FLOW DESIGN TEAM – VECTOR VX-3

TECHNICAL REPORT

1. MISSION REQUIREMENTS

The mission simulates the following event: emergency services are handling a forest fire and have tasked an Unmanned Aerial System (UAS) to locate a person needing rescue and suppress the fire by releasing water on it. Basic requirements can be listed as follows:

- autonomous take-off, flight and landing in geo-fenced boundaries – important for easy setup and operation by possibly untrained personnel and lack of professional UAS crews
- Stationary obstacle
- First Person View (FPV) system – enables real-time broadcast of the video for the on-site team and enables the pilot to take over when needed
- timeline – as the situation is extremely time sensitive, it is important that all mission requirements can be executed in the shortest time as possible
- manual object detection, classification and localization – UAS must be able to recognize a person or alphanumerical character, pinpoint the exact location of detected object, and to execute assigned action (in this case, releasing water)

Additional requirements enable Moving Obstacle Avoidance, Autonomous Target Detection, Classification and Localization, Imagery, and Actionable Mode.

The competition rules credit these requirements as stated in Table 1 and were an important guideline by making design decisions and engineering trade-offs.

Table 1. Mission Requirements

CATEGORY	TASK	%	INTERPRETATION	ORGANISATION AND ENGINEERING DECISION/ TRADEOFF
TIMELINE		10%	Mission is a restricted time scenario	Blended Wing Body configuration enables higher speed, and consequentially shorter mission time
	Setup Time	-	Restricted time window for UAS setup (15 min assembly + 5 min pre-flight mission)	Detachable wings, use of simple release/lock mechanism, competence in team roles and clear understanding of assignments
	Mission Time	80%	Complete the mission in shortest flight and post-processing time, respectively	Using previously stated configuration and on-board avionics and payload capabilities
	Mission Time Penalty	3% /second over 45min	Completing the mission in 45 minutes	Organize time and tasks for each member so the 45 minutes limit is not breached, practice mock missions
	Timeout	20%	Avoiding timeouts	Using tested procedures with physical checklists to avoid human errors
	Teardown Time	-	Restricted time window for UAS teardown (10 min)	Detachable wings, use of simple release/lock mechanism
AUTONOMOUS FLIGHT		30%	Avoiding and minimizing pilot takeovers	Redundant autonomy system
	Autonomous Flight	40%	Minimizing pilot takeovers	Using reliable and previously tested autopilots adapted for our UAS
	Waypoint Capture	10%	Flying over given sequence of waypoints	Using safety pilot feedback, improve maneuverability of the UAS
	Waypoint Accuracy	50%	Accurately position the UAS over waypoints	Using double GPS sensor system to precisely determine UAS location, correlate with other sensor inputs (pitot, ground speed calibration), practice manual operation with mission planning software
	Out of Bounds Penalty	10% per violation	Avoiding risks caused by geo-fence breach	Using double GPS sensor system to precisely determine UAS location, minimize the UAS response time, warn the pilot that the UAS is approaching the geo-fence
	Things Falling Off Aircraft Penalty	Up to 25%	Avoiding risks caused by unauthorized airdrop	Using tested procedures and physical checklists to avoid human errors

Crash Penalty	Up to 35%	Implementing safety systems and procedures during unexpected events	Using emergency parachute at crashing, warning sounds, bench testing the procedure in a simulated environment
OBSTACLE AVOIDANCE	20%	Integrate with national airspace	Using reliable and previously tested autopilots adapted to our UAS
Telemetry Prerequisite		Upload valid telemetry during the mission at 1Hz frequency	Using 433 MHz band to upload the telemetry data to Ground Control Station (GCS), gaining experience with the Interoperability system and developing software code for the procedure
Stationary Obstacle Avoidance	50%	Avoiding geometrically predefined objects at given location	Using reliable and previously tested autopilots adapted to our UAS
Moving Obstacle Avoidance	50%	Avoiding geometrically predefined objects at random location	Same as Stationary Obstacle Avoidance, with implementation of algorithm that changes flight plan in minimum time regarding to new obstacle appearance
OBJECT DETECTION, CLASSIFICATION, LOCALIZATION	20%	Standard and emergent object DCL	Using HD camera mounted on a gimbal, on-board image processing, custom implementation of software algorithms to detect objects
Search Area & Off-Axis	-	Flying the UAS in given search area	Using double GPS sensor system to precisely determine UAS location, minimize the UAS response time, warn the pilot that the UAS is approaching the geo-fence
Object Matching	-	Comparing submitted objects with real ones	Testing and upgrading image recognition software using flight logs and safety pilot feedback
Imagery	-	Submit cropped image that fills 25%+ of the image	Develop the code to automatically send cropped image to GCS at positive object detection
Characteristics	20%	Matching given characteristics of the submitted object to the real one	Testing and upgrading image recognition software using flight logs and safety pilot feedback
Geolocation	30%	Accurately provide GPS location of the object	Using double GPS sensor system to precisely determine UAS location, develop the code to fetch sensor data and calculate object location
Actionable	30%	Submit targets via Interoperability System	Connection to autopilot telemetry system to identify locations of the targets that maximizes f(0, $\frac{100ft-distance}{10ft}$)
Autonomy	30%	Provide information about the object without pilot takeover and/or intervention	Pre-programming the UAS behavior in case of given action (object detection followed up by i.e. payload drop and return to base)

