Technical Design Paper

AUVSI SUAS 2018

VAMUdeS

Université de Sherbrooke

Figure 1: Orion

Abstract

This paper describes the approach undertaken by VAMUdeS to attain the goals of the 2018 edition of the AUVSI Student UAS Competition. The process breaks down to three main parts. First, the design rationale conveys the team's mission requirement analysis and the motivation behind the major decisions and engineering considerations. Notably, the choice of a brand new custom hexacopter platform, Orion (Figure 1), to better suit VAMUdeS skills, logistical concerns and other needs. Second, the system design section covers each subsystem conception and testing. Among the subsystems are Orion's state-of-the-art imagery system, as well as open source autopilot. Third, the safety and risks section presents the mission and developmental risks identified by VAMUdeS, as well as action taken to mitigate them.

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2 Systems Engineering Approach

2.1 Mission Requirement Analysis

A brief analysis of the tasks that affect aircraft design and development choices is presented in the table below. The analysis is limited to the material and mechanical aspects of the mission, and the tasks have been regrouped and weighted according to the competition rules to orientate design choices in a way that maximizes the team's mission demonstration score.

Table 1: Mission requirements impacting aircraft design

Tasks / Constraints	Hardware requirements	Favorable flight characteristics	Tradeoffs	Weight
Obstacle Avoidance	Autopilot	High maneuverability	Lower speed	20%
Waypoint Navigation	Autopilot	High precision	Lower speed	18%
Autonomous Flight	Autopilot	-	-	12%
Air Delivery	Delivery mechanism	High precision	Lower speed, higher weight	10%
Mission Time	-	High speed	Lower maneuverability and precision	8%
Object DLC: Actionable	Dedicated antenna	-	Higher weight	6%
Object DLC: Localization	Autopilot and camera controller data link	-	-	6%
Object DLC: Detection and Off-Axis	Camera controller, camera, gimbal	Low vibration	Better, bigger camera and gimbal means more weight	4%
Object DLC: Automatization	Onboard computer or dedicated antenna	-	-	4%
Timeout and Operational Excellence	-	-	-	12%

In addition to the requirements presented in Table 1, an additional module must be designed to provide electrical power to each subsystem. The Obstacle Avoidance task requires additional software that will fetch obstacles from the Interoperability System and calculate a new route or alert the aircraft operator in case of an upcoming collision. The camera controller should also be powerful and versatile enough to control the gimbal for Off-Axis target detection and to control the Air Delivery subsystem. Furthermore, a synchronization mechanism must be designed and tuned for the Object DLC: Localization task. An autonomous image analysis algorithm must also be designed to accomplish the Object DLC: Autonomy task. Finally, maximum score for the Timeout and Operational Excellence tasks will be achieved with adequate planning, simulations, and numerous hours of practice throughout the year and especially before the mission demonstration.

2.2 Design Rationale

2.2.1 Environmental Factors

Several factors affect the team's solution to this year's challenge: budget, requirements for another competition and the team members' fields of expertise.

The first factor, the budget, is a very favorable factor. After winning AUVSI SUAS two years in a row, the team's bank account is doing very well, due to both the gains from the competitions and the sponsors that the team can reach with its standing. The monetary constraints are therefore limited, which greatly facilitates development.

The second factor has a major impact on this year's design. Unmanned Systems Canada (USC SUAS), a Canadian competition, requires teams to "spy" through a window and to land at a specific location to deposit a delicate payload. Considering that the competition is only one and a half months before AUVSI-SUAS's mission demonstration, the team cannot afford to develop two separate flight platforms. Therefore, to meet the requirements of both competitions, the proposed solution needs to be capable of stationary flight. Furthermore, USC SUAS requires aircrafts to weight no more than 10 kg, which is another limiting factor that needs to be considered when designing a solution for both missions.

Finally, the team's composition and expertise greatly affects what can be done. This year's team is composed of about fourteen members. Those members combine good expertise in PCB design, software design and control of peripherals, as well as plate assembly, 3D design and 3D printing design. However, one expertise that is lacking is in aerodynamics design, which makes designing a fixed-wing solution quite complicated.

2.2.2 Aircraft type choice

At this point, the main criteria that guides the design of the UAV are defined and presented in Table 2. Propulsion system redundancy has been added to the previously described requirements since no one is completely safe from a hardware failure that could cause a crash. Either while preparing or competing, it would be a catastrophe in terms of money and time. These criteria naturally lead to the choice of a rotary-wing platform. A fixed-wing aircraft would be unable to achieve stationary flight and a hybrid solution would require a lot of aerodynamic design. Since neither a helicopter nor a quadcopter offer a propulsion system redundancy, a hexacopter or an octocopter would be the most adapted platforms to comply with the requirements [1]. A hexacopter design was finally chosen to achieve propulsion system redundancy while reducing weight.

