Flint Hill School *Animus Ferus* 2016 AUVSI SUAS Journal Paper

Abstract

Following the struggle team Animus Ferus had with their fixed wing aircraft at last year's competition, a whole new UAS has been developed. Instead of using a fixed wing aircraft, team Animus Ferus has chosen to use an octacopter as the core of their UAS. Our new UAS has consistently completed all primary mission tasks as well as the airdrop task. Acquisition and installation of a new primary camera has given the team the highest quality images to date, and the installation of a three axis camera gimbal ensures all images are well aligned. A new communications system ensures the UAS never loses contact with the ground station nor safety pilot. Design and construction of a rail-system allows for a quick swap from image collection to air-drop capability. Extensive flight and ground testing has given team Animus Ferus the confidence that this system will excel at all primary tasks and the airdrop secondary mission task of the SUAS 2016 competition. The team has worked very hard to develop a system we are proud of. We look forward to successfully demonstrating our work during this year's flight demonstration.

I. System Requirement and Analysis

A. Mission Requirement Analysis

In preparation for the 2016 Student Unmanned Aerial System competition (SUAS), team Animus Ferus agreed that we would perfect the primary tasks, and set ourselves the secondary goal of executing a successful airdrop. Additionally, because of the school's proximity to Interstate 66 (approximately 200 yards), we decided that a safer choice for our platform would be a multirotor. After much research and deliberation the team decided on a large octocopter as the platform for this year's competition. Our current configuration has consistently given us twenty minutes of flight time with a three pound payload. The payload consists of a camera and gimbal or a water drop system. In order for our large platform to achieve a twenty minute flight time, carry a three pound payload, and reach a speed greater than fifteen knots we have adapted the design to accommodate two 16000mha six cell LiPo batteries. This increase in battery capacity has also increased the vehicle's overall weight. **Team Animus Ferus would like the SUAS committee to note that our vehicle weight now differs from that specified in the Fact Sheet. The Aircraft gross weight is now 21.6lbs.**

The team considered several pros and cons of the octocopter platform detailed in the chart below.

Multi-roter design			
Pros		Cons	
1)	High-precision waypoint navigation	1)	Power Consumption
2)	Open space for payload		- Mitigated by using majority of payload for battery capacity
	- Easy to swap for different tasks	2)	Multiple landings and takeoffs required
3)	Safer to operate	3)	Slow airspeed
	- Flyaway risk is limited & easily mitigated	4)	High cutting risk (multiple propellers)
4)	Ability to Hover		- Mitigated by using folding props (reducing damage)
5)	Indoor testing	5)	No crash recovery
6)	Can still fly if up to 2 motors fail	6)	Small payload capacity
7)	VTOL and pinpoint landing		

B. Design Rationale

1. OctoCopter

We decided to go with a multirotor design for several reasons, the first of which is safety. With our flying area in close proximity to roads we wanted to mitigate the risk of a fly away with a fixed wing device and flying into a roadway. Furthermore, with a multirotor design we could test the systems on smaller quadcopters inside to ensure our system would perform properly, while getting valuable practice flying a similar platform. There are numerous other pros for our Octocopter design as shown in the chart above. The main drawback of an Octocopter platform is the power consumption. At first, we placed a four cell battery on the platform to try and reduce the all up weight (AUW). However, in this configuration the system browned out after five minutes of flight time. After more research we decided to use two six cell batteries which extended our flying time to over twenty minutes. The weight of the batteries takes the AUW of the vehicle to its max with the camera payload attached. Despite this longer flight time we will still need to land once to replace our batteries in order to achieve fifteen knots during the airdrop task. Swapping out the camera allows us to reduce the vehicle's AUW and allows the team to start analyzing pictures taken during the search area task while the vehicle performs the airdrop task.

With eight propellers we increase the risk of a person being cut, however, we mitigate this by using nylon folding propellers which greatly reduces damage in the event of contact while in operation, we also follow strict safety protocols everytime we fly to avoid contact with spinning propellers. An added benefit of the folding propellers is the ability to protect the motors from contamination by covering them with plastic bags while the propellers are attached.

