VAMUdeS 2016
Journal Paper for AUVSI Student UAS Competition

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Figure 1 : Artemis

Abstract

This paper describes the approach undertaken by VAMUdeS in order to attain the goals of the 2016 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, systems tests and test results analysis. Safety was a major consideration during each phases in order to provide the safest solution to both people and hardware components. VAMUdeS unmanned aerial system, Artemis (figure 1), is a battery-powered fixed-wing aircraft designed to provide reliable autonomous flight, high quality imagery and high redundancy ground communication. A completely redesigned payload allows for live transmission of geotagged pictures from multiples cameras to a ground-based server, while improved ground software allows for real-time analysis of incoming pictures by multiple clients and precise target localization and identification. The seamless integration of both air based and ground based hardware and software creates a highly effective solution for providing crucial intelligence, surveillance and reconnaissance information to a ground-based coordination center.

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SYSTEM ENGINEERING

To develop a complete and complex system, three major steps need to be considered: preliminary analysis, development and testing. A mistake in any of these steps could have severe consequences. Programmatic risk and mitigation methods help to minimize the probability and the consequences of these mistakes.

MISSION REQUIREMENTS ANALYSIS OF PLANNED TASKS

The mission proposed for the AUVSI competition includes a lot of tasks and each of these tasks has from one to six sub-tasks. It's nearly impossible for a team to do all of them. Tasks have to be prioritized according to their value, complexity and time needed to complete the development required to achieve them.

Referring to "AUVSI 2016 Rules for SUAS Competition" document, it could be difficult to see which task offers the best trade-offs of points vs complexity. To simplify analysis, Table 1 : Task global weight gives a good idea of the global weight of each task if the threshold or the objective is achieved. In this table, tasks are divided in three groups:

- Will accomplish: Tasks that require none or minimal development
- Will attempt: Tasks that require development
- Will not attempt: Tasks that will not be attempted at the competition

Priority	Tasks	Threshold (%)	Objective (%)
Primary	Autonomous Flight	15	30
Primary	Search Area	15	30
Secondary	ADLC	n/a	8
Secondary	Actionable Intelligence	3	6
Secondary	Off-Axis	2	4
Secondary	Emergent Target	2	4
Secondary	SRIC	n/a	4
Secondary	Air Drop	1	2
Secondary	Interoperability	2	4
Secondary	Sense, Detect and Avoid	4	8

Legend
Will accomplish
Will attempt
Will not attempt

Table 1 : Task global weight

DESIGN RATIONALE

The VAMUdeS team participates at two competitions each year, the AUVSI SUAS competition and the Unmanned System Canada SUAS competition. Tasks must be planned considering this to be able to perform well in those two competitions. Due to their large number of requirements, the most complex tasks for this competition were abandoned to focus on primary tasks and simpler secondary tasks. Four major development axes were prioritized to achieve them:

- Reduce the global weight of the aircraft
- Replace the autopilot with a simpler and newer one
- Upgrade the imagery system to a more precise and powerful one
- Develop and test new system solutions to achieve secondary tasks

Related to these aspects, multiple projects were done during this year:

- New Odroid XU-4 computer-on-board
- Add secondary camera for the off-axis task
- Improve geo location with better algorithms and sensors
- New Pixhawk autopilot and associated components
- Develop autonomous landing and takeoff capabilities
- New centralised power supply module and distribution
- Improved fuselage and wings fabrication methods
- Add software automation for report generation

Each of these projects were tested many times to ensure the reliability and the safety of the solutions.

EXPECTED TASK PERFORMANCE

This year, the same airframe that was used last year will be used to perform the mission. Some modifications were made to reduce its weight, extend its battery life and improve its maneuverability. Combined with major improvements obtained with the new Pixhawk autopilot and new sensors associated with it, the global stability of the plane is a lot better than previous years. Autonomous takeoff and landing is now possible and the autonomous flight is smoother in this new configuration. The steady speed, altitude and attitude of the plane also allow a better performance of the imagery system. Moreover, the airplane can take pictures at lower altitudes due to the work done to increase the acquisition rate of the imagery system compared to previous years. With a lower flight altitude, better images will be available for real time image analysis at the ground station.

Moreover, the type of airframe used for this mission allows additional payload to do secondary tasks that the standard payload is unable to do. A secondary camera has been added to perform the off-axis task easily and a secondary Wi-Fi transmission module allows communication with the SRIC. Obviously, software development was also done to achieve all secondary tasks planned to an objective level except for the SDA task.

PROGRAMMATIC RISKS AND MITIGATION METHODS

In the planning phase of the year, risks are analysed according to Table 2 to find how to minimize them during the year and to schedule which actions need to be taken to reduce their importance.

Table 2 : Risk description and mitigation methods

Risk description	Impact Probability	Risk mitigation strategy
Not meeting the requirements of the competition.	Severe 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.
Delay on the critical path.	High Medium	Every deliverable has a due date and all derogation to these is highly followed. A three weeks buffer has been introduced in the schedule to give time to the team in case critical difficulties are encountered.
A crash causes significant damage to key systems.	Catastrophic Low	The team has at least one back-up of every system. Systems more vulnerable to crashes (like airframes, wings, tails, autopilots and such) have more back-ups. We are able to rapidly produce and repair any mechanical pieces.
New software features could be incompatible with some systems.	Low High	A lot of unit tests were done to ensure the individual functionality of each new module. Integration tests follow to prevent any conflict with other parts of the system months prior to the competition.
The flight team is not experienced enough for the mission.	Severe High	More tests were planned and extensive flight sessions were planned to ensure flight team capability. Software is developed to be as user friendly as possible. Software developers are also operators during mission.
There is no time left for an AUVSI simulation before the real competition.	Very low Medium	Simulations are made whenever a new feature is available, and the team also participated in the USC competition and had the occasion to practice there, making a lack of AUVSI simulation less problematic.

Moreover, an iterative process was chosen for global development. A new iteration of a part of the solution must be tested before starting the next one. This way, the airplane was always ready to fly with functional payload. The number of tests resulting by this method is much higher than traditional cascade method where it is an obligation to wait after all the solution to test it. The integration of new components to the global solution is easier because, if new problems occurred, it's simpler to know which module cause problems.

DESIGN DESCRIPTION

AIRCRAFT

DESCRIPTION

The aircraft we use for this competition is a custom fixed-wing plane made by our group. Our plane, Artemis, has been used for the past three years. It has competed to 6 competitions and won three times the USC Canadian competition. We are doing continuous improvement to the plane to upgrade the production, the assembly and the flight mission. This year, we have worked on the optimisation of the mass of the plane, specifically by reducing the mass of the wings and fuselage.