Table 2: Preliminary design criteria

Criteria
Good maneuverability
Weight under 10 kg
Stationary flight ability
Simple aerodynamic design
Has room for delivery and gimbal
Propulsion system redundancy

2.2.3 Specific Design

Table 3 shows several platform specific criteria that were added once the aircraft type was known. An off-the-shelf multirotor was quickly discarded since a lot of them, as example Tarot models, are built with little room for electronics and are not easily demountable, which leads to hardly accessible electronics and difficult to replace arms. Easy to swap batteries is also one of the criteria, as one of the main disadvantages of a multirotor platform versus a fixed-wing platform is the reduction in autonomy and speed. Being able to quickly change the batteries during longer missions is a great advantage in this case. Also, VAMUdeS previous experiences and observations with multirotors showed that they are vulnerable to dynamic rollovers during takeoff and landing, which is why the landing gears should be as wide and low as possible. Additionally, after talking with several teams and drone pilots and browsing various RC forums, the minimum Thrust-to-Weight Ratio (TWR) was established at 2.0 at any time, which means with almost empty batteries. Finally, the motors and propellers shall be chosen to optimize the distance the UAV can go in one flight while maintaining the minimum TWR, as most competitions require a lot of movement.

Table 3: Final Design Criteria

Criteria
Easy to repair arms
Easy to access electronics
Easy to swap batteries
Resistant to rollovers
Thrust-to-Weight Ratio over 2.0
Distance optimized

In the end, it is the addition of the criteria from Table 1 to Table 3 that lead to the design of the UAV presented in the next section of this paper.

3 System Design

3.1 Aircraft

As previously mentioned, the chosen aircraft type is a hexacopter due to its ability to support a motor failure and still land safely while using minimal weight for motors and Electronic Speed Controllers (ESC) compared to an octocopter configuration. This weight can then be used to add additional battery capacity while staying under the target weight of 10 kg to use the aircraft at both USC SUAS and AUVSI SUAS competitions.

3.1.1 Motors, ESC and Propellers

To perform the initial motor and propeller choice, the team first used a tool called ECalc.ch [2], an online, well-reviewed, popular and versatile calculator that lets users perform initial choices of motors, propellers, ESC and battery for their aircraft and estimate the TWR, autonomy and range of operation while also ensuring that no part will be used beyond its capacity. Using this tool, an initial optimization of the motors and propellers size was performed so that the aircraft would fly as far as possible without the need of spending hundreds of dollars for test parts.

On a side note, it was observed, using this tool, that using lower KV motors and bigger propellers would lead to higher hover autonomy and TWR, but lower optimal cruise speed. On the other hand, higher KV motors and smaller propellers lead to higher optimal cruise speed, but lower TWR and hover time. The trick here was to find the best balance between endurance and speed to maximize the range.

After the initial motors, propellers and ESC list were completed, the development team contacted the various selected companies to enquire about possible sponsorships. The team got interesting offers from two companies, Scorpion Power System and Xoar. Scorpion was the only one of the two companies that could offer ESC, while Xoar was the only one that could offer propellers. As for the motors, three similar parts were tested from the two suppliers: Scorpion's M4215-320KV, Xoar's Titan T5010 and Xoar's Titan T5012. Their respective weights are 223 g, 165 g and 225 g. All three motors were tested on the team's test bench and the resulting thrust vs power curves are presented in Figure 2. All tests were performed at 22.2 V (3.7 V per cell with 6S batteries), using Scorpion's Tribunus 06-120A OPTO ESC and Xoar's PJP-T-LU 18x6.5" propellers, which were chosen using ECalc.ch's estimations.

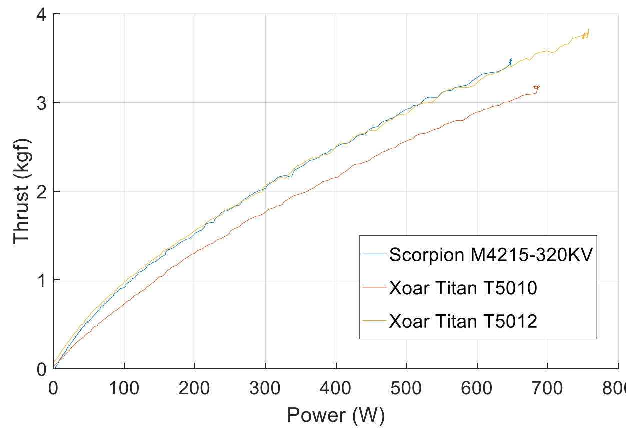

Figure 2: Motor comparison of thrust vs power curves

Looking at this graph, it becomes more obvious that the Xoar Titan T5012 is more adapted to the requirements. It can output up to 3.75 kgf of thrust per motor (2.25 TWR at 10 kg with 6 motors), better than the Scorpion M4215-320KV's respectable 3.47 kgf (2.08 TWR at 10 kg) and the T5010's insufficient 3.10 kgf (1.86 TWR at 10 kg). Furthermore, the Xoar Titan T5012's efficiency in hover (1.66 kgf per motor for a total of 10 kgf) is 1% better than the Scorpion M4215-320KV's 229 W, at 220 W.

3.1.2 Frame Design

Carbon fiber was chosen as the material to build the frame, as it is lightweight, rigid, and has high yield strength, which makes it a very popular material used in many multirotor designs. However, this material is also hard to work with as it cannot be laser cut or machined and special care must be taken when drilling carbon fiber tubes. Furthermore, as carbon fiber is an electrical conductor, it also blocks RF signal. However, the presence of a waterjet cutting machine and the availability of special drill bits at the University alleviates the first concerns. Also, all electronics and antennae were placed on an elevated, lightweight and rigid fiberglass plate, far from the carbon fiber frame and from the high currents passing through the motors to alleviate the RF interference concern.