If we were to crash due to loss of power there would be little to recover in comparison to a fixed wing aircraft. However, due to our rigorous testing with smaller platforms and following strict safety protocols we have never had a catastrophic crash.

2. PayLoad

When using eight Tarot 5008 kv:340 motors in conjunction with two MultiStar 6s 16000 MaH 22.2v 10c LiPo batteries and fifteen inch propellers with a pitch of 5.2, our UAV has an optimal AUW of 22 lbs. With a craft weight of 18.6 lbs with batteries our UAS has a 3.4 lbs of useable payload capacity before performance is compromised. The primary search area task requires the presence of camera and camera gimbal. The secondary air-drop task requires a swap to an airdrop system. To accomplish the addition of both systems, we implemented a hot swap rail system. The UAS will begin the mission with the camera equipped. After running the waypoint path it will then complete the search pattern before returning to the launch point. The batteries will be swapped for a fully charged set and the camera and camera gimbal will be detached. The water drop apparatus will be equipped and the UAS will run the airdrop task.

3. Image Sensing

To capture images during flight, a Samsung NX 500 camera is mounted to a gimbal connected to the UAS. Team Animus Ferus chose to use this camera because of its high resolution and light weight. The camera is a mirrorless DSLR which saves significant weight without any loss in performance. High shutter speed was also a big factor in deciding which camera to purchase. Samsung's NX 500 has a shutter speed of 1/6000 of a second which allows for incredibly clear images with no motion blur and is above the frequency of the motors. Pictures are stored on an SD card, which is taken out of the camera post search area task. The images captured during flight are then analyzed by team members.

4. Communication

The aircraft communicates with the ground control station (GCS) via a wireless frequency. The telemetry, autopilot and APM controlled functions of the multicopter are routed through a 915 mHz transmission system that includes a 3DR transmitter and 16dbi directional patch antenna. This transmitter communicates with a net-ID matched 3DR receiver located on a spar of the copter. EMI protection is implemented using snap-on ferrite bead. All manual control is run through a 2.4ghz link. Manual control runs point to point between a receiver on a spar of the copter and the handheld controller (Spektrum DX7s 2.4ghz). Allowing manual control to be completely independent from the GCS computer. In case of emergency or loss of GCS connection, control will be switched to the 2.4ghz failsafe and the copter will be operated in manual mode.

5. Autopilot

Team Animus Ferus chose to use Mission Planner because it is a free open-source, community supported application developed by Michael Osborn for the open-source APM autopilot project. Mission Planner allows the ground station to connect to the onboard Pixhawk issuing MAVLink commands via connection through a 915 mHz antenna. Mission Planner uses point-and-click waypoint entry with the option to manually enter data points to plan autonomous flights. Mission Planner's flight screen displays the platform's status throughout the flight, producing data to show the GPS location, height, connection strength, flight mode, and battery status. Telemetry logs produced during flight can be viewed post-mission with the option to watch the platforms status for the duration of the flight as well as create graphs of information displayed in the status tab of Mission Planner, such as the motor outputs. Mission Planner provides failsafe options to control and land the platform in the event of low battery, breach of the geofence, or loss of GCS signal.

C. Expected Performance

After team Animus Ferus' terminal crash during last year's flight demonstration this year's team took the opportunity to consider many different platforms for our UAS. Since we would be spending much of our time on the construction and testing of our new platform the decision was made to focus on achieving the primary tasks at objective level with the stretch goal of completing the secondary airdrop task at threshold level. After field testing each element of the planned mission and running several mock missions team Animus Ferus is confident they will achieve all of their goals during this year's flight demonstration.

