University of Calgary

Schulich UAV

Technical Design Paper

2022 SUAS Competition

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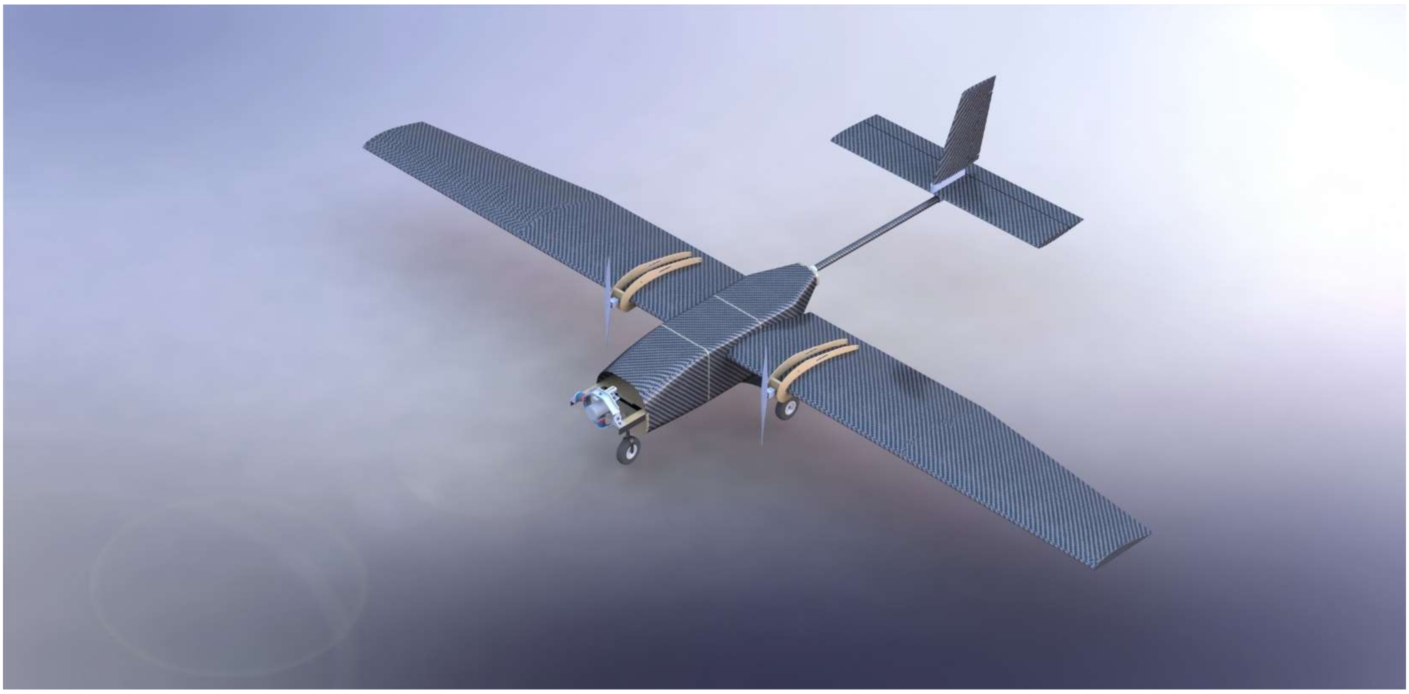

The Schulich UAV from the University of Calgary designed an Unmanned Aerial system that is capable of autonomous flight, obstacle avoidance, area mapping, and accurate airdrop. The multidisciplinary development team has worked to achieve a safe and reliable system for the air delivery mission of AUVSI SUAS 2022. This document will describe the UAS system components, alternative solutions, testing, and risk mitigation.

1. Requirements and Acceptance Criteria

Over the last two years, the Schulich UAV club has designed the plane to successfully execute the flight mission provided by the AUVSI SUAS competition. The 2022 mission is a package delivery simulation using a UAS system. The designed solution must autonomously avoid obstacles, classify specified objects, map the surrounding area and accurately drop the UGV to the given location. After the airdrop, the UGV must drive the simulated package to the given site. From the rulebook, the team has identified requirements for a successful mission [1]. Table 1 summarizes the weighted requirements from the competition and successful execution requirements defined by the team.

