University of Alberta Aerial Robotics Group Unmanned Aerial System

2018 AUVSI SUAS Competition Paper

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Abstract

The Unmanned Aerial Vehicle industry is an expanding industry with many opportunities emerging in mapping, agriculture, law enforcement, and aerial inspection. This paper describes the Unmanned Aerial System (UAS) engineered by the University of Alberta Aerial Robotics Group (UAARG) for the 16th Annual Student Unmanned Aerial Systems Competition (SUAS) by the Association for Unmanned Vehicle Systems International (AUVSI) Seafarer Chapter. Our final iteration of our Mothra Class Lightweight Fixed-Wing Unmanned Aerial Vehicle (UAV) will be used to preform the various mission tasks. With the combination of avionic instrumentation and onboard processing, this UAS will photograph objects, geo-locate their position, survey areas, and navigate waypoints.

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Acronyms

AED – Automated External Defibrillator
AES – Advance Encryption Standards
AGL – Above Ground Level
CSTS – Construction Safety Training System
DSSS – Direct-Sequence Spread Spectrum
EHS – Environmental, Health, and Safety
EPP – Expanded PolyPropylene
ESC – Electronic Speed Controller
FPV – First-Person View
GCP – Ground Control Point
GCS – Ground Control Station
GPS – Global Positioning System
GUID – Globally Unique Identifier
HTTP – HyperText Transfer Protocol
IMU – Inertial Measurement Unit
Li-Po – Lithium Polymer
MCS – Modulation and Coding Scheme
MP - Megapixel
MSL – Mean Sea Level
PFD – Primary Flight Display
PLA – PolyLactic Acid
PoE – Power over Ethernet
PPE – Personal Protective Equipment
R/C – Radio Controlled
RF – Radio Frequency
SDS – Safety Data Sheets
SFOC – Special Flight Operations Certificate
SUAS – Student Unmanned Aerial Systems
TC – Transport Canada
UAARG – University of Alberta Aerial Robotics Group
UAS – Unmanned Aerial System
UAV – Unmanned Aerial Vehicle
WHIMS – Workplace Hazardous Materials Information System

1 Systems Engineering Approach

1.1 Mission Requirements

UAARG plans to complete all competition tasks except for the Air Delivery task. Due to a large turnover of the group in the past year, UAARG has focused this year on training new members to understand the current system and its components. A list has been developed to ensure that the chosen UAS can complete the various tasks at competition:

1. The UAV should be quick to assemble and limit human error during assemblage.
2. The UAV should be able to fly autonomously including takeoff and landings.
3. The UAV should be able to capture, store, and transfer photographs of ground targets during flight to permit real-time imaging processing.
4. The UAV autopilot should be able to avoid obstacles that are both stationary or moving.
5. The design should be within the financial budget of UAARG.
6. The design should be able to be transported to the competition via aircraft.

As the air delivery task has never been completed before, UAARG will not be completing this task due to the difficulty of designing, engineering, and seeking permission to complete these tests. As a Special Flight Operations Certificate (SFOC) is required to test within Canada, permission must be given by Transport Canada (TC) before testing may occur. In addition, the apparatus required for the air delivery task will add significant weight to the aircraft, complicating the integration of such a system. As such, with limited manpower and funding, UAARG will look at developing such systems at a future date.

1.2 Design Rationale

1.2.1 Environmental Factors

Various environmental factors restricted UAARG's development in the year preceding the Mission: team composition, available funding, and climate conditions. During this year, UAARG has taken on new undergraduate students with little or no prior experience with UAS, while many senior members have retired from the club. The remaining core members spent a significant amount of time training newer members to operate on the UAS. Although promoting and proliferating knowledge on UAV is a core component of UAARG's platform, this process limited development time on the UAS.

Table 1: UAS Cost Estimate Breakdown

Airframe		Imaging		Autopilot		Ground Station	
EPP-FPV Frame	$89.00	Odroid Processor	$60.35	PCB Board	$401.48	Laptop	N/A
Motor	$56.98	Camera	$716.50	GPS Module	$15.56	Antenna	$52.90
Servos/ESC	$28.72	Lenses	$144.25	Antenna	$42.45	Router	$115.90
Battery	$134.55	Wi-Fi Module	$128.90	Air Speed Sensor	$35.00	Charger	$20.00
Propeller/Wires	$40.00	Cables/Connectors	$50.00				
							Total: $ 2032.54 (CAD)

Regarding finances, UAARG has been fortunate to consistently receive funding from various sources; however, time taken in applying for funding takes from time that could be used for development and testing. Funding amounts are also limited, with the total cost of research and development being less the cost to travel. Keeping the cost of the UAS down allows for UAARG to continue designing and adapting the UAS should sources of funding become sparse. Although this limits the complexity of the UAS, ensuring the club's sustainability is more significant.

Furthermore, the climate in the region of Alberta where UAARG is based presents an obstacle to year-round testing. Snow, wind, and cold temperature during winter from November to March inhibits flight testing without prior permission from TC and an amended SFOC. During this time the club instead focuses on software and airframe development. These restrictions on development and testing time result in preference towards design options that take less time to develop, or general developments that may be easily reused in future designs as opposed to more specialized additions. Once again this ensures the sustainability of UAARG by the simplicity or the quick development time of the chosen design should membership numbers fall.

1.2.2 Airframe

The airframe supports the UAV's electronics, power supply, and other mission-critical payload. The airframe was chosen to provide a platform capable of sweeping all mission waypoints and following any unexpected flight path corrections while carrying the payload weight of 3.11 lbs. (1.41 kg). The following factors were also considered in this year's airframe: The airframe should be reliable to minimize the possibility of system failure, be highly modular such that individual systems and parts are replaceable in cases of failure, the platform should be highly compact, transportable and easily deployable while minimizing interference between systems.

Decisions were made between improving upon the existing fixed wing airframe design, using a new fixed winged design, and using a multi-rotor design. UAARG presently uses a modified single motor expanded polypropylene (EPP) foam fixed-wing (Mothra Class) airframe acquired from Hobbyking (online shop). The frame is already highly modular, lightweight, transportable and can support all systems required by the competition except for payload delivery. UAARG decided to continue to use the existing design due to its historical success at meeting mission criteria consistently, and current budget and manpower constraints limiting new developments [13]. UAARG opted to omit the payload delivery system due to manpower constraints and its complex nature as mentioned in *1.1*. Instead, focus was put towards improving the reliability of the new modifications and making assembly streamlined.