D. Programmatic Risks and Mitigation Methods

During the testing of Animus Ferus' platform and ground station system, the team worked to reduce the possibility of a dangerous and expensive crash with the competition platform by testing manual and autonomous flight missions using a 3DR quadcopter test platform. During this testing phase, the safety pilot was able to gain confidence and flight ability while maintaining a safe environment. Autonomous mission tasks were tested on a smaller scale using the same quadcopter as to better understand the Mission Planner software layout and test the failsafe capabilities. Safety measures such as a battery failsafe and protective geofence with return to launch instructions were put in place prior to any autonomous flights to ensure the safety of those around the test area.

Within the ground station, the status of all on board systems are available to be displayed on the mission status screen. The Mission Planner software allows for failsafe options that direct the UAV to return to launch and land in the event of an emergency including battery faults, Geofence breach, or any onboard system failure. For successful completion of the planned mission tasks, all necessary and auxiliary components must be functioning properly. The following table displays the steps taken should the platform experience a system failure.

Action to be taken upon component failure

Component	Necessary/ Auxiliary	Action Upon Failure
Pixhawk / Main Power	Necessary	Immediate Uncontrolled Descent
3DR GPS	Necessary	Abort Mission - Manual Flight and Landing
LiDar	Auxiliary	Continue Mission - Lands using information from barometer
NX500 Samsung Camera	Auxiliary	Continue Mission - Photos will not be taken
Tarot 5008 kv:340 motors	Necessary	Motor Failure - Return to Launch Two non-opposite motor failures and/or multiple motor Failures - Rapid Uncontrolled Descent
Arris Zhaoyun Pro 3 Camera Gimbal	Auxiliary	Continue Mission - Pictures will be misaligned
Airdrop Device	Auxiliary	Continue Mission - Abort water drop task
Nx7s Spektrum Controller (Manual Controller)	Necessary	Abort Mission - Return to Launch and Auto Landing
GCS/9.15 mHZ Transmitter	Necessary	Abort Mission after 3 seconds - Return to Launch and Auto Landing