Extra Object Penalty	5% per false DCL	Avoiding false-positive detections	Testing and upgrading image recognition software using flight logs and safety pilot feedback
AIR DELIVERY	10%	UAS must be able to drop an object to a specified position taking into account geo-fence and altitude limitations	Custom-designed release mechanism
Payload	-	Geometrically predefined object is known and must not be modified	Define cargo space in fuselage and implement adequate release mechanism. Test with attached sensors to the bottle and derive data for statistical analysis
Delivery accuracy	-	The bottle must open upon landing and be as close as possible to given GPS location	Testing and precisely timing release mechanism opening using field results, flight logs and safety pilot feedback
OPERATIONAL EXCELLENCE	10%	Team professionalism, communication, attention to safety and reactions to unexpected events	Develop procedures for all stages of the mission, practice frequently, educate and research the topic, transfer knowledge from advisors and industrial partners

2. DESIGN RATIONALE

Design Rationale was written about five main design points and one secondary. Flow Design prioritizes its points, starting from the mission requirements, in accordance to the team's budget.

Team will focus on the mission requirements of 'Autonomous Flight', 'Object Detection, Localization and Classification' and at the end 'Air Delivery'. Team will not put in focus 'Object Avoidance' as one of the design requirements.

The first design question was; how to achieve 45 minutes flight autonomy while carrying a payload for an Air Delivery and having enough space to accommodate the on-board equipment? After thorough research, team concluded that mission requirements will be easier fulfilled with a fixed wing over classic quad, hexa or octa-copter design. 'Having more aerodynamically efficient UAS secures more flight time' was a guideline for the fixed wing design. After grading various approaches, such as monoplane, biplane, canard or flying wing (BWB – Blended Wing Body), BWB had the highest grades of them all. Although BWB has its downfalls such as directional stability or manufacturing difficulties, it has the most efficient aero dynamical airframe and highest Lift-to-Drag Ratio. Such advantages are making BWB to carry more cargo in the same UAS category as the other designs. More about the design decisions made upon choosing the right airframe can be found in 2.1 Aircraft chapter.

The second design decision was made again on the behalf of maximizing endurance by making custom-made power supply. Our electrical engineering came up with the idea of designing the Li-ion battery pack (18650 design), since its energy density is approximately 40 % higher compared to an off-the-shelf Li-Po pack. The drawback of these batteries is low discharge rate, which is compensated by a power supply balancing unit, running several battery packs in parallel. In case of high-discharge rate operations, such as ascending, the pack delivers necessary power output from all resources, and for cruise mode, it can balance power consumption and longevity. This feature also allows maximum usability of the cargo bay and aids in trim settings, since it can be spatially distributed within the bay as needed.

The third design decision made was the choice of an optimal autopilot system. Pixhawk Cube 2.1 was chosen for its customizability, ease of use and large support community. This autopilot system provides reliable and accurate navigation for flying wings, which can be adopted and customized in the Mission Planer. While Cube 2.1 is a new design with less users then the old v2 models, it is still possible to reuse and adapt much of the solutions from the old codebase. Overall, v2.1 Cube presents significant design improvements with justifiable financial difference.

To enhance the payload's capacity, the UAS is made of ultra-light weight composite materials, reducing the airframe mass down to 1 kg on the 2.2 m wing-span construction. Since UAS's MTOW is just under 5 kg, 4 kg of payload, propulsion and avionics are on disposal.

Considered fifth, payload servo controllers are located underneath the fuselage, holding the payload in the neutral position. Cargo should be carefully trimmed before and after the drop, since the flying wing design has tight balancing boundaries. The cargo mode flight and post-drop mode flight trim are described previously in the chapter, and later in the 'Air Delivery' section.

3. SYSTEM DESIGN

3.1. AIRCRAFT

In this section, design of the aircraft, its principles and performance characteristics are described.