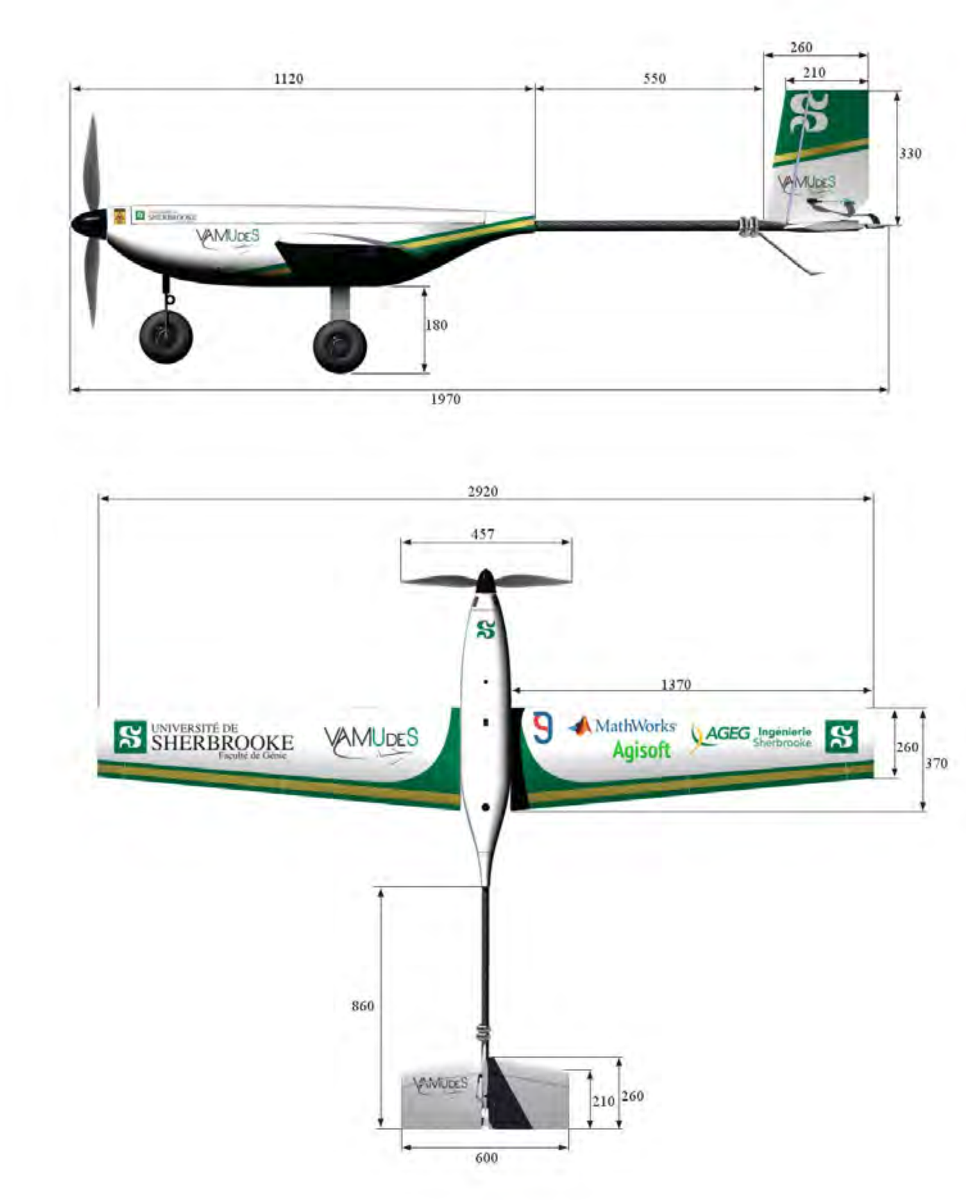

Figure 2 : The Artemis (all dimensions in mm, may not be scale accurate)

General characteristics	
Crew	1 Safety pilot 1 GCS 1+ Playload operators
Length	1.970 m
Total Wingspan	2.920 m
Empty Weight	6.5 kg
MTOW	13 kg
Cruise Speed	70 km/h | 38 kts
Maximum Speed	97 km/h | 52 kts
Stall Speed	61 km/h | 33 kts
Maximum flight Autonomy	30 minutes
Operational Range	6 km
Operational Ceiling	450 m | 1500 ft
Minimum Turn Radius	60 m

Empennage	V. Stab.	H. Stab.
Length	0.330 m	0.300 m
Tip Chord	0.210 m	0.210 m
Root Chord	0.260 m	0.260 m
Wings		
Length	1.370 m	
Tip Chord	0.260 m	
Root Chord	0.370 m	
Total Wing Area	0.8505 m^2	

Fuselage	
Length	1.370 m
Width	0.260 m
Propulsion	
Motor Power	50A x 4.2V x 6
Propeller Size	18x8
Batteries	8000 mAh Li-Po (x2)

Table 3 : Airframe characteristics overview

CONCEPTION

Our aircraft is a standard fixed-wing plane composed of a fuselage, two wings, an empennage, a tricycle landing gear and one electric motor. We are using a plane instead of a rotary-wing aircraft mainly because we prioritize high cruising speed. Our plane has a cruise speed of 21 m/s, 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 2.5 m wingspan. Our plane is designed to carry the requisite payload, the unmanned system and to be more stable and easy to fly.

In order to have the lightest and most resistant platform, we chose fiber glass as principal 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, we saw that carbon fiber has a better performance factor, Young modulus versus density, 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 give core to this fiber glass fuselage, we use a lightweight composite foam core material. We are using carbon fiber where there is no communication signal, like in the wings and the tail.

PRODUCTION

Artemis 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 a particular mission. The wings were dimensioned with an analysis software, to give the aircraft agility, an adequate lift and minimum drag.

The fuselage is made with an 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 way 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 way 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.

AUTOPILOT SYSTEM

Historically, the team had used Paparazzi-based autopilots since its beginnings. Until last year, the team's autopilot had been using thermopile-based attitude estimation for its autonomous flights. However, due to stagnation in Paparazzi and increased difficulty to procure parts, the team has evaluated replacement solutions and has chosen the Pixhawk platform to replace its aging "Johnny" custom autopilot. The main advantages are:

- IMU based attitude estimation, requiring less tuning compared to thermopiles
- More features such as automatic takeoff and landing
- More sensors supported out-of-the-box
- Complete solution requiring less in-house development
- Lighter weight

However, the team had to deal with disadvantages such as reduced simulation capabilities, weaker log replay capabilities and small connectors prone to breakage. The team also had to forgo all previous experience with its autopilots. The final major feature that is dropped is the better flight plan management from Paparazzi, which allowed the user to package a mission in blocks for easier management.

The team also evaluated newer solutions from Paparazzi (Lisa M) but found the programming languages used to be obscure and difficult to learn. A third solution was evaluated, the MicroPilot platform, but was found to be a "black box", difficult to customize.

The Pixhawk is loaded with sensors and functionalities in a very small package. It uses an IMU to estimate the UAV attitude. Additionally, its 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 gyrometer 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.

