TECHNICAL DESIGN PAPER

VAMUDES – UNIVERSITÉ DE SHERBROOKE

ASSOCIATION FOR UNMANNED VEHICLE SYSTEMS INTERNATIONAL STUDENT UNMANNED AERIAL SYSTEMS COMPETITION

Figure 1 – Artémis type aircrafts ready for take-off

ABSTRACT

This paper describes the approach undertaken by VAMUdeS to attain the goals of the 2017 edition of the AUVSI Student UAS Competition. The process spans over three major phases: breakdown of the mission objectives, design of the UAS systems in order to achieve the mission tasks, and finally, system tests and test results analysis. Safety and cyber-safety was a major consideration during each phase in order to provide the safest solution to both people and hardware components. VAMUdeS' unmanned aerial system, Artémis (figure 1), is a battery-powered fixed-wing aircraft designed to provide reliable autonomous flight, high quality imagery and high redundancy ground communication. An improved payload allows for live transmission of geotagged pictures to a ground-based server, while custom ground software allows for real-time analysis of incoming pictures by multiple clients and precise target localization and identification. A recent addition to the UAV is the integration of a water bottle drop system, based on a tried and tested releasing point algorithm.

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1. SYSTEMS ENGINEERING APPROACH

1.1. MISSION REQUIREMENT ANALYSIS

The first step toward succeeding at the competition is analyzing the requirements and their feasibility. In the table beside, the tasks are presented in terms of their weight on the mission demonstration score and whether the team will attempt to get full points for them, partial points, or will simply discard them.

Table 1: Mission requirements analysis

Objective	Weight
Mission time	8 %
Timeout	2 %
Autonomous Flight, Takeoff, Landing	12 %
Waypoint Capture	3 %
Waypoint Accuracy	15 %
Stationary Obstacle Avoidance	10 %
Moving Obstacle Avoidance	10 %
Object DLC, Characteristics	4 %
Object DLC, Geolocation	4 %
Object DLC, Actionable	2 %
Object DLC, Automatic	4 %
Object DLC, Interoperability	6%
Air Delivery	10%
Operational Excellence	10%

1.1.1. TASKS ANALYSIS

A quick analysis shows that the team is confident about the autonomous flight capabilities of their aircraft, since this part of the mission was fully accomplished last year with Artémis. This year, resources were spent on developing new obstacle avoidance algorithms, although moving obstacle avoidance is trickier than stationary obstacle avoidance and it may simply be impossible to avoid a collision. The team's image capture and analysis system has proved its efficiency over the years and its precision has been increased this year, however ADLC has been abandoned due to its high level of difficulty and low reward. The increase in the drop's importance from last year forced the team to develop a system capable of handling a water bottle, although drop tasks in other competitions show that the team is already capable of calculating drop locations. Finally, operational excellence and mission time points are achieved through practice and preparation throughout the year and especially before the competition.

1.2. DESIGN RATIONALE

1.2.1. ENVIRONMENTAL FACTORS

Every year, VAMUdeS is looking for monetary or material sponsorships to help the team buy, build, and repair its systems. Fortunately, the area around Sherbrooke is filled with companies specialized in microelectronics, carbon fiber and fiberglass as well as machining. These companies allow the team to create, at low cost, complex parts and systems such as printed circuit boards, glass fiber fuselages and machined steel parts for the ground station. Cash sponsorships from the University and various organisations allow the team to develop new systems with few budget-related restrictions, although care must still be taken to ensure the financial health of the group.

1.2.2. MISSION REQUIREMENTS

Although VAMUdeS participates in various competitions, these competitions all have similar requirements: good battery autonomy, aerial photography capabilities, cruise speed and stability, and average manoeuvrability. Artémis was designed with three main requirements in mind: ability to transport a large DSLR camera or its equivalent, remain below 10 kg / 22 lbs at full load for other competitions and have a large, accessible cargo bay for extra payload and flexibility.

1.2.3. DECISIONS FLOW AND TRADEOFFS

The main objective of the plane is to be able to perform aerial photography. For this reason, Artémis was built to be able to transport a large DSLR camera. The availability of expertise and the requirement for a lightweight, large, and solid fuselage led to the decision of using fiberglass, as carbon fiber blocks radio signals. Tests and previous experience showed that a tricycle was the most stable wheel configuration. Carbon fiber-reinforced foam was chosen to make the empennage and wings as a great compromise between lightness and rigidity. A middle-high wing design was chosen as a compromise between stability and manoeuverability. A front propeller is used for better stability. As controlling an aircraft is not a trivial task, the team decided to reduce the required efforts on this side to a minimum by using the Pixhawk 2.1 (upgrading from last year's Pixhawk) autopilot and the Mission Planner control software, due to their high versatility, customization capability and the high availability of compatible sensors. Details about these decisions will be presented in later sections of this paper.

1.3. PROGRAMMATIC RISKS & MITIGATIONS

As the project progresses through the year, the risks associated with it are assessed and the appropriate mitigation strategies are applied, as presented in the following table.

Table 2 - Programmatic risks analysis -

Risk description	Impact	Probability	Mitigation strategy
Failure to meet competition requirements	Very high	Very low	A list is made by all the members when first reading the official rules. A mid-year review in which we check the advancement on each project and verify if we meet each requirement is done in mid-January. Adjustments are made to reach the updated objectives by the competition
Divergence from project planning	High	Medium	Every task has a due date and any delay is closely followed. A three-week buffer is also included at the end of the schedule.
Lack of needed expertise from team members	Medium	Low	Every team member has abilities in most aspects of the project. They are also repeatedly required to acquire abilities outside of their field.
Insufficient pilot training	Medium	High	The extensive testing of UAS components with a more experienced pilot and his role as a tutor with the newer pilot shall mitigate his lower experience.
Insufficient financial resources	High	Very low	Thanks to stable relationships with our sponsors and the revenues from last year's competitions, the group has a healthy base budget. To mitigate the risks associated with unplanned costly events, such as a crash, a buffer of 3000$ is maintained.

Moreover, new system components and new iterations of existing components are tested as an iterative process. An airplane with a functional payload was therefore ready to fly at all times. This made it easier to pin-point new issues during development.

2. SYSTEM DESIGN

2.1. AIRCRAFT

2.1.1. FABRICATION OF THE AIRFRAME AND SURFACES

Our aircraft is a standard fixed-wing plane composed of a fiberglass fuselage, two carbon-reinforced foam wings, an empennage, a tricycle landing gear and an electric motor. We use a plane instead of a rotary-wing aircraft mainly because we prioritize high cruising speed. Our plane has a cruise speed of 41 knots, which allows us to cover a bigger zone than a copter for the same flight time. Also, the wings are fixed above the center of mass of the plane, which makes for a more stable plane than a low wing design. When the wings are above the center of mass, the latter is under the roll axis, and vice versa. This principle makes a high wing design stable and a low wing design unstable. An unstable plane performs well in acrobatic competition. For this type of mission, a stable plane is more desirable, because the UAV needs to be stable and easy to fly, and we don't need to do tight maneuvering.