II. UAV Design

A. Air Vehicle

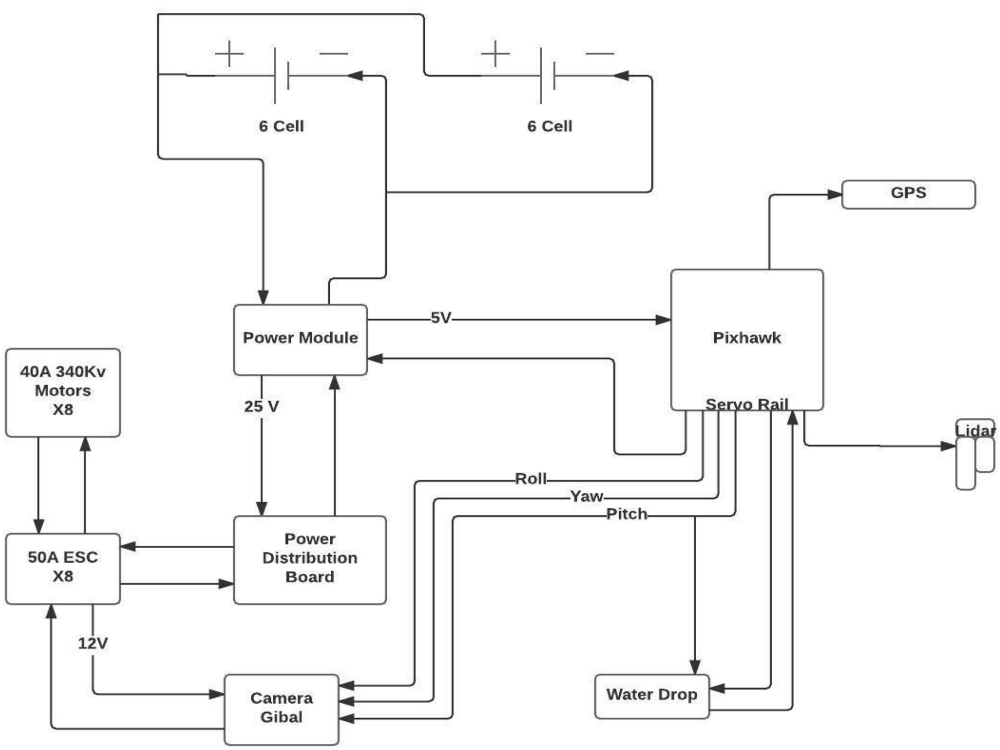
1. Octocopter

Our platform consists of a Tarot Ironman 1000s frame with eight Tarot 5008 kv:340 motors. The system is powered by two six cell 16000mah lipo batteries. We are using a pixhawk system with an external 3DR GPS module. The GPS is attached to a platform designed to breakaway in the event of a crash to protect the GPS. Attaching the GPS with this system also minimizes interference from the magnetic field of the motors and batteries.

We followed the instructions from ArduPilot to connect our LiDar to the Pixhawk.

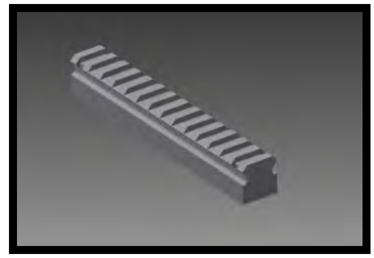
LIDAR-Lite Pin	Pixhawk Pin
J1	CH6 Out V+
J2	CH6 Out Signal (internal pin 55)
J3	CH5 Out Signal (internal pin 54)
J4	(not used)
J5	(not used)
J6	Ch6 Out Ground

Below is the wiring diagram of our platform



2. Payload Specifics

I. Rail System



The integrated rail system employs a Nato standard 20mm Picatinny rail (MIL-STD-1913) printed from a 3D printer in PLA plastic with an infill of 33% in a 3D hexagonal pattern. The use of a standard and commercially common rail allows us to easily find and adapt professionally designed components. It also allows for a wide variety of mountable system beyond what we will be using for this competition, giving the copter a mission flexibility that will be useful for future implementation.

The decision to fabricate the rails on a 3D printer was made with consideration to our payload weight limitation. The goal was to create a mounting system that allowed strength enough to support bulky items such as the camera and gimbal, while not being so heavy or bulky itself that it encroached on the size and weight limitations allocated to the payload itself. This goal was accomplished. The rails are small but sturdy and the aforementioned infill allows for a good strength to weight ratio.

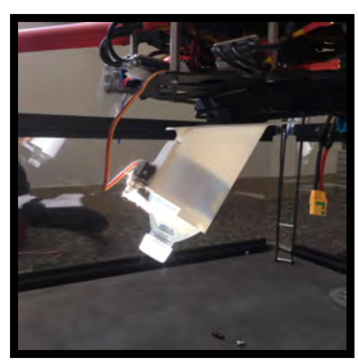
Images of the rail system are located to the right

II. Camera and Gimbal

The picturing system is composed of a Arris Zhaoyun Pro 3 axis brushless gimbal housing a Samsung NX500 equipped with a 30mm 1:2 fixed lense. The system is outfitted with a matching 3D printed Picatinny rail receiver which meshes and locks with the rails on the underside of the copter. The attachment and detachment of the system requires only the removal of a single pin and coupling/de-coupling of the servo controller wires. This means the process can be completed quickly and effectively under pressure. The gimbal receives power from a 12v lead extending from one of the eight BESC's, thus eliminating the need for a separate battery. The gimbal and camera have a combined weight of 3 lbs.

An image of the camera and gimbal system is located to the right.

III. Water Drop



The water drop apparatus is a 3D printed housing capable of carrying an 8 oz water bottle and five feet of 1.5 inch ribbon. The payload (bottle) is held in place during flight by a turnigy micro-servo. When the craft reaches the drop zone, the servo receives a signal from the pixhawk and rotates to release the bottle. The apparatus has a unique 40 degree design that allows the bottle to be dropped in a vertical orientation while the UAS is traveling at 15 knots. The apparatus weighs 0.6 lbs with water bottle.