In addition to these basic sensors, the current Artemis configuration uses a sonar to accurately measure distance from the ground. A magnetometer is also used for stationary heading estimation for the automatic takeoff. At higher speed, GPS heading is used because of the higher potential of error from the magnetometer.

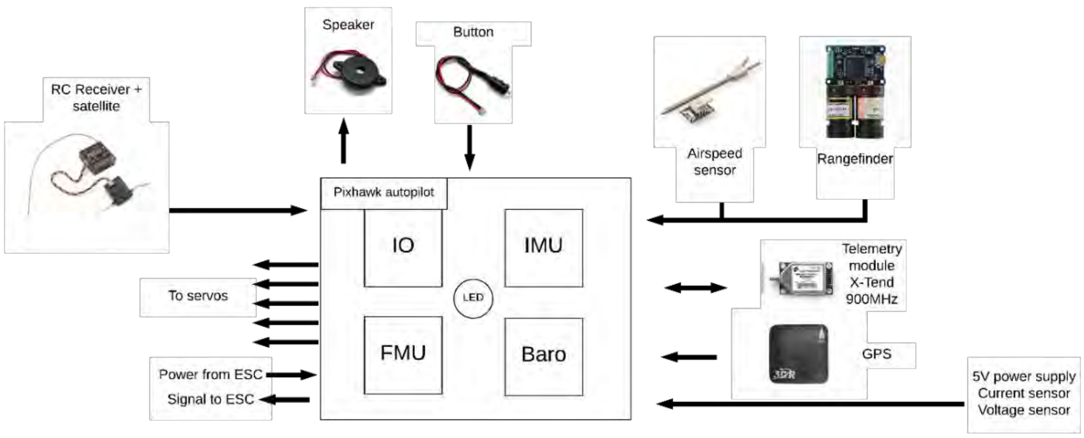

Figure 3 : Autopilot diagram

DATA LINK

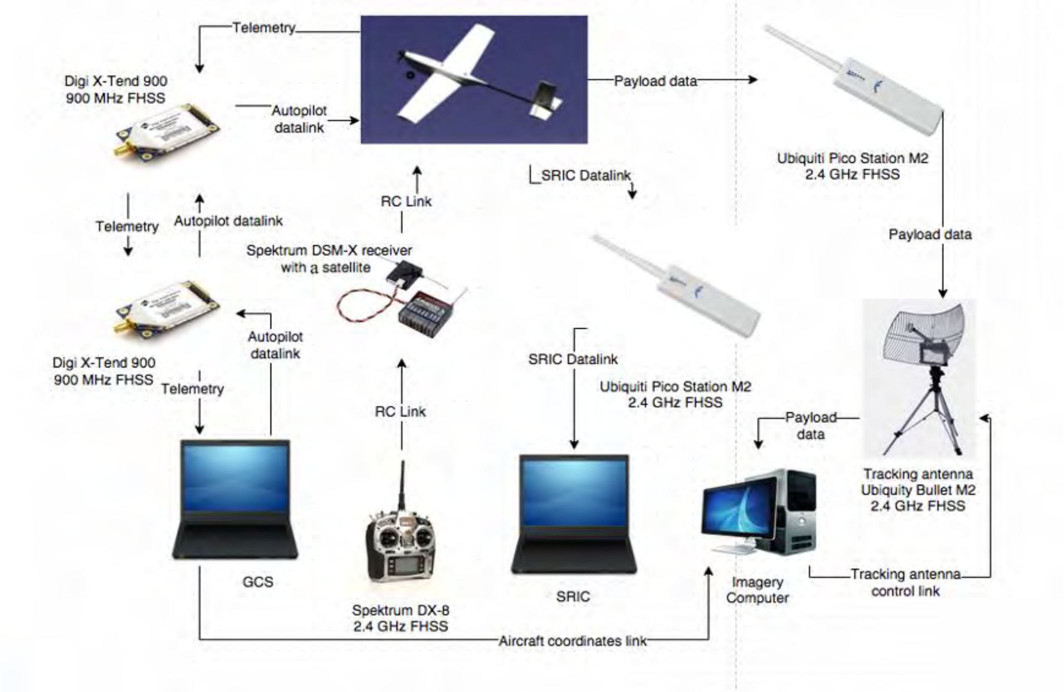

Figure 4 : Global data link system

TELEMETRY DATA LINK

This data link plays three main roles. The first role is getting telemetry in real-time, which is crucial for the GCS operator. The second role is performing modifications to the flight plan in real time, which provides a way to change the aircraft's flight plan, getting it back home or, in certain circumstances, killing it. The last role is to provide a heartbeat to the aircraft, enabling essential failsafe that should activate if the datalink is lost. This datalink is provided by a Digi X-Tend 900 module.

Digi X-Tend 900 Overview	
Transmitting frequency	900 MHz
Transmitting technology	FHSS (902 – 928 MHz), modulated in FSK, using 10 hop sequences totaling 50 discrete frequencies
Transmitting power	1 W
Line-of-sight range	22 km (14 miles)
Data rate	57.6 kbps

Table 4 : Digi X-Tend 900 Overview

This particular module was chosen for its high power (1 W), which allows an excellent range. This is as powerful as antennas can get without a license being required for its 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. The RF module is directly mounted on a custom breakout board that provides power management, USB and UART connectivity, and signal intensity readings. The module on the GCS is connected on the computer's USB port. Finally, the team has a lot of experience with this module and it has been working reliably for many years. This is extremely important for a link as crucial as this one.

IMAGERY DATA LINK

The SSH protocol is used to communicate between the GVS and the XU4 computer-on-board. The protocol has been successfully used in the previous years and its reliability was proven many times, regaining connection when it was lost after only a few seconds. The Ubiquiti Picostation M2 Wi-Fi module communicates with an Ubiquiti Bullet connected to the GVS network. The Bullet's antenna is an 8º of aperture tracking antenna controlled by the GCS. This communication system has been successfully tested at ranges of up to 4 km (2.5 Miles), where the data transfer rate exceeded the minimum of 20 mbps required to transfer both the 24.2 MP and the 5 MP images to the Ground Video Station in real time. The connection between the GVS and the XU4 often reaches 100% uptime.

Figure 5 : Tracking antenna

SAFETY PILOT DATA LINK

The aircraft has RC connectivity in case the safety pilot needs manual control over the aircraft. The pilot uses a Spektrum DX-8 remote control with 100 mW of transmitting power. The receiver on the aircraft is a Spektrum DSM-X with a satellite receiver. Both use 2.4 GHz frequency band with frequency hopping. The communication was tested to up to 1.5 miles.

