Clark College Aerospace 2019
AUVSI SUAS Competition
Penguin Porter Mk1 Technical Design

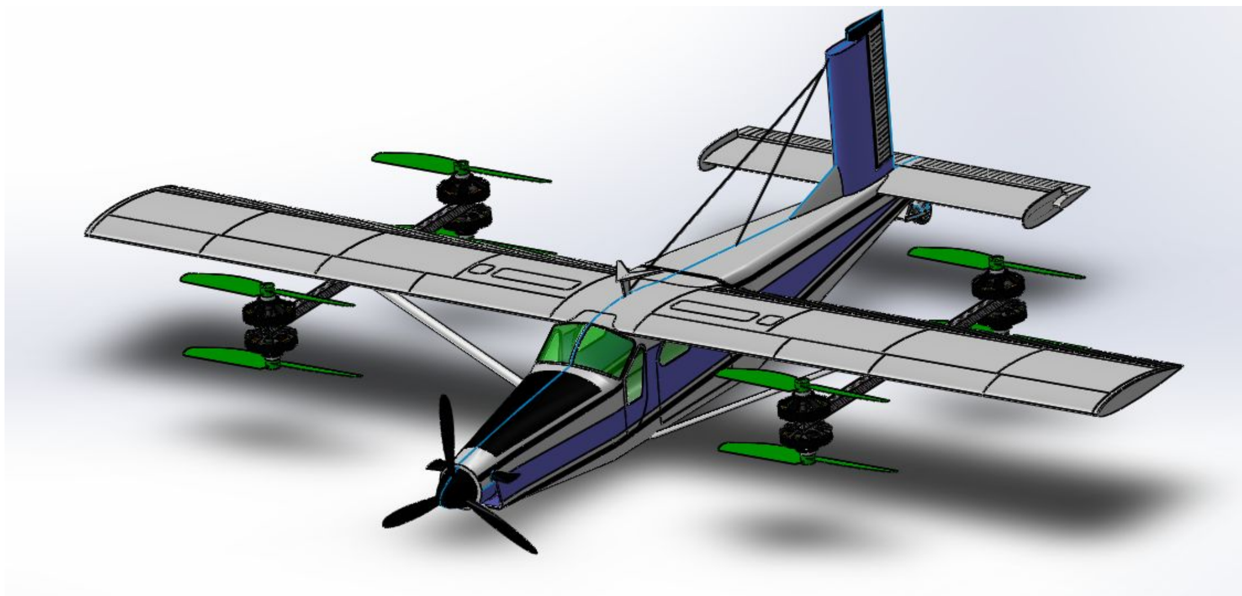

Figure 1: Penguin Porter Mk1 Aircraft

1 Abstract

The Clark College Aerospace Program's SUAS team (i.e. the team) designed and manufactured a vertical takeoff and landing (VTOL) aircraft and unmanned ground vehicle (UGV) with accompanying ground stations to participate in the 2019 AUVSI SUAS competition. The team consists of 6 first and second year undergraduate students in the fields of Mechanical Engineering, Computer Science, Electrical Engineering, and Systems Engineering. No current members of the team have first hand experience of the AUVSI SUAS competition. Utilizing prior professional experience in telecommunications and hobby level experience in the fields of RC recreation, the team designed and manufactured the Penguin Porter. The Penguin Porter is a VTOL fixed wing aircraft, designed to simplify the learning process of operating and manufacturing a safe system capable of performing the tasks assigned by AUVSI. Due to the team's limited number of members and experience the decision was made to base the Penguin Porter off a proven open source design to streamline the design and development process. The Penguin Porter is able to autonomously takeoff, travel through waypoints, deploy a UGV from 100 feet above ground, return to launch, and land without human intervention. The team created multiple subscale airframes and systems to prove the viability and safety of each component and software system of the Penguin Porter.

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2 Systems Engineering Approach

Focus was directed at completing a reliable and cost efficient platform from a proven design concept. The system was inspired by an open source project manufactured and designed for a similar set of parameters to the AUVSI SUAS competition.

Minimal hardware and design concepts were reused from the 2018 competition year due to the change in mission parameters increasing the overall flight distance requirement, as the last year's model was not optimized from long distance flight. The following sections define the SUAS mission requirements, and justify design decisions implemented to satisfy those criteria.

2.1 Mission Requirements Analysis

The mission demonstration simulates an unmanned aerial package delivery system operating in a cluttered airspace requiring: navigation around potential hazards, identifying potential drop locations, dropping the payload to ground level in a safe manner at a desired location, then finally transporting the customer package over the remaining distance in a timely manner. **Table 1** defines the requirements of each mission task including a scoring breakdown, a corresponding description of success, and explanation of penalties that can be assigned.