A first draft of the frame was produced before the team browsed various suppliers to find the raw materials that would best suit its needs. The draft was then adjusted to match the materials' dimensions and specific mechanical properties.

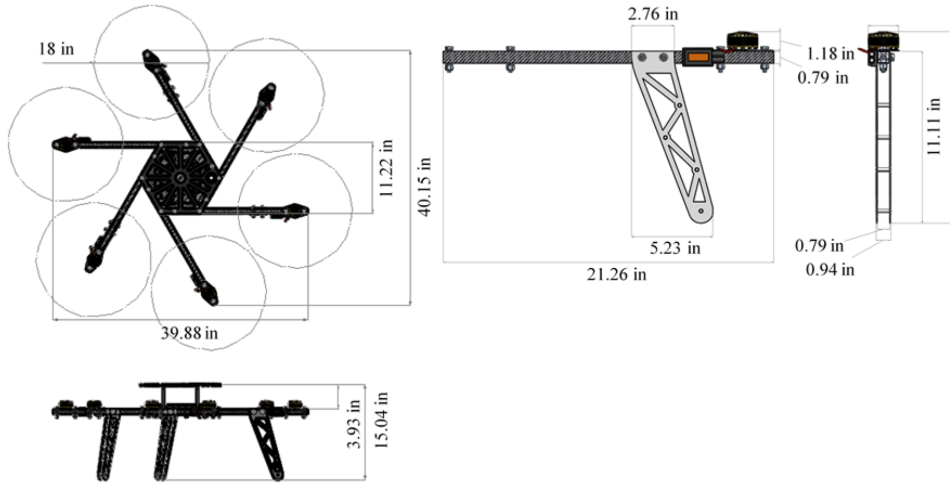

Figure 3: Orion dimensions

The first noticeable aspect of the drone is, as illustrated on the figure 3, the spiral pattern of its arms and their square shape. This pattern allows easy replacement of the arms as all nuts and screws are close to the outside. This pattern also frees space between the arms for a power distribution board and gimbal fixation. The cubic shape of the arms, on their part, allow for easy, precise alignment of the motors and easy fixation on the core of the hexacopter.

The width and length of the arms were chosen to allow minimal deformation under full load, and leaving no more space between the propellers than required. A distance of ½ inch between the propellers was deemed sufficient. A simulation with twice the maximum torque that the motor can apply at full power, as measured with the team's test bench, showed that the maximum warping of the arms reached 0.022", which is less than 10% of the available space.

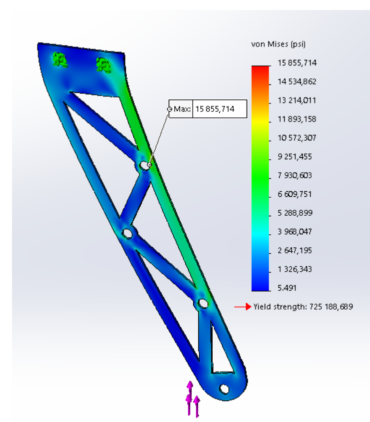

Figure 4: Landing gear stress simulation

The landing gear style has been chosen because it is lightweight, it leaves a lot of free space under the UAV and gives a lot of stability to the platform. Simulations have been made to minimize the amount of material used while still ensuring a 110 lbf static load. This load has been determined to be compliant with a rough landing without putting at risk the expensive camera or other payloads usually installed under the UAV. The simulation on the final design for the landing gear alone is illustrated on the Figure 4. On that simulation the max stress reach 15 855 psi, which is way below carbon fiber's 40 000 – 90 000 yield strength.

Because of the high yield strength of the landing gear, there is a high probability that the arm will break before the gear does. Simulations have been run once again to determine the stress during a rough landing. The first result, presented in Figure 5, shows a possibility of breaking the arm during a rough landing, with a stress of 51 751 psi. To prevent this, we added 2mm carbon fiber plates on each side of the arm, lowering the stress by nearly 60%, as shown in Figure 6, with a maximum stress of 22 561 psi.

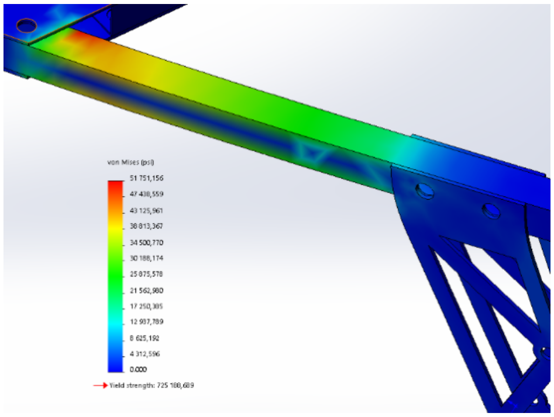

Figure 5: Rough landing with no reinforcement

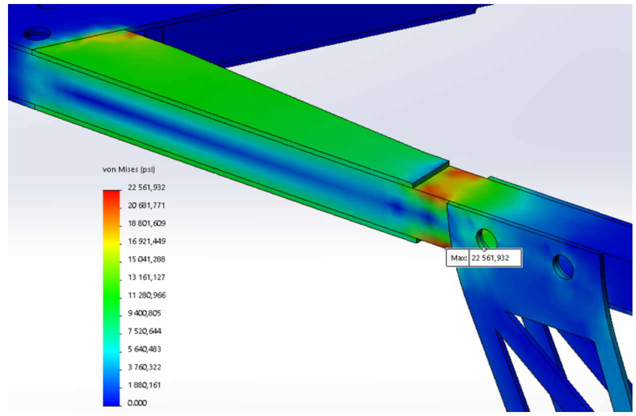

Figure 6: Rough landing with reinforced arms

Finally, aluminum bolts and nuts have been chosen to obtain the greatest rigidity with the lowest weight possible. Over more to obtain tight fit of bolts between carbon parts without scraping the carbon fiber, nylon's washers and sleeve bearings were choose.

