avis Impar utilizes a suite of custom algorithms to avoid all obstacles. Throughout its flight, Trochilidae constantly scans its environment to determine if its current path intersects with any obstacles. It then calculates any avoidance paths that are deemed necessary by the initial environment scan. If the determined avoidance altitude is within 50' of craft's current altitude, an avoidance path over/under the obstacle is calculated and pushed to Trochilidae. For all other cases, Trochilidae reacts by avoiding the obstacle with the circular path shown in **Figure 7**. In order to ensure that all images taken in the search area meet the minimum resolution set forth by the team, all avoidance paths calculated in the search area are restricted to an altitude of 150'. The optimal safety distance needed to keep Trochilidae from hitting the obstacles was calculated to be 15' for stationary obstacles and 30' for moving obstacles.

***Figure 7:** Obstacle Avoidance Algorithm*



During testing, Avis Impar found that the computations made by the OAA required a minimum processing power that was unable to be supplied by the Pixhawk 2.1. Thus, the OAA was developed to run off of the GCS and utilizes the 900 MHz frequency to communicate with Trochilidae. Before being implemented into the OAA, all algorithms and computations were simulation tested in Mission Planner. Through testing in the software in the loop (SITL) environment, Avis Impar was able to fine tune the OAA and test all corner cases without risking any physical damage to the craft. To determine the success rate of the final OAA, simulations were conducted on over 1,000 waypoints and 100 obstacles. Results from these simulations can be seen in **Table 5.** As of the current development, Avis Impar has not been able to test the OAA for moving obstacles in real life tests.

***Table 5:** Obstacle Avoidance Results*

	Simulated Obstacles	**Real World Obstacles**
Stationary Obstacles	80 | 86.25% Avoidance Rate	10 | 90.00% Avoidance Rate
Moving Obstacles	20 | 25.00% Avoidance Rate	Not Test Against as of Current Status

2.4. Imaging System

By choosing to allocate much of the approved funding towards the autonomous flight capabilities of Trochilidae, the team was limited in its imaging system selection. During the design phase of the imaging system, the team decided that the optimal imaging system would be of low cost and consist of a high megapixel and wide FOV camera within a controllable 2-axis gimbal. After researching the available options, the team narrowed the decision down to the following 3 action cameras: GoPro Hero5 Black, HawKeye Firefly 8s Wide FOV, and ThiEYE T5e. To finalize the decision, the team utilized the comparison chart shown in **Table 6** to visualize the benefits and drawbacks of each system..

***Table 6:** Camera Comparison*

Characteristic	GoPro Hero5 Black	HawKeye Firefly 8s*	ThiEYE T5e
Image Resolution (MP)	12	12	16
Video Resolution	4K	4K	4K
Video Frame Rate (FPS)	30, 25, or 24	30	30
Diagonal FOV (°)	149.2	170.0	170.0
Dimensions (mm)	61.7*44.4*32.3	59.0*41.0*21.0	61*42*23
Weight (g)	118.0	70.0	78.2
Price (USD)	299.99	110.99	169.99

** Wide Angle FOV Version*

As shown in **Table 6**, the team found no absolute advantages of the GoPro Hero5 Black that could justify its comparatively high cost. The GoPro Hero5 Black was also eliminated as a choice because of its lower diagonal FOV - leading to less area being captured within the camera's sensor. This was a problem because it would cause Trochilidae to either fly at a higher altitude or travel a longer path during search area - thus decreasing the efficiency of its flight. When comparing the final two choices, the team found that the ThiEYE T5e's higher image capture resolution was not justified by its increased cost. Thus, the team decided to use the HawKeye Firefly 8s as the camera for Trochilidae's imaging system. To complete the imaging system. the action camera was mounted on a Walkera G-2D Camera Gimbal. This addition minimizes motion blur and equips Trochilidae with the ability to direct the camera's FOV towards the off-axis object. Due to the gimbal's recommended operating voltage of 12.6V, an additional voltage step down from 25.2V to 12.6V was added to the electrical subsystem. Once powered, the gimbal then interacts with the Pixhawk 2.1 through its auxiliary output ports - allowing for manual and autonomous directional control of the camera's FOV. As shown in **Figure 8** and Trochilidae's imaging system has been optimized for a small footprint and minimal obtrusion from the base frame.

***Figure 8:** Onboard Imaging System*

In order to determine Trochilidae's maximum flying altitude in the search area, the team conducted several flight pathing simulations and real life tests. Images were taken from 100' - 400' above ground level (AGL) and used to determine Trochilidae's cruising altitude during search area. Avis Impar determined that an altitude of 150' AGL allowed the camera to capture large areas within its FOV, while also allowing for objects to still be detected and characterized. At this altitude, the imaging system was able to produce pictures with a minimum resolution of 2.0 pixels per square inch. In order to maintain this altitude and image quality throughout the entirety of search area, Trochilidae has been restricted in its obstacle avoidance paths during search area. Sample images taken from Trochilidae at this height can be seen in the *Object Detection, Classification, Localization* section of this paper.