Table 1: Mission Requirements Analysis Grading Criteria

Tasks		
Mission Requirement	**Specifics**	**Team Definition of Success**
Timeline [10%]	• Time spent for mission and post processing [80%] • Not using allotted timeout [20%]	• Completion of all attempted tasks within 40 minute timeframe • No penalties for procedure or safety violations
Autonomous Flight [20%]	• Autonomous operation of system with minimal manual overrides [40%] • Flying within 100 feet of each waypoint along flightpath [10%] • Proximity to waypoints (accuracy) in sequence [50%]	• Zero manual overrides • 100% first attempt in sequence accuracy
Obstacle Avoidance [20%]	• Avoid stationary simulated obstacles [100%]	• 100% of obstacles avoided
Object Detection, Classification, Localization [20%]	• Determine characteristics, shape, color, etc [20%] • Geolocation of object [30%] • Objects classified during first flight [30%] • Automated classification submissions [20%]	• The Penguin Porter will not attempt this task

Airdrop [20%]	● Safely drop UGV and payload from 100 feet [50%] ● UGV drives payload to <10 feet from final GPS destination [50%]	● Airdrop safely within 25 feet of target ● UGV does not travel out of bounds ● Delivery to waypoint within 10 feet
Operational Excellence [10%]	● **All Scores Subjective** ● Operation professionalism ● Communication between members ● Reaction to system failures ● Attention to safety	● Ground station excellence acknowledged ● Operation professionalism and performance acknowledged

Penalties

Mission Sub Category	Portion of Score Lost
Timeline	● Exceeding 40 minutes operations time or 10 minute teardown time [3% for each second over] ● Using Timeout [100% of timeout points]
Autonomous Flight	● Manual override [10% each] ● Failure to adhere to mission boundary [10% each] ● Unsafe restricted airspace breach [100%] ● Things falling off aircraft (TFOA) [25%] ● Crashing [35%]
Obstacle Avoidance	● Failure to upload valid telemetry to interoperability system (average of 1hz while airborne) [100%]
Object Detection, Classification, Localization	● No points awarded for objects detected by leaving mission boundaries ● Superfluous object detected submissions [5% for each]
Airdrop	● UGV landing greater than 5 feet from GPS coordinates ○ 5+ to 25 feet [50% Drop score] ○ 25+ to 75 feet [75% Drop score] ○ 75+ [100% Drop score] ● UGV leaves 100 foot boundary of target coordinates [100% Drive score] ● UGV does not transport payload to within 10 feet of target coordinates [100% drive score]

The team's assessment is that the competition encourages the precision, agility, and payload delivery characteristics of a rotorcraft, while still heavily relying upon the efficiency and stamina associated with a traditional fixed wing aircraft. The 100 foot minimum UGV and payload (rover) airdrop is most easily performed by a rotorcraft at hover rather than requiring additional logic designed around weather variables and projectile calculations needed by a traditional fixed wing craft. However, the four mile potential mission length combined with forced restart of waypoints for each landing discourages the use of standard multirotor designs seen in previous competition years. The requirement of ground based object detection requires the use of powerful cameras, rigs, and accompanying software which will not be present in the Penguin Porter.

2.2 Design Rationale

Due to limitations of resources such as personnel, the decision was made to omit all object detection and classification systems for the 2019 competition. This choice was made when analyzing what was feasible and effective for the team.

Preconstructed, fully-integrated mobile ground control stations help to reduce setup and teardown time for operational flights. Flight testing resulted in a refined tuning of the autopilot program to most efficiently carry out the mission parameters for the Penguin Porter. The aircraft had to be designed to accurately hit multiple waypoints, drop a payload, takeoff/land safely, and fly a minimum of 4 miles. VTOL aircraft have the capacity to hover allowing for greater accuracy on the airdrop and improved agility for waypoint flight plans. The efficiency of forward flight capabilities increases the maximum range. Both the UAS and rover are controlled via free, open source control software, allowing for both reduction of cost and development time. The airdrop is deployed via parachute due to its mechanical simplicity and minimal hover time requirements. The rover is 3D printed and will adhere to the 3 lb payload restriction. The decision to 3D print the rover frame also provided greater flexibility in manufacturing and design, allowing for multiple design iterations during testing and implementation.