3.1.1. DESIGN

The design of the UAS VECTOR VX-3 was made with the purpose of maximizing endurance while staying in the category of SUAS, MTOW <5 kg. At the same time, those were the main calculation requirements. For that purpose, various airplane designs were taken into the consideration, but the one who has collected most of the points was BWB (Blended Wing Body) or Flying Wing. [1]

Table 2. Design Selection

Characteristic	Weight Factor	Monoplane	Biplane	Canard	BWB
Flight Autonomy	10	7	6	5	10
Payload	5	6	7	5	5
Stability and Control	6	7	7	7	4
Ease of manufacture	4	7	5	6	6
L/D (Lift to Drag Ratio)	7	6	5	4	9
Total Score	**-**	**212**	**192**	**169**	**236**

BWB design is known for its aerodynamic cleanliness and contour smoothness that brings the highest L/D ratio. All lifting surfaces coupled with minimized drag secure advantage when it comes to power consumption. Sometimes, if the design is done properly, BWB planes with the similar capacities as the conventional ones create up to 30% less drag. [2] Since the drag is equally opposite of thrust, and thrust is nothing else but power consumption, 30% less energy can be consumed, extending endurance. On the other hand, there is a price to be paid. Since not having a tail, vertical or horizontal, stability and control are harder to achieve. Experienced UAV pilots can control them manually, but with today's technology of autopilots, stability is the problem of the past.

Design had seen many changes as it developed through the different stages of conceptual and preliminary iterative phases. With the help of CFD calculations and wind tunnel facility tests, it was possible to test the quality of aerodynamics and obtain all the necessary graphs, such as L/D graph, or finding the cruising speed. During the one of the first test flights with the previous design, lack of the model's sweep angle resulted in poor pitch stability, while inadequately tall winglets diminished yaw stability. Both lapses were amended with the next prototype.

So far, latest design is satisfactory. Well-chosen air-foils, minimal geometrical twist and optimized fuselage enabled VECTOR to set itself in front of the competition in terms of range, power consumption, overall design efficiency and flight time.

Design development and VECTOR's characteristics are shown.

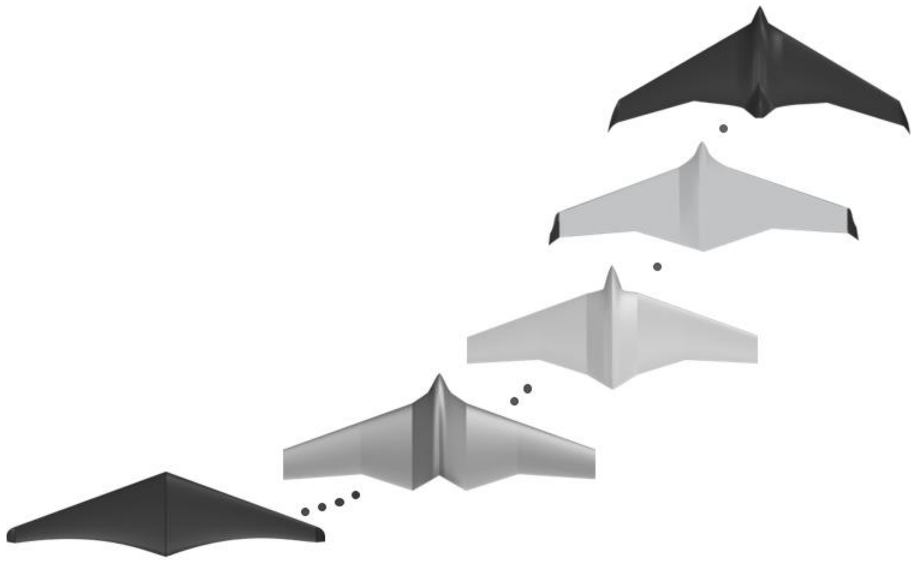

Figure 1. Design development

Table 3. Aerodynamical and geometrical characteristics

Type: BWB (Blended-Wing Body) flying wing	
MTOW	5 kg
Wingspan	2.2 m
Lifting surface	0.7 m^2
Air-foils used	MH-60 (root), MH-45 (tip), GOE-741 (fuselage)
Leading edge sweep angle	30^o
Aspect ratio (AR)	6.5
Taper ratio (TR)	0.35
Performance characteristics	
Cruise speed	60 km/h
Top speed	120 km/h
Estimated endurance	120 min
Control surfaces	Dual-use Flaperons
Engine	electrical out-runner, 870 W
Propeller	12x8 CW
T/W (Static Trust)	0.7
$(L/D)_{max}$	23

Standard flaperons are used for the control of the airplane. On the outer side, flaperons are made slightly larger than on the inner one. Bigger surfaces at the end of the wings enable better control over the manoeuver. They are good in pitch and roll control and can be used for yaw steering. The problem of loss of altitude while banking can be solved by adding a new set of control surfaces, drag rudders. Drag rudders are small surfaces set at the end of the wings to obtain as large torque as possible, relatively to the center of the mass. Beside them, flaps will be added to reduce stall speed and to rise maximum lift coefficient.