1.2.3 Electronics

Since various control systems are needed to carry out the mission requirements, it was decided to integrate all core electronics onto a single board unit to simplify the logistics of containing the required technology on the UAV. Individual systems however should still be powered independently, so that they may be isolated for troubleshooting and development as well as be provided with voltage levels tuned to each of their needs. The following criteria will be considered in the board design:

- The size and shape of the board should minimize the volume taken by the electronics. This allows for a smaller, lighter and more aerodynamic fuselage, as well as more volume for additional payloads.
- Subsystems should be assembled neatly and securely such that wired connections and overall structural integrity of the setup is reliable and as failsafe as possible.

The options meeting the requirements are to use the current electronics board or producing a new one. As it was already decided to keep the previous year's airframe, it was also decided to keep the electronics board from 2017. This decision was based on the board's optimized volume saving fit to the current airframe which already meets the desired criteria, as well as working within manpower and budget constraints.

1.2.4 Autopilot System

The autopilot provides the UAV with automated navigation without pilot intervention. To do this it must be capable of freely manipulating all control surfaces on the UAV. UAARG has decided on the following criteria for the autopilot to successfully meet mission requirements:

- Allow for immediate takeover by the safety pilot if needed.
- Uninterrupted access to telemetry information and upload rate to interop server.
- Ability to plot received obstacle information.
- Ability to respond to updates from ground station to perform tasks such as flight path re-routing.
- Fail-safes in case the aircraft goes out of bounds or loses a datalink connection with the ground station.

To meet the requirements, UAARG had the option of keeping the old autopilot system, Paparazzi, or modifying it to be able to respond to obstacles and avoid them automatically. Such a modification was deemed too complex to be achievable with this year's available manpower, so UAARG opted to keep the previous year's version of Paparazzi.

1.2.5 Imaging System

The following specifications were determined for the imaging system:

- The minimum object size specified in the rules is 1ft x 1ft; an object of such size should be at least 8x8 pixels for a human operator to successfully determine its properties.
- The height at which object searches are performed must remain between 88-728 feet (26.8-221.9 meters) AGL, which is between 100 and 750 feet (30 and 228 meters) MSL at Webster Field.
- Searching for ground targets must take less than 15 minutes. From previous years' flight data [13], it takes ~10 minutes to complete the waypoint navigation, takeoff, return to home from search area, and landing portions of the mission. Subtracting an additional 20 minutes to complete image post processing, this leaves 15 minutes out

of the total allowed 45-minute mission time to complete a search. Based on previous years' provided search areas, the search area will be approximately 0.12 square miles (0.3km^2).

- Camera shutter speed should be controllable and, based on empirical data, should be at least 1/1000 of a second, to avoid motion blur.
- The camera aperture and ISO should be controllable to compensate for decreased exposure due to increased shutter speed.
- The camera frame rate should not exceed more than twice the update rate of location and attitude information from the autopilot system, which is currently at 2Hz.
- An image should not be tagged with data that is more than 100ms delayed from the time that the image was captured. Ideally, the camera should provide a millisecond-resolution timestamp on captured images.

1.2.6 Communications System

To meet the mission requirements, UAARG will focus on three lines of communication between the ground control station and the plane:

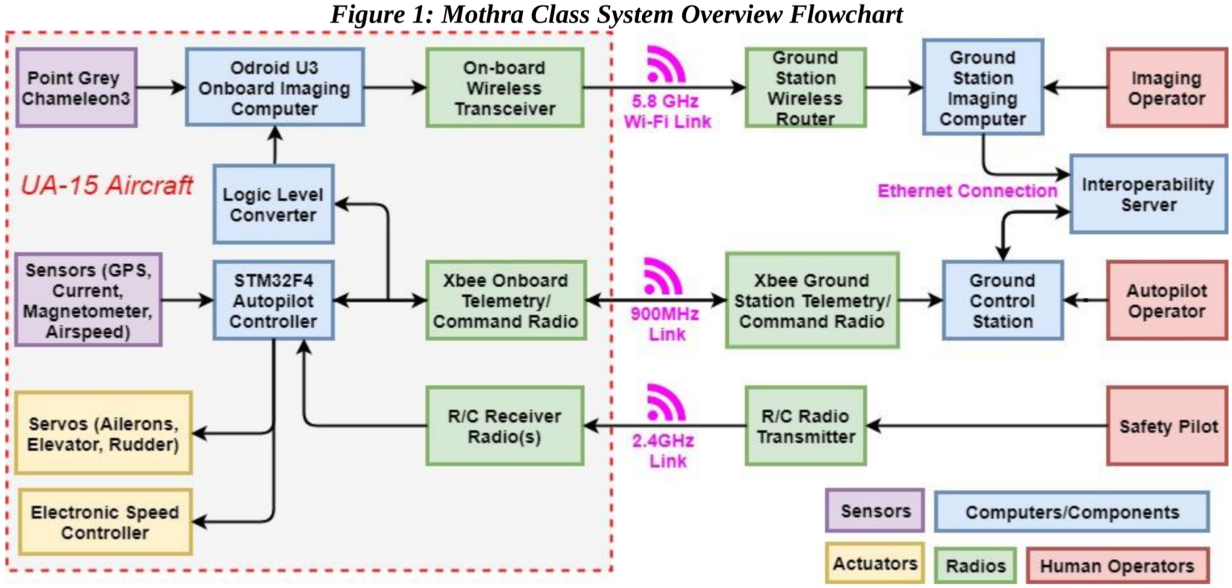
- A Control Link to facilitate manual takeover in an emergency. This is particularly important for takeoff and landing, during which a fatal collision is most likely and would have the largest cost to mission success. As UAARG has previously experienced a crash during takeoff, the safety link has been deemed an important countermeasure. The link should include signal strength testing and failsafe contingencies in case of link failure.
- A Control and Telemetry Data Link to ensure the onboard autopilot is up to date with flight plan changes and the ground station is up to date with the UAV's status. A minimum throughput of 200kbps has been deemed adequate.
- A Control and Image Data Link to transmit image data from the UAV to the ground station. For ideal performance, images should be transferred in real time, so the data transmission rate must be equal to or greater than the image capture rate. As UAARG is employing a 2.8-megapixel camera operating at about 0.40 fps, an average throughput of 0.05 MB/s would be needed to transmit the data in real time.