3 System Design

3.1 Aircraft

The Penguin Porter was inspired by the Canberra UAV entry for the 2018 UAV Outback Challenge in Australia [1], which proved that a scale replica of the Pilatus PC-6 (herein called the Porter) running open source flight control software and equipped with VTOL lift motors could perform similar missions as required by the AUVSI SUAS competition. Using an online power and propulsion calculation tool called eCalc [2], the forward flight time for the aircraft at 25m/s was determined to be approximately 30 minutes. Based off flight simulations provided by AUVSI, the determination was made that this provided a margin of safety large enough to proceed with the given system design. The motors chosen using this software provided high efficiency at mid throttle settings and could handle the necessary power output.

The initial proof of concept for the team's VTOL platform was based off of an "aged" Eflite "Super Cub" with race quadcopter motors attached via paint sticks (nicknamed Frankenplane) shown in **Figure 2**. This platform served as the proof-of-concept showing that the design can operate properly. This model was eventually decommissioned for having extremely low flight times due to very small battery compartments restricting the maximum capacity of the battery.

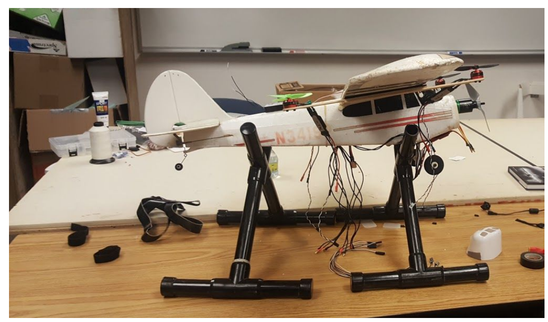

Figure 2: Frankenplane Prototype

A modified Flite Test "FT Explorer" was chosen as the successor to Frankenplane shown in **Figure 3**. Flite Test is a popular YouTube content creator and manufacturing company centered around low cost entry to aviation.

Figure 3: FT Explorer Prototype

This airframe had many advantages over the previous prototype, namely: larger wing area for increased lift, larger avionics bay to house the necessary electronics needed to ultimately operate the Penguin Porter, low cost, and the ability to be manufactured quickly following a failure or design modification. The FT Explorer also introduced larger battery capacity along with the addition of more efficient motors. This improvements resulted in significantly increased flight times allowing the team to begin autonomous flight testing. Ultimately this model proved the capabilities of the team's autopilot software, and all instruments and sensors necessary to fly the mission waypoints at competition.

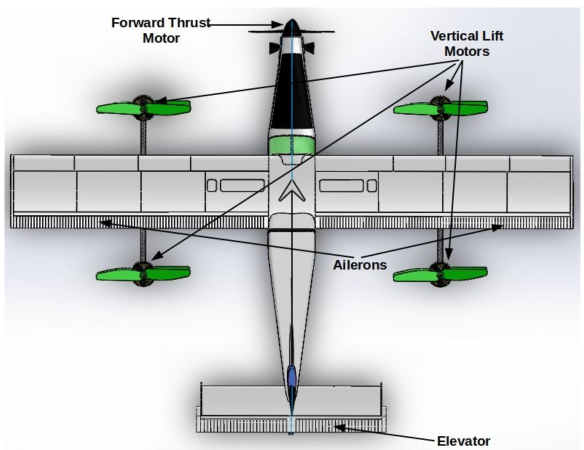

Figure 4: Labeled Top View

The competition aircraft selected shown above in **Figures 4** and right in **Figure 5** (the Penguin Porter) consists of an aircraft grade plywood skeletal structure. When all the electrical systems (control, power, etc.) were installed and tested the frame was then covered in a lightweight plastic covering material called MonoKote. The MonoKote covering was applied using a heat gun, and an iron made specifically for this purpose.

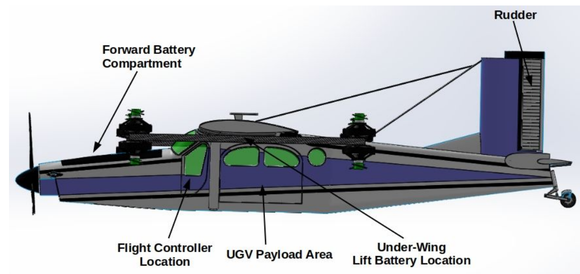

Figure 5: Labeled Side View

All of the propulsion systems for the Penguin Porter make use of electric motors as seen below in **Tables 2 and 3**. Electric motors have several advantages over traditional internal combustion engines, including: consistent center of gravity during flight due to no fuel being consumed, reduced mechanical complexity and maintenance, and eliminating the need to use flammable hazardous fuels.

During vertical flight mode lift is provided by 8 coaxially mounted motors. While in forward flight mode one nose mounted motor generates the necessary thrust to provide airflow over the wings generating lift.