Following 'blend-all-you-can-blend' philosophy, fuselage is made of series of reflex air-foils that contribute to lift, while adjusting the form of the tail so the engine would blend into the design of the fuselage itself. Having engine placed in the pusher form, plane has clean, undisturbed flow coming over it.

3.1.2. STRUCTURE AND MANUFACTURING

Many different approaches were taken into the consideration until the right one had been found. VX-1 was the very first scaled model tested on the field. Its wings were 'hot-wire' cut out of polyurethane block, while having carbon laminated fuselage. Wings were glued to the fuselage, not having satisfactory structural strength. Relatively simple method of wing construction is CNC milled polyurethane foam coated with a layer of carbon fiber. On the other hand, making a fuselage of BWB airframe demands some knowledge in molding manufacture and composite materials. Current model used in test flights has the described configuration, but the VX-3 is going to be built completely out of composite sandwich structure at Rimac's factory. VX-3 will be built with pre-preg composite technology, followed up by autoclave method. VX-3 is the plane that will be used on the AUVSI competition.

Beside the advanced aerodynamics this design carries, having an extremely light airframe would significantly increase potential payload mass, while keeping in mind the airframe strength. Some developmental numbers are stated, for perspective; first VX-2 airframe weighed in at 3 kg (made completely out of composite materials), while the second one weights 2.1 kg. VX-3 will weigh at around 1 kg, a 66% decrease in weight over one year and three models of development.

3.2. AUTOPILOT

The team opted for the Pixhawk 2.1 Flight Controller (http://www.proficnc.com/), which is the leading open source autopilot system, as the UAS autopilot, since it provides fully autonomous capabilities to the UAS, while reducing possible development and mission risks. The aircrafts takeoff will be achieved with a custom-made catapult while the autopilot corrects the flight trajectory because of calculations made from data received from sensors. The Pixhawk also offers a pilot manual override which can be activated at any given moment of flight directly from the pilot's radio controller. Pixhawk software is based on the open-source ArduPilot (http://ardupilot.org/plane/index.html), currently running version Plane 3.5.2.

Fail-safe options, if the primary RC link is lost, the UAS will postpone its mission to circle in an assigned radius for 30 seconds until the link is restored. If it happens that the link is not established in the given time interval the Return to Launch (RTL) directive will be activated.

Other than that, the Pixhawk autopilot is a small and lightweight piece of airborne hardware, with low power consumption and no special cooling requirements.

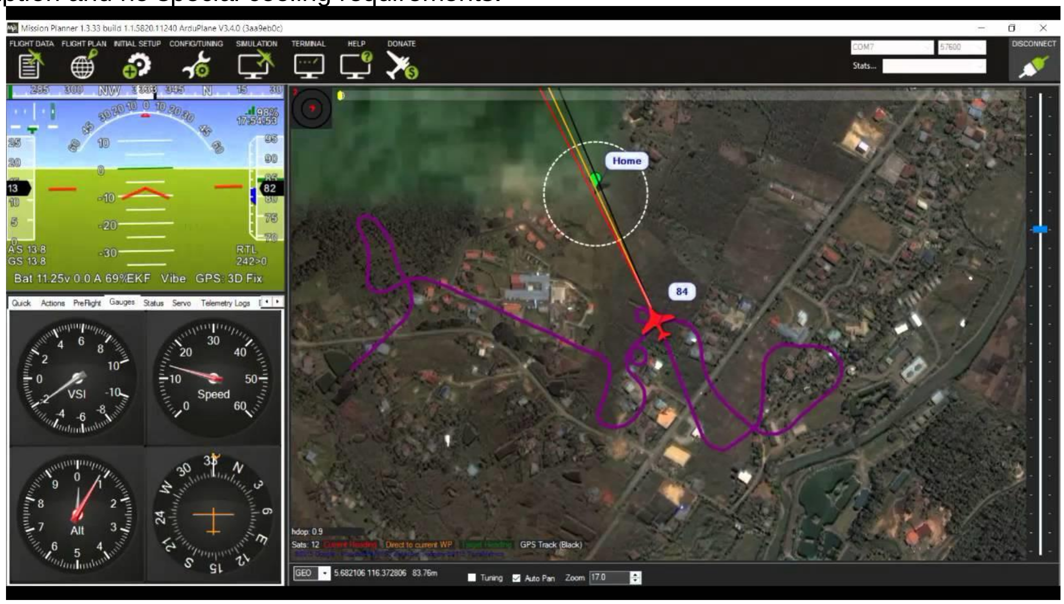

Figure 2. Mission Planner

Table 4. Autopilot characteristics

IMU:	Connectivity:
3 x accelerometers	5 x serial ports
3 x gyroscopes	2 x CAN ports
3 x magnetometers	2 x I2C ports
2 x barometers	2 x power ports
	1 x ADC port
	8 x dedicated opto capable PWM out
	6 x GPIO that can also be used for PWM