An important part of the plane is the empennage; our plane has a standard shape comparatively to wing-plane. The concept is that the tail counteracts the instability of the wing and makes the aircraft longitudinally stable, which makes the unmanned mission easier. The fuselage is the main piece of the UAV. It contains the payload, the autopilot and it links all the parts together. The wings create the lift of the plane with a 5 ft 6 wingspan.

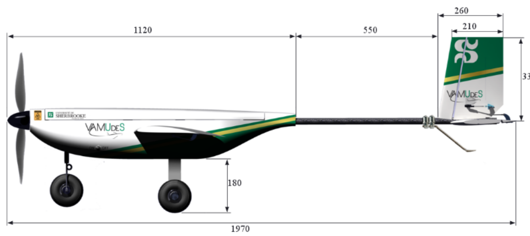

Figure 2 - Artémis [Side]

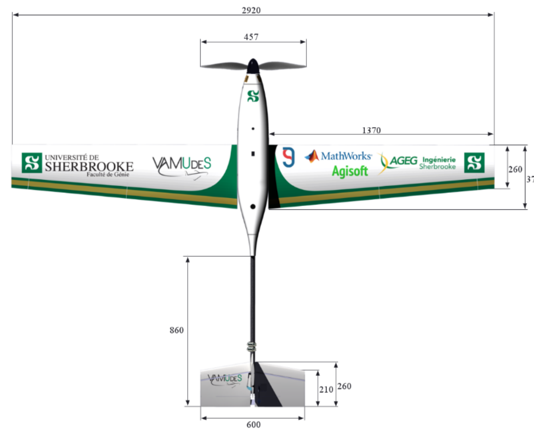

Figure 3: Artémis [Top]

To have the lightest and most resistant platform, we chose fiberglass as main material. This choice is based on the fact that composite materials allow us to have a bigger cargo bay with similar mechanical properties as balsa. Moreover, composite materials are well developed in Sherbrooke, which gives us the opportunity to have a lot of sponsors and their expertise. Based on the Ashby method [1], we saw that carbon fiber has a better performance factor, Young modulus versus density than fiberglass, but in our first ground test we have learned that carbon fiber creates a Faraday cage and blocks the communication signals. Therefore, fiberglass was the best. To add rigidity to this fiber glass fuselage, we use a lightweight composite foam core material. We are using carbon fiber where there is no communication signal, such as in the wings and the tail.

Artémis was designed using a 3D modeling software to be as aerodynamic and as light as possible while maintaining a very accessible and spacious cargo bay. This large cargo bay, with a two-story design, is perfect to contain different types of payload as required for different missions. The wings were dimensioned with an analysis software, to give the aircraft agility, an adequate lift and minimum drag.

The fuselage is made using vacuum resin infusion. The infusion is done in a CNC (computer numeric control) cut mold. All fiber glass layers and the core cell are strategically placed in the mold and the mold is sealed with a bag and some infusion material. The fuselage is infused with epoxy resin. The wings are also a production of our group. They are each made of 1.35 PCF foam and one unidirectional carbon strip. This is one of the easiest ways to build wings. The foam is the main body of the wing, and is cut with a hot wire CNC. A carbon fiber strip is fixed with epoxy resin all around the wing starting from the center of mass. A thermoplastic film is used to cover the foam. This creates a light and strong wing. They are linked to the fuselage with a carbon rod. The tail is made with foam, a carbon rod and glue. This composition is one of the easiest ways to build a tail. We are using the best strength-weight ratio materials since it gives us a light and strong tail. The rod comes from a distributor and it's the main frame of the tail. The elevator and rudder are made with 1.35 PCF foam. The foam is cut with a hot wire CNC (computer numeric control) and the pieces are glued to the carbon round rod. We use thermoplastic film to cover the foam for a better finish.

2.1.2. AERODYNAMICS

The wings were dimensioned using many references. The open software XFLR5 made by a MIT searcher was used to analyze the 2D and 3D aerodynamic performance using vortex lattice method (VLM). Although it neglects all viscous effects of the fluid, this method is still a good reference to compute the lift and drag of an early design. Also, the book *Aircraft Design: A Conceptual Approach* written by Daniel P Raymer was used as an important reference for the design of the complete aircraft. Moreover, all equations and calculations were verified by a graduate engineer from Sherbrooke University and GeorgiaTech.

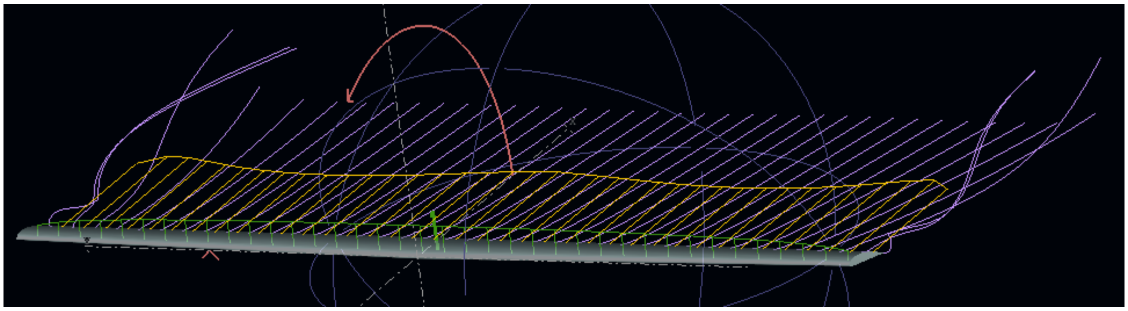

Figure 4: Simulation of the airflow around the wings, neglecting the fuselage.

The first step of the design was to determine the stall speed. With a maximum of 35° roll angle in turn, it was determined that the stall speed is 22 knots. Also, it was estimated that the lift was equal to the drag at the cruse speed. With this assumption, it is possible to isolate the wing surface in the equation.

$$L = W$$

$$1/2\, \rho V^2 S C_l = mg$$

$$S = \frac{2mg}{\rho V^2 C_l}$$

The first lift coefficient (Cl) was determined with a realist 2D analyze on XFLR5. Then with the stall speed (V), knowing that the plane will weigh a maximum of 13 kg (m) and the air density (ρ) at the flight altitude, a first iteration of the minimum wing surface can be achieved. The next step was to determine the aspect ratio needed.

$$AR = \frac{b^2}{S} = \frac{b}{c}$$

Where AR stands for aspect ratio, b is the wingspan and S the wing surface. Also, it was assumed that the thickness of the wing is 9% of the chord(c). For fabrication and structural reasons the minimum thickness is 25mm, which limits the cord to a minimum of 250 mm. The iterations were made with different configurations to reduce the power required at cruise speed. The optimal aspect ratio found was 8.57 with a taper of 0.7. Finally, with some iterations with 3D simulations on XFLR5 to reduce the C_L/C_D ratio, a proper airfoil was chosen. After all calculations were done and verified, the first wings were made and Artémis has been flying for three years with this design, which confirms its reliability.