An image of the water drop system is located to the right.

B. Method of Autonomy

1. Pixhawk & Mission Planner

Autonomous operations are enabled by the Mission Planner program and onboard technology. All missions are constructed in Mission Planner's flight data tab, coordinating autonomous take-off, waypoint navigation, altitude control, search areas and autonomous landing. The flight platform is equipped with a pixhawk that communicates directly to Mission Planner on the ground station computer. The pixhawk includes an internal compass which is used in conjunction with a primary, external compass with GPS to maintain accurate positioning. A rangefinder is located on the underside of the platform to relay precise altitude readings below 80ft back to the ground station.

C. Data Link

1. Interoperability

Team Animus Ferus focused on hardware design this year, and the decision was made to only implement the interoperability features necessary for the primary tasks. After thorough testing and debugging, the team was able to achieve a rate of 12hz and upload location, heading, and altitude data to the interoperability server consistently.

2. Communication with UAS

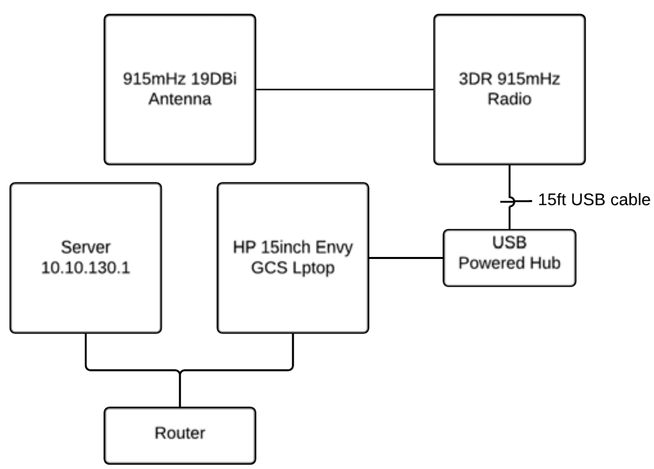
- *Copter*

  The UAS is equipped with 915 mhz and 2.4 ghz receiver/transmitter technologies. The 915 mhz data link is used to transmit and receive commands and autonomous flight information. The signal originates at the pixhawk, is directed as data through the TELEM 1 port to a 3DR 915mhz radio where it is converted to radio waves and emitted from a 4bdi rubber duckie antenna. The TELEM to radio connection has been wrapped with a ferrite bead to eliminate electromagnetic interference.

D. Ground Station

1. Design & Components

The ground control station (GCS) is comprised of three main components. The antenna assembly, control computer and support cart. The antenna assembly is comprised of a 16dbi 915 mhz patch antenna which is supplied signal by a 3DR 915mhz radio. This assembly is connected to the ground control computer, a 15 inch HP Envy laptop. The laptop is running APM (Mission Planner) which communicates to the UAV on the 915 mhz band utilizing the MAVLink protocol. All of these systems are housed on the control cart, a 3x5 foot rolling cart with APS backup battery, which allows the systems to be portable and independently powered for upwards of half an hour.



2. Implementation

Our GCS system is operated by a four person team. Two individuals control the copters mission interface using APM running on the GCS laptop. Having two people fill this role allows one individual to monitor the status of the aircraft (speed, altitude, ect.) while the second loads and modifies missions. This cuts down on the time it takes our team to recognize and react to in flight complications. The third member of the GCS team operates the antenna. This individual uses the rotating mount of the 16dbi patch antenna to maintain the antenna's alignment with the airborne copter. The swiveling tripod allows the antenna 360 degrees of horizontal motion and 90 degrees of vertical motion. Allowing it to be pointed in any direction the copter may be. The fourth and final member of our GCS crew is our safety pilot. This individual has met all of the requirements set by the SUAS competition and is capable of landing the copter using the Spektrum DX7s controller operating on the 2.4gHz band.