Considerations for ideal performance across all communication lines have been determined:

- All links must have a range of at least 1 mile (1.6km) to span the competition flight area.
- Link performance should not be significantly degraded by changing aircraft orientation.
- Systems/protocols to prevent interference with foreign communications due to the lack of RF management.
- Tradeoff between link range vs. throughput and antenna gain vs. directivity based on chosen systems.
- Ease of integration with the autopilot and imaging systems.
- Operation frequencies will be limited by available hardware and legal regulations, however selection from the available frequencies should account for properties including range and bandwidth to optimize link performance according to the previously stated parameters.

2 System Design

Figure 1: Mothra Class System Overview Flowchart



2.1 Aircraft

Figure 2: Mothra Class Fuselage Close-up

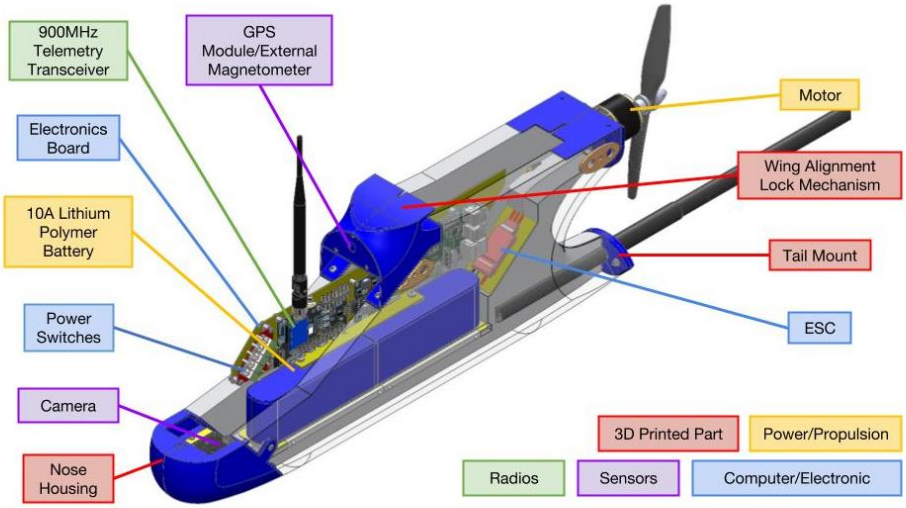


Table 2: UAV Specifications

Category	Fixed Wing (Electric)
Wingspan	6.2ft (1.9m)
Fuselage Length	4.6ft (1.4m)
Rotor Diameter	10in (25.4cm)
Max Takeoff Weight	8.8lb (4kg)
Gross Weight	6.2lb (2.8kg)
Landing Method	Belly Landing
Takeoff Method	Hand-Launched
Max Speed	49 knots (25m/s)
Max Range	1.2mi (2km)
Absolute Max Endurance	50 Minutes

2.1.1 Aerodynamics and Propulsion System

The airframe is propelled by a GF Series - 10X7 propeller driven by a NTM Prop Drive Series 35-36A 800Kv brushless DC motor controlled and powered by a 60A electronic speed controller (ESC) and a single 10,000 mAh Lipo battery. This combination results in a current-draw safety factor of ~1.70 and flight times up to 40 minutes in clear weather conditions. The motor propeller assembly is located at the rear of the main airframe body just above the tail boom. This propulsion design allows greater flexibility in the placement of the main imaging camera and onboard electronics.

2.1.2 Materials and Manufacturing

Like the previous 3 years [13], UAARG will be utilizing a modified EEP-FPV commercial airframe, Mothra Class. All major joints in the original Mothra Class were replaced with custom designed 3D printed polylactic acid (PLA) plastic components. This makes the airframe components highly reproduceable and replaceable in case of part damage. The modifications also allow the electronic systems of the UAV to be easily accessible. This year, the 3D printed components were modified to address their reliability and fitting issues. Weak joints were also reinforced to reduce the possibility of component failure.

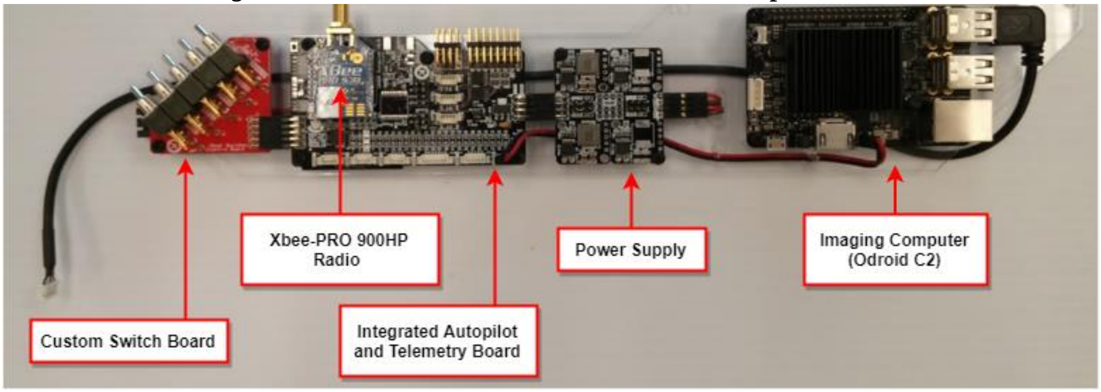
2.1.3 Assembly

The fuselage houses the battery and all primary electronic systems, and mounts the tail, camera and propulsion assemblies. The camera assembly consists of a 3D printed housing with the imaging camera and an airspeed sensor mounted on the front of the fuselage via 3D printed and bolted joints. The tail assembly consists of a carbon fiber boom and EPP elevator and rudder and are connected to the fuselage via bolted connections. The wings are connected to each other and a center wing module using carbon fiber rods and 3D printed housing.

2.2 Electronics

The electronics baseboard consists of the UAV's power supply board, integrated telemetry and autopilot board, switchboard and imaging computer mounted onto a thin lightweight acrylic sheet which installs into the fuselage. The acrylic provides a sturdy foundation ensuring reliable connections between the components while still being lightweight. The planar layout of the components also keeps connectors and pins easily accessible and facilitates easy removal from and insertion into the UAV. This ease of access makes debugging much easier and contributed to faster and more seamless development of the onboard system. Troubleshooting during the mission will also be fast and easy with this setup, which will greatly increase UAARG's ability to recover from any errors encountered during execution of the mission.