2.1.3. PROPULSION

Artémis uses a single motor in a tractor configuration to pull itself through the air. The power needed from the motor to maintain the cruise speed V_c depends on the wings factor C_L and C_D, the mass m of the plane, the efficiency of the propeller η_H, the efficiency of the motor η_M and the efficiency of the batteries η_B.

$$P = \frac{mg}{C_L/C_D\ \eta_B \eta_M \eta_H} \cdot V_c$$

Using efficiency factor of around 70% in all cases, the desired power calculated from the equation is around 305W at 39 knots. To obtain this kind of power, the motor used is an E-flite power 90, a 325Kv brushless motor with a maximum current of 50A, 65A in burst. The motor is powered through a JIVE 80+ LV Kontronik ESC by two 6s 8000 mAh lithium polymer batteries. Therefore, the maximum input power of the motor is 50A*24V or 1200 Watts, although is it limited by the batteries at 1150 W. Considering again the efficiency of the motor and the propeller, the maximum output power of the motor is 1200*0.7*0.7 = 588 Watts, which is enough to maintain constant speed with Artémis.

Table 3 - Artémis characteristics

General characteristics	
Crew	1 Safety pilot 1 GCS 1+ Payload operators
Length	6.46 feet
Total Wingspan	9.58 feet
Empty Weight	14.33 lbs
MTOW	28.66 lbs
Cruise Speed	38 kts
Maximum Speed	52 kts
Stall Speed	33 kts
Maximum flight Autonomy	30 minutes
Operational Range	3.73 miles
Operational Ceiling	1500 ft
Minimum Turn Radius	60 m | 200 feet

Empennage	V. Stab.	H. Stab.
Length	0.330 m | 1.08 feet	0.300 m | 0.98 feet
Tip Chord	0.210 m | 0.69 feet	0.210 m | 0.69 feet
Root Chord	0.260 m | 0.85 feet	0.260 m | 0.85 feet
Wings		
Length	1.370 m | 4.5 feet	
Tip Chord	0.260 m | 0.85 feet	
Root Chord	0.370 m | 1.21 feet	
Total Wing Area	0.8505 m^2 | 9.15 $feet^2$	

Fuselage	
Length	1.370 m | 4.5 feet
Width	0.260 m | 0.85 feet

Propulsion	
Motor Power	50A x 4.2V x 6
Propeller Size	18x8
Batteries	6s 8000 mAh Li-Po (x2)

2.2. AUTOPILOT

2.2.1. AUTOPILOT

To achieve the autonomous flight mission requirement, the aircraft needs to be controlled by an autopilot. The autopilot must be able to control the plane autonomously from takeoff to landing and be able to fly to predetermined waypoints. It must also be able to change its flight plan at any time to avoid the moving obstacle throughout the mission. To achieve these requirements, the chosen autopilot must have:

- An IMU (inertial measurement unit) to fly autonomously
- The proper firmware available to control a UAV in a plane configuration
- A radio controller receiver to allow for manual takeover
- A GPS unit to fly to the waypoints and stay in the flight boundaries

Last year, the team used the Pixhawk autopilot to meet these specifications. This controller is a commercial board using the Arduplane firmware which as worked very well with Artémis. This year, it has been decided to upgrade the autopilot to the Pixhawk 2.1 for multiple reasons. The IMU is now damped with a triple redundancy to improve reliability in flight. It also now supports up to 2 GPS for additional redundancy. Finally, the IMU's temperature is regulated, which is quite important for us since we do most of our testing in the cold temperatures of Canada in winter.

The Pixhawk 2.1 is an affordable solution with a lot of functionality in a very small package. Additionally, it's enhanced Kalman filter can use data from the GPS, the airspeed sensor and the barometer to fuse all the data and reject faulty measurements, protecting the UAV from problems such as GPS glitches and gyroscope drift. This is essential in maintaining safety when operating the vehicle. Once attitude is established, customizable PID controllers operate the control surfaces of the vehicle.

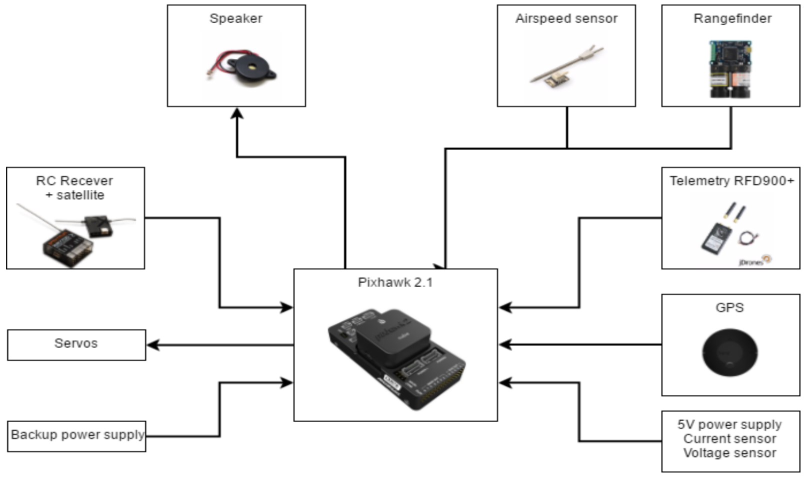

Figure 5: Autopilot Pixhawk 2.1 and its sensors

2.2.2. GROUND CONTROL STATION

Figure 6 - Mission Planner software

The autopilot ground control station uses the Mission Planner software. The team chose this software because it was already implemented with the Pixhawk autopilot and because it can easily display all important flight information (such as aircraft's speed, altitude, heading and climb rate) on top of a map showing the position of the platform at any time. It's also used to create flight plans and upload them to the platform. Finally, it gives a great overview of all the autopilot's parameters, each with their complete description, possible settings and actual settings. The software also contains a simplified window giving access to all tuning parameters for quick in-flight tuning of the platform. Finally, this software is open source and supports plugins, which allows the team to customize the software for the various requirements of the mission and the team's systems.