Table 2: Aircraft Motor Characteristics

Penguin Porter Motor Characteristics					
Part	Weight	KV Rating	Power	Max Thrust	Quantity
KDE4213XF-360	242g	360 RPM/Volt	1,125 Watts	2.60 kg	8
KDE600XF-530-G3	441g	530 RPM/Volt	3,905 Watts	12.30 kg	1

Table 3: Aircraft Wing Characteristics

Penguin Porter Wing Characteristics	
Airfoil	Clark K
Wing Span (m)	2.72
Wing Area (m^2)	0.814
Aspect ratio	8.08
Chord Length (m)	0.335

Modifications to the airframe were needed to perform the required mission. Two pieces of carbon fiber mounting plates were added to the wings to support the lift motors. The main wing had the spar extended to redistribute the load path of the lift motors.

3.2 Autopilot

The Penguin Porter uses the Navio2 flight controller [3] shown in **Figure 6**, which is a hardware attached on top (HAT) board with a Raspberry Pi 3B+ [4] as the host computer. This hardware was chosen over a dedicated flight controller (FC) such as the 3DR Robotics Pixhawk [5] used by the 2018 team, due to its increased computing resources.

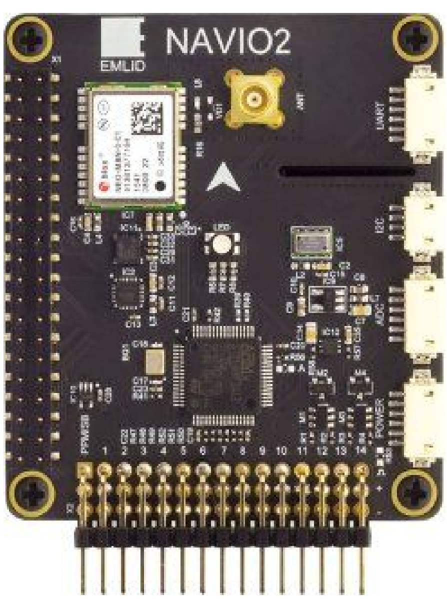

Figure 6: Navio2 Flight Control Board

Even with the added computing capability this FC still provides hardware interfaces for all of the same sensors as the Pixhawk including: triple redundant power supply, redundant inertial measurement units (IMU's), global positioning system (GPS), compass, and barometer. The benefit of this design choice is that it gives future teams the option to implement more advanced control algorithms onboard the aircraft without having to purchase new hardware, while simultaneously performing the necessary flight control functions required for this year's competition.

The Penguin Porter's FC makes use of the ArduPilot flight control software (specifically Arduplane 3.9.7) [6]. ArduPilot is the most widely used open source flight control software in the UAV development community with a long history of stable flight operations. The software is feature rich supporting: numerous VTOL airframe configurations, autonomous flight capabilities, and numerous flight safety features such as mission geofencing and emergency landing. The combination of track record, available features, and ease of use ultimately led the team to choose this software over similar open source flight control software systems, namely PX4.

The team made use of a combination of ground control software (GCS) applications for this year's competition in order to satisfy all mission requirements for the ground station. The lack of sufficient team member availability to build a single custom solution to fit the missions need also meant that off-the-shelf open source free solutions were required.

The first major requirement that needed to be satisfied was the ability to send UAS telemetry to multiple GCS applications simultaneously, including the judge's Interop server. The Mavproxy GCS application [7] was used to satisfy this need as this feature is built in and takes up minimal computing resources due to its lack of a GUI front end. Mavproxy has the added benefit of being able to handle loading of mission and geofence files to the UAS, minimizing the amount of development resources required to develop software to handle incoming mission plans from the Interop server during the competition.

Other requirements for the ground station are the abilities to present relevant mission telemetry data to the ground support crew while also giving operators the ability to update mission parameters and flight characteristics of the UAS and UGV in real time. QGroundControl [8] as seen below in **Figure 7** was chosen to fill this role as it satisfied these requirements while providing the operator with a more intuitive user interface than other similar GCS applications including APM Planner, Mission Planner and UgCS.