3.3. OBSTACLE AVOIDANCE

Since this is the first year of competition for Flow Design Team, the team did not consider autonomous Obstacle Avoidance for the competition, due to lack of manpower and focus on the mechanical/aerodynamic part of the UAS. The resulting effort was to provide best possible training to the mission operator and complete the avoidance manually from the Mission Planner software. For that purpose, multiple test flights will be flown and at best, two students will be able to perform the tasks by the end of the flight campaign. Metrics for training will be the reaction time, from receiving the message, to time for plotting a new waypoint, executing the command, and finally, the accuracy of avoidance. A limit of 30m was set for accuracy of avoidance. In the future, there are plans to either use the algorithms available in the ArduPilot open-source software, or to use them as basis and adapt our own solution.

In case the development schedule allows for an implementation of obstacle avoidance, an open-source version of the Traffic Collision and Avoidance Resolution Advisory (TCAS RA) algorithm in a simplified form will be considered. [3]

3.4. IMAGING SYSTEM

The imaging system is composed of the Raspberry Pi3B+ (rPi) on-board computer (OBC), GoPro Hero 5 digital camera, which contains a GPS module, and communications system operating on 2.4/5 GHz frequency. While choosing the right camera for this competition a couple of alternatives, such as a 'lens-style' camera, or a smartphone camera, were considered. The lens-style option was discarded because it is out of the teams' price range. As for the smartphone camera, its compact size, durability, performance, and ultimately price is all lower-rated than the GoPro Hero 5 which is regarded as an ideal action camera.

Moreover, one of the reasons the GoPro Hero 5 camera was chosen is because it is well documented, hence information about the camera is easily obtained. Also, it can be connected to the Raspberry Pi which is an important factor for constructing a fixed-wing aircraft. Furthermore, this camera has best-buy specifications considering its price, weight and size. Specification shows that the 12 MP, 24 mm lens, 30 fps pre-programmed mode which automatically captures photos at set time intervals from 0.5 to 60 seconds can be used with the OBC and was tested with the rPi. This is possible because of rPi's improved CPU/GPU performance. The pre-programmed mode which will be controlled over a Python library provides a maximum of 94.4° on the vertical axis, 122.6° on the horizontal axis and 149.2° for the diagonal field of view which should be more than enough for the mission. The GoPro also enhances the UAS's safety features by having an IP6x class casing (waterproof and shock resistant).

Captured photographs are transferred via the application programming interface (API) to the OBC. For establishing a connection between the camera and the rPi, General Purpose Input/output (GPIO) pins are used.

For choosing an OBC device, following options were considered: Odroid XU4, Nvidia TX2 and Raspberry Pi3B+. The Odroid XU4 OBC system would also work with the designed aircraft platform but it is difficult to acquire in Croatia (no local reseller, tax duties) and it isn't as widespread as the Raspberry system. As for the Nvidia hardware, it is possibly the best choice there is, however, it is several magnitudes more expensive, and does not fit the budget constraints.

Other than the before told reasons the Raspberry Pi3B+ was chosen as the OBC, due to its affordable price and the following specifications which suit the competition criteria:

Table 5. Raspberry Pi3B+ characteristics

SOC Type	Broadcom BCM2837B0
Core Architecture	ARMv8-A (64/32-bit)
GPU	Broadcom VideoCore IV 1080p60
CPU Clock	1.4 GHz Quad Core ARM Cortex-A53
RAM	1 GB
POE (Power over Ethernet)	Yes
Approx. Power Requirements (Min – Max) (A)	0.450 - 1.2

3.5. OBJECT DETECTION, CLASSIFICATION AND LOCALIZATION

This section describes the modes of operation the team will use to achieve mission objectives.

3.5.1. MANUAL DETECTION

The team opted for the primary method of Object Detection, Classification and Localization (ODCL) to be manually operated with a dedicated Payload Operator position in the GCS. Since this is the first year of the competition for the team, and for previously stated reasons of focusing on the mechanical design and lack of manpower, it was decided that it’s not within the teams’ primary focus to conduct autonomous ODCL. Due to budget constraints, the gimbal is also not implemented on the UAS. An effort to expand the field of view (FOV) was made by choosing a camera with a wide lens. The choice was settled on a GoPro 5 Hero camera with 122.6° FOV. All the factors led to a low probability of success with the autonomous mode.