Task (%)	Description	Successful Execution Requirement
Timeline (10%)	• Setup the system within 15 minutes and tear down within 10 minutes • Complete the flight mission within 40 minutes without using timeouts	• Have easy to assemble and modular parts • Rehearse mission simulations • Optimize software algorithms to lower search time for each waypoint and object
Autonomous Flight (10%)	• Complete the mission without using emergency manual takeover • Travel to each waypoint in the correct sequence and as accurate as possible (within 100 ft of GPS coordinate)	• Autopilot travels to all waypoints autonomously and completes mission using only data received from ground control station • Repeat mission simulations for waypoint accuracy
Obstacle Avoidance (10%)	• Upload of valid telemetry data through interop system constantly • Avoid all stationary obstacles and other UAS	• Obstacle avoidance module submits UAV telemetry data to interoperability system; retrieves and uploads entity positions into ground control station software
Object Detection, Classification and Localization (30%)	• Identify standard and emergent object's characteristics and geolocation accurately • Submit objects autonomously and before the end of flight mission	• Detection algorithms successfully detects, classifies and geolocates all standard and emergent objects and submits to interoperability system within time limit
Mapping (10%)	• Generate 16:9 high resolution map of the area of interest as a single photograph through Interop System	• Map stitching program successfully creates high quality orthographic photo of correct aspect ratio and submits within time limit • Optimize imaging system for high quality photo
Air Drop (20%)	• Drop the UGV safely and accurately at drop location • Drive to given GPS location after airdrop accurately (<10 ft) and autonomously	• Drop algorithm and mechanism accurately drop UGV to drop location. • Capable UGV with autonomous control.

Table 1. Weighted Competition Requirements and Successful Execution Requirements

2. System Design

2.1. Imaging System

To meet the object detection and mapping requirements, the UAV is equipped with a machine vision camera system. The camera is a Point Grey Chameleon3 with a 5MP Sony IMX264 sensor, 35FPS, and USB 3.0 connection. The Chameleon3's low weight and small footprint makes it ideal for mounting on the UAV. The Fujinon 12.5mm machine vision lens was paired with the camera due to its low distortion and large depth-of-field that aids in capturing in-focus images that keep the size and shape of objects consistent across the image.

Calculations were run to determine how large of an area on the ground one pixel would represent to ensure the camera has enough resolution for the image recognition algorithms to identify all required objects,. It was determined that the camera and lens combination have a horizontal field of view (FOV) of approximately 37 degrees. At a cruising altitude of 100 ft (30.5m), this FOV captures 32ft (9.8m). The number of pixels along the horizontal axis divided by this length gives a resolution of approximately 76.5 pixels/foot (~251pixels/meter). These same calculations were performed for the vertical axis and returned an identical resolution. This is enough to resolve to 1-inch-thick lettering on the smallest standard objects, at 6.37 pixels/inch, and can easily identify larger objects.

The camera is mounted within a custom 3D printed two-axis gimbal located at the front of the aircraft. The gimbal was specifically designed for the weight distribution of the camera body and lens combination. Ensuring the camera is stable throughout the mission provides consistent and level images that maximize the object detection and mapping results. A STorM32 gimbal controller connected to the flight controller is to stabilize the system. Mission Planner provides options for camera gimbal orientation so that the camera can be pointed to help object localization.

The camera interfaces with the Raspberry Pi 4 on-board computer through a USB connection and SDK provided by the camera manufacturer. The SDK provides options for configuration, shutter trigger, and image saving through a Python library interface. After the camera is initialized, it is ready to be triggered using a hardware trigger connected to the flight controller. The Python program will send the image to the ground station for processing. Image processing is done on the ground station due to greater processing power, more available storage, making the process easier to monitor.

2.2. Object Detection, Classification, Localization

After receiving the image from the aircraft, algorithms on the ground station will be used to determine the various characteristics of any detected objects, including the shape, letter, colors, compass direction, and GPS location. Images will be processed along an image processing pipeline as depicted in

Figure 1.