Figure 3: Electronics Baseboard with Custom Autopilot Board



Testing of the electronics began with ground tests to check the status of the telemetry link, RC link, PWM servo output, IMU output and power supply. This is depicted in Table 3.

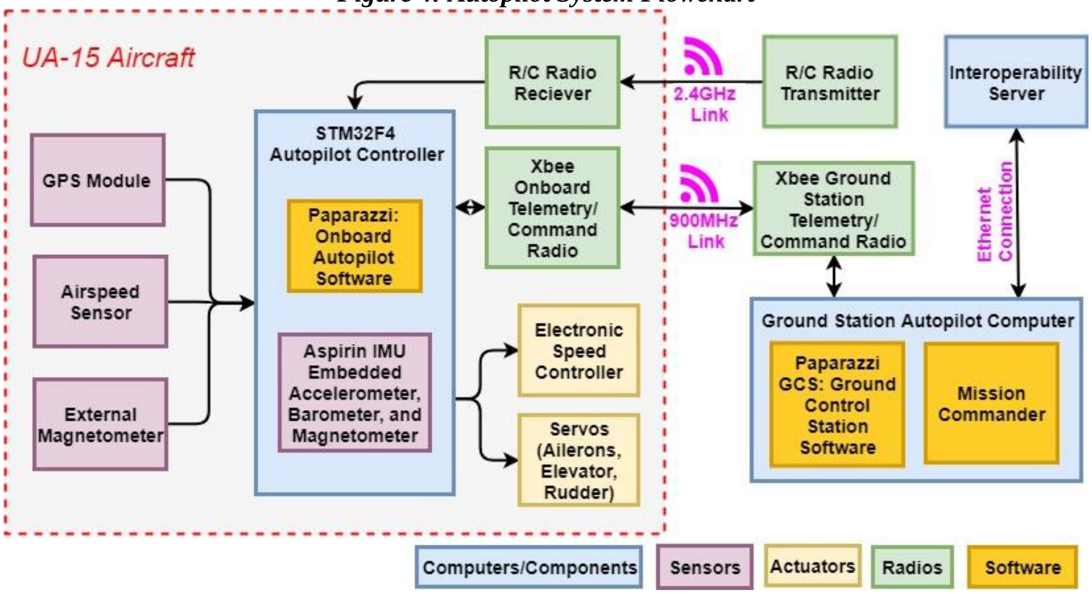
Table 3: Electronic Component Test Conditions

Component	Baseline test	Pass Condition
Servo Output	All servo channels operate independently and can move a servo	Min. PWM output <= 1000 us Max. PWM output >= 2000 us
IMU	Primary flight display (PFD) has the correct orientation.	Orientation within 1 degree of accuracy.
RC Link	Ability to control all servos.	Ability to control servos at 30 meters away with a transmitter in low power mode.
Power Supply	Both 5V power rails provide 5 $\pm$0.05 V of power.	Power supply can regulate with 2A test load for 10 minutes.
Telemetry Link	Send and receive any commands to the autopilot.	Send and receive any commands to the autopilot at 30 meters away with radios in low power mode with a data rate > 150 kbps.

After confirming each to be functional, a 1 hour long burn-in test was performed and the pass conditions were reevaluated.

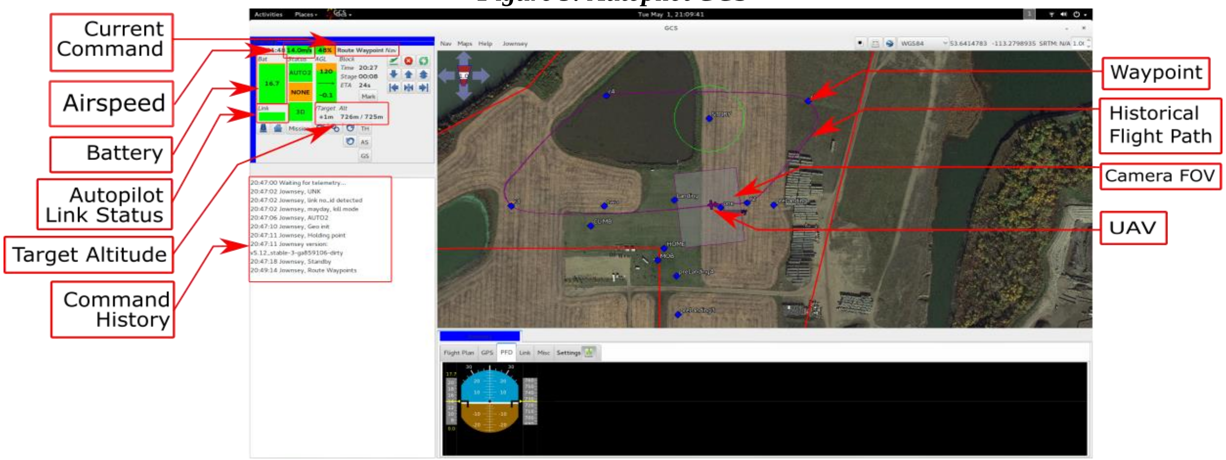
2.3 Autopilot

Figure 4: Autopilot System Flowchart



The autopilot uses an STM32F4 microcontroller running Paparazzi. Paparazzi was chosen as it is readily available freeware that meets the basic requirements of automated flight control for the mission; as well it is open-source and so may be modified to better meet mission requirements. The capabilities of the autopilot system include automated navigation to waypoints, displaying the UAV's status, and handling automatic take-off and landing. If the link to the ground station is lost, the autopilot will return the aircraft into standby mode. Various sensors such as an inertial measurement unit (IMU), barometer, GPS, airspeed sensor, and external magnetometer are utilized by the autopilot. The external magnetometer is needed as the power supply cables that are near the autopilot board induce an appreciable magnetic field which would interfere with the embedded magnetometer.

Figure 5: Autopilot GCS



The ground control station (GCS) controls and tracks the UAV. It displays data such as the historical flight path, expected camera field of view, and the PFD. The GCS also allows the UAV to perform preprogrammed actions such as automatic takeoff and waypoint route execution. A 200-kbps telemetry link (900MHz) allows the GCS to send and receive data (such as commands from mission commander) through a software structure called Ivy bus. Mission commander is UAARG's custom interface on the ground station used to modify the UAV's current flight path by communicating with Paparazzi. Being able to modify the mission in real-time provides greater flexibility which will contribute to easier completion of mission objectives even if unexpected developments occur. This function will prove useful in obstacle avoidance, discussed later in this report.