3.1.3 Fabrication

As previously mentioned, the carbon fiber plates were cut using high pressure water jet. This allows for easy machining of complex shapes with high precision. However, this method has the downside of causing separation of layers at the jet's entry point. This is a problem for small holes and slits, as the entry point cannot be moved to an unused part of the plate. However, with high enough pressure, the separation can be controlled and small holes usually don't have to withstand high levels of stress.

The arms are drilled using a standard milling machine, with a carbon-ended mill tool. With the square shape of the tubes, this method allows for high precision with no fiber separation, ensuring that all arms are identical and without defects

Also, parts that need to be permanently assembled together are fixed using epoxy glue. Epoxy glue, once hardened, is highly resistant and doesn't allow part to move.

Finally, the assembly of the drone, once the carbon fiber plates are cut, is a quick procedure. Drilling the carbon fiber tubes and gluing carbon plates together is a full day of work for one person plus 12 – 24 hours for the epoxy to harden. Putting together the electronic takes about 2 days for another person. In the end, for a small team, putting together and flying a full frame of Orion can be (and has been) done in two days, which is just another bonus of the platform.

Table 4: Orion main specifications

Characteristics	SI	Imperial
Diameter (without prop.)	106 cm	42 in
Diameter (with prop.)	127 cm	50 in
Empty Weight	4.7 kg	10.3 lbs
Maximum Takeoff Weight	11.2 kg	24.6 lbs
Cruise Speed	8 m/s	15.55 knots
Maximum Speed	15 m/s	29.15 knots
Operational Range	7 km	4.35 Miles
Maximum Flight Autonomy	30 min	
Batteries	32 – 40 Ah, 6S batteries	

3.2 Autopilot

Being able to fly autonomously is one of the big requirements of the competition. To do so, an autopilot needs to be installed on Orion. With the gain of popularity of drones in last few years, there are a lot of pre-made solutions available on the market. Based on the team's experience and on the mission requirements presented in Table 1, the following autopilot specifications were identified:

- Ability to provided fully autonomous flights
- Allow manual takeovers
- Have real time communication with the ground station
- Ability to implement a GPS to follow a predetermined flight plan
- Ability to change said flight plan throughout the flight

Last year, the team's plane, Artemis, used a Pixhawk 2.1 (Figure 7) to fulfill these requirements with success. This controller is a commercial board which is very popular in the drone community and can control either a plane or a multicopter, depending on its firmware. Since the autopilot is still able to meet this year's competition requirements, combined with the team's previous experience on the system, it was decided to keep it instead of searching for a new one.

Three different tasks had been identified in Table 1 which needed an autopilot to be accomplish. The first one, the obstacle avoidance, can be performed using the ability of the autopilot to be re-guided at any moment by the ground station. The complete methodology is presented in section 3.3.

Figure 7: Autopilot Pixhawk 2.1

The second task, the waypoint navigation, is already implemented in the autopilot with the ArduCopter firmware. Before the flight, the waypoints are uploaded in the autopilot, who can then navigate through them with a parametrized precision. An advantage of using the Pixhawk 2.1 is the ability to easily use a RTK GPS system, which can be bought with the autopilot. This system allows a very good precision in the waypoint capture.

The last task, which is the autonomous flight, is also implemented in the firmware. In addition to the standard "auto" mode, where the autopilot follows all the waypoints in order, it offers the option to loiter for as long required if needed in the competition flight. The firmware also comes implemented auto-takeoff and auto-landing functions.

In addition to the established requirements, the Pixhawk 2.1 provides great redundancy with a triple redundant IMU and the ability to blend two GPS signals. Furthermore, the IMU's temperature is regulated, which is quite important since most of the testing on the UAV is done outside in Canada's cold temperature.

On the ground, a custom version of the software mission planner, shown in Figure 8, is used to control the autopilot. This program can show in real time the position and the attitude of the UAV, allows the operator to change the flight plan and changes any configuration of the autopilot.