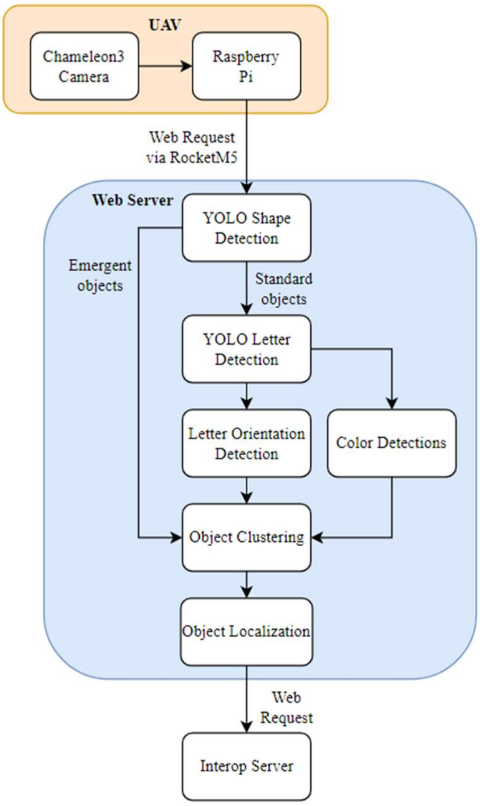

Figure 1. Image Processing Pipeline

The first steps are You Only Look Once (YOLO) object detection models trained on images containing sample objectives. The first model will detect the main shape outline of standard and emergent objects. Areas of an image where a standard object is detected will then be processed by a second model that is trained to detect the letter on the object.

Standard objects will also be analyzed using k-means color clustering to determine the colors of the shape and the letter. The determined dominant color codes will then be looked up in a color name map to determine the name of the color they correspond to. This converts raw RGB values into human-readable colors such as ‘red’ or ‘blue’.

Once the letter of a standard object is determined, a cropped selection of the image is sent to machine learning models trained to calculate the letter’s compass orientation. There are 36 models for determining the orientation of the alphanumerics, one for each possible alphanumeric. Each model was trained using a base model of MobileNetV2. This base model was chosen for being small, so the 36 models do not consume too much memory. Additionally, they take less time to run the inference steps. Based on which alphanumeric was classified, the corresponding model will then determine the orientation. The images will be rotated to a standard mapping orientation, with North being up, before being classified with these models.

Detected objects are then clustered according to determined characteristics by combining multiple images of the same object. This process is needed for geolocation and avoiding repeated submissions of the same object. Detected characteristics of standard objects are compared and clustered by the same shapes, colors, letters, and relative GPS coordinates. Detections of emergent objects are clustered as one object as only one emergent object will be within the competition area. Single object detections without nearby similar objects are considered incorrect detections and are discarded.

Using the clustered sets of detected objects, the GPS coordinates of objects are triangulated. The object’s location within the image is used to calculate the angle of the object relative to the camera’s direction. This is done using the GPS location and orientation of the camera stored in the image metadata, and camera parameters including field of view and distortion. Using the resultant vectors that the object can lie upon, the object’s location is calculated as the closest intersection point of the vectors.

Manual selection and submission of objects are available through an operator interface. The interface also allows for viewing of any detected objects. This allows for manual submission of objects that the detection algorithms do not pick up, or manually edit incorrectly detected characteristics.

2.3 Mapping

The mapping solution uses various image stitching techniques to combine aerial photographs into a high-quality map. Specifically, given a set of photos that cover the entire survey area, the algorithm will first organize the photos into a matrix, ordered by their GPS coordinates. This step is important because the GPS coordinates allow the program to determine the relative position of each photo, which will improve the efficiency of finding matching images to stitch. Then, the SIFT (Scale-Invariant Feature Transform) features are computed for each image, and they are used to find matching key points for adjacent images. Using the matching key points, a homography between each pair of images is estimated and used to project each image onto a planar surface. Finally, the program renders the map by blending the overlapping area of the adjacent images, and it crops the map into the 16/9 ratio based on the center coordinates and the pixels/inch parameter of the camera.

2.4 Airdrop

The Unmanned Ground Vehicle is designed to fit into the allotted volume and weight restrictions set by the aircraft while remaining intact after the impact with the ground. An inexpensive prebuilt tracked base is purchased to serve as a basis for the design to save development time. Additionally, custom parts are 3D printed out of PLA plastic for rapid iterations. If the UGV has a failed drop that leads to a destroyed vehicle, a new UGV can be quickly rebuilt. Apart from the tank base, the other major component of the UGV is the landing sled, which is directly attached to the parachute. Upon landing, the UGV can to separate itself from the sled, leaving behind the sled and the parachute and free to drive away unhindered. The landing sled simplifies the release mechanism and allows for the parachute to be left behind at the site of landing, with some added weight to ensure that it does not fly away.