2.3.1 Waypoint Accuracy Testing

Waypoint navigation requires the UAV to fly within 100 ft of each waypoint, thus accuracy is critical. To minimize the distance error from the waypoint, the 2015 AUVSI SUAS competition was analyzed. Using a flight log, the flight was replayed in Paparazzi and the UAV's closest location to the waypoints were recorded. Since the autopilot records GPS readings in centimetres (0.01m) a precision of 1cm (0.03 ft) was used. The UAV's location nearest to the waypoint was compared to the location of the waypoint. Points from the autonomous navigation section (wp1-6) and select points from the search area (swp1-15) were included. When flying through the search area only select waypoints were meant to be flown through, thus only these were included [13].

Table 4: Waypoint Accuracy Analysis

Waypoint	Desired Location			Nearest Location			Error between waypoint and nearest pass [ft]
	Easting [m]	Northing [m]	Height [ft]	Easting [m]	Northing [m]	Height [ft]	
wp1	374419.455	4222603.634	200.00	374404.017	4222604.55	243.23	66.66
wp2	374520.102	4222451.06	200.00	374523.217	4222450.05	224.40	26.66
wp3	374996.464	4222473.01	500.00	374984.217	4222473.05	477.23	46.19
wp4	375282.625	4222715.25	400.00	375291.617	4222703.55	393.86	48.79
wp5	374875.579	4222592.03	300.00	374887.517	4222586.55	282.03	46.69
wp6	374777.705	4222814.54	300.00	374781.417	4222811.55	274.03	30.33
swp1	374772.417	4223519.95	285.43	374768.217	4223508.55	287.69	39.93
swp3	374752.317	4222804.05	285.43	374748.617	4222820.55	288.36	55.56
swp5	374676.317	4223527.95	285.43	374670.217	4223518.05	291.46	38.63

swp7	374670.817	4222754.05	285.43	374667.617	4222768.55	276.09	49.59
swp9	374565.317	4223532.35	285.43	374556.417	4223517.05	289.89	58.23
swp15	749617.542	8446336.75	285.43	374724.817	4223486.55	303.26	55.06
Max Error: 66.66 ft		**Min Error: 26.66 ft**			**Mean Error: 46.86 ft**		

Note: Eastings and Northings are referenced to UTM zone S18. Height is in feet above ground level.

The above results indicate that the average distance to the waypoint is roughly 50ft. This is significantly below the 100ft maximum as required by the competition. The error can be further mitigated by fine-tuning the flight plan to give the UAV more time to orient itself and by further developing the control systems within paparazzi.

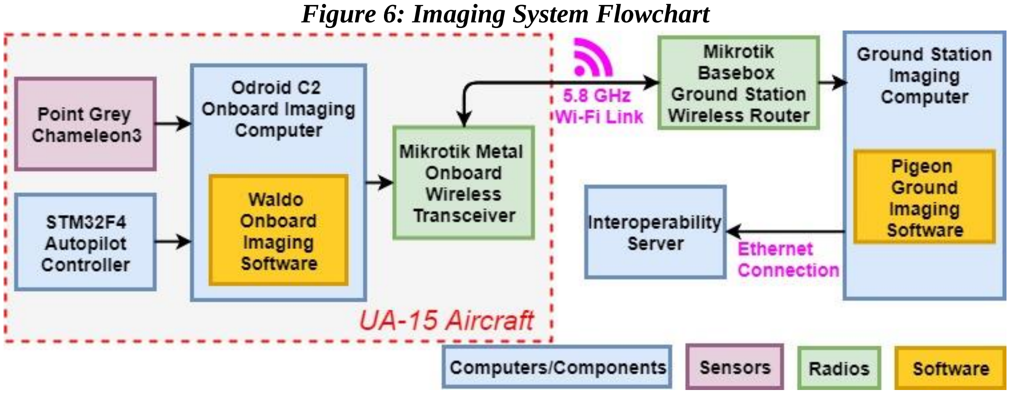
2.4 Obstacle Avoidance

UAARG has not developed any algorithms to path-find around obstacles due to insufficient resources. Static obstacle avoidance is done by creating and simulating a flight route using Paparazzi. If the simulated UAV navigates the route without colliding for several simulations, then that flight plan will be utilized during the mission demonstration. Should the UAV collide with an obstacle, the flight plan is modified, and the simulation is repeated.

This procedure is sufficient for static obstacles but cannot be used for avoiding moving obstacles. However, UAARG's autopilot and ground control system is unique in that it allows modification of the flight plan at any time. To take advantage of this, UAARG will employ two monitors to display the GCS for both the judges and the autopilot technician. Avoidance of moving entities will be accomplished by the autopilot technician relocating or creating new waypoints. This is done using mission commander, which receives the obstacle locations and parameters from the interop server and displays them on screen. This method's dependence on human input, however, is still not consistently effective and reliable, so in the future this action will be automated to ensure reliable obstacle avoidance and to reduce the autopilot technician's workload.

2.5 Imaging System

Figure 6: Imaging System Flowchart



The imaging system consists of:

- A Chameleon3 2.8 MP onboard camera.
- An Odroid C2 single-board computer. Custom onboard software, called Waldo, is responsible for controlling the camera for image capture, telemetry data tagging, and transmitting image data to the ground imaging station.
- A pair of wireless transceivers used for the imaging datalink. These are described in detail in the Communications section.
- A laptop serving as the ground station imaging computer which is receiving imagery information via the imaging datalink. A human operator at this computer uses custom software, called Pigeon, to view received images, mark objects of interest, and automatically generate and export geolocation data to the interop server.

Table 5 shows specifications and imaging performance for the current system, assuming flight at 164 ft (50 m) AGL and 30 knots (15m/s), 20% vertical ground overlap and 10% horizontal ground overlap between images, and a 20 Mbps data link. Since the same camera was used for the 2017 competition [13], UAARG decided to reuse it since it has already been tested and is sufficient in resolving the objects that are present in the competition. Calculations using *table 5* lead to a theoretical 8.7 px/feet and testing gives 7.84 px/feet. This is enough to resolve the required objects.