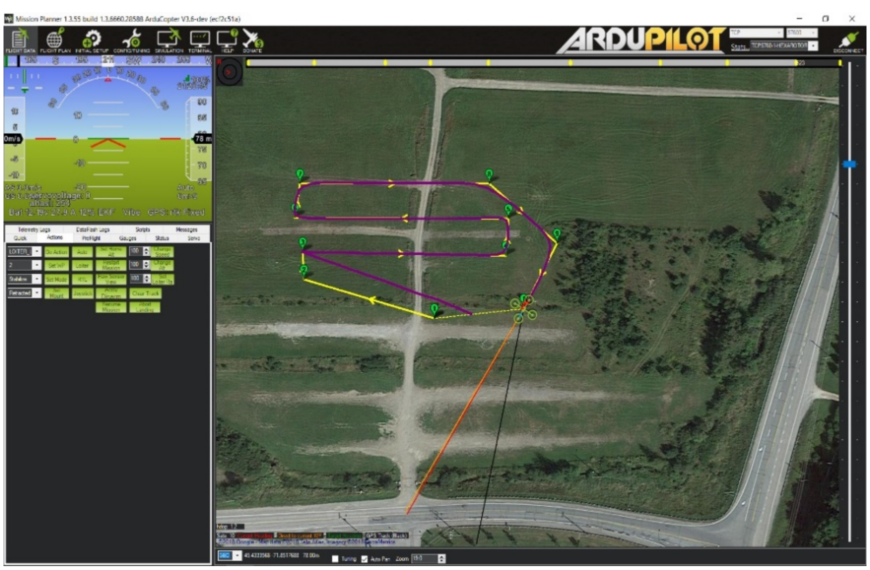

Figure 8: Mission planner interface

Three features were added in this custom version. Firstly, it can connect and talk to the competition's interoperability server, a very important feature to meet the competition requirements. Secondly, the SDA functions with parameters are directly accessible from mission planner's interface. This addition allows the operator to be very reactive to any problem in flight and adapt how the SDA functions affect the UAV's flight performances. Finally, mission planner can be connected to a tracking antenna and broadcast the UAV's position, so the antenna can be correctly positioned.

3.2.1 PID Tunings

To achieve great stability, precision and power economy, PIDs for each control loop of the autopilot have been tuned. The calibration is done using an implemented procedure in the ArduCopter firmware. Figure 9 shows the behavior of the roll axis on one of the first flights of the aircraft. The oscillation response from the aircraft caused flagrant stability issues on sight. It would have impacted the UAV's ability to reach waypoint precisely since the general navigation would have been compromised. The result of the tuning is shown in the second part of the same figure. The aircraft follow its desired roll position in a more controlled way. As presented in Figure 10, the error decreased considerably from the original PID settings, with the root-mean-square error (RMSE) decreasing over sevenfold, from 2.29^{o} to 0.30^{o}.

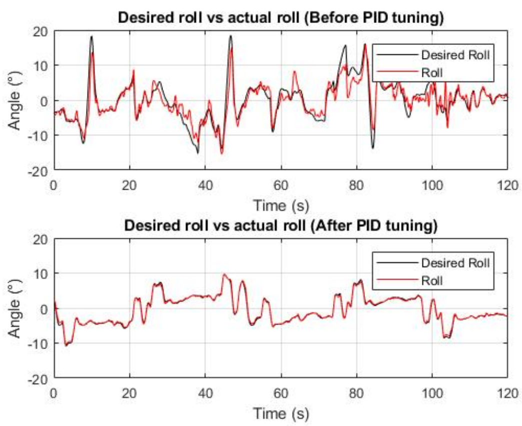

Figure 9: Aircraft roll response

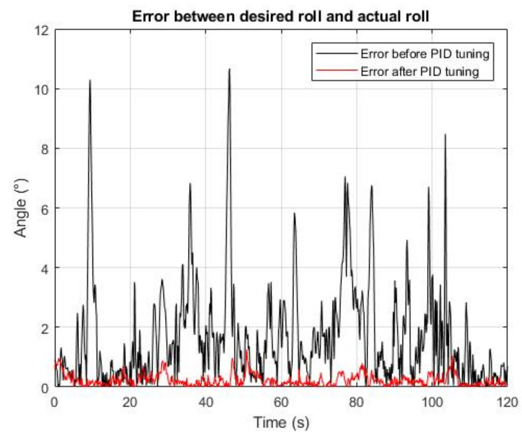

Figure 10: Aircraft roll error

3.3 Obstacle Avoidance

3.3.1 Static obstacles

Avoidance of the obstacles is done by modifying the trajectory of the aircraft through new waypoints calculation, creation, and upload to the autopilot. The obstacle avoidance algorithm also smoothens the planned trajectory of the aircraft so that real behavior is as close as possible to predicted behavior. This strategy was chosen to avoid modifying the internal control loops of the copter, reducing risks of unwanted behavior, and crashes.