The release mechanism comprises of two primary parts: the drawbridge and the C-channels with bearings. The drawbridge has been placed at the exit of the UGV in a way such that it can be lowered to let the UGV through or raised to keep the UGV from slipping out. The C-Channel is placed at an incline and is lined with bearings to reduce friction between the UGV and the base of the UAV and ensure an efficient and smooth deployment. Furthermore, the C-Channel is provided with a hook shaped curvature that will hold on to the base plate so that there is no vertical displacement of the UGV while the UAV is in motion. The release mechanism is dependent completely on gravity and the reduction of friction to ensure that the UGV is smoothly released from the UAV.

The UGV is controlled by its own set of electronics and a Pixhawk controller running the ArduRover ground vehicle autopilot. This allows the UGV to autonomously drive to the predetermined final waypoint. The UGV mission is monitored by a second instance of the Mission Planner that is connected to the UGV through a 900 MHz telemetry radio connection. Other key electronics include the GPS module, motor controller, and LiPo battery.

To determine the ideal release location of the UGV from the aircraft, a drop algorithm is used that considers the velocity of the aircraft and the UGV's drag coefficient. Derived force balance equations are used to calculate the maximum distances the UGV will travel after release. During the mission, the flight controller re-calculates and compares the target and predicted landing location to find the optimal release location. The UGV's drag coefficient was calculated through a series of drop tests from predetermined altitudes.

2.6 Autopilot

The UAV will utilize ArduPlane, a subset of ArduPilot controlled by a PixHawk. ArduPilot is a popular and flexible open-source software system, it has been developed over many years and provides reliable software for implementing autopilot for a variety of autonomous systems. ArduPilot can handle all flight control surfaces and motors as well as communicating with the Mission Planner ground control station software. It was chosen as it includes many features useful for the competition, including obstacle avoidance and camera trigger integration. ArduPilot is also one of the most stable and reliable autopilot software available for UAVs. It is also entirely open source, allowing for additional features such as air drop calculations to be added to the software. The UGV will run ArduRover, a branch of ArduPilot that performs similarly to ArduPlane.

Figure 2. Mission Planner Snapshot

2.7 Obstacle Avoidance

Obstacle avoidance is achieved by applying an exclusion geofence around any objects to avoid. The autopilot will then adjust its flight path accordingly to avoid entering the geofences. Static obstacles will be retrieved from the interop system and entered into the flight plan. Flight waypoints will be set to help determine a rough flight path before takeoff that avoids static obstacles. The autopilot will navigate around the set obstacles as it flies along the waypoints. Moving obstacles, such as other aircraft, will be downloaded from the interop system during the flight and sent to the aircraft via the ground control software. The position of entities will be retrieved from the interop system by a ground station module that will then add the entities as cylindrical exclusion geofences to the autopilot. These geofences will be updated as new entity positions are available, and the autopilot will adjust its flight path to avoid these moving obstacles.

2.8 **Communications**

The telemetry communication link is the primary interface to exchange flight data and mission commands with the ground station. Data is encoded using the MAVLink protocol. The telemetry link is provided by two RFD900+ radio modems connected with two unidirectional quarter wave monopole 2.1dBi antennas. These modems operate between 902 - 928MHz and utilize frequency hopping to protect against interference. Mission range requirements are exceeded by the modem's 1W maximum transmit power and a 40km range. Manual RC connection for the safety pilot is provided by a FrSky Taranis X9D Transmitter which operates at 2.4GHz. The high-level communication component interfaces are shown in Figure 3.