UAARG chose a Linux-based single-board computer as the onboard imaging computer due to the availability of image processing libraries and the need to interface with and control many different types of hardware. The Odroid was chosen due to its high performance and low price relative to other single-board computer options on the market at the time (the original Raspberry Pi, the Pandaboard, the Beaglebone). The placement of the Ethernet and USB ports on the same side of the Odroid C2 also helped its integration into our system, allowing for much more flexible placement for the camera and wireless transceiver modules. Waldo triggers image capture and reads telemetry data via a serial port connected to the Odroid from the autopilot board. Captured images and corresponding telemetry data are then sent over the imaging datalink to the ground station.

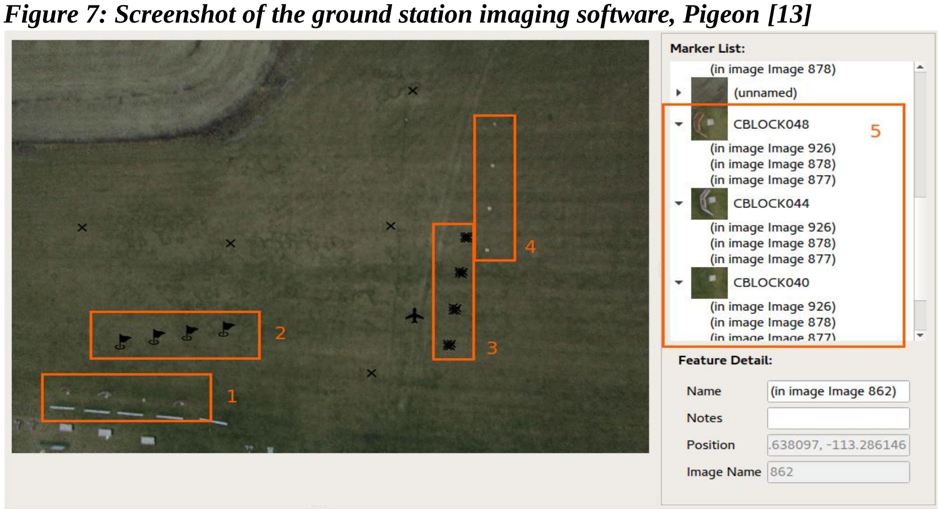
Table 5: Chameleon3 Camera System Specifications

Chameleon3 2.8 MP CM3-U3-28S4C-CS with a Fujinon DV3.4x3.8SA-1 lens	
Focal length (mm)	3.8
Megapixels	2.8
Horizontal and Vertical angle of view (degrees)	107 x 58
Horizontal and Vertical Pixels	1928 x 1448
Horizontal and Vertical Pixel Size of Standard Object	7.84 x 4.28
Required Capture rate (fps)	0.34
Time taken to fly search area (min)	3.1
Total # images captured	62
Time to transfer all images (min)	0.5

The ground station imaging software, Pigeon, automatically loads images as they are transferred from the aircraft. A human operator then analyzes the images and places markers on any features of interest; Pigeon then uses the metadata associated with that image to geolocate the placed marker. When a certain feature appears across multiple images, the operator can associate the markers for each of those appearances together. Pigeon will then use all the associated markers across all images to calculate a more accurate average position for the ground feature. Pigeon can also be configured to load Ground Control Points (GCPs), i.e. reference coordinates of objects.

2.6 Object Detection, Classification, and Localization

Figure 7: Screenshot of the ground station imaging software, Pigeon [13]



1. Ground Features of interest, corresponding to GCPs CBLOCK036, CBLOCK040, CBLOCK044, and CBLOCK048.
2. Marked locations of ground features in 1, from a previous image in which those same features were observed. Note that there is enough error here that the actual GCPs for those features are not visible in the image.
3. Ground features of interest, corresponding to the GCPs shown in 3.
4. Location of GCPs for the cinder blocks shown in 4.
5. List of all ground features found in the flight, with a list of images in which that feature appears.

To evaluate the imaging system's geolocation accuracy, a test flight was performed at a R/C testing field. Prior, the field was surveyed to determine the locations of visible features such as fence posts, cinder blocks, and sprinkler boxes. During a test flight, it is possible to use these as GCPs, known locations that can be used as references for images taken on the field.

In the test shown in figure 7, the 4 corner points of a cinder block were used as GCPs for a localization test. Whenever a set search point appears in an image captured by the aircraft, a marker is placed in Pigeon. Pigeon then calculates a location for each placed marker and compares it against the known location of the GCPs as reference. Doing this with all the associated GCPs in each applicable image calculates an average position for the markers. Error in average position was calculated by comparing the calculated average position to the true location of the GCPs.

Table 6: Comparison of Georeferenced Locations of Marker to Surveyed Marker Positions

GCP Name	GCP Position (Lat, Lon)	Calculated Position from Markers (Lat, Lon)	Number of Markers	Distance Error from GCP (ft)	Bearing from GCP to calculated position (°)
CBLOCK062	53.63816076, -113.28626089	53.638328, -113.286338	4	63.25	344.71
CBLOCK063	53.63816188, -113.2862882	53.638325, -113.286374	4	62.33	342.68
CBLOCK064	53.63818213, -113.28628574	53.638341, -113.286350	3	59.61	346.51
CBLOCK048	53.63844083, -113.28724673	53.638677, -113.287079	3	93.50	22.83
CBLOCK044	53.63844172, -113.2871223	53.638693, -113.286972	3	97.44	19.53
CBLOCK040	53.63844247, -113.28700646	53.638707, -113.286868	3	101.04	17.24
CBLOCK036	53.63844304, -113.28689239	53.638722, -113.286758	3	105.97	15.94

The above results demonstrate the imaging system's capability to achieve geolocalization accuracy within 150ft. With an increased number of passes over a ground feature of interest, the system would have a greater geo-localization accuracy.

2.7 Communications

Refer to Figures 1, 4, 6 for maps of connections between the subsystems

R/C Link

The R/C link system consists of:

- 2x Hobbyking orange RX R110XL receivers, with 2x whip antennas on each, connected via a serial link to the autopilot.
- A Spektrum DX8 R/C transmitter, with a single omnidirectional dipole antenna, operated by a safety pilot.