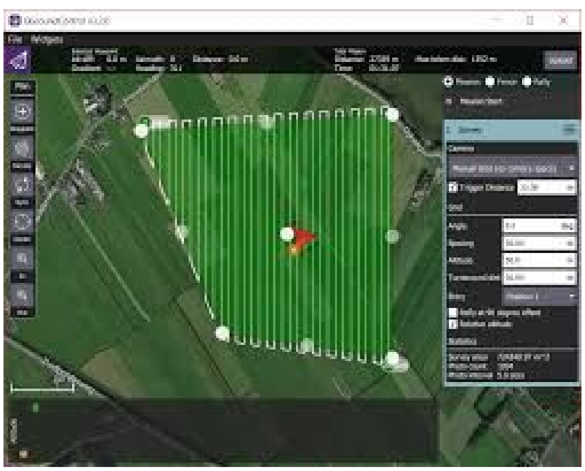

Figure 7: QGroundControl GCS

The autopilot and GCS applications were extensively tested utilizing ArduPilots included simulation suite Software In The Loop (SITL) [9]. This allowed the team to verify the behavior of these software components. New operators were also able to utilize this simulation environment to familiarize themselves with aircraft operations in a low risk environment prior to test flight.

3.3 Obstacle Avoidance

The obstacle avoidance system uses an algorithm in order to generate the optimal path through mission waypoints with the logic stated below:

- Determine where two lines intersect (flight paths)
- Determine whether two line segments cross
- Find the length between two waypoints
- Determine whether the direct path between two waypoints crosses through an obstacle at a given geographical location and radius
- Find the two tangent lines a point makes with an obstacle at a given point and radius
- Compare paths and choose the shorter distance

A flow chart of the algorithm is provided below in **Figure 8**.

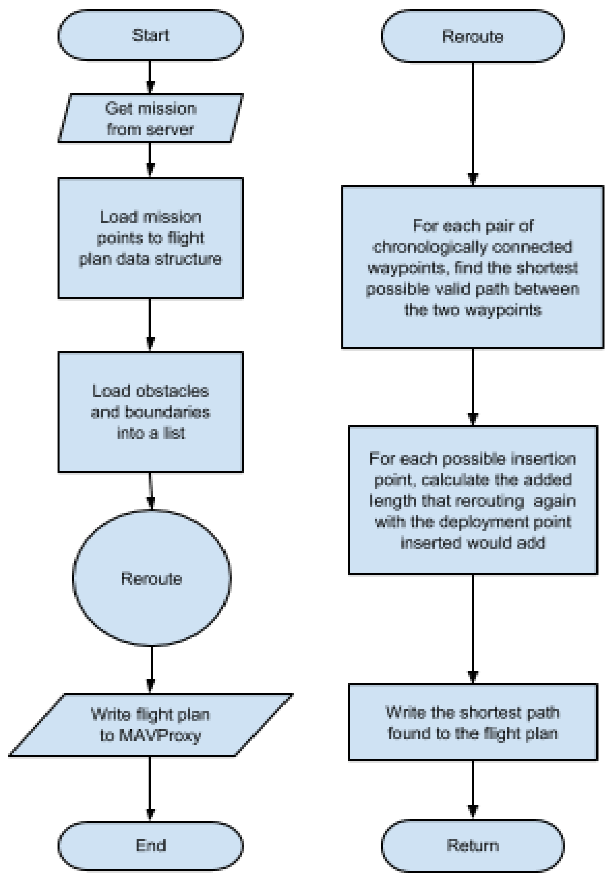

Figure 8: Obstacle Avoidance Algorithm Flow Chart

When receiving a mission, the data will be loaded and interpreted accordingly: an obstacle will be represented with the point and radius the plane needs to avoid, with a small buffer added to the circle. The edges of the mission boundaries, as well as the runways, will be marked as lines, and the points of interest throughout the mission will be placed in order on a queue. To increase algorithm fault tolerances, overlapping obstacles will be assumed to have boundary lines from radius point to radius point. For paths with obstacles or boundary lines between them, the algorithm will add waypoints using the following process:

- Check if the offender is an obstacle or boundary line
- If it is a boundary line, assume a circle of buffer radius from each of the boundaries.

The algorithm was then tested utilizing an Interop server image along with the Ardupilot SITL application to verify the viability of the path planning process.

3.4 Communications

In order to ensure communications are maintained between the ground station and the aircraft at all times, reliability and redundancy are of the utmost importance in the communications system. To facilitate this the UAS has two wireless links between the aircraft and the ground station with redundant telemetry connections. A diagram of the system can be seen below in **Figure 9**.