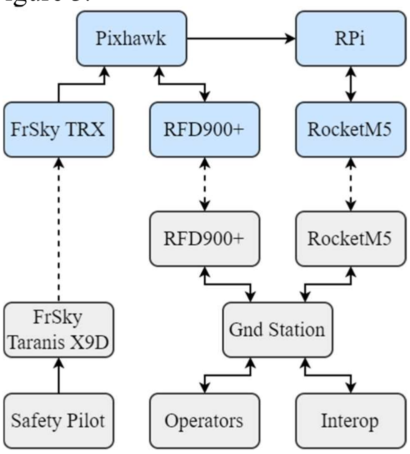

Figure 3. High Level Communication System Diagram

Image and backup telemetry data will be transmitted via a Wi-Fi bridge using an Ubiquiti Rocket M5 in PtP mode with PoE. The ground station will use a HyperLink Wireless 10 dBi Dual Polarized Mini Panel Antenna at frequencies 4.9-5.8MHz. The antenna, directed by an antenna tracker, provides omnidirectional coverage. This setup supports range above mission requirements and allows optimal position for the antenna.

The ground station will include computers running the ground control station software Mission Planner that interact with the UAV and UGV via telemetry. UAV location data will be uploaded to the competition's interoperability system, and location data of other aircraft will be retrieved and uploaded into Mission Planner to provide obstacle avoidance information to the UAV. A web server will also be running at the ground station, receiving images from the UAV, and performing object detections on the images. The web server will also include an interface for operators to view and manually submit detected objects. Automatically detected objects and the map orthographic photo will also be submitted by the web server to the competition's interoperability system.

2.5 Aircraft

The airframe was custom designed and manufactured by the team for this mission. Design decisions relating to the airframe were mainly governed by the following considerations: 1) Gimbal Placement and Payload Deployment, 2) Manufacturability, 3) Transportability, and 4) Cost.

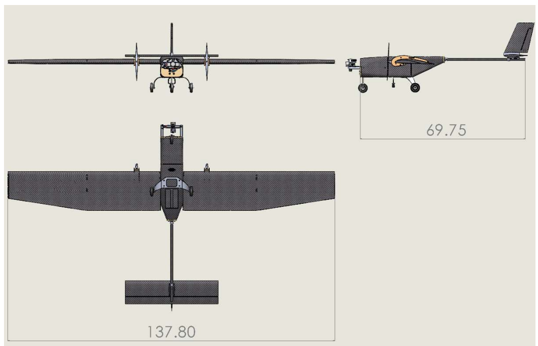

Figure 4. Schematic of Aircraft from Solidworks (in inches)

Component placement relative to the fuselage was done in reference to the center of gravity (CG) of the overall UAV such that the CG of the UGV, the CG of the overall UAV, and the center of lift of the wings were all lined up vertically. Table below summarizes the main mechanical design specifications for the plane.

Table 2: General Mechanical Specifications

Maximum Takeoff Weight (MTOW)	12.5 kg
UGV Weight	1.5 kg
Wingspan	3.5 m
Length	3.3 m
Cruise Speed	60 km/h
Mission Time	43 mins

2.5.1. Aerodynamics

The wing geometry and airfoil selection happened in conjunction to optimize and tailor the specifications of one to the other. As flight endurance was mission critical for this UAV, drag ratio was the primary consideration in airfoil selection and was optimized to be the highest around the cruise operating condition. The airfoil S4310 met these needs at the geometry defined in Table 3 below. A tapered wing design was chosen for increased wing-tip efficiencies, and a higher aspect ratio. For a MTOW of 12.5 kg, a coefficient of lift of 1.17 was required to take-off at 45 kph, and appropriate values of angle of attack for the S4310 airfoil wing were chosen to generate that lift.

Table 3: Wing Specifications

Wing Geometry		
Aspect Ratio	9.7	
Span	3.5 m	
Mean Aerodynamic Chord	0.39 m	
Taper Ratio	0.69	
Lift Properties	**Operating Condition**	
	Cruise at 60 km/hr.	*Take-off at 45 km/hr.*
Angle of Attack	2.3º	8º
Coefficient of Lift	0.67	1.19
Coefficient of Drag	0.00721	0.01284

Once wing and fuselage design were finalized, an estimate for the CG could be made, leading to tail design and stability analysis. The NACA 0009 airfoil was chosen for both stabilizers in the tail. Other specifications are summarized in below. Stability analysis was done using XFLR5 [2] software. A conventional tail design was chosen because it has a low component count while retaining empennage rigidity.