IMAGERY SYSTEM

The imagery system consists of a computer-on-board (COM), a DSLR camera, a GPS, an IMU and a high speed communication system. The Odroid XU4 COM was, at the time of development, one of the most powerful computer-on-board available and its multiple cores allow for completely parallelized operation of the imaging, position and attitude measurement and communication units, allowing for faster operation which, in turn, allows for reduced flight altitude and higher image quality during search tasks. The XU4 supports Linux as an operating system, giving it access to a plethora of development and debugging tools (Qt, RSync, libgphoto2 camera control library, Unix shell access via SSH). Furthermore, the XU4 has 3 USB ports, an Ethernet port, a SPI port, an I^2C port and a UART port. In the standard payload configuration, only two USB ports are used as well as the UART port. The remaining connectors are therefore available for additional devices needed for secondary tasks.

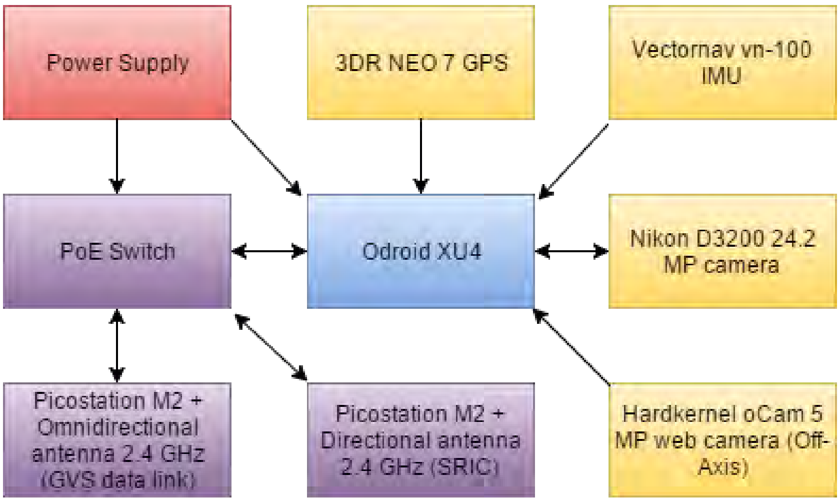

Figure 6 : The Imagery system

The Nikon D3200 DSLR camera has a 24.2 Megapixel CMOS sensor and a 18-55mm lens. The lens is locked at 18mm, providing a Field of View of 76º. The purpose of this camera is to take pictures of the area below the plane during the search task to find alphanumerical and QRC targets with a resolution high enough to read them. The D3200 was chosen over other more compact cameras because the size of its sensor allows for higher quality pictures due to better light sensitivity. Although a mirrorless camera would have been preferable for better quality images and smaller weight, currently available libraries do not allow sufficient control over those cameras for missions such as the Search Task. The D3200 is connected via a USB 2.0 cable to the XU4 COM.

The synchronization of the GPS module with the captured images is a critical task and is ensured by comparing the timestamps of the 24.2 MP pictures with the last GPS measurement. Exact camera position is then estimated by linear interpolation using previous measurements. The altitude of the IMU, mounted on the 24.2 MP camera, is then added to the image's metadata along with the GPS coordinates and altitude, allowing instant calculation of the position of every pixel for the Search Task (given that the lens parameters are known). The IMU was preferred over a gimbal because of its much smaller weight and lower complexity, while also being less prone to failure than any mechanical part. Both the IMU and GPS modules communicate with the XU4 COM via UART, with the IMU being connected through a USB-UART adapter.

Captured images are sent to the Ground Video Station (GVS) through the communication module, which includes an Ethernet switch providing passive PoE to a Ubiquiti PicostationM2 2.4 GHz Wi-Fi module, a lightweight antenna providing the maximum legally available antenna power (1 W). Both the 24.2 MP and 5 MP pictures are transferred through a RSync over SSH connection for a secure, encrypted and reliable file transfer.

GROUND CONTROL STATION (GCS)

The ground control station main objective is to control, supervise and communicate with the flight platform at any stage of the flight. In order to achieve all three of these tasks, two different computers are used by the ground control station team.

MISSION CONTROL CONSOLE (MCC)

The MCC is the computer running Mission Planner, the autopilot 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.

A second MCC is used by the GCS operator’s assistant, which primary role is to create flight plans for secondary objectives. In case of problems with the main MCC, the second MCC can be used as the primary one by the GCS operator. However, only one of the MCC is connected to the Artemis at once.

Figure 7 : MCC’s interface

TRACKING ANTENNA CONSOLE (TAC)

In order to get the best possible real time picture analysis, the ground team has to get the said pictures in real time. To ensure the stability of the connection between the imagery system and the ground imagery station, a tracking antenna is used. The antenna gives the team the best connection possible at any time by constantly following the Artemis.

This tracking antenna is controlled by its own computer, the TAC. Using a second station allows quick problem solving without interfering with the MCC if there's any calibration problem with the antenna.

The TAC and the main MCC are connected together with an Ethernet cable through Ivybus. This allows the TAC to know the exact position of the Artemis and align itself in the right position. Ivybus was chosen because of its flexibility. It is a software bus that broadcasts on the network and thus allows any number of nodes to receive messages from the other nodes. Its main advantage is the flexibility it provides: any program on any computer using a popular programming language can connect to another and send messages. It was then an obvious choice!

SAFETY PILOT

In addition to these computers, the GCS also has a safety pilot to take back control of the platform if there is any problem. The pilot has the power to take back the control of the Artemis at any time through his RC controller, because his transmitter has priority over any action the autopilot could take.

GROUND VIDEO STATIONS (GVS) AND DATA PROCESSING

The Ground Video Station consists of a network in which as many computers as possible are connected. One of these computers, the Payload Operator's computer, acts as a server. The Payload Operator remotely starts the image capture loop and the SRIC script on the onboard imagery and starts receiving the pictures from the imagery system in real time. Mapus Ground, a custom software developed in-house, is started as a server on the Operator's computer while other GVS members run the software as a client. During the mission, pictures are shared in real time by the server via TCP-IP, ensuring safe data transfer, and are analyzed for targets on each computer. A list of identified targets with their properties (location, orientation, color, shape, character) is shared across the network. At the end of the mission, a report is automatically generated by the server, containing all required data to be submitted to the judges.

Figure 8 : Mapus Ground image analysis software

Although targets' geolocation is usually precise enough to attain the Search Task objectives, coordinates are fine-tuned using Google Earth. At the beginning of the competition, several coordinates will be taken on the ground to estimate Google Earth's precision and average deviation from real coordinates. Before the report is submitted, the location for each target will be corrected to ensure maximum precision.

ADDITIONAL SOLUTION DEVELOPMENTS

AUTOMATIC DETECTION, LOCALIZATION, AND CLASSIFICATION (ADLC)

The ADLC task is something new at VAMUdeS and, although it is still in experimental phase, it is very promising. The target recognition runs on one of the GVS client computers. Since 24 MP images are too large to be directly analyzed, they are first processed by a blob extraction algorithm based on the Two-Pass algorithm. Regions of interest are then analyzed with OpenCV libraries to find the target's shape by comparing the number of lines, arcs and circles and their relative lengths. Colors are determined by finding the most preponderant colors. Alphanumerical characters are found by using the Tesseract character recognition engine.