2.3. POWER DISTRIBUTION MODULE

Artémis is equipped with a power distribution module called the DC512, which distributes 2x 5V to the Pixhawk 2.1 autopilot and the Odroid XU4, as well as a 12V output to the Bullet-M5. Furthermore, this module includes voltage and current sensors that give information about the batteries ot the autopilot. The module also includes various protections such as TVS diodes and Schottky diodes. The 5V submodules are rated at 6 A each, while the 12V module is rated at 3 A, which is, in every case, more than twice the peak current for each connected system.

2.4. OBSTACLE AVOIDANCE

2.4.1. DETECTION

Collision detection is done continuously throughout the mission. For stationary obstacles, the process is quite simple: the path between each waypoint is analysed to see if it goes through any of the cylinders. Moving obstacles are more complex.

Reverse engineering of the interop server allows near perfect prediction of the moving obstacles movement. This process led to the discovery that moving obstacles are generated from human-defined waypoints, which are used to define a cubic periodical spline. The latitude, longitude, and altitude of moving obstacles between two waypoints in function of time is therefore a third order polynomial. Obstacle movement between two waypoints is predicted from only 4 known positions and is refined as more positions are acquired. Positions for each obstacle are stored within a local data structure and outlier detection is used to detect the crossing of waypoints, where a new polynomial starts. Once a full loop has been completed by an obstacle, its spline is fully defined and its future positions are fully predictable, although its position is still updated to compensate for any approximation error. By evaluating the future positions of the moving obstacles and the plane, collisions can be predicted up to 30 seconds prior (depending on the obstacle's trajectory) and can be avoided.

2.4.2. AVOIDANCE

Avoidance of the obstacles is done by modifying the trajectory of the plane through new waypoints calculation, creation, and upload to the autopilot. This strategy was chosen to avoid modifying the internal control loops of the plane, reducing risks of unwanted behavior, and crashes. New paths are created using known parameters of the plane, such as maximum climb rate and minimum turn radius. The obstacle avoidance algorithm also smoothens the planned trajectory of the aircraft so that real behavior is as close as possible to predicted behavior.

Preliminary static obstacle avoidance is performed at the beginning of the flight, with the GCS operator validating newly created waypoints before uploading them to the autopilot.

During the mission, a time projection of the trajectory of the plane and moving obstacles is continuously computed. When a collision is predicted, avoidance through flyover is tried first, as otherwise, some areas of the search zone may be unreachable. In case the climb rate of the aircraft or the height of the obstacle does not allow the flyover, avoidance by flying beside the obstacle is tried using the least deviation path. Should this path not be valid, because it crosses flight boundaries or creates another collision, a path that avoids the obstacle from the other side is tried. Should this path also be invalid, no modification to the trajectory of the plane will be made so as not to disturb the other objectives of the mission.

2.5. IMAGING SYSTEM

The imaging system onboard the plane has to be able to control a camera connected via USB, communicate with various sensors through UART or similar protocols, as well as being capable of communicating via ethernet protocol to communicate with the ground video station.

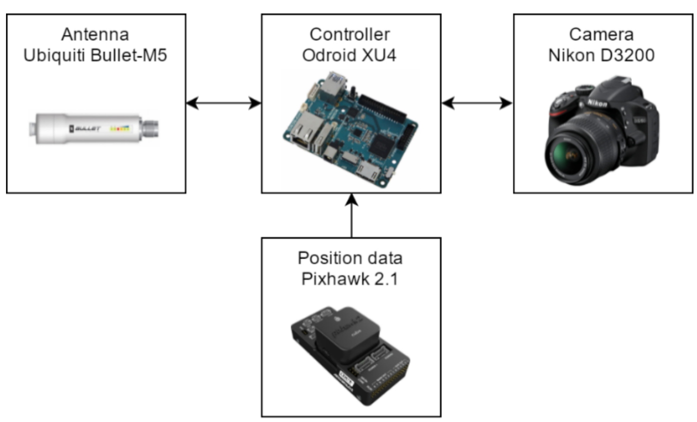

Figure 7 - Imaging system components

2.5.1. CAMERA

The camera must be able to photograph small targets (roughly 5 to 10 sq. ft.) in a large field. In the past years, which camera also has to be able to photograph a QR code with pixels as small as 2 square in. The camera used by the team is the same as previous years, the Nikon D3200 DSLR camera. The camera was chosen for its high resolution of 24.2 MP and its large sensor, which allows more light to reach each pixel than smaller, lighter cameras and captures sharper, noise-free images. Furthermore, the camera offers control over options such as optical zoom and angle of the aperture, shutter speed, exposure and ISO. Below is a table summarizing the most important specifications of the camera for the mission.

Table 4: Nikon D3200 specs

Specification	Value
Pixel Count	24.2 MP
Max horizontal FOV (18 mm)	63.3°
Sensor size	23.2 x 15.4 (DX)
Continuous shooting speed	4.0 fps
Pixel resolution at 200’ at max FOV	0.49” per pixel

These specifications show that the camera is physically capable of resolving targets of the size required by the competition. However, the main advantage of the D3200 is that it is supported by the libgphoto2 camera control library, which allows the team to customize the camera settings in flight and perform continuous shooting streaks to capture images of a target at low altitude or during a turning pass to find the Off-Axis target. Use of this library also reduces stress on the team members throughout the year, allowing more resources to be spent on other tasks.

2.5.2. CONTROLLER

The onboard computer that runs the payload needs to have the processing power to handle large files and to transfer them via ethernet while controlling multiple devices. For this task, several single-board computers (SBC) were evaluated.

Table 5: Evaluated Single-Board Computers for Payload Controller

Feature	Odroid XU4	Raspberry PI 3 B	Udoo x86 Ultra
Price (USD)	74 $	59 $	259 $
Architecture	ARM x86	ARM x64	Intel x86
Processor specs	Octa-Core 2 GHz	Quad-Core 1.2 GHz	Quad-Core 2.6 GHz
RAM	2 GB	1 GB	8 GB
Storage	32 GB	32 GB	32 GB

It is important to note that the Odroid XU4 was used by the team last year as a first prototype. After weeks of testing, the performance gains, compared to the previous controller, were so tremendous that the team decided to use it in competition. In the goal of further improving their design, the team re-evaluated their choice this year. While all three evaluated devices can be used as fully integrated development platforms, the Raspberry PI did not have the multithreading nor the processing power required by the team. The Udoo, with its four cores, was not guaranteed to have the required multithreading capabilities either. Therefore, we decided to stay with the field-tested Odroid XU4.