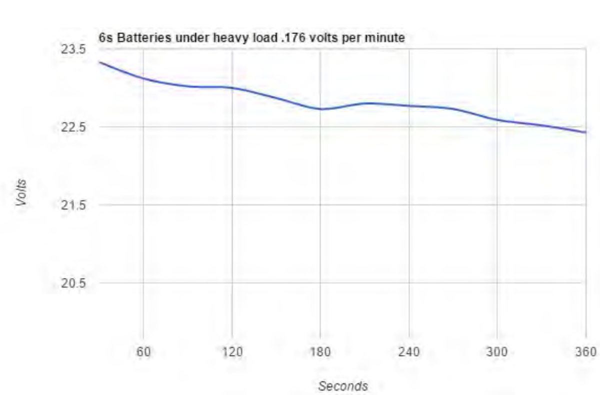
III. Test And Evaluation Results

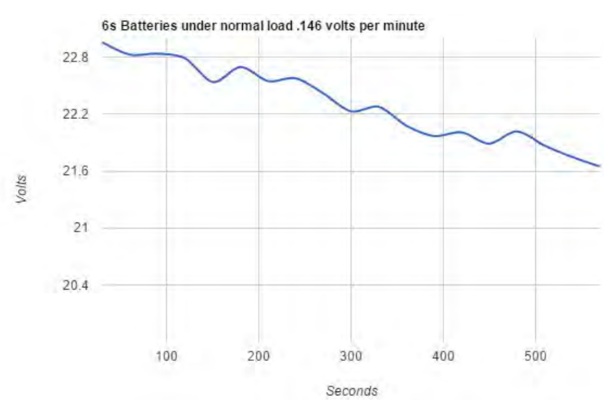
A. Mission Task Performance

1. Flight Testing

One of the biggest drawbacks of a multirotor is there is no crash recovery, which makes crash mitigation a high priority for our team. To facilitate testing without undue risk to our platform we built a smaller quadcopter that runs the same hardware and software for testing, this allowed us to make some mistakes before testing on the competition platform. Not only did the smaller UAV give us a safer test platform, it could also be flown inside allowing us to test on days when the weather did not permit outdoor flights. We have over four hours of autonomous flight time on the quadcopter. Because so much testing was done on the quad when we began flying with the competition platform it has been flawless. We have over fifty successful autonomous takeoffs and landings, without a single failure of either. In addition during testing we experienced failure of one of our propellers when it flew apart during takeoff. The platform remained stable and was able to land with ease. The propeller in question had been damaged during a previous manual landing. The damage hadn't been noticeable during a visual inspection after the incident.

As of the writing of this journal paper we have logged two and a half hours of autonomous flights on the competition aircraft at competition weight. All aspects of the flight mission demonstration have been tested. Our most current tests have the UAV performing missions requiring it to travel a total of three miles with altitude changes totaling more than fifteen hundred feet. These tests have allowed us to gather important information about the UAV's battery discharge rate under different conditions. In the first graph the UAV flew a six minute mission under a heavy load. The second graph is a longer flight time but illustrates the discharge rate under what we consider a normal load.





The team decided that a heavy load would be calculated from rapid ascent descent maneuvers. Under heavy load the UAV uses an average of .176 volts per minute giving the UAV a maximum flight time of twenty minutes. The normal load was calculated from a waypoint navigation simulation based on the distance and elevation change at last year's competition. The average volts per second is .146 which would give the UAV a twenty eight minute flight time. Both tests were performed at full competition weight. Under these conditions the UAV would be able to perform both the waypoint and search area tasks before requiring a battery swap. This assumes the waypoint and search area tasks will cover equivalent distance and elevation changes.