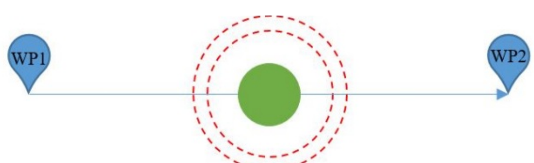

Figure 11: Initial path encountering an obstacle

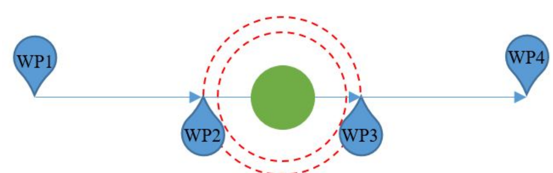

Figure 12: First iteration of the avoidance algorithm

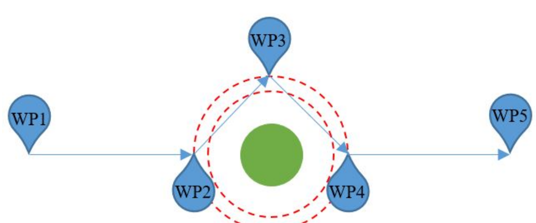

Figure 13: Second iteration of the avoidance algorithm

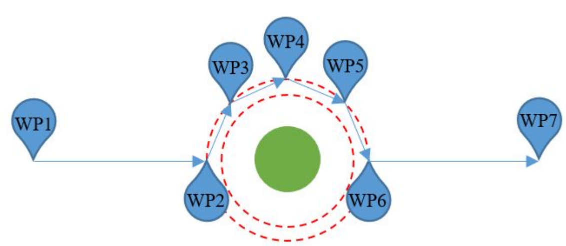

Figure 14: Third iteration and chosen path

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. If a collision is predicted, avoidance through flyover is tried first, as otherwise, some areas of the search zone may be unreachable. In case the height of the obstacle does not allow the flyover, avoidance by flying beside the obstacle is tried using the smallest deviation path. If the height of the obstacle does allow the drone to fly over it, the smallest deviation between the side and above avoidance is chosen, unless the obstacle is over a point of interest. As shown on the Figure 11 to Figure 14, the developed algorithm is a recursive algorithm that adds waypoints until the path completely gets around the obstacle. The green circle represents the obstacle and the inner red dotted line represents the zone we consider to be inaccessible due to the size of the copter and the tolerance of our position. Finally, the outer red line represents the reference path the copter is going to follow. The first iteration, Figure 12, is useful to keep the trajectory as close to the initial plan as possible, then the algorithm proceeds to add waypoints. The added waypoints are always in the middle of the smallest arc of the outer circle. If there is still conflicts on the path of the added waypoints, as shown in Figure 13, the algorithm, once again, adds waypoints in between them as is illustrated in the transition between Figure 13 and Figure 14. The distance between the reference line for the path and the inaccessible line is incremented by 2 feet each time the number of waypoints added for an obstacle exceeds 5 waypoints. This ensures that the avoidance does not slows the drone by having to many waypoints to follow.

3.3.2 Moving obstacles

During the mission, for the moving obstacles avoidance, time projections of the trajectory of the drone and moving obstacles are continuously computed. If a possible collision is detected, the avoidance sequence is engaged. The avoidance sequence starts by identifying a conflict between the path of the UAV and an obstacle. It then estimates where the collision is going to take place and where the drone should stop to avoid it. Afterwards, the algorithm calculates if the waiting period of the drone is causing a new possible collision. If that is not the case, the flight mode of the drone is changed from “auto” to “loiter” which means the drone stops pursuing the waypoints of the flight plan and stand at his current position. Once the calculations no longer identify a collision, the flight mode is turned back to “auto” and the drone then continues his flight plan until he encounters a new obstacle. If the drone cannot loiter due to another obstacle, the algorithm will propose different alternative path to the operator and the solution will be manually adopted. Should there be no valid path with an acceptable margin of error, no modification to the trajectory of the copter will be made to avoid disturbing the other objectives of the mission.

3.4 Imaging System

3.4.1 Camera

The camera used by the team is the Sony Alpha A5100 mirrorless camera. The main specifications of this camera are presented in Table 5. This camera replaces last year’s Nikon D3200 with the same resolution and sensor size, but with a little more than half the weight of the previous camera, it is much better suited for installation on a gimbal. The A5100 is operated to obtain the same resolution as last year at 2.00 pixels per inch, as that resolution has proven to work well enough to be able to correctly identify both the alphanumeric values and the colors of the targets.

Table 5: Camera specifications

Characteristic	Value
Resolution	24 MP
Sensor dimensions	APS-C (2/3)
Angle of opening (H x V)	73° x 52°
Weight	400 g
Pixels per inch at 170 ft.	2.00

3.4.2 Gimbal

The other part of the imaging system is the team’s custom made two-axis gimbal, designed to be as lightweight and small as possible. The use of a fixed yaw increases the accuracy by removing possible drift of this axis, while also allowing the subsystem to be sturdier than a three-axis gimbal. The camera Inertial Measurement Unit (IMU) is located on the camera itself so that mechanical imperfections do not affect the orientation of the camera.

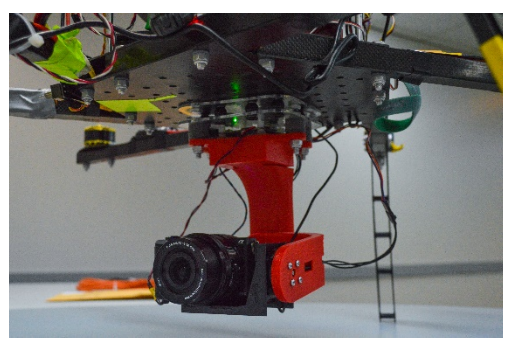

Figure 15: The custom gimbal

3.4.3 Synchronization

Synchronization of the camera with geolocation data from the autopilot is performed by comparing timestamps between the reception of position data by the camera controller and the camera trigger timestamps, both showed in orange in Figure 16. However, photos are not synchronized with the position data that is closest in time, but with a delayed version. This delay is due to the fact that the timestamps only account for a small portion of the total delay between sensor acquisition and the camera trigger, both showed in green boxes.