2.5.3. POSITIONING

While being capable of taking quality pictures is critical, being able to precisely position them on a map is almost as important considering the short duration of the mission. Over the past years, the team has used a combination of GPS and IMU to measure the position and orientation of the plane and project the pictures on the ground. This year, an isolated UART link to the Pixhawk 2.1 autopilot allows the team to receive the same data while drastically increasing its precision. This increase in performance is due the combination of multiple sensors, including 2 GPS, 3 damped 3 axis IMU, 2 barometers and a Pitot tube, all processed through an Extended Kalman Filter (EKF) with a higher frequency (20 Hz) than a GPS alone (10 Hz).

2.6. OBJECT DETECTION, CLASSIFICATION, LOCALIZATION

2.6.1. GROUND VIDEO STATIONS (GVS)

The Ground Video Stations consist of many computers linked through a network which performs pictures analysis tasks. All stations run Mapus Ground, a custom image analysis software developed by VAMUdeS and improved every year to meet the new mission requirements. The payload operator's computer, which receives the pictures from the aircraft, acts as a server and distributes the pictures to the other machines on the network.

Figure 8 - Mapus Ground

2.6.2. MANUAL OPERATIONS

A reliable solution for automatic target detection and classification has yet to be implemented in Mapus Ground. Ground operators scan through the incoming pictures and tag targets as they are discovered. Targets' characteristics are entered in the software, as well as a rectangle marking the area of interest. The networked environment allows for a faster research conducted by many members, as well as spreading tasks across multiple operators.

2.6.3. AUTOMATIC OPERATIONS

Even if the targets are not recognized automatically, the GVS software performs multiple tasks to reduce the stress on the operators. As targets are identified, they are shared across the network for cross checking. Their location is also calculated according to the "click" position of the operator on the picture. When targets are saved, a cropped image of the area of interest is generated and uploaded to the interoperability server along with the other target's characteristics. The HTML response of the server is also processed to assert that the uploading process was successful.

2.7. COMMUNICATIONS

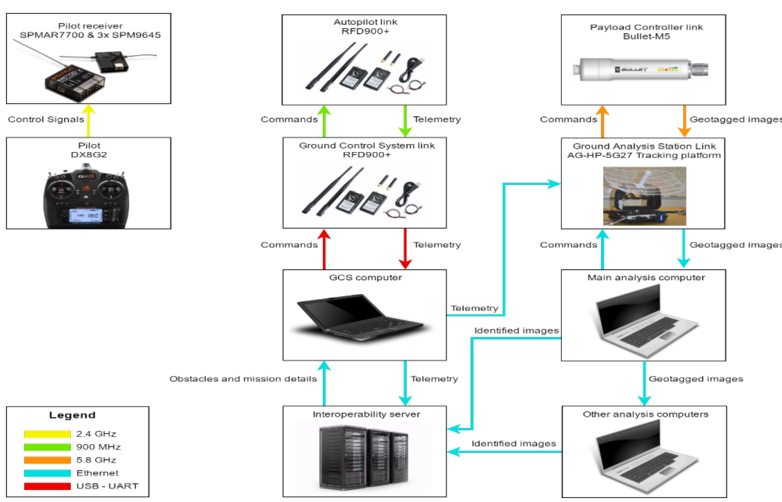

Figure 9: Communication systems

2.7.1. PILOT COMMUNICATION

The pilot uses a Spektrum DX8G2 radio controller to communicate with the autopilot in case of a manual takeover in flight. The on-board receiver is a Spektrum AR7700 sending data with a PPM output directly to the autopilot. Both devices work on the 2.4 GHz bandwidth using the DSMX communication protocol, which provides reliable communication at all time.

2.7.2. AUTOPILOT COMMUNICATION

This data link has three main goals:

- Giving the GCS operator a real-time telemetry
- Allowing the operator to modify in the flight plan mid-flight
- Sending a heartbeat to the aircraft, so it can activate proper failsafe if communication is lost

The telemetry communication between the autopilot and the ground control station uses the 902 – 928 MHz band. The antennas are RFD900+, which has a transmitting power of 1000mW and a selectable data rate which can go between 4 and 250 kbps.

This is as powerful as antennas can get without a license being required for their usage. Its excellent form factor gives us the opportunity to easily integrate the module in custom breakout boards, which is a great asset when using a custom airframe. Finally, this module uses external antennas for a better range and ease of replacement. However, these modules are quite expensive. So, if they were damaged in any way during transportation or during a crash, a backup solution has already been tested. The backup antennas are the 3DR sik radios v2, which also operate in the 902-928 MHz band. Their transmitting power is only 150mW, which is still enough to communicate at a range of 3.2 miles.

2.7.3. IMAGING SYSTEM COMMUNICATION

To prevent any interference between the three communication links used by the team, the payload data link uses 5.8 GHz frequencies. Furthermore, the payload data link should be able to achieve a transfer rate of 22 mbps over up to 1 km / 0,62 miles to maintain real-time images transfer to the ground analysis station, with heavily compressed 24 MP images taken every 2 seconds. Since the team has had positive experiences with Ubiquiti antennas over the past years, the link uses two of the company's products, detailed in the table below.

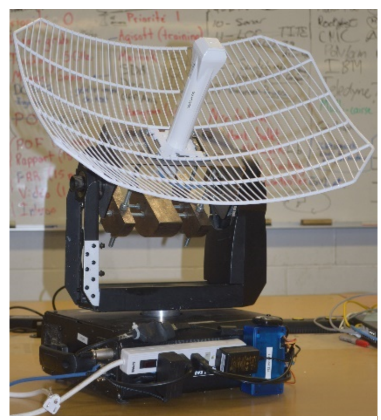

Figure 10 - Tracking antenna

Table 6: Image transfer link specifications

Image Transfer Link Specifications	
Frequency	5 GHz
Air antenna model	Ubiquiti Bullet-M5
Air antenna power	28 +/- 2 dBm / 600mW
Air antenna type	Omnidirectional, 5 dBi (40^{o})
Ground antenna model	Ubiquiti AG-HP-5G27
Ground antenna power	25 dBm / 316 mW
Ground antenna type	Directional, 27 dBi (6^{o})

The ground antenna is mounted on a fully integrated tracking platform that follows the aircraft using data from the ground control system.

2.8. AIR DELIVERY

2.8.1. PROTECTION SYSTEM

The air delivery of the 8oz water bottle is a tricky task to do with an airplane. In fact, the bottle is going to be dropped at an altitude of around 115 feet (or 15 feet above the minimum altitude) at a speed of around 30 knots. Initial testing showed that the bottle would not survive such a fall onto concrete pavement. Two options were identified to solve this problem: creating a protection system for the bottle or using a parachute to slow it on the way down. However, using a parachute would affect the precision of the drop and would not be as reliable as the other option, so it was discarded. Foam seemed like a great idea to protect the bottle, but it was decided that PoronXrd extreme impact protection, the same high-impact foam we use to damp our motor, offered a better protection for less mass. This allowed us to make a protection case for the water bottle under 8 oz. Furthermore, the case is yellow, which makes it easy to find on the ground.