2. Endurance

In an effort to save weight we originally built the platform with one 20000mah 4 cell battery, it seemed to give us an advantage in weight and max speed. We were mistaken, the platform had reduced power with the 4 cell batteries and we experienced a brownout after five minutes of flight. We spent several weeks reevaluated our electronics needs. We decided to upgrade the entire electrical system. The 4 cell battery was replaced by two 6 cell batteries giving the motors much more power, but in doing so we had to change all the Electronic Speed Controllers and the power supply for the pixhawk to hold up to the more powerful batteries. We also integrated a no spark connector between the batteries and the power module. With the larger batteries, despite the weight increase, our flight time has increased from around five minutes to over twenty minutes. The increased motor power also allowed us to meet the speed requirements of fifteen knots for the airdrop task.

B. Payload System Performance

1. Camera

In order to complete the localization, classification, imagery, and secret message search area parameters we have chosen to visually inspect pictures taken at an altitude of 700ft. After testing our camera at 100 foot increments we have projected that with the quality of the pictures we are getting that we will have the necessary resolution at 700ft to visually identify targets. At this height we calculate that each picture will cover an area of 201,575 square feet. In order to make it easier to identify the orientation of the targets, we use MAVlink commands to ensure our camera is always pointing north during the search area task.

Once we determine which pictures contain targets we will use a printed map of the search area with coordinates to determine the location of each target.

2. Water Drop

When designing the mechanism for the airdrop we wanted an apparatus that would attach to the bottom of our platform. We decided to use 3D design to print our own system. Do to the concerns of a fail safe, we have decided to manually trigger the drop. When we trigger the drop, the pixhawk will cause a servo to release the bottle.

When first testing the system we discovered that the bottle inside the tube created a suction and the watter bottle would be slow to release, to mitigate this problem we designed a hole in the top of the system to relieve the suction. When our platform is moving at high speeds it leans in the direction of travel, to ensure our air drop system would deploy the water bottle straight down we designed the system to attach to our platform at an angle.

C. Guidance System Performance

1. Waypoint Navigation

Through the use of our smaller test platform and prior experience waypoint navigation has been flawless since our first flight with the competition platform. In every test flight we have successfully set and reached waypoints at various distances and heights. We have also tested point to point speed during waypoint navigation and achieved over the 15 knot requirement for the airdrop task

2. Search Area

This was the only element of the competition tested for the first time using our large platform. Despite not using the smaller quad to test this there were no issues in running a search mission. We have our camera mount perfected to keep the camera stable while it takes pictures of the search area

D. Evidence of Likely Mission Accomplishment

Throughout the past 2 months, team Animus Ferus has conducted as many flight tests as possible with the competition UAV, all of which have been successful. As of this point in time, we have not crashed a single time. However, we have had numerous precarious manual landings.

Mission Task	Sub-task	Threshold achieved	Objective achieved
Flight time	n/a	100% (<15 min)	100% (<20 min)
Interoperability	Download display time and obstacles	100%	0%
	Upload UAS position data	100%	100%
Airdrop	Release	100%	100%
	Accuracy	100%	0%
	Bull's eye delivery	0%	0%
Search area	Localization	100%	100%
	Classification	100%	0%
	Classification (QRC)	n/a	n/a
	Autonomous search	100%	100%
Autonomous flight	Waypoint navigation	100%	100%
	Auto takeoff	100%	100%
	Auto landing	100%	100%
	GCS display	100%	100%

Throughout testing, every individual component has been thoroughly tested, in normal and edge scenarios. Over 50 test flights have been conducted, with seven airdrop simulations, over fifty waypoint navigation tests, multiple image-related tests, a few miscellaneous tests, and fifteen full-tests where all primary tasks were tested. Further, multiple tests were full competition tests, which involved testing of all aspects of the competition tasks. Overall, in all but manual tests, team Animus Ferus has achieved a flight accuracy of 100% success rates. In manual, this is 90% because of numerous hard landings due to high winds resulting in the UAS rolling over. During a rollover damage to the UAS has included broken propellers and GPS mounting plate. The GPS mounting plate was designed by us and is printed using our 3D printer. It has intentionally been designed as the failure point to preserve the GPS unit.