2.5. Object Detection, Classification, Localization

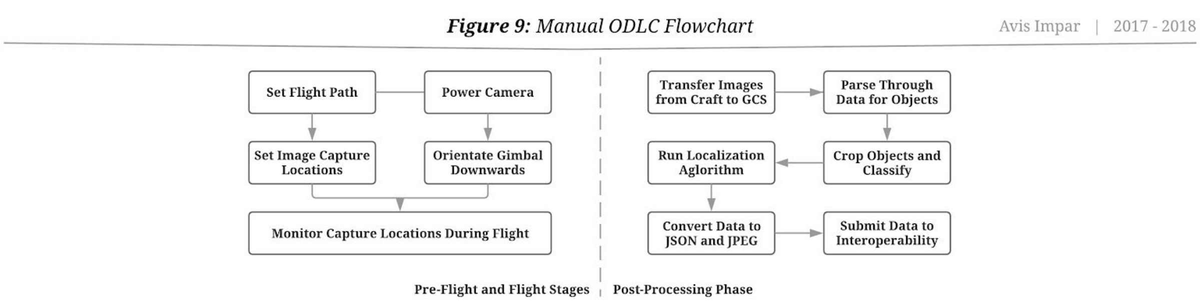
In order to delegate a majority of the team's focus towards developing a craft capable of autonomous flight, Avis Impar determined at the onset of development that the ODCL task would be conducted manual. This decision would allow the software subteam to spend most of their efforts on the interoperability integration and obstacle avoidance algorithm. Once all captures taken by Trochilidae's onboard imaging system are transferred to the base GCS, users are able to manually parse through the data and create crops of any detected objects. To simplify the techniques used behind orientation classification, Avis Impar has opted to fix the imaging system's direction throughout the entirety of the flight. This gives the team a predetermined relationship between the cardinal directions and the orientation in which the images are taken in. Once an object has been detected and classified by a user, a localization algorithm pairs the metadata of the image with the flight logs from Trochilidae. This allows users to pinpoint the exact location of Trochilidae during the time at which the picture was taken. Since the imaging system is pointed directly to the ground at all times, Trochilidae's location corresponds to the location of the image's center. This information, along with the fixed PPSI value determined by the altitude during search area, allows the localization algorithm to calculate the pinpoint location of any pixel within the image. Avis Impar then utilizes this position data, and compiles it alongside the other classifications into a JSON for data submission.

In order to ensure the reliability of the system, Avis Impar has run multiple ODCL missions and tests upon the localization algorithm. The team found that they were able to detect and classify objects in almost all of the tests. In its final iteration the localization algorithm was able to localize all objects with an average localization error of 20'. During testing our members were able to detect 29 of the 30 objects tested against. Detection and classification results from all ODLC testing can be seen in **Table 7**. In addition to mission tests, the flowchart shown in **Figure 9** has been created to simplify and streamline the ODCL process.

Table 7: *Detection and Classification Results*

Element	Number Correct	Success Rate
Object Detection	29	96.67 %
Object Shape	28	96.55 %
Object Color	29	100.00 %
Object Orientation	27	93.10 %
Alphanumeric	28	96.55 %
Alphanumeric Color	28	96.55 %