SRIC

The SRIC is split in two parts: the hardware part and the software part. On the hardware part, a second Picostation M2 was added to the airplane, connected to the same switch that provides passive PoE to the first Picostation. However, because the access point is a polarized patch and the aircraft needs to fly over the patch to establish a connection, a Circular Polarized Directionnal antenna was chosen. This way, the aircraft can loiter above the patch for as long as needed to establish connection. Although it would be possible to connect to the SRIC during a fly-by, the high amount of RF pollution on the 2.4 GHz frequency during the competition and the difficulty of the task led to the decision of loitering above the SRIC for greater chances of success.

On the software part, the connection and file transfer is done through an automated python script. When the aircraft starts loitering around the access point, the photo transfer to the GVS is stopped to reduce bandwidth usage and interference. The script, started on the XU4 COM at the beginning of the flight, tries to download and upload the files from and to the SRIC until it succeeds. It then uploads the downloaded file from the aircraft to the GVS and notifies the operator of the task's success through the Unix shell.

OFF-AXIS TARGET

In order to accomplish the Off-Axis Target secondary objective, a secondary camera was added to the payload. The Hardkernel oCam 5 Megapixel web camera has a 3.6mm M12 lens providing a 42º vertical FOV and 54º horizontal FOV. Fixed on the side of the plane, its purpose is to snap pictures of the Off-Axis Target on fly-bys. The camera is connected via USB2.0 to the remaining USB port of the XU4 computer-on-board. The camera is positioned at an angle of approximately 65º in relation with the normal angle. This way, the ground area captured by the camera extends from 200 feet to 2800+ feet with the center of the image at 425 feet, making sure the Off-Axis Target will be spotted whenever the plane is aligned with the latter while keeping maximum horizontal aperture.

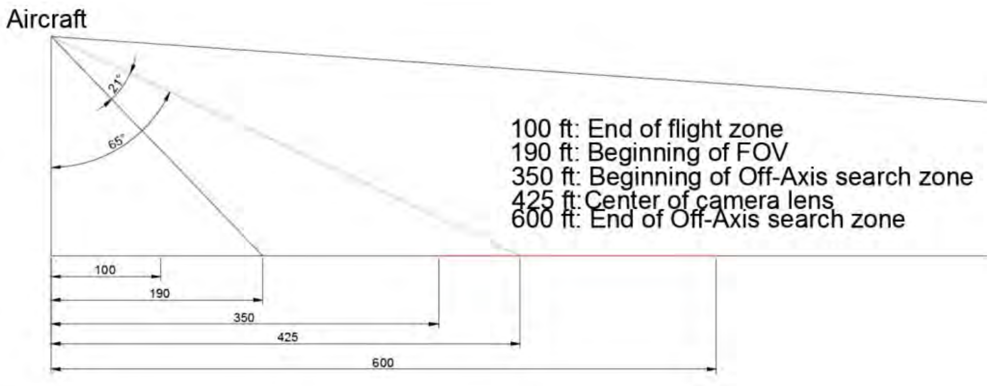

Figure 9 : Field of View of the Off-Axis camera

INTEROPERABILITY

Last year, a python code was used to perform the interoperability task. The solution had to be changed this year, even though it was working great last year, because the task changed a lot. The new solution is an addition to the mission planner code, allowing for an easy access to the mission interface. Adding targets to the mission planner's interface becomes much easier. At this point, the code is able to download the targets from the server, but bugs in the displaying parts of the code prevent the task to be done perfectly. The server time and description are also going to be added later this week. The code for this part is already working, but is not integrated.

SENSE, DETECT AND AVOID

This year, the team has chosen to let the GCS Operator manually rewrite the flight plan to avoid the stationary obstacles. To do so, the team modified the source code of the GCS software Mission Planner so the software will display the stationary obstacles as soon as a connection to the server is made. Once the obstacles tags are shown on the flight plan, the GCS Operator can easily modify the previous path to avoid contact with the obstacles.

The platform is not able to dodge the moving obstacles at the moment, so this part of the task will not be attempted this year.

MISSION PLANNING

The art of mission planning starts with accurate time estimations of each leg of the UAV path. It is also a dynamic task, with conditions that may change frequently. The team relies on experienced members to lead the team and make the calls concerning remaining flight time. Flight planning takes place the day before the competition to account for winds and mission data.

The following flowchart specifies the expected mission progress. The steps in red are high priority and will be executed. The steps in yellow can be dropped in extreme circumstances. Finally, the steps in green will be executed if there is enough time, that is, if there is at least five mission minutes left. The team expects to use the whole mission time available.

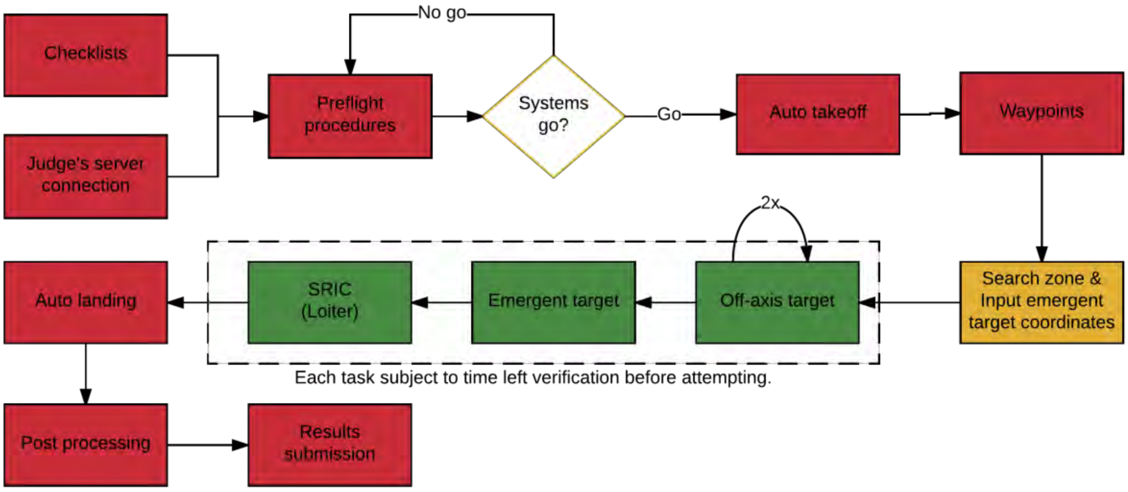

Figure 10 : Mission planning chart

TEST AND EVALUATION RESULTS

MISSION TASK PERFORMANCE

AUTOMATIC DETECTION, LOCALIZATION, AND CLASSIFICATION (ADLC)

As the ADLC is still in an experimental phase, its performance is highly dependent on the quality of the images that will be captured. At the time of writing, in good conditions, three target characteristics plus geolocation can be found. By the time of the competition, four characteristics are expected to be detectable. However, the weather conditions and target colors and characters being unknown, the ADLC could simply not work. Furthermore, the need to remain below 50 % of false positives hinders the capabilities of automatic target detection. To reduce the chances of false positives, target locations are first analyzed to eliminate false positives outside the search area. As for QR codes, VAMUdeS will not attempt to decode them automatically as they are extremely hard to detect and even harder to decode.