3.5.2. AUTOMATIC DETECTION

If the testing conditions and progress allow, the team will conduct a field test with a pre-trained neural network, already tested on an rPi computer, based on OpenCV library, and attempt to operate the system in a hybrid operator-in-the-loop mode, where final decision making and cropping for object submission rests on the Payload Operator. Selected objects are then to be submitted to the Interop server.

3.6. COMMUNICATIONS

Two separate communication channels are used between the aircraft and GCS. First one, the 433 MHz DragonLink v3, is used as a telemetry connection between the Mission Planner (http://ardupilot.org/planner/), running version 1.3.56 and the Flight Controller. It is also used as the RC control by a safety pilot in manual mode. Second one, a dual-band 2.4/5 GHz Ubiquiti AirMax link, which consists of the Rocket base station and a Bullet transceiver in the UAS, is used as an imagery data link, such as FPV and photo/video stream. To guarantee adequate range, both the Rocket and the Bullet are attached to the 11dB gain omni-directional antenna. The GCS is used to control the UAS via three separate stations, the Mission Planner station, the Payload Operator station, and the Mission Commander station. This is done by setting waypoints and target altitudes and changing autopilot modes. Common ArduPilot Plane modes are: Stabilize, AltHold, Loiter, Auto, Circle, Land, PosHold, SmartRTL. Each serves a specific function within the flight envelope of the UAS and will be used during the mission profile.

Table 6. Communication Channels

	RC and flight telemetry link	Imagery data link
Model	DragonLink v3	Ubiquiti RocketAC base station Ubiquiti BulletAC UAS module
Transmitter power / Gain	1500 mW	11 dB
Frequency	433 MHz	Dual-band 2.4/5 GHz

Data rate	N/A	300-500 Mbps
Range	40 km	Up to 20km

3.7. AIR DELIVERY

Flow Design Team decided to use a tongue-based release mechanism, as depicted in Figure 3.

Figure 3. Release mechanism

The release mechanism must safely secure the cargo to the aircraft and enable quick and precise drop. Its main advantage is the possibility of mounting different types of cargo – bottles, boxes, bags, with limit only in cargo weight, but not shape. It also provides lesser impact on stability and flight characteristics after performing the drop.

Cargo geometry influences flight autonomy, so design tradeoff of placing cargo outside instead in the belly was meticulously studied. It was proven that placing the type of cargo used in AUVSI SUAS 2018 competition, 2oz water bottle, has little impact on flight autonomy because of VECTOR VX3's superior aerodynamic characteristics.

The mechanism is mounted on the belly of the aircraft and aligned with the center of mass to ensure stability both before and after the drop. To prevent excessive weight addition, focus was on optimizing structure and using materials such as aluminum to ensure lightweight, but rigid structure that can withstand the bottle weight and wind rush. The mechanism is controlled by servo-motor positioned inside the aircraft and connected to the OBC.

To ensure precision of the drop, the team performed series of tests to calculate the right time to release the bottle. The position of the UAS regarding target, along with wind direction and speed, were the key variables in developing and implementing an algorithm which controls the release mechanism. The algorithm continuously calculates the flight equations in real time. In case of need, the algorithm can be manually overridden by pilot on GCS.

3.8. CYBER SECURITY

Cyber security is an essential requirement in UAS missions such as defense, reconnaissance or surveillance. Major necessities to accomplish are security of life, property and equipment, integrity of data and availability of communications during the mission. The goal is to secure the communication channels and physical security of both the UAS and the supporting Ground Control Station.

3.8.1. UAS

Most vulnerable component is the Flight computer, which can serve as a gateway to intruders, and a means of control for all sub-systems on the UAS. The computer runs on Linux, with an active firewall and connects via a WPA2-AES secure Wi-Fi channel to the GCS. This assures there is no free-to-air transmissions without encryption. The Flight computer also serves as a backup and failsafe for the unencrypted Autopilot communication which can be exploited. In that case commands are sent via Wi-Fi instead of Autopilot link and have a higher priority of execution to the Autopilot link commands.

3.8.2. COMMUNICATION

Links are classified as Payload Link, RC Link, and Autopilot Link. Elements of the communication package are the GPS and RC receiver – on-board, and Autopilot and Wi-Fi transceiver – on-board and on ground.

Payload Link communication is based on a commercial 2.4/5 GHz range Wi-Fi Access Point with 1Gbps Ethernet backplane to the GCS. Since EU in general bans 5 GHz range for public use, those radios were not considered. Link is encrypted with WPA2-AES encryption, which is by all practical means, except military action, unbreakable until now. To prevent channel jamming and potential bandwidth problems, Frequency Hopping Spread Spectrum (FHSS) technology is employed. Receivers and transmitters are physically paired in advance.