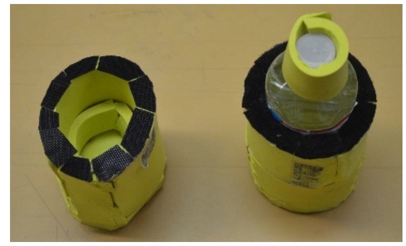

Figure 11 - Water bottle impact protection

2.8.2. RELEASE MECHANISM

The release mechanism must safely secure the water bottle to the aircraft and allow for a quick and precise drop. In addition, the system must be lightweight and avoid adding dangerous parts to the water bottle assembly. An electromechanical system composed of an electromagnet and a metal plate was tested, but was judged unstable and unreliable. The final solution is composed of a slotted disk and a servo in the aircraft. Locking pins are installed at each end of the case and inserted into the belly of the plane, the water bottle and its case staying on the outside. The assembly is aligned with the center of mass of the aircraft to ensure its stability both before and after the drop. To release the drop, both servos on the inside must rotate, releasing the locking pins.

Figure 12 - Bottle locking pin

To ensure the efficiency and the precision of the drop, the dropping sequence has been automatized. The position from which the plane drops the water bottle is calculated using ballistic trajectory equations and faces the wind when possible. The impact of the wind and air resistance is not negligible here. Since it is quite hard to mathematically obtain the drag coefficient of the water bottle, it was estimated with his height and diameter, but it was then adjusted with the first drops effectuated from the plane. To ensure the reliability of the drop algorithm, it is executed on the ground by a team member before takeoff and then uploaded into the plane. The wind is measured on the ground with an anemometer.

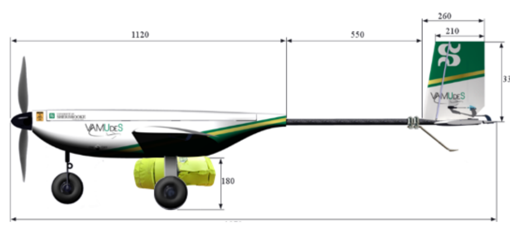

Figure 13 - Water bottle on Artémis

2.9. CYBER SECURITY

2.9.1. COMMUNICATION LINKS

2.9.1.1. PILOT COMMUNICATION

Hobbyist level controllers do not support modification of their communication protocol or hardly do so and, therefore, their communication cannot be encrypted. Furthermore, the DSMx protocol used by many controllers, including ours, can be hacked [2] by malevolent entities without any specific hardware requirements other than a radio. However, because the pilot's signals are processed through the autopilot before acting on the control surfaces, the GCS can override the pilot's commands in case of problems and bring the aircraft home, or crash it, depending on the situation.

2.9.1.2. AUTOPILOT COMMUNICATION

The RFD900+ radios use AES encryption out of the box, which makes this link protected from hijacking by design. The NetID that is used for pairing between the ground and airborne devices being protected, other users cannot, voluntarily or not, control the aircraft.

Also, since there will not be any control over any frequency at the competition this year, the RFD900+, with its 30 dBm / 1 000 mW output power, is as powerful as antennas get at the hobbyist level, ensuring optimal communication. Furthermore, its twin antenna configuration ensures constant data transfer, regardless of the plane's position of orientation. Not using default frequencies, or using frequency hopping, is also a very easy way to maintain good connection.

2.9.1.3. PAYLOAD COMMUNICATION

The payload data link uses WPA2-AES encryption, the most secure Wi-Fi encryption protocol and the current Wi-Fi encryption standard. Furthermore, the picture transfer protocol itself is done through RSync over SSH, which is also encrypted using AES256. In the event someone would be able to access the network from another entry point, that person would still have to decrypt the SSH protocol within the network to get access to the pictures from the plane.

To prevent interference with the pilot's or autopilot's links, this link uses 5.8 GHz Wi-Fi instead of the traditional 2.4 GHz. This prevents the image link from burying the pilot link and losing control of the aircraft.

2.9.2. GPS SPOOFING

GPS spoofing is a very easy thing to achieve and can be used against civilian drones, as their GPS signals are not encrypted. Using a very simple guide [3], the team could achieve GPS spoofing on its own GPS, using the HackRF, a multipurpose radio. The ease of performing GPS spoofing on such large aircraft is worrying and poses a real threat to safety. However, GPS spoofing can be countered using tools as simple as Extended Kalman Filters (EKF), as we do. A simple bit of software, added to the filter, could detect a discrepancy between the GPS and other sensors such as Pitot tubes and IMU. Navigation without GPS, while not optimal, would allow, at this point, to perform an emergency landing or a flyaway, until true GPS signal comes back. Another solution, used by the military, is to use proprietary GPS signals which are encrypted, such as GPS P(Y), M-code, or PRS signals, and require authentication. However, this solution is not available to civilians. [4]

2.9.3. JAMMING

At the civilian level, it is very hard to protect against jamming. Frequency hopping and spread spectrum are possible ways to reduce its impact. The best way, however, to ensure safety in this situation is through proper failsafe protocols. Depending on the situation, one may want to crash instantly, return to land, or return to home.

2.9.4. NETWORK DISRUPTION

Any alien entity who could manage to connect to the team's network could disrupt connectivity between the systems or alter the performance of the team's computers. To prevent such issues, during the competition, Wi-Fi access to the network is disabled and the remaining ones, such as the image transfer link, are hidden, password protected and encrypted using WPA2-AES encryption. Remaining devices are connected using ethernet cables. Lack of access to the internet and proper firewall configuration on the router and each of the team member's computer also ensure reliable connectivity.

3. TEST & EVALUATION PLAN

3.1. DEVELOPMENTAL TESTING

3.1.1. AIRCRAFT

3.1.1.1. WINGS STRENGTH

Several pairs of wings were made during the development phase, each with a different coating, before the final recipe was established. Although all wings are cut from high-density foam, the first pair of wings was not strengthened in any way, and broke before supporting half the weight of the aircraft, four years ago.

Following this first failure, the second model was entirely covered in fiberglass, which made the wings very strong, but very heavy. The latest design consists of high-density foam wings reinforced with a strip of carbon fiber that goes around the whole wing's length, directly on its center of mass. This design has the advantage of being very lightweight at half the weight of the previous design, while being very resistant. To ensure it could withstand any emergency manoeuver, static weight tests were performed on this new design, with 3G or 30 kg (66 lbs) spread across the wings with the latter showing no signs of weakness.