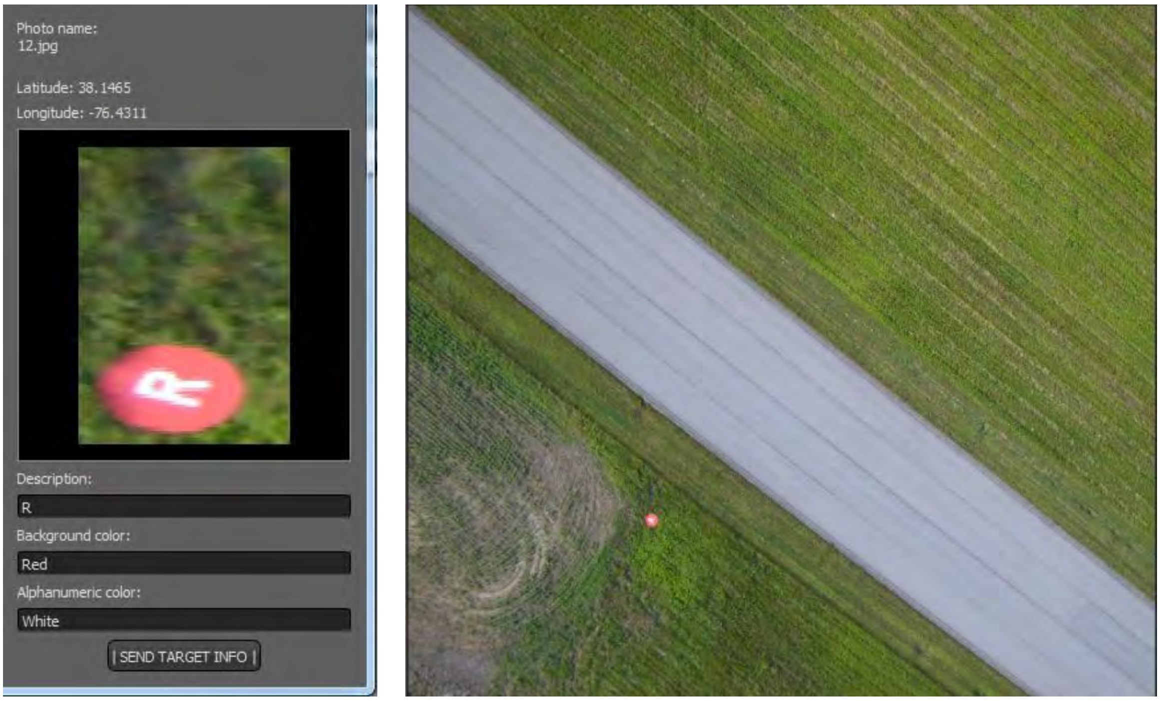

Figure 11 : Images and results obtained with the current automatic analysis algorithms

SENSE, DETECT AND AVOID

Since the GCS Operator has to rewrite the flight plan before the take off to avoid stationary obstacles, several test flights were made to ensure no mistake would be made in the modified flight plan, especially in stressful environments. SDA simulations were made on almost every flight day, with a success rate of almost 50%, most of the failures being caused by human mistakes in the first trials.

ACTIONABLE INTELLIGENCE

The Actionable Intelligence task is considered to be a routine task. The custom image analysis software developed by VAMUdeS (see Figure 8) allows for quick and easy target characteristics identification. With good quality pictures, all five characteristics can be found and saved in a matter of seconds. Analysis could however be made difficult by bad quality pictures, due to a high banking angle or high altitude.

EMERGENT TARGET TASK

With mission planner, the UAV can be redirected mid-flight to the emergent target location. With 3 waypoints, the UAV can fly in a line over the target at least 2 times to ensure ideal pictures of the target are taken.

The emergent task has been tested almost every flight day, since it’s quite an easy task to test. In the simulations, it was determined that the emergent task could be achieved 19 times out of 20. However, it can sometimes take up to 2 minutes to safely redirect the plane to the designated area. In the meantime, the Artemis can loiter over the flight zone.

The Actionable Intelligence task is considered a routine task. The image analysis software developed by VAMUdeS allows for instant target identification with a mouse click through a simple interface where the user can enter the five target characteristics in a matter of seconds. With a single good quality picture, the task can be easily accomplished, while bad quality pictures, due to, for example, high altitude or a high banking angle, may make the task more difficult.

PAYLOAD SYSTEM PERFORMANCE

IMAGING

In the chosen configuration (see Imagery System Design Description), the D3200 camera’s images have a resolution of 0.5” per pixel at an altitude of 200’, with an additional 0.5” for every additional 200’. At a cruise speed of 41 knots, altitude of 200 feet and with a fixed delay of 2 seconds between each image capture, there is 30 feet or 17% vertical overlap between two successive pictures, with a covered width of 255 feet. Flight path is adjusted to obtain about the same horizontal overlap.

While the oCam web camera is calibrated every other flight day due to the low number of possible adjustments, the D3200 is adjusted before every flight to ensure proper focus and exposure. The D3200 is set to shutter-priority mode with a 1/1600th of a second opening time to effectively remove motion blur while keeping ISO values in an acceptable range (below 400) to obtain desired exposure.

Images are saved in the JPEG BASIC format, allowing for real-time image reception at the GVS due to reduced file size. However, contrast is lost between pixels due to the level of compression. Given the high resolution of the pictures, this downside has little impact on the overall Search Task. However, QR codes need to be processed before they can be read.

Table 5 : From left to right : original QRC capture, QRC with various exposure settings modified, reconstructed QRC during simulation and original QRC with ruler for scale. Photo taken at 140 ft. with a size of 1.3” per pixel.

GEOPOSITION MEASUREMENT

The GPS connected to the payload is set to operate at its maximum of 10 Hz. At a flight speed of 41 knots, it means the maximum precision attainable with the GPS is 7 feet, not accounting for measurement uncertainty itself, which is usually around 5 feet. To compensate for this uncertainty, plane position is interpolated using previous GPS coordinates and taking into account the average camera capture delay, measured over more than a hundred of pictures, to estimate exact camera location. Considering the large minimum turning radius of the aircraft, no further calculations, such as SLERP, are considered necessary since any imprecision caused by rotation is negligible compared to other sources of uncertainty. The precision obtained with this method usually reaches five feet.