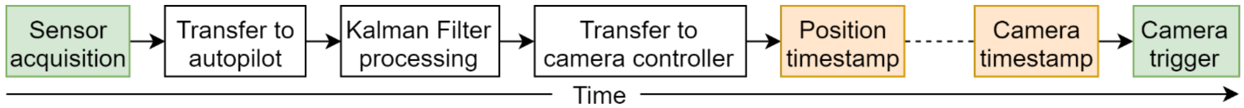

Figure 16: Timeline of synchronization between autopilot and camera

The right amount of delay is estimated using Agisoft, a photogrammetry software. By stitching images together, Agisoft estimates the location and orientation error of each photo. Several flights were performed with various experimental delays to find the optimal one. At the time of writing, the delay used to synchronize locations and camera is 275 ms, with interpolation being performed between the two locations with timestamps closest to (camera timestamp + delay). This calculation allows the imaging subsystem to reach, at the time of writing, an average raw accuracy of 1.28 m (4.2 ft.) on position and 3º on orientation, which translates to an average ground projection accuracy of 4.00 m (13.1 ft.) at 170 ft., assuming that the two errors add-up (which is not always the case). By the competition date, the team will evaluate the added benefit of further correcting photo locations with a quick photo alignment using Agisoft. This method would, however, conflict with the *Timeline* and potentially with the *Object DLC: Actionable* tasks.

3.5 Object Detection, Classification, Localization

Images will be analyzed with both manual and automatic method to ensure the good proceedings of the operation.

3.5.1 Manual

Figure 17: Mapus ground interface

Manual analysis of the photos is performed using Mapus Ground, the team's image analysis software. This software implements communication with the Interop System for quick target submission, and reads exif data from the photos to quickly locate the targets. It also implements network image sharing to allow many people to analyze the incoming images at the same time, which reduces the risk of missing a target. Identified targets are also shared between stations to keep everyone up to date, prevent duplicate target submission and optimize the processing flow. Furthermore, the graphical user interface is optimized for AUVSI SUAS, with the software auto filling the Object Localization field, cropping the targets, and removing the need to type with adapted combo boxes.

3.5.2 Automatic

The images will be automatically analyzed by our ground station. Incoming images will be treated progressively as the mission unfolds. The analysis is made in four phases. These phases consist of: the detection of zones of interest, the detection of the target shape, detection of the letter inside the target and the target and letter color detection.

As specified in the rules, penalties are given when false positives are detected and sent to the servers by an autonomous target detection system. The solution developed has been designed to ensure that any potential target that does not match our thresholds set for each of the phases are not sent.

Table 6 outlines the different tools and manipulations used in each phases of the analysis.

Table 6: Image processing phases

Phases	Used Processes	Fail cases	Expected time range (ms)
Interest points	HSV conversion, dilate, erode, HSV thresholding and blob detection	Size of the blob not matching the possible size of targets	700 – 800
Shapes	Laplacian transform, automatic re-centering, template matching, bilateral filtering	No shape found or unconventional shape	300 – 800 depending on the template matching shape order
Letters	Tesseract library	No letter found or invalid character found	N/A
Colors	Histogram analysis	Can't identify two colors ranges beyond a certain threshold	Negligible

3.6 Communications

The teams' UAS has three major data links. First, the safety pilot uses a Spektrum DX8G2 to communicate with the autopilot through an AR7700 receiver. This feature allows the safety pilot to take back control of the aircraft at any time if necessary. These devices work on the 2.4 GHz band using the DSMX communication protocol.

The second link, the autopilot telemetry, has three main goal:

- Give the operator real-time telemetry
- Allow the operator to modify the flight plan mid-flight
- Send a heartbeat to the UAV, so it can activate proper failsafes if communication is lost

To accomplish these missions, two RFD900+ radio modems are used between the ground and the UAV. These radios, with an emitting power of 30 dBm, can successfully provide a stable data link up to at least 3 miles, which is more than enough for the competition. They operate in the 902-928 MHz band and have a selectable data rate which can go from 4 to 250 kbps. To fulfil the telemetry mission requirement, the RFD900s uses a data rate of 100 kbps, enough to have a telemetry rate of 1 Hz.