The primary link is a 5.8 Ghz 802.11AC WiFi link. The secondary link is a 900 Mhz Frequency Hopping Spread Spectrum (FHSS) point-to-point serial radio system. The WiFi link consists of a Ubiquiti M5 Rocket [10] inside the aircraft and a Ubiquiti M5 Bullet [11] at the ground station. This link carries a video feed for safety pilot situational awareness during flight and both air and ground vehicle telemetry channels. The 900 Mhz link consists of a pair of RFD 900x radio modems [12]. The link carries a redundant vehicle telemetry channel as well as a pass-through RC channel. This pass-through channel allows the safety pilot to manually take control of the Penguin Porter in the event of a system anomaly. Additionally the ground station utilizes a Mikrotik RB4011 wireless router [13]. The unit provides Ethernet connectivity between the various ground support equipment ground station equipment (GSE) and the Interop server, as well as a 2.4 Ghz Wireless LAN specifically used by the teams wireless headsets for verbal communications during mission operations. All wireless links utilize AES encryption to minimize both accidental and/or intentional interference with the UAS during flight operations. **Table 4** provides a summary of all frequency bands used.

Table 4: Communication System Frequencies

Link	Equipment Used	Frequency Band Used
Primary Telemetry	• Ubiquiti M5 Bullet • Ubiquiti M5 Rocket	• 5.8 Ghz WiFi (5180 Mhz to 5825 Mhz)
Secondary Telemetry	• RFD 900x Modem Pair	• 900 Mhz ISM Band (902 Mhz to 928 Mhz)
Aircraft Video	• Ubiquiti M5 Bullet • Ubiquiti M5 Rocket	• 5.8 Ghz WiFi (5180 Mhz to 5825 Mhz)
RC Pass Through	• RFD 900x Modem Pair	• 900 Mhz ISM Band (902 Mhz to 928 Mhz)
Local Headset Voice Traffic	• Mikrotik RB4011 Wireless Router	• 2.4 Ghz WiFi (2412 Mhz to 2462 Mhz)

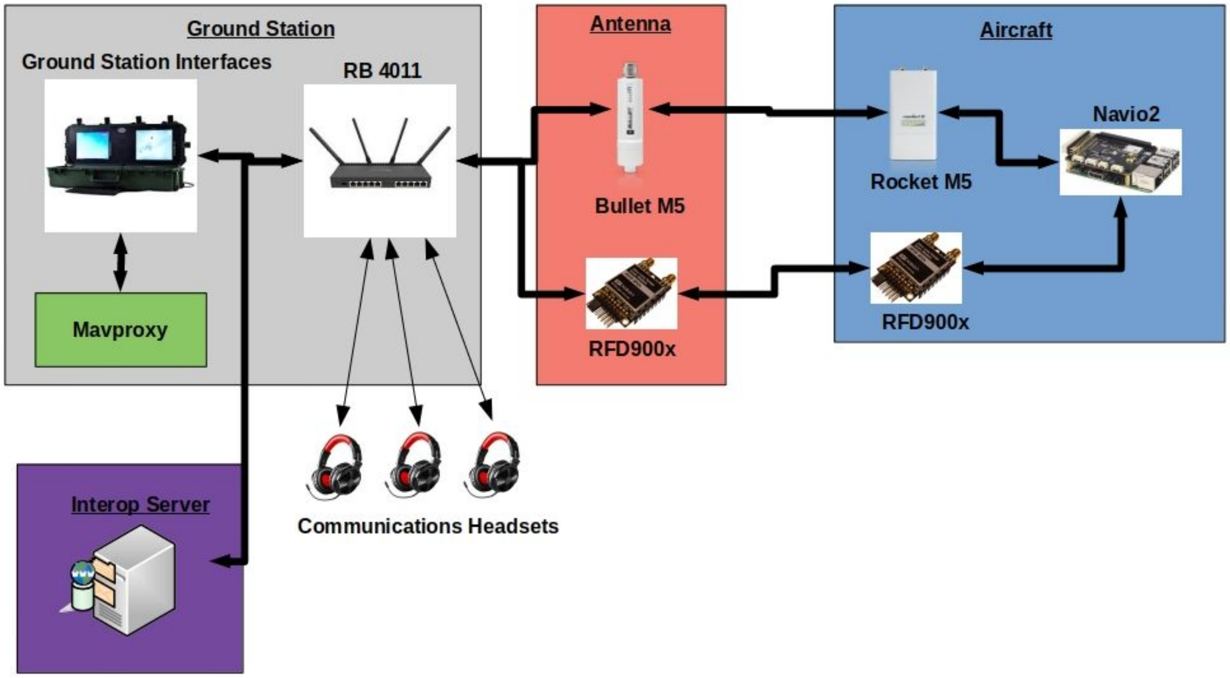

Figure 9: Communications System Diagram

The radio systems makes use of a combination of various antennas at the ground station and in the aircraft to help facilitate reliable communications during flight operations. The ground station radio systems are mounted to a self supporting 14 foot antenna mast. By elevating the systems above the ground, potential RF interference from the ground station can be reduced while simultaneously helping improve line of site between the ground station and the aircraft and rover during the mission.