RC Link consists of a Dragon Link package, a transceiver in the UAS with an antenna, and a matching pair on the ground, connecting to the GCS. The data stream includes control commands only, either for autopilot or manual operation. It operates in the 433 MHz range, with FHSS security, generated by pseudo-random number generator after pairing. Both ground and on-board equipment need to be paired before operation, ensuring security.

3.8.3. GROUND CONTROL STATION

GCS runs entirely as an isolated network, separate from the Internet, with Ethernet router and disabled wireless segment. A firewall with static IP assignment and MAC filtering is running on all computers within GCS. OS (Unix-based or Windows) is updated to the latest version and all non-essential software is not permitted for installation or uninstalled on the computers. Access to the work stations (Pilot, Mission and Communications Computer) is secured by strong passwords, and two-factor authentication, along with biometric readers (facial recognition, thumbprints, voice pattern matching). Access to information by 3rd party is denied during the mission time, and in case of need, can be transferred by means of a formatted USB drive offsite. Antenna tracker equipment is also physically connected via serial port or Ethernet connections and do not pose an outside security risk. All data is regularly backed-up to various media (RAID 1 NAS, USB drives, Cloud storage if available).

Physical security is assured by assigning access only to verified personnel, a log sheet with times of entry and exit with signature and without access to unauthorized personnel during non-flying hours.

Table 7. Security threats and mitigations

No.	Threats	Resolution
1	physical radio interference	WPA2-AES encryption, FHSS technology.
2	Communications interception (injection of malware, Trojan, virus software)	Redundancy in mission equipment both on-board and on ground at the GCS.
3	Eavesdropping, man-in-the-middle interference	Develop proper failsafe measures and contingency for each eventuality.
4	Hacking of consumer equipment (RC link DSMx, unencrypted autopilot command link)	Identify proper equipment that is out-of-the-box secure to a reasonable standard. Avoid untested equipment. Develop GCS override actions for backup communications link (Payload link as backup).
5	GPS spoofing	GPS receiver with encryption. HackRF Software Defined Radio for detection, verification of readings with other on-board instruments, execution of intentional crash, emergency landing, Return to Home, Return to Land.
6	Loss of signal	Twin antenna configuration, amplifiers.

7	Bandwidth restriction	Separate RC, autopilot and payload channels, with failsafe switches.
8	Jamming	FHSS as a deterrent for channel intrusion, proper failsafe actions.
9	Network disruption	Failsafe and redundancy options.

4. SAFETY, RISK AND MITIGATIONS

4.1. DEVELOPMENTAL RISKS AND MITIGATION

Safety and risk-free environment is one of the most important features in the process of design, development, production and operating Flow Design Team's UAS VECTOR VX-3. Team members were encouraged to propose risk mitigations as new safety hazards arose and improve existing ones to ensure maximum safety and avoid injuries. Using previous experience, senior team members along with trained professionals oversaw and trained production team at using power tools or at processes that included toxic chemicals.

Along with team members' safety, focus was on organization as it proved itself as a good practice to prevent developmental risks such as human errors and missing deadlines. Safety check list were implemented and improved during the process, and Gantt charts were used to keep track of tasks and deadlines.

Overall risk detection and mitigation is presented in Table 8.

Table 8. Developmental risks and their mitigation

	Risk	Occurrence	Severity	Mitigation
Design	Team Integration Issues	Infrequent	Medium	As team members are enrolled at different study programs, class schedules are taken in consideration when setting up meeting times, and schedules are adapted when possible to ensure availability as needed.
	Components Integration Issues	Rare	High	Team communication is encouraged to prevent cases of UAS components to be unable to work together. Design review meeting are held weekly between sub-team leads and potential contradictory requirements are solved by faculty advisor. Systems engineering approach ensured that each component is tested and operational before using it in a subsystem, and each subsystem is functional before integrating into UAS, so the operator risk is minimized.
	Delays in development of subsystems	Infrequent	Medium	Use of project and time management tools such as Gantt charts, collaborative messaging and file sharing has proven effective regarding meeting defined timeframes and deadlines.
Manufacturing	Exposure to toxic chemicals	Frequent	High	Use of appropriate safety equipment (gas mask with canister, gloves, security glasses, protective clothes…)
	Fabrication Error	Infrequent	Medium	Developing Safety Manual and Safety Check List, using clearly visible posters at workstations to indicate possible hazards and/or injuries.
	Personnel Injury	Rare	High	Mandatory training in a tool or process before using it, obedience to rules and procedures stated in Safety Manual.