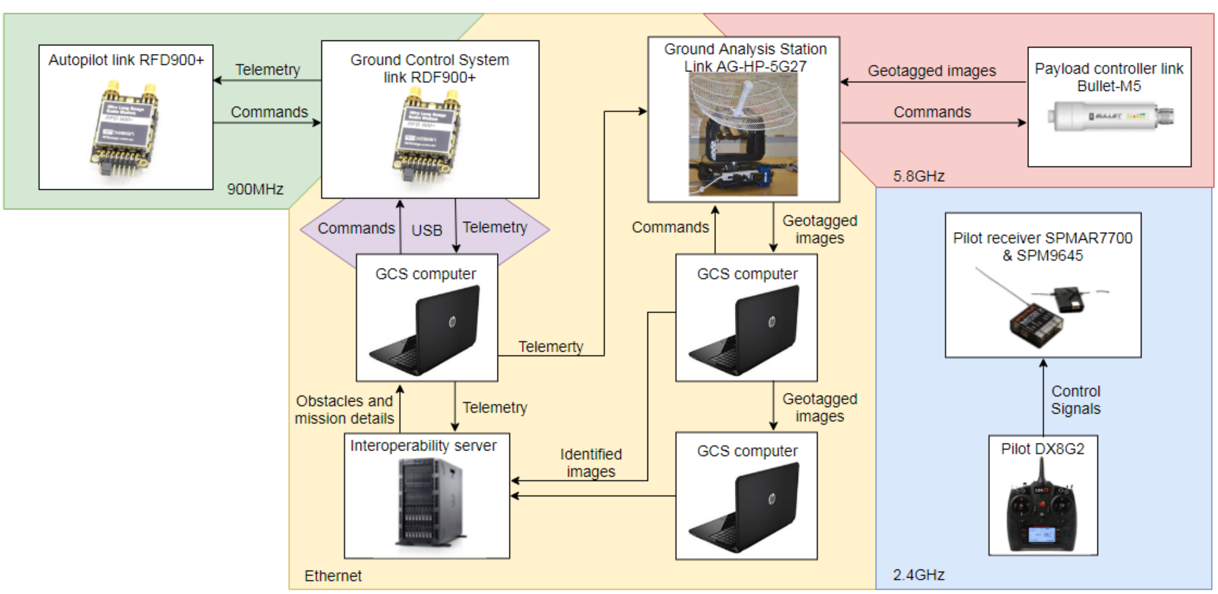

Figure 18: Communication Systems

The images taken by the UAV are sent back to the ground station using Ubiquiti antenna on the 5.8 GHz frequency band to avoid any interference with the other communication link. To maintain real-time image transfer to the ground station throughout the mission, this data link needs to achieve a transfer rate of 22 mbps over up to 1 km. To do so, the ground antenna is mounted on a tracking antenna that follows the aircraft using data from the telemetry link.

On the ground, all the different workstations and the interoperability server are connected on an ethernet network to share data in real-time.

3.7 Air Delivery

The cap of the water bottle is the least impact resistant, since it the smallest area and the least flexible. The team therefore aimed at breaking the cap during its tests, by attaching fins to the bottom of the bottle that create drag and angle the cap towards the bottom. Several recorded impacts showed that the minimum distance from ground that guarantees that the bottle will break is 130 ft.

Since the cruise altitude of Orion (170 ft.) is higher than the altitude required for the water bottle to break, the delivery will be made from the first height. While going lower would add accuracy, the gain in accuracy is not deemed to be worth the trouble of changing altitude, mainly because the aircraft has hovering capabilities, which means the bottle will be dropped while being still over the target.

Finally, the bottle will be released with a simple trapdoor mechanism, as it is both simple and reliable, and was previously used to release a different payload (an egg) for a different competition.

3.8 Cyber Security

Cyber security is a major threat these days. An analysis of potential cyber security risks shows three main access point that can be intercepted by a malicious entity. Communication links with the aircraft (RC, GCS and payload), GPS spoofing or jamming and network disruption.

Table 7: Cyber security criteria

Sections	Risk	Consequence	Mitigation	Fallback
Pilot communication	Hijack	RC control lost	None	Disable RC from GCS and the aircraft lands in RTL
Autopilot communication	Hijack	Autopilot control lost	NetID pairing	Safety pilot performs a manual landing
Payload Communication	Hijack	Data theft, payload control lost	WPA2-AES encryption	Aircraft lands in RTL
Autopilot navigation	Gps spoofing	Aircraft positions in automatic mode	None	Safety pilot takes control and lands
Ground station network	Collecting data and computer infection	Data leak or destroyed, lost of GCS and payload communication	Wired network for most of connected device. WPA2-AES encryption and hidden devices.	Safety pilot takes control and lands

4 Safety, Risks, & Mitigations

4.1 Developmental Risks & Mitigations

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 8 below shows the most common of them and measures that were taken to mitigate them.

Table 8: Developmental risks and mitigations strategies

Risk	Frequency (0 - 4)	Severity (0-4)	Criticality (0-16)	Mitigation Strategy
Exposure to toxic chemicals	1	4	4	Use of appropriate safety equipment, such as gas mask with canister, proper gloves, security glasses, etc.
Injury due to bad usage of tools	2	3	6	Mandatory health and safety formation in the first few weeks after joining the group. Safety guards installed on dangerous tools
Injury due to misunderstanding of new components behavior	3	4	12	Integration of dangerous parts such as propellers and Li-Po batteries only at the end of the development process, with proper safety equipment and qualified member supervision

4.2 Mission Risks & Mitigations

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 9: Mission risks and mitigations strategies

Risk	Frequency (0-4)	Severity (0-4)	Criticality (0-16)	Mitigation Strategy
Temperature too hot / too cold	3	1	3	Pre-flight briefings, water bottles, sunscreen and hot blankets in the default flight kit. Cars with AC / heating available (during tests).
Pests	1	3	3	Pre-flight briefings, bug spray in default flight kit.
Dangerous or incomplete UAV preparation	2	4	8	Checklists for each primary system of the aircraft, pre-flight tests and validation, including hardware, structural integrity and propeller rotation direction.
Mistake from the pilot	3	3	9	Everyone within reach of the aircraft is required to pay attention, autopilot override.
Injury from propeller	2	4	8	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	1	4	4	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] P. S. Kanaiya Agrawal, "Multi-rotors: A Revolution In Unmanned Aerial," *International Journal of Science and Research (IJSR)* , vol. 4, no. 11, pp. 1800-1804, 2015.

[2] "eCalc," [Online]. Available: https://ecal.ch.