3.1.1.2. FUSELAGE FABRICATION TECHNIQUE

The first prototype of Artémis, called Blackbird, was built by riveting plastic plates together to create a fuselage very similar in shape to the current one. However, this fuselage had the disadvantage of having its cargo bay very difficult to access. This situation forced the team to review its design. A partnership with a local company specialised in composite resin allowed us to try a new process, called vacuum composite infusion. This technique allows the creation of very large cargo bays with very fine control over their sturdiness using varying amounts of foam core.

3.1.1.3. GROUND STEERING CONFIGURATION

Nose and tail dragger configurations were tested on ground for maneuverability. Straight lines and curves were performed on different surfaces, such as pavement, grass or dirt to evaluate the performance of both configurations. Nose dragger was selected because it offered better ground control, as well as a more tolerant behavior when performing a landing, making the development of autonomous landing easier.

3.2. INDIVIDUAL COMPONENT TESTING

3.2.1. AUTONOMOUS FLIGHT

The aircraft and its control system performed many autonomous flights before the competition. The autonomous take-off and landing has notably been tested thoroughly before last year's edition and proven efficient during the mission demonstration. The Canadian competition, in April, is also a good stress test for the autonomous operation of the aircraft and its control systems. Over the past twelve months, Artémis has flown over 100 minutes in autonomous flight and more than 200 minutes in manual and assisted flight. Safe operating limits of the aircraft were evaluated during those flights and are presented in the table beside.

Table 7 - Safe operating limits

Parameter	Safe limit
Climb rate	6.6 feet/s
Sink rate	16.4 feet/s
Max pitch angle	22°
Min pitch angle	-30°
Max bank angle	50°
Min turn radius	200 feet

3.2.2. IMAGING SYSTEM

Tests of the imaging systems have two main objectives: ensuring the reliability of the system, its accuracy and that the final design respects the original resolution requirements. Communications tests are presented in their own section. The reliability of the system is ensured by having the system run for extended periods of time and measure things such as camera battery life and ensuring they allow the team to run the full mission, which they do, with a capability of 64 minutes of continuous, uninterrupted run.

Figure 14 : Target from last year at 224 feet above ground level

Accuracy and synchronisation are measured in the air, by commanding an image capture at a precise location at low altitude, below 5 meters. Delay is added to either the GPS measurement or the image capture until the target is precisely at the exact center of the image. This experimental validation technique gives results that were found to be better than theoretical methods, such as synchronizing the flash of the camera with the positioning data acquisition.

Finally, resolution is tested through multiple flyovers at various altitudes to take pictures of small targets. This test is mostly qualitative and may lead to minor adjustments such as the camera's focal length, aperture, or shutter speed. Up to now, using the minimal focal length of 18 mm (widest FOV) available on the D3200 shows that this resolution is enough for the mission demonstration. At 200 feet, max FOV, cruising speed and with a 2 seconds interval between captures, each picture overlaps the previous one by 17%, which is enough to ensure no part of the search zone will be missed by a flyover.

However, image compression has been reduced from last year as the low-pass filter used by the JPEG compression algorithm tends to blur sharp borders, which means small details such as letters or small color variations are harder to distinguish and a second low altitude flyover may be required for some targets. This increase in image quality is possible due to the higher data rates achieved by the new 5.8 GHz antenna system.

3.2.3. OBJECT DETECTION, CLASSIFICATION, LOCALIZATION

Tests of the image analysis software include proper interpretation of the EXIF data, capability to upload cropped pictures to the interoperability server and network processing. The network processing capability was tested by measuring the time required to transfer a certain quantity of data using the software. Upload to the interoperability server was verified with the team's own server and EXIF data interpretation was verified by comparing true GPS coordinates with the ones shown by the software, taking into account the imprecision of the measurement. No problems were detected whatsoever during these tests.

Furthermore, the efficiency of the user interface is a major concern during missions where the available time is limited. Over the years, Mapus Ground has been optimized using comments from its various operators to be as efficient and user-friendly as possible, while bug fixes are issued as soon as they are detected.

3.2.4. COMMUNICATIONS

3.2.4.1. PILOT COMMUNICATION

Due to its importance, the radio link between the pilot's controller and the aircraft has been thoroughly tested in multiple conditions using various receiver configurations. Frame lost and hold counts are logged by the receiver and used as a metric to evaluate radio performance. In a normal 15-minute flight (~40 909 frames at 22 milliseconds per frame) with a receiver and one satellite, there would be an average amount of 255 antenna fades on the receiver and more than 999 antenna fades on the satellite with around 200 frames lost. However, with 3 satellites around the receiver, the antenna fades on the satellite go down to around 400 antenna fades with at most 15 frames lost (~0.036 %). These results are measured with a Spektrum SPM9540 flight logger plugged directly into the receiver.

3.2.4.2. AUTOPILOT COMMUNICATION

The Autopilot / Telemetry link was tested over a large valley with varying distances with the plane at ground level. Performance was measured in percentage of packets received and results are shown in Table 8. Furthermore, a study [5] performed by independent testers shows that the RFD900+ could work at ranges up to 80 km (50 miles).

Table 8: Packets received vs distance

Distance (feet)	Packets received (%)
6 562	100
9 843	98

3.2.4.3. PAYLOAD COMMUNICATION

The 5.8 GHz data link was first tested using a two-way Bullet-M5 connection. However, a transfer rate test showed that the data throughput dropped to below 15 mbps after only 500 meters (roughly 1640 feet), which is way below the team's requirements. The ground end of the connection was therefore replaced by the AG-HP-5G27 directional antenna. Range tests were also performed over a large valley, with the results presented in Table 9 showing that this antenna configuration complied with the team's requirements.

Table 9:Transfer rate vs distance from the aircraft

Distance (feet)	Transfer rate (mbps)
1640	96
3281	88
6890	65
8858	57
10171	33

3.2.5. AIR DELIVERY

More than 17 drop test have been performed up to now to test the dropping mechanism and the bottle protection strategy. In all those tests, the water bottle was never damaged in any harmful way. The precision of the drop varies between five and forty feet. The following figure shows all of those drop locations around the desired target.

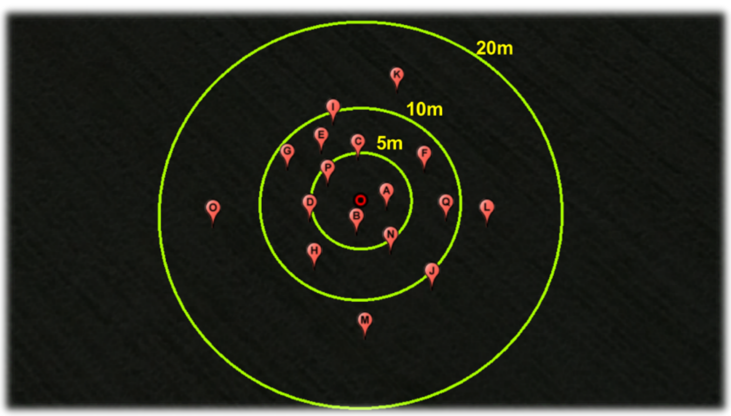

Figure 15 - Drop repartition, with markers at 16, 33 and 66 feet from the target.