Both the Ubiquiti M5 Bullet and RFD 900x are connected directly to the mast in weather resistant enclosures with Ethernet and serial connections respectively back to the GSE. The Ubiquiti M5 Bullet is connected to a single 9 dBi end fed dipole antenna. While the RFD 900x is connected to two 9 dBi end fed dipoles configured for spatial diversity with both horizontal and vertical polarity. Omnidirectional dipole antennas were chosen for the ground station instead of directional antennas because they eliminated the need to implement an antenna tracking system simplifying the development requirements for the communications system. Additionally the maximum distance from the ground station to the aircraft during any portion of the mission falls within the acceptable receive range of the receivers for both radio links. This was confirmed by performing SITL simulations to determine the maximum expected flight distance between the Penguin Porter and ground station, which was determined to be approximately 650 meters. Then range tests were performed for both communications systems out to 800 meters with no dropouts in the communications links, proving the reliability of the communications.

All of the aircraft's antenna arrays are housed in the tail section of the aircraft. This location was chosen as it moves the antennas as far as possible from the aircraft's propulsion system, in turn minimizing RF noise interference. Both radio systems are configured for spacial and polarity diversity in order to help mitigate both multipath issues and signal fade caused by a polarity mismatch between the ground station and the aircraft which is continuously changing orientation during flight. The Ubiquiti M5 Rocket makes use of 3 dBi end fed dipole antennas, while the RFD 900x uses low profile flexible patch antennas .

3.5 Airdrop

Delivery of the payload consists of two primary operations, aerial deployment followed by ground delivery to target, location as shown to the right in **Table 5**. A rover housing the payload will act as the ground transport and as shielding for the payload during the drop as seen in **Figure 10** to the right. The chosen design for the rover is a three wheeled model. The wheels and body are 3D printed to maximize the tradeoff of structural integrity to weight inherently necessary to deliver the payload safely during the drop while adhering to the 3 lb rover and payload combined weight restriction. An exploded diagram of the rover is seen to the right in **Figure 11**. The rover is driven by two compact drone motors. The internal flight control board and payload are on a removable tray for ease of access. The rover is controlled by a Raspberry Pi that will communicate with the ground station via WiFi.

Table 5: Rover Deployment Process

Part 1 Air Deployment	Part 2 Ground Delivery
GPS recognizes arrival at drop coordinates, initializes drop sequence	Rover rolls to stable position then orientates the rear of the rover up relative to ground
Upon Penguin Porter reaching stable hover over dropsite, rover drives along a track towards exit of aircraft	Solenoid release rear strut
Rover exits aircraft and parachute deploys	GPS will determine where rover is facing relative to the destination. Rover will rotate to face destination
When GPS indicates that the rover is 5 ft above the ground two solenoids activate releasing the parachute.	Rover will transport (via ground) payload to exact destination

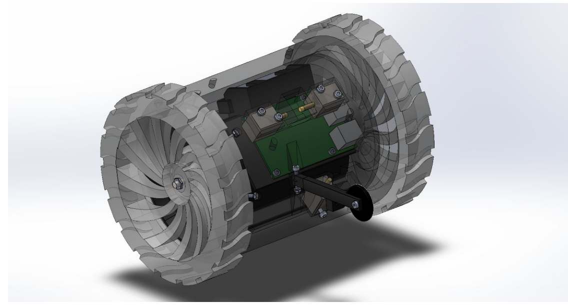

Figure 10: Rover Functional Assembly

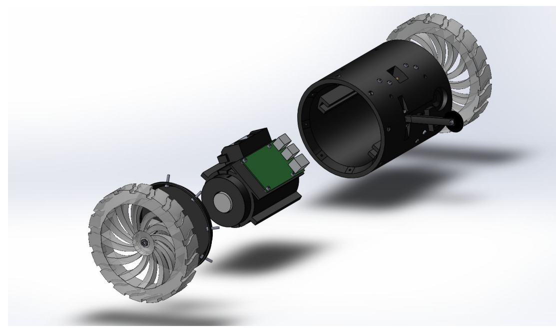

Figure 11: Rover Exploded Assembly

3.6 Cyber Security

Security is key in any mission critical system. The first major threat posed to the system from a cyber security perspective is accidental or intentional interference during operation. The attack vectors by which this threat is potentially realized are namely: RF interference to wireless communications, GPS and ADSB systems, intentional spoofing of the transmitted signals to these wireless systems, and physical impairment to different portions of the system.