Table 7: Summary of Wireless Communication Links and Properties

Name	Frequency	Function	Protocol
R/C	2.400 - 2.483 GHz, Frequency-hopping spread spectrum	Manual control for the safety pilot, switching between manual and autonomous modes.	Spektrum DSMX
Autopilot	902.4 - 927.6 MHz, 400 kHz channel width, fixed-channel [8]	Receives telemetry, sends autopilot commands.	Digi proprietary, based on IEEE 802.15.4
Imaging	5.260 - 5.720 GHz, 20MHz channel width, Dynamic Frequency Selection	Receives captured images and metadata, sends commands to onboard imaging computer.	IEEE 802.11n

The R/C link operates on a frequency-hopping spread-spectrum protocol; a different channel within the band is hopped to after every transmission of a packet [7], to avoid interference with other 2.4GHz systems. The autopilot monitors the link strength at the receiver and initiates the failsafe protocol if the link is lost. To ensure matching polarization with the transmitted R/C signal regardless of aircraft orientation, the 2 OrangeRX receivers and their antennas are arranged perpendicularly to each other. The autopilot board supports diversity among its satellite receivers, reducing losses from polarization mismatch and multipath propagation. The OrangeRX receivers also support diversity among the two antennas [9]. These features add redundancy and reliability to the connection, which will help counteract connection-based problems.

Autopilot Telemetry / Control Link

The autopilot telemetry/control link system consists of:

- An Xbee-PRO 900HP radio and omnidirectional dipole antenna at the ground station, connected via a USB to serial adapter to the ground station autopilot computer.
- An Xbee-PRO 900HP radio and omnidirectional dipole antenna onboard the aircraft, connected via a serial link to the autopilot board.

The Xbee-PRO 900HP series was chosen due to the long ranges available with dipole antennae. Very low data rates are required for the telemetry and control link; the Xbee radios are operated in transparent mode, introducing no additional link overhead [5], and the Paparazzi direct serial message format has a very low (4-5 byte) overhead [6]. At a distance of 4 miles (6.5km) with 2.1dB omnidirectional dipole antennas, the Xbee radios are able to sustain a 200kbps link. Paparazzi allows configuration of the rates at which telemetry data is sent. As the link range far exceeds the minimum 1 mile (1.6km) required and the throughput of the link can be configured, there is a margin of error in the link which will greatly reduce the probability of severe autopilot link issues during the mission.

Imaging Datalink

The imaging datalink system consists of:

- A Mikrotik Metal 5SHPn wireless transceiver and cloverleaf antenna onboard the aircraft.
- A Mikrotik Basebox 5 wireless transceiver and 2x omnidirectional dipole antennas at the ground station.

A 5.8GHz band was chosen for this datalink due to higher available bandwidth and smaller physical size of the antenna compared to the 2.4GHz band; this is especially important for the ground station, where a directional antenna may be used in the future and where ease of transportation is a concern. A smaller antenna is also lighter, thus decreasing the weight of the UAV. The Mikrotik brand was chosen because of its well-documented command system and built-in scripting language. It also has an API for remote and automated commands and configuration, which is useful for setting up performance tests. The Mikrotik Metal 5HSPn has regulators and variable voltage input (9-30V), allowing it to be powered via battery. Both the onboard module and the ground module support Power over Ethernet (PoE), allowing transfer of data and power over a single cable.

To resolve polarization mismatch, one circularly polarized cloverleaf antenna [3] is placed onboard, and two linearly polarized antennas, oriented perpendicularly from each other, are installed the ground module. This configuration has a maximum loss of 3dB resulting from polarization mismatch [1].

Table 8: Link Budget for the Chosen Imaging Datalink Hardware Configuration

** Based on a maximum length between transmitter and receiver of 2.00 km*

Combination	Onboard Metal 5HPn + Cloverleaf, Ground BaseBox 5 + Omni Dipole	
Link Characteristics	**@ MCS0**	**@ MCS7**
Frequency (GHz)	5.805	5.805
Standard	802.11n	802.11n
Channel Width (MHz)	20	20
Modulation Method	MCS0	MCS7
Data Rate (mbits / s)	6.5	65
Free Space Path Loss (dB)*	-114	-114
Tx Power (dBm)	30	28
Tx Antenna Gain (dBi)	1.2	1.2
Rx Antenna Gain (dBi)	5	5
Polarization Loss (dB)	-3	-3
Total	-81	-83
Rx Sensitivity (dBm)	-96	-75
Link Margin (dB)	15	-8

A note on the MCS values in the table: for wireless communications, modulation method is related to desired theoretical throughput. For 802.11n, these can be represented by a standard Modulation and Coding Scheme (MCS) value, which associate a code with a certain modulation method and a set of data rates [2]. Generally, a higher desired Tx power or a higher required Rx sensitivity means a lower achievable MCS index value - i.e. lower achievable data rates.

The data link between the ground station and interoperability server was tested by logging HTTP requests between the mission commander software and the interop server. The data frequency was found to be an average of 2.00 Hz using the time stamps of the recorded log files, and the maximum and minimum latency was found to be 669 ms and 115 ms respectively (corresponding to a frequency of 1.49 Hz and 8.70 Hz). Telemetry information sent is taken directly from the autopilot software on the same computer, thus minimum losses are expected on the flight line.

2.8 Air Delivery

As stated in section *1.1*, the air delivery task will not be executed by UAARG. This is due to the limited funding, experience, and manpower available. Furthermore, the team requires permission from TC to perform the drop. UAARG plans to develop the air delivery mechanisms for its UAS in the future.

2.9 Cyber Security

The UAV system may be compromised if an attacker were to broadcast a sufficiently strong signal on the same frequencies of the system communications links, thus preventing the transfer of information from the ground station. The GPS signal to the UAV system may also be blocked. To mitigate this, the Paparazzi autopilot allows redundant links for telemetry but does not allow multiple control links [10].

Another possible attack is using an R/C transmitter to transmit messages to the R/C receiver, forcing a mode switch from autonomous to manual flight, and then continuing to transmit control messages from the hacker's receiver. This attack has serious consequences, as the autopilot system always respects a switch to manual flight requested over the R/C link. A successful proof-of-concept of this attack using a has been demonstrated against R/C systems using the DSMx protocol by exploiting a timing vulnerability in the protocol [4]. To mitigate this, R/C link frequency-hops are employed with a unique GUID to ensure the safety pilot always can control the UAV [13].

It is possible that an attacker with knowledge of the Paparazzi messaging protocol may be able to decode the autopilot telemetry and control messages using an Xbee. This is prevented by using AES when messages are sent and received by the ground station and onboard Xbees.

To prevent an attacker from accessing the autopilot system through the imaging computer, the imaging and autopilot computers are connected via a 1-way link using a single wire; Tx port of autopilot board is connected to the Rx port of the imaging computer only.