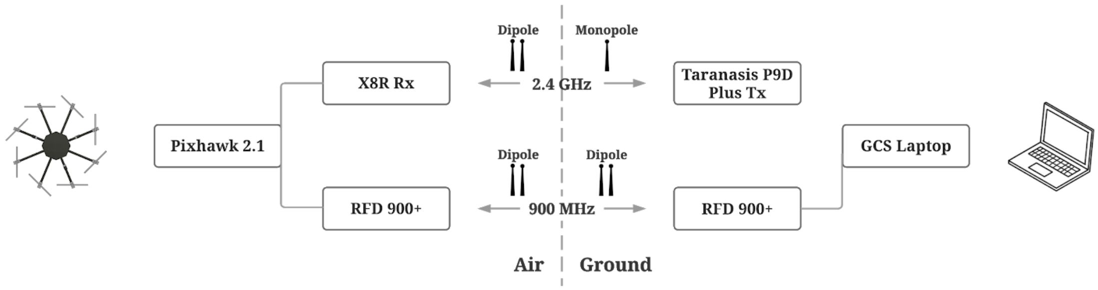
Figure 9: *Manual ODLC Flowchart*



2.6. Communications

In order to successfully complete autonomous flight, two wireless links have been established between Trochilidae and the ground. These links have been designed to perform with additional backup options in the event of unforeseen connectivity issues. All communications between Trochilidae and GCS are transferred over an encrypted 900 MHz frequency hopping link established through the addition of two RFD 900+ modules. Both the ground and air modules are connected to dual half wave dipole 3dBi antennas to ensure connectivity at long ranges. In addition, the dual antennas have been placed orthogonal to each other to ensure that Trochilidae's orientation does not affect connectivity. In the rare event that the 900 MHz communication pipeline were to be broken, the safety pilot will always have manual control over Trochilidae through a 2.4 GHz link. This communication pipeline is established using a FrSky Taranis X9D+ Transmitter and a X8R Long-Range Receiver on board Trochilidae. Further characteristics of the communications system can be seen in **Figure 10**.

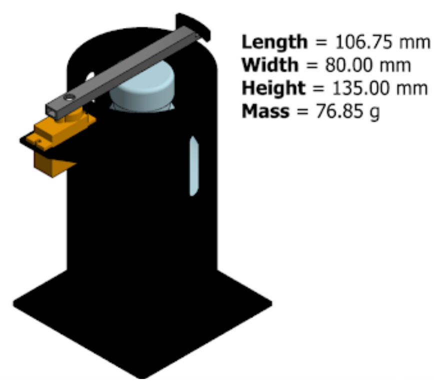
Figure 10: *Communications System Diagram*



2.7. Air Delivery

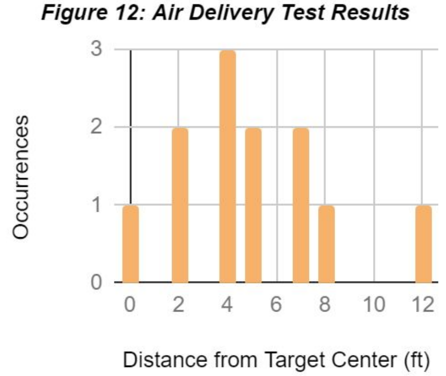
To ensure an accurate and reliable delivery of the payload, a custom airdrop mechanism was designed and drafted using Autodesk Inventor 2018. Throughout the year, the team prototyped many renditions of the mechanism, focusing specifically upon reducing the footprint and mass in each iteration. For the final rendition, the water bottle sits within a cylindrical enclosure that is closed off by a pin. When signaled to release, a servo actuates and removes the pin from under the water bottle - thus releasing it from the enclosure. Further specifications and a rendering of the air delivery mechanism can be seen on **Figure 11**.

Figure 11: *Air Delivery Mechanism*



Without the need to compute complex dynamic equations, Trochilidae is still able to reliably achieve accurate drop results. This is because, unlike a fixed-wing, Trochilidae is able to hover above its drop location. Since the water bottle is required to explode upon impact, the team decided to not modify the payload in any way. To minimize the effects of wind and drag, the water bottle is always dropped from 100’ AGL - unless this altitude is obstructed by a stationary obstacle. In order to ensure the reliability of the air delivery, tests were conducted in varying weather conditions and on different terrains. Following all tests, the team found that the water bottle would always explode on impact and land an average of 5’ away from the target’s center. In the chance that a stationary obstacle were to force Trochilidae to deliver the water bottle from a higher altitude, the team conducted additional delivery tests from the maximum altitude of 750’. It was found that, in all high altitude tests, the water bottle landed no more than 12’ away from the target’s center. Results from all delivery tests can be seen in **Figure 12**.

Figure 12: Air Delivery Test Results



2.8. Cyber Security

In order to ensure that UAS is secured against external cyber attacks, Avis Impar has worked diligently to encrypt and bind each communication pipeline. By using RFD modules, the team has been able to secure the 900 MHz communication between the GCS and Trochilidae with frequency hopping AES encryption. As per the 2.4 GHz bandwidth, both the controller and transmitter have been specifically bound to each other with an encrypted passcode. This makes it virtually impossible to disrupt the link - unless the attacker has physical access to either the transmitter or receiver. The GPS modules used upon the craft are also secured against location spoofing and jamming. In addition to these safety measures, Avis Impar has equipped the GCS and Transmitter with external communication cut off switch. When activated, this switch commands the craft to isolate itself from all external communications and react in one of the following ways: land, return home, emergency stop. By applying all of these cyber safety measures, Avis Impar is confident that Trochilidae and the GCS are secured against all cyber attacks.