AUTOPILOT SYSTEM PERFORMANCE

Multiple tests were conducted with the Pixhawk to assure it would provide safe flight conditions at any time. Since the autopilot had never been used in the Artemis platform, all of the initial tests were made on the ground to ensure system effectiveness and responses to different situations. Once those tests were deemed conclusive by the flight team, the autopilot was tested in flight with a smaller foam platform bought online. The first flight tests on this platform proved the effectiveness of the autopilot's different flight modes. The data of each sensor was analyzed after every flight to ensure every aspect of the flight had gone according to plan. The Pixhawk was then incorporated in the main flight platform, where the rest of the test were made.

SAFETY

The team has been impressed with the Pixhawk performance this year, except for an update from the Ardupilot team that introduced a major glitch in the attitude estimation. The team rolled back to a previous version of the software and decided to introduce a "version freeze": no external updates to any software the team is using shall be done when a competition occurs in less than 4 months. Combined with a skilled ground control operator, the autopilot isn't directly responsible for any crash as of yet.

NAVIGATION

At the beginning of each flight day, the Artemis was flown in stabilized mode to allow the team to manually calibrate its PID controller. Most of the flights were then made in autonomous mode to ensure waypoint navigation performances were up to the standards of the competition. The system is able to achieve a 75ft precision on waypoint navigation in very windy conditions. To ensure safety throughout the flights, the system has a maximum climb rate of 13.2 feet per second and a maximum sink rate of 16.5 feet per second. If a higher climb rate is required, the system can achieve it while doing a circle to ensure its safety. The maximum bank angle of the plane is 45 degrees, giving it a minimum turn radius of 200 feet.

Specification	Value
Maximum roll angle	45
Maximal pitch	18° (up) and 30° (down)
Minimum turn radius	200 ft
Stall speed	23 knots
Maximum wind speed	15 knots

Table 6 : Navigation specifications

AUTO TAKEOFF AND LANDING PERFORMANCE

The team has successfully achieved autonomous landings. The test platform used has been able to land on a grass surface gracefully every time and the safety pilot didn't need to intervene. Accurate control of airspeed is essential for this task and this is the reason a pitot tube has been added to the UAV.

However, some difficulties have been encountered when attempting the automatic takeoffs. Firstly, a magnetometer had to be added because the autopilot cannot otherwise accurately know its heading while stationary and thus cannot keep the gear straight. Secondly, the team doesn't have access to a cement runway and must deal with grass surfaces which don't give a good contact with the ground. This confuses the autopilot when attempting to keep the plane straight.

The last step required is for the team to migrate the automatic takeoff and landing procedures to its main fully loaded UAVs. This is expected to be done very soon. To solve the takeoff problems, it is planned to used bigger wheels on the UAV.

EVALUATION RESULTS SUPPORTING EVIDENCE OF LIKELY MISSION ACCOMPLISHMENT

The **Table** 7 present a summary of the achievement rate for all tasks planned to be done at the competition. Those results are based on two complete mission simulations and more than 50 flights where some subsystems were tested. The group also done a real competition one month ago at the Unmanned System Canada SUAS competition were it finish first with an average of 5 ft. on targets geo location and five on five successful QR decoding in two beautiful autonomous flights. More tests and simulation will be done before the competition to train the team and fine tune systems.

Task planned	Sub-task	Threshold achievement rate	Objective achievement rate
Autonomous flight	Takeoff	100 %	30 %
	Flight	100 %	100 %
	Waypoint navigation	100 %	100 %
	GCS display	100 %	80 %
	landing	100 %	50 %
Search area task	localize	100 %	85 %
	Classification	100 %	100 %
	Imagery	n/a	100 %
	Autonomous search	n/a	100 %
	Secret message	n/a	100 %
ADLC (Experimental)	Automatic location	n/a	25 %
	Automatic classification	n/a	15 %
	Automatic classification QRC	n/a	0 %
	FAR	n/a	80 %
Actionable intelligence	--	100 %	60 %
Off-axis	Imagery	n/a	100 %
	Classification	80 %	15 %
	Payload autonomy	n/a	0 %
Emergent target	In-flight re-tasking	n/a	100 %
	Autonomous search	n/a	100 %
	Target identification	100 %	75 %
SRIC	Download	n/a	80 %
	Upload	n/a	55 %
	Autonomous	n/a	100 %
Interoperability	Download & display server info	100 %	100 %
	Download and display obstacle	100 %	100 %
	Upload target details	n/a	100 %
SDA	Stationary obstacle avoidance	50 %	Don't attempt

Table 7: Results from pre-competition flights

SAFETY CONSIDERATIONS

SPECIFIC SAFETY CRITERIA FOR BOTH OPERATIONS AND DESIGN

Flying a platform like the Artemis pose multiple risks and that is why safety has been a main concern for the team all year long. Both the operations and the design of the platform had to respect safety criteria to ensure the safety of every member of the team at all time.

OPERATIONAL SAFETY CRITERIA

Multiple verifications have to be made before each flight to ensure the safety of the plane. These tests' main goals are to ensure the plane has the ability to takeoff, fly and land safely.

- General inspection of the fuselage, the wings, the tail and both landing gears to ensure their complete integrity. If one of these parts is problematic, it has to be repaired before the platform is allowed to takeoff.
- Inspection of all the wiring in the platform.
- Verification of the RC link and the responses of the control surfaces.
- Verification of the telemetry link and responses of the control surfaces in stabilized flight when the plane is moved.
- Inspection of the batteries general condition and their voltage.
- Verification of the platform center of mass.

All of these point are more precisely described on the 2 pages long pre-flight check list the flight team has to go through before each flight. Li-Po safe bags and a fire extinguisher are also available at all time next to the safety pilot in case of emergency.

DESIGN SAFETY CRITERIA

The current airframe is the last built frame of the Artemis which was designed in 2014 and has already proved its reliability in 6 national and international competitions. The design went through many improvements in the last year, mostly towards weight reduction. All new or modified components were rigorously tested multiple times on the ground and in flight with simulated and real payload, ensuring strength and reliability in various and extreme conditions and situations. Compatibility of electronic payload and on board communication systems was also tested on several occasions and prevented many problems.

In order to prevent injuries due to the propeller, a safety switch was installed between the power source and the ESC to mechanically prevent the propeller to turn on.

SAFETY RISKS AND MITIGATION METHODS

LI-PO BATTERIES

Using Lithium-Polymer batteries as a power source is a quite efficient way of powering the plane and on board systems, but they bring multiple risks. Handling and recharging the batteries has to be done with special precautions to ensure the safety of everyone implied in the process. All batteries, when unused, are kept in Li-Po safe bags, which are specifically designed to contain eventual battery fires. The Li-Po bags themselves are transported inside of a metal briefcase to protect the batteries against shocks and impacts. While Li-Po batteries are being used, a fire extinguisher is always kept within easy range in case of emergency.