Table 4: Tail Specifications

Tail Geometry	
Static Margin Achieved	13%
Tail Arm	1.2 m
Horizontal Stabilizer	
Volume Coefficient	0.448
Chord	0.23 m
Span	1.01 m
Setting Angle	-1º
Vertical Stabilizer	
Volume Coefficient	0.027
Root Chord	0.23 m
Tip Chord	0.18 m
Span	0.32 m

2.5.2. Propulsion

The propulsion system uses twin propellers mounted on each wing rather than a single propeller at the front to reduce size of the fuselage, allowing it to be monocoque and reducing overall weight, as well as eliminating asymmetric propeller thrust and thus adding stability to the system. The blade geometry, battery capacity, and motor selection were all optimized using eCalc to meet the thrust and runtime requirements. The final propulsion setup consists of a LiPo 8000mAh 80/120CC battery connected to an Avroto LIFT 35120-400kV motor which powers a 14" diameter and 14" pitch propeller to run at 58 km/h for 45 mins. This closely matches the desired cruise speed, while also having 15 extra minutes of battery capacity than the required 30 mins of flight time.

2.5.3. Structural

An in-depth finite element analysis (FEA) study was conducted on the wing assembly using Femap/Nastran. The mesh and geometric setup account for the composite materials used, as well as the added inertial forces that a mounted propulsion system would add to the structure of the wing. The force of lift was distributed along the span of the bottom and top of the wing such that the inboard sections took on more force than the outboard sections as to represent the gradient of lift along the span. 11 limit load cases were created and simulated that account for all possible maneuvers. All components successfully held up under the load cases with a factor of safety of 1.5 or greater, confirming the structural integrity of the wing assembly and its mounting system to the fuselage.

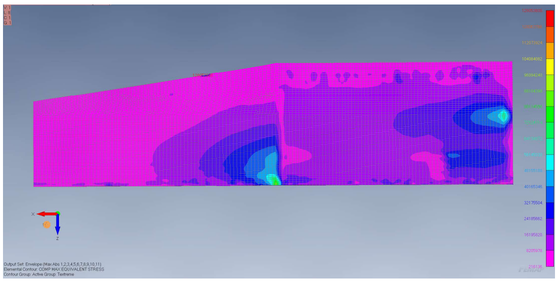

Figure 5. Comp Max Equivalent Stress FEA Plot of Envelope Max Abs Load Case, plot shown on Femap, solved using Nastran

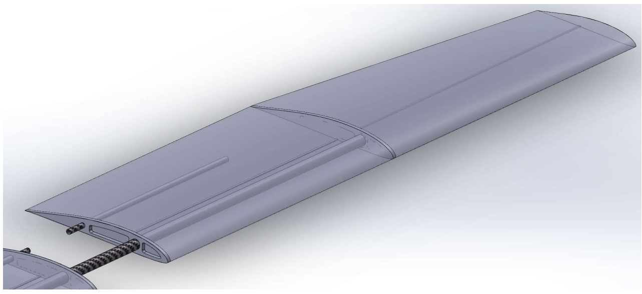

Figure 6. Left Wing Internal Structure, designed in SolidWorks

The wing structure consists of two carbon fibre tubular spars that run through the wing made of XPS foam. The main spar takes on the main loads of lift and drag and extends to the aluminum bulkhead located midspan of the wing. The aft spar resists the pitching moment only, and thus is not as structurally important to the wing itself. However, it's mounting to the fuselage must be fixed because displacement of the aft spar results in torsion of the carbon fibre and would likely cause failure, according to our FEA study. Therefore, it extends about 1/3 of the wing and has a fixed connection to the fuselage by a threaded mount. The XPS foam is laid up with plain weave Textreme carbon fibre and painted over for a protective layer and smoother finish.

Figure 7. Fuselage, designed in SolidWorks

The fuselage itself was designed as a monocoque structure, with wood frames inside only to provide mounting space for other components such as the tail, electronics, and camera gimbal (although in reality they would provide extra support). The shape of the fuselage is more rectangular for ease of manufacturing and for flat mounting surfaces for multiple components. The corners were rounded to reduce stress risers, as confirmed by the FEA study. The FEA study was conducted on the fuselage using 2 load cases this time, one representing the maximum force coming from the wings and the other the maximum landing force from the landing gear. In both limit load cases, the fuselage held up with a factor of safety of greater than 1.5 without including the additional supporting structures such as the bulkheads and landing gear. The layup of the fuselage is done with a twill weave carbon fiber with several other fabrics underneath for shock absorption and