3. Safety, Risks, and Mitigations

3.1 Developmental Risks and Mitigations

In order to ensure the safety of all personnel, strict guidelines were set in place by Avis Impar prior to the development period. In order to gain access to the lab and all the tools held within it, each member was required to take an extensive training course that lasted approximately three hours. After completing this course, the members were drafted on the safety risks posed by the development and flight of UAVs, and were required to sign a safety contract unique to the team itself. At all times, Avis Impar had a designated safety lead and kept all necessary safety equipment on hand - fire extinguisher, safety glasses, Li-Po safe bags, etc. To mitigate the major developmental risks specified in **Table 8**, Avis Impar conducted individual component testing on all items before implementing them onto the UAS. In order to mitigate the safety risks posed by the UAV, all personnel were required to stand at least 15' away from the craft in flight. This, along with the additional safety criteria and checklist mentioned in Section 3.2, allows for a safe and efficient developmental period.

Table 8: *Mitigation Strategies for Developmental Risks*

Developmental Risk	Occurrence	Severity	Mitigation Strategy
Lack of Personnel Training	Medium	Medium	All members were required to read the safety manual, attend a safety training, and sign a safety contract.
Injuries caused by Flight Testing	Low	High	All crafts were flown within a netted cage, with all flight personnel standing outside of said cage.
Injuries caused by Manufacturing Error	Low	High	Personnel never worked alone and all attachments and fabrications were checked by all subteam members.

3.2 Mission Risks and Mitigations

As a large multirotor, Trochilidae poses many safety risks during its autonomous flight and testing. To mitigate risks associated with the craft's proximity to others in flight, Avis Impar always begins each flight with a debrief to ensure all team members are aware of the craft's planned flight path and payload deliveries. At all points of the mission, Avis Impar periodically consults the safety checklist, shown in **Table 9**, to ensure that the UAS is cleared for flight and reacts predictably during all stages of the mission. In case the UAS starts malfunctioning, the team has also designed the craft with many failsafes and backups. For one, the electrical system has been developed around the goal of redundancy. This gives the UAS the ability to safely land in the case of motor or battery failures. In case the UAV were to land with damaged components, Avis Impar keeps spares in inventory to replace parts as needed. In order to ensure the safety of others during the competition mission demonstration, Avis Impar has practiced every flight with high safety protocol.

Table 9: *Safety Checklist*

Stage 1: Pre-Flight	
- GCS and Transmitter Checks -	- UAV Checks -
Enure GCS is Sufficiently Powered and Plugged In	Inspect Propulsion System for Damage and Secureness
Ensure Transmitter is Charged and Connected to UAV	Inspect Airframe for Damage and Loose Connections
Load Mission Planner is on Latest Firmware	Ensure Payload is Secured
Connect to UAV and Ensure High Connectivity	Ensure Imaging System is Oriented Downwards

Confirm that all Failsafes and Geofences are in Place	Verify Batteries are Charged and Powering Craft
Verify connection to Interoperability Server and OAA	Ensure Craft is Calibrated and has GPS Lock
Stage 2: Takeoff and Flight	
- GCS and Transmitter Checks -	- UAV Checks -
Clearing Landing and Takeoff Area of Obstacles	Enable Power to Propulsion System via Safety Button
Verify all Antenna Orientations and UAV Connections	Arm the UAV via GCS and Transmitter
Verify Battery Level and INteroperability Connection	Conduct Spin Test to Ensure All Motors are Spinning
Ensure All Members Return to Flight Line	Initiate Autonomous Takeoff and Flight
Stage 3: Post-Landing and Image Processing	
- GCS and Transmitter Checks -	- UAV Checks -
Disconnect from the UAV and Power Off Transmitter	Dis-Arm UAV and Propulsion System
Initiate Manual Image Processing	Power Off UAV and Check Battery Conditions
Submit all Image Data to Interoperability	Transport Craft Back to Flight Line
Return Ethernet Cable to Judges and Finish the Mission	Transfer Imaging System Data from Craft to GCS

4. Conclusion

Throughout this season, Avis Impar has worked diligently to create a fully custom octocopter named Trochilidae. With the ability to perform autonomous flight, payload delivery, obstacle avoidance, and image capture, Trochilidae has been designed and developed around the elements of reliability and redundancy. Numerous flight simulations and testings have ensured that Trochilidae will perform well in the mission demonstration and is ready to safely participate in the 2018 AUVSI SUAS Competition. The tests conducted provide an opportunity to model the crafts performance at competition, and allows Avis Impar to make better informed decisions based upon the craft's projected performance. Overall, Avis Impar has achieved the goals set forth by the team for this year, making it a successful year going into the competition. Although Avis Impar is a first year team, Avis Impar is optimistic about Trochilidae's chances at competition, and are proud of the work that they have completed this year.