The batteries are recharged with a TP820CD battery charger from Thunder Power, which are safe and are designed to cut the power to the batteries in case of any problem. The batteries are also always kept in a Li-Po safe bag throughout the entire charging process.

On board of the plane, the batteries are fixed to the floor by strong Velcro and straps that prevent them from moving during the flight while allowing them to be placed and removed easily. The batteries are separated from the motor by a thick foam block. In the event of a crash or displacement of the batteries during the flight, this protection keeps the batteries from touching the motor, particularly its rotating shaft, which could cause cells perforation, fire and leakage of highly toxic Hydrofluoric Acid gas. In response to the last risk, a HF gas detector is kept close to the batteries at all time with the fire extinguisher.

FLIGHT SAFETY

The UAV itself is the major risk, especially during taking off and landing. In addition to being the most risked phases of flight those are also the times where the plane comes the closest to people on the ground while going at high speed. Once the plane is on the landing strip, coming in final approach or taxiing, everyone is required to be looking at it during the whole takeoff or landing maneuver. Obviously, everyone present has to stand aside from the landing strip and keep a good distance between themselves and the plane trajectory.

The propeller becomes dangerous as soon as the plane is powered on. To prevent any accident while the plane is parked, nobody except for the pilot is allowed in front the wings once the batteries are plugged in, even if the safety switch is in the off position.

AUTOPILOT SAFETY ISSUES

If, for some reason, the code in the autopilot would crash mid-flight, the UAV would become a huge threat for everything around and under it. However, the Pixhawk platform allows for manual takeover of the plane even if it is booting up. This feature is possible because the Pixhawk is equipped with two processors. So, in case of emergency, the safety pilot can take back the control of the UAV and bring it back home safely.

The communication between the GCS operator and the safety pilot is also very important. If anything weird happens with the UAV and the safety pilot has to take it back, there is no time for confusion. This is why, every time the team flies, the GCS operator and the safety pilot communicate through a cell phone.

CYBER-SECURITY APPENDIX

CYBER SECURITY IN UAS

UAS are characterised by a lot of different communication systems, some for the control of the UAV, some for positioning and other for sending data to the ground. These communication links must be protected against jamming, spying and hijacking.

CONTROL LINK

If the control link is jammed, usually, the UAS has fail safes to return to base or to continue its mission. This problem is difficult to prevent and there is usually no solution if the jammer is strong enough. On the other hand, the problem is important, but does not cause harm to the UAV.

To prevent hijacking, it is possible to encrypt messages. Even with encrypted messages, it is possible for a third party to register the signal the GCS sends and to use it to control the drone. In that case, it could be very interesting to use One Time Pairing (OTP) to protect the command. This consists of sharing a very long list of long keys before the flight and use them to encrypt each command or message. If all the keys are longer than all the messages, this system is virtually unbreakable. This system can be heavy to process, but the autopilots are now very powerful.

GPS

Probably the biggest menace to UAS is the loss of GPS. If there is no manual control, the UAS relies solely on the GPS position. If this system is jammed or spoofed, the UAS is in trouble. An interesting cyber attack combo is the jamming of control link and the spoofing of GPS. In that case, the UAV will enter "lost control mode" and will eventually land autonomously. Therefore, with GPS spoofing, it is possible to change the landing point where you want.

First of all, you need to detect this attack. It's probably possible to study the characteristic of satellites signal and detect a sudden change. Another way is to use the Extended Kalman filter (EKF) used in some autopilot to estimate the validity of the new GPS position. If a potential attack is detected, a signal can be sent to the GCS and if the GCS signal is jammed, automatic procedure can be taken.

Second, if you consider your GPS as unavailable, the UAS will need alternative ways of positioning. It is possible to go in dead reckoning mode and with barometer altitude, compass and past wind estimation, go to the approximated GCS position. Another acceptable way could be to climb as high as possible to get new GPS signals and lose spoofing signals. But this latter solution is only possible if the spoofing signal is relatively weak and ground-based.

Eventually, Simultaneous Localization and Mapping (SLAM) could replace GPS. But this requires a powerful computer and real-time video dedicated to that. It is possible to also use LIDAR for that use. A weaker aspect of optical analyses is the optical odometer, which can give an estimation of heading and speed of the UAV.

IMAGERY LINK

Regarding the imagery transmission, modern encryption systems are strong enough to give a reasonable security. It is very difficult to use OTP for encryption, because usually the imagery transmission is usually very heavy and that could be an incredibly big key to use. Therefore, it is very important to keep in mind that every transmission could be registered and eventually cracked in the future. Supercomputers, time or future technology can decrypt anything. Probably the safest way to keep the information safe is not to send them to the ground through data links that can be spied upon.

CYBER SECURITY IN VAMUDES SYSTEMS

For any UAS developer, communication is very important and very tricky. Some bad weather or equipment can alter the communication up to the point where a mission has to be cancelled. Therefore, we have developed systems can endure loss of connection between our systems. On the other hand, the team is not faced with cyber-attacks, but we have some security systems that can prevent these attacks. Here are how we cope with these problems.

The RC control link is more a safety in our case than a vital link. As the UAV can takeoff and land autonomously, there is no need for control link. Nevertheless, this function can be useful to prevent a crash or to take off and land in risky situation. We chose Spectrum communication systems on 2.4 GHz with the DSM X technology. This system uses frequency hopping to limit interference and improve communication reliability. As 2.4 GHz is a very used frequency, the team plans to change to 433 MHz Dragon link communication to ensure a better range and reliability. In case of cyber-attack, the RC control can be deactivated manually via telemetry to continue the mission.

The telemetry link is probably the most important communication system. In case of loss of signal, it’s very difficult to have any information or to do anything to correct a situation. This is why we use X-Tend 1W modem on 900 Hz with a directional patch antenna to maximize the reliability of this link. The X-Tend modem can use 256-bit AES encryption to prevent cyber-attack on communication system.

GPS is a critical function system and must work properly to execute a mission. First of all, our team uses SBAS technology to ensure a better positioning system. In case of lost of GPS, the actual solution is to flying in circles at a fixed altitude using barometer and a RC takeover to land. This solution is not acceptable if the UAS is too far, this is why the team is working on a signal finder who could be used to give the home direction to the aircraft. With the barometer altitude and the home azimuth, the UAS using is compass can safely return home to be manually landed. This system is based on the tracking antenna and imagery link.

Imagery link is a standard Wi-Fi with a powerful 28 DB tracking antenna. As this communication is used for imagery and SRIC only, it is not a critical communication system. Nevertheless, cyber-attacks can be made to spy on imagery. There is a double security system to prevent this situation. The first one is composed of the wireless security system which uses Wi-Fi Protected Access 2 (WPA2) with AES security and MAC address filtering. Inside the network bridge, the SSH protocol is used to control the payload and the connection is therefore protected. Finally, the aerial images feed is encrypted with arcfour 128 bit protocol.