3.2.6. OBSTACLE AVOIDANCE

Obstacle avoidance is tested through software-in-the-loop (SITL) simulation directly on the Mission Planner software. This technique allows not only the visualization of the trajectory by showing newly created waypoints, but also reduces development time through instant realistic feedback. Furthermore, good replication of the behavior of the plane allows for fine-tuning of parameters such as waypoints radius or max allowable climb rate before the competition.

3.2.7. POWER DISTRIBUTION MODULE

The maximum load of each submodule of the DC512 was tested using a user-controlled active charge. The maximum current output of each submodule was found to reach 96.7% of the nominal output in the worst case. Furthermore, visualization of the module using a thermal camera showed that the DC512 never reached a temperature above 32 degrees Celsius which is way below the thermal rating of its components.

3.3. MISSION TESTING PLAN

3.3.1. FULL MISSION TESTING PLAN

The full mission testing plan includes all steps of the mission, from preparation to the end of the mission and packing. This simulation includes all tasks, including automatic flight, waypoint navigation, image capture and analysis, interaction with the interoperability server, obstacle avoidance and drop. During this simulation, observers, as well as crew members, are tasked with writing down any mistakes or delays made by the crew members.

3.3.2. PREDICTED RESULTS

It is to be expected that the coordination between team members will not be on point during mission simulation. While all tasks should be accomplished as presented in section 1.1 of this paper, the time needed to coordinate all actions will be longer than allowed or initially planned. The notes taken by every involved team member will serve to guide the team towards fluid operations during the competition by helping them improve any detected weakness.

3.3.3. BACKUP STRATEGIES

VAMUdeS has a backup for each of its systems and subsystems. Therefore, should any mechanical or electrical system fail, a replacement is instantly available. However, in case of software problems or uncompleted systems, few options are available. One solution is to abandon the system and switch to a previous version / system that could achieve, in whole or in part, the functionality of the defective one. However, such events are unlikely, as the team has a history of never using a system in competition if it was not thoroughly tested beforehand and does not handle all limit cases.

4. SAFETY, RISKS AND MITIGATION STRATEGIES

4.1. DEVELOPMENTAL RISKS & MITIGATION STRATEGIES

Developing a new aircraft poses a lot of risks, which is why many safety measures are taken to ensure the team maintains a safe, injury-free environment. The table below shows the most common of them and measures that were taken to mitigate them.

Table 10 - Developmental risks and mitigation strategies

Risk	Mitigation Strategy
Exposure to toxic chemicals	Use of appropriate safety equipment, such as gas mask with canister, proper gloves, security glasses, etc.
Injury due to bad usage of tools	Mandatory health and safety formation in the first few weeks after joining the group
Injury due to misunderstanding of new components behavior	Integration of dangerous parts such as propellers and Li-Po batteries only at the end of the development process, with proper safety equipment

4.2. MISSION RISKS & MITIGATION STRATEGIES

The mission itself, while being attended when the team and its technology are at their peak performance, reliability, and experience, still poses many risks, as no single system is completely failure-proof. Below are some of the most dangerous or probable situations and the measures taken to mitigate the associated risks.

Table 11 - Mission risks and mitigation strategies

Risk	Mitigation Strategy
Loss of control over the plane	Four-stages pilot link redundancy, connectivity tests at least at twice the required range, proper failsafe protocols.
Unexpected water bottle drop	The bottle is held by two servos at a time, meaning a double failure is required for accidental drop.
Unexpected aircraft behavior due to obstacle avoidance	Stationary obstacle avoidance must be verified by the GCS operator before being sent to the plane. Moving obstacle avoidance paths are automatically validated before being sent to the aircraft, and can be overridden at any time by the GCS operator or pilot.

4.3. OPERATIONAL RISKS & MITIGATION STRATEGIES

Operating an aircraft poses many direct and indirect risks that must also be considered by the team. Below is a list of the most common risks the team must be prepared for and the solutions retained to mitigate them. These risks, while present when testing the aircraft, are also present during competition.

Table 12 - Operational risks and mitigation strategies

Risk	Mitigation Strategy
Temperature too hot / too cold	Pre-flight briefings, water bottles, sunscreen and hot blankets in the default flight kit. Cars with AC / heating available (during tests).
Pests	Pre-flight briefings, bug spray in default flight kit.
Dangerous or incomplete plane preparation	Checklists for each primary system of the aircraft, pre-flight tests and validation, including hardware, center of mass verification, control surfaces.
Mistake from the pilot	Everyone within reach of the aircraft is required to pay attention, autopilot override.
Injury from propeller	Four levels of safety switches, including one mechanical switch. Strict pre-flight testing procedures (i.e. everything behind the plane's wings, out of the propeller's axis).
Li-Po battery fire	Transportation in Li-Po safe bags, charging into designed location with special ventilation system and non-modified specialized equipment, HF gas detector within the charging and storage locations, fire extinguisher in charging station, transportation kit, and default flight kit.

5. REFERENCES

[1] M. Ashby, Materials Selection in Mechanical Design (3rd ed.), Burlington: Butterworth-Heinemann, 1999.

[2] D. Goodin, "There's a new way to take down drones, and it doesn't involve shotguns," ars technica, 26 October 2016. [Online]. Available: https://arstechnica.com/security/2016/10/drone-hijacker-gives-hackers-complete-control-of-aircraft-in-midflight/. [Accessed 14 April 2017].

[3] RTL-SDR, "CHEATING AT POKÉMON GO WITH A HACKRF AND GPS SPOOFING," 20 July 2016. [Online]. Available: http://www.rtl-sdr.com/cheating-at-pokemon-go-with-a-hackrf-and-gps-spoofing/. [Accessed 14 January 2017].

[4] S. Cole, "Securing military GPS from spoofing and jamming vulnerabilities," 30 11 2015. [Online]. Available: http://mil-embedded.com/articles/securing-military-gps-spoofing-jamming-vulnerabilities/. [Accessed 15 05 2017].

[5] EDGE Research lab, "EDGE Reseach Laboratory," 28 February 2013. [Online]. Available: http://www.edgeresearchlab.org/our-projects/edge4-16-feb-2013/rfd900/. [Accessed 14 April 2017].