4.2. MISSION RISKS AND MITIGATIONS

Mission risks and their mitigations are presented in Table 9.

Table 9. Mission risks and their mitigation

RISK	DESCRIPTION	LIKEHOOD	IMPACT	MITIGATION METHOD	FALL BACK PLAN
Major System Malfunction	A major crash before or during the competition, disables the aircraft and prevents it from completing the mission	Low	High	Extensive flight tests as a preventive measure. Safety Pilot present always to avoid crashing. Parachute deployed.	Experience gained in quick on-field repairs so there aren't any further complications
Minor System Malfunction	A component on the system malfunctions and prevents accurate flight from being achieved	Medium	Low	Checklist to eliminate or mitigate any potential threat or malfunction before leading to a larger one.	On-field tools and a collection of spare parts
Loss of Manual Control	The ground crew may lose control of the plane by exceeding its max range or the depletion of the battery	Low	High	Pre-flight range tests Ground team will plan to land with at least 20% battery reserve.	If no connection is established within 15 s the UAS will return to home, if it takes longer than 30s for connection establishment activate the FTS (control surfaces put into default position for a spiral landing)
Loss of communication	2.4/5 GHz link is lost for telemetry and imagery or Loss of 433 MHz DragonLink	Low	High	The equipment will be tested for range. Return to Range or Return to Home and Return to Land is activated in case of Loss of Communication.	Range is kept within a safe margin at the competition.

Autonomous Navigation Malfunction	The UAS fails to hit its required waypoints	Low	High	The UAS will be landed and recalibrated. Backup GPS is carried on-board and the autopilot checks for discrepancy between the two.	APM planner 2.0 will be kept on hand Use flight view to navigate the UAS to return to home.
Wind Interference	Strong wind gusts could change the plane's trajectory and may cause it to miss the waypoints or violate the no-fly zone boundary	Low	Medium	The embedded weather station of the ground station will monitor wind direction and speed. It will adjust the flight trajectory accordingly.	UAS can take wind gusts up to 15-17 m/s. Anything over requires landing of UAS.
Sensor Malfunction	A sensor on the UAS returns incorrect data or no data	Medium	High	Backup sensors are kept on hand. Possibility of deactivating non-essential sensors.	
Loss of Autopilot or OBC Power	The autopilot or on-board computer suddenly lose power	Low	High	Power system is kept simple. Extensive flight tests prove its robustness.	Manual landing attempt. If failed, FTS activated.
Air Delivery Mechanism Malfunction	The servo burns out or the package gets stuck	Low	Medium	The ADM will be tested pre-flight to ensure that everything works	Skip the delivery part of the mission. Perform the rest of the mission as required. Recheck range with payload.
Pitot Tube Malfunction	Pitot tube doesn't return accurate value for airspeed	Low	Low	Pitot tube will be calibrated and tested pre-flight	Back up equipment available.
Failing to meet the mission time limit	Failing to meet the 20-min setup, or 45 min mission time, or 10 min teardown.	Low	Low	Flight time will be tested before the competition with full mission simulations. Training of flight personnel is mandatory.	UAS is a robust three-piece design. Pre-flight procedure takes under 10 minutes. Incur time penalty if the problem is unsolvable in allocated time.

Human Safety	A member is in an unsafe situation due to the nature of operating an autonomous system	Low	High	A checklist will be kept regulating safe interactions with the UAS	Safety equipment such as first aid, hard hats and safety vests will be brought to the competition
Insufficient Training	A member of the team is not sufficiently trained for their task and makes a mistake during the mission	Low	Medium	Weekly meetings to train each member of rules and roles. Rigorous adherence to procedures and safety. Advisory oversight and mock mission training.	Team captain will have to coordinate team on field. Discipline and accurate implementation of actions is mandatory.
Testing Area	Finding an area to practice flying and mission test	Low	Low	Contact a local airfield to establish a working relationship	Relationship with local airport established. Community support established.

5. REFERENCES

[1] Anderson, John: Aircraft Performance and Design, McGraw-Hill Series in Aeronautical and Aerospace Engineering, 2010

[2] Beard, Randal W. & McLain, Timothy W.: Small Unmanned Aircraft - Theory and Practice, Princeton University Press, 2012

[3] Baker, Alan A. & Scott, Murray L.: Composite Materials for Aircraft Structures, Third Edition, AIAA Education Series, 2016

[4] https://www.nasa.gov/vision/earth/improvingflight/x48b.html, last access date: May 1st, 2018

[5] https://shemesh.larc.nasa.gov/people/cam/publications/gnc2013-draft.pdf, last access date: May 1st, 2018

[6] http://tec.gov.in/pdf/Studypaper/UAV.pdf, last access date: May 1st, 2018