The other major type of threat to the UAS is the intentional infiltration or access by a malicious actor into a part of the system. The main attack vectors for the realization of this threat being: physical access into a portion of the system, access of computational systems through the wireless links present into the UAS and GSE portions of the system during operation, and access to computational or software components of the system during or outside of normal operation periods.

The team has several technologies and protocols in place to minimize the risks mentioned above when operating a UAS. These mitigation techniques fall into one of three main categories:

physical access control, wireless security, and software access control. Physical access control specifically deals with the security policies and practices related to mitigating the potential theft or impairment of the system. Wireless security relates to the security technologies and resiliency inherent in wireless protocols used to communicate among the various subsystems of the UAS. Software access control is the area of security that deals with access of legitimate users (or malicious actors) to the different software applications within the system. This process is illustrated in **Table 6.**

Table 6: System Security Considerations

Threat Vector	Consequence	Defensive Strategy
Physical Access Control		
Unauthorized personnel, infiltrates, modifies, steals or damages a portion of the system during transport	• UAS may become impaired or unsafe to operate • Potentially lose control of UAS to malicious agent • Proprietary information may become compromised.	• Transportation cases for all equipment are locked during transport or when not in use
Authorized personnel accidentally damages or negatively modifies a portion of the system	• UAS may become impaired or unsafe to operate	• Strict adherence to access and maintenance procedures while working on the UAS
Wireless Security		
Malicious agent attempts to gain access to, or snoop on traffic through wireless communications links	• Potentially lose control of UAS to malicious agent • Information about mission operations may become compromised	• AES encryption enabled on all wireless communication links • Use wired links when possible
Intentional or unintentional RF interference or spoofing present in the frequency band of a communications link or receiver	• Loss of communications with the vehicle • Malfunctioning GPS receiver	• Use of frequency hopping or spread spectrum techniques to avoid interference • Use of interference tolerant GPS

Software Access Control		
Malicious agent attempts to access computing systems in the ground station or flight controller	• Loss of control to vehicle or other subsystems	• All computing systems password protected

4 Safety, Risks and Mitigations

Safety is fundamental to any engineering process, especially when developing an UAV. Personal safety is the first priority of the team. Protocols were used during the development and operation of the UAS, first to ensure the safety of personnel involved, followed by the safety of the equipment utilized. Various risks and mitigations were studied and evaluated both prior to and during the testing and operations process to provide a comprehensive approach to managing risk. The criteria for characterizing each risk was broken into likelihood of occurrence and severity, both classified by Low, Medium, and High.

4.1 Developmental Risks & Mitigations

The risks encountered during the development process of the Penguin Porter were various and ranged from low to high severity. The largest risks are listed in **Table 7** along with the mitigation strategies employed.

4.2 Operational Risks & Mitigations

After consolidating comprehensive analysis of potential safety risks throughout the design process a list of key risks were combined with their mitigation strategies below in **Table 8.**

Table 7: Summary of Developmental Risk Analysis and Mitigation Strategies

Developmental Risk	Occurrence	Severity	Mitigation
Personal injuries resulting from component testing	Low	Medium	• Testing of hazardous systems is always performed with proper equipment such as thrust stands • Use of adequate shielding between operator and equipment being tested
Fabrication errors resulting in personal injury	Low	High	• Adherence to safety protocols and training • Use of PPE strictly enforced during manufacturing process
LiPo power system fire	Low	High	• Complete battery logs for maintenance • Balance charging only • All storage and travel utilized LiPo fireproof bags

Table 8: Summary of Operational Risk Analysis and Mitigation Strategies

Mission Risk	Occurrence	Severity	Mitigation
Loss of communication between airframe and ground station	Low	High	● Return to Launch (RTL) override of flight path if airframe breaches digital fence ● Safety pilot override
Crashing airframe during testing/mission	Moderate	High	● Preflight checklist of all systems ● Safety pilot override during autopilot anomalies ● Enforced minimum safety perimeter from flight path and takeoff/landing locations ● Real time monitoring telemetry
Pilot error	Low	High	● Only fly when safety pilot deems weather conditions satisfactory ● Redundant disarm capabilities from ground station ● Pilot has access to telemetry and flight plan in real time
Release of debris or payload during flight	Low	Medium	● Flight testing in approved airspace only ● Adherence to safety perimeter during testing and competition.

5 References

[1] “Canberra UAV entry for the 2018 UAV Outback Challenge in Australia” [Online]. Available: http://canberrauav.org.au/outback-challenge-2018-debrief/

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