IV. Safety

Safety is one of our top priority during our flights and throughout our design. In each step of the design and manufacturing process of the platform risk and safety assessments were performed before the finalization of any part.

A. Operational Safety Criteria

During all practice flights team Animus Ferus has complied with the Academy of Model Aeronautics National Model Aircraft Safety Code except as noted in 9.5.1. Team Animus Ferus practices at Flint Hill School's Upper School campus which is outside the DC security zone and is not within five miles of an airport. Flint Hill School has registered all of our aircraft flown outdoors with the FAA. We are also in compliance with FAA memorandum dated May 4th, 2016 addressing the use of unmanned aircraft for hobby or recreational purposes at educational institutions.

Before each flight the team is briefed on the exact mission goals for that flight and reminded of the safety procedures. During flights we have ensured that the proper safety equipment such as, safety glasses, extinguisher and first aid kit are in close proximity and members of our team have been properly trained on how to use them. Before each flight the UAS is inspected to ensure no damage has been caused to it. Our team has developed checklists to ensure flight safety. Some key items for the checklists are found below.

1. Pre-Flight Check

- Inspection of motors and motor mounts, frame, and propellers for damage and wear.
- Inspection of propellers, motors, and frame to ensure everything is fastened tightly
- Inspection of all electrical components ensuring everything is hooked up properly and firmly.
- Check batteries to ensure they are properly charged
- Testing failsafe and other ground functions

2. Pre-Takeoff Check

- Check motor and propeller rotations
- Ensure that the flight path is clear of other aircraft, people, or other obstacles
- Ensure Pixhawk is properly communicating with the GCS and has GPS lock and is not displaying any error messages on the GCS.

3. Post-Flight Check

- Ensure the platform is unarmed before approaching
- Inspect platform for any damage that might have occurred.

B. Design Safety Criteria

Multiple test of each individual component of our platform were tested before a full flight. Before each flight a spin test is performed to ensure each motor is performing as expected. With the safety procedures we have in place, we have never had a catastrophic crash, furthermore, the only time minimal damage occurred was as we were performing PID calibration and during a manual hard landing.

C. Safety Risks and Mitigation Methods

The main reason our platform is an Octocopter is for safety. Our test flight area is close to roads and an Interstate highway. In the event of failure a fixed winged vehicle has the potential to glide into one of these roads. However, with our Octocopter in the event of failure or loss of power, the platform's crash site would be directly below the point at which it lost power, staying inside the operation area. Furthermore, our platform can lose two motors or propellers and still maintain flight and return to land safely. As shown in mythbusters episode 230 deadly drones, our platform with carbon fiber propellers are not safe. With personal safety in mind we are using folding nylon propellers which will be much safer and will cause little damage. With a multirotor design we were able to practice with smaller platforms to ensure our safety pilot was fully trained before flying our competition platform.

In the event communication with the GCS is lost for more than five seconds the aircraft will enter a failsafe state and return to launch. After returning to launch and a continued twenty seconds of no contact with the GCS the aircraft will land.

In the event of low battery the aircraft will enter a failsafe state and return to launch and land.

To mitigate the risk of a flyaway, a geofence with a mile radius from the flight line and an altitude of 750ft will be established for the flight demonstration. In the event of a breach of this geofence the aircraft will enter a failsafe state and return to launch.

V. Conclusion

This project is the capstone of Flint Hill's robotics program. Using knowledge gained from the previous year our UAS has been completely redesigned. The platform not only meets the requirements for testing at our school but also is able to accomplish both primary tasks at objective level and the airdrop task at threshold level. Team Animus Ferus has tested each aspect of the planned mission and run full mock missions. With both autonomous and manual practice team Animus Ferus is confident in their ability to operate the platform safely and effectively. Team Animus Ferus is confident in their ability and that of our UAS to complete the primary tasks at objective level and the airdrop task at threshold level as set by the AUVSI SUAS committee.