3 Safety, Risks & Mitigations

Development of the UAV imposes a complex environment with many safety considerations. As the small space we use is shared with 7 other clubs, safety is paramount in this diverse working environment.

3.1 Developmental Risks & Mitigations

During the development of the UAS, UAARG ensures its member's safety via various means including the development of Working Alone Procedures, Emergency Procedures, Lab Space training, Hazard Assessments, Personal Protective Equipment (PPE) Procedures, and supporting an overall safe working environment. Members receive training in Construction Safety Training System (CSTS), Workplace Hazardous Materials Information System (WHIMS) 2015, and Lab/Task Specific Training. As UAARG is governed by the University of Alberta, its members are required to comply with safety regulations at both the university and provincial level including requirements set by Environmental, Health, and Safety (EHS) [12].

Table 9: Developmental Risks Summary

Risk/Hazard:	Probability	Severity	Controls:
Short Circuit	Low	Medium	**Engineered -** All wire connections are insulated or covered by electrical tape and power from each component on the UAV can be cut individually.
Chemical Exposure	Low	Low	**Administrative** – All personnel have proper training and experience using glues, adhesives, tools, and cleaners. Relevant Safety Data Sheets (SDS) are present. Each task has procedure and documentation for workers to reference.
Unexpected UAS Behavior	Medium	Low	**Engineered/Administrative/PPE -** All testing is done without propellers mounted. Component power can be easily cut individually using the custom switch board. Members must wear the appropriate PPE and know to follow standard emergency response procedures. Documentation outlines procedures.
Injury	Low	Medium	**Administrative/PPE -** All personnel are trained in the proper procedure for all tasks to prevent injury including proper PPE. Several personnel have First Aid, CPR, and AED training. All injuries must be reported, and proper action will be taken to prevent a future incident from occurring again.

3.2 Mission Operations Risks & Mitigations

During operations of the UAV, the safety pilot has final authority to terminate the flight at any time and chooses the best method of landing the UAV. Members of the flight team may also end the flight but must first consult the safety pilot. UAARG performs a hazard assessment and writes an emergency action plan in case an emergency develops during UAS operation or transportation. Part of these documents assess the potential and severity of hazards present at the competition and are prepared to meet University of Alberta Standards [11, 12].

Table 10: System Communications Risks Summary

Risk/Hazard	Probability	Severity	Controls:
Lost Telemetry	Low	Medium	**Engineered/Administrative** - If telemetry is lost for >10s, the UAV will enter the Standby State. At this time, Telemetry may be regained, or the Safety Pilot will take manual R/C control of the plane. Links will be tested on the ground between the UAV and the ground station before launch.
R/C Uplink Failure	Low	Medium	**Engineered -** The UAV is programmed to go into an automatic mode wherein the autopilot will continue its mission. If no mission is active, it will enter the Standby State. If R/C uplink failure persists, the flight will be terminated by setting the UAV into the Termination State. Before takeoff, the pilot will do a control surface check to ensure R/C link in functioning. Transmitter uses DSSS modulation, frequency hopping.
Lost GPS	Low	High	**Administrative** - The autopilot ground station will indicate loss of GPS and the Safety Pilot will initiate manual R/C control until GPS is re-acquired. If GPS communication continues to be absent but no other safety concerns occur, the vehicle can continue the mission in manual flight mode. A stable GPS lock will be checked before the UAV can takeoff.
Imaging Link Loss	Medium	Low	**Engineered/Elimination -** The stability of the link between the UAV and the imaging computer on the ground will be verified. If the link is lost, images will be stored in the onboard computer and will be downloaded once the link is reestablished or the UAV completes the mission and lands.

Table 11: Hardware/Software Risks Summary

Risk/Hazard	Probability	Severity	Controls:
Autopilot Malfunction	Low	High	**Engineered/Administrative** - If the UAV is flying but behaving erratically, the UAV will be switched to manual flight. If the erratic behaviour is resolved, then it is the pilot's call to either resume or abandon the mission.
Imaging Malfunction	Low	Low	**Administrative -** If the imaging system fails, the UAV may continue to complete other tasks or may be landed to troubleshoot the issue. As the imaging system does not directly control the UAV, there is little danger to personnel or property.
Structural/ Servo Failure	Low	High	**Administrative** - Structural integrity and proper configuration of control surfaces will be checked to ensure the airworthiness of the UAV prior to takeoff. The UAV is insured to cover damages to property should it crash.
Runaway UAV/ Outside Mission Boundary	Low	High	**Engineered/Administrative** - The UAV will return to the standby waypoint if it leaves the mission boundaries. If it is unable to do so, the flight termination failsafe will automatically activate after 20s of being out of bounds. Before the UAV completes the assigned course, a simulation will be run to ensure the UAV remains within the boundaries.
Li-Po Fire	Low	High	**Elimination/Administrative/PPE** - Li-Po batteries are charged and transported in fire resistant bags. Proper procedures have been established with the handling and charging of Li-Po batteries.

Table 12: Human Risks Summary

Risk/Hazard:	Probability	Severity	Controls:
UAV Hand Launch Injury	Medium	High	**Administrative/PPE** - The individual throwing the UAV will be wearing safety glasses, gloves, and will have experience throwing the UAV. The high-mounted push prop prevents hand-prop contact in normal operation. If the individual sustains minor injuries, it is the decision of the team to halt the mission. Severe injuries require the mission to be halted. A motor kill switch will stop the motor from turning on until the UAV is ready for launch.

Human Error	Medium	Medium	**Administrative/Engineered -** In cases where human error leads to the wrongful placement of a waypoint causing the UAV to behave erratically, the safety pilot will take over. In cases where human error leads to improper placement of airframe components or configuration of the control surface, the safety pilot will perform a control surface check and inspect the airframe before takeoff. Many components have been engineered to prevent miss alignment or wrongful placement.
Personal Injury	Low	Medium	**Administrative/PPE -** All personnel are trained in the proper procedure for all tasks to prevent injury. A first aid kit will always be present on all missions and local emergency services will be available. All injuries must be reported, and proper action will be taken to prevent a future incident from occurring again.
Extreme Weather	Medium	Medium	**Engineered/Administrative -** In cases of extreme weather when the UAV is airborne, the autopilot will be instructed to bring the UAV back to land. Otherwise, the safety pilot may land it manually in a nearby clearing. Members will ensure that they are properly hydrated and remain in cool shaded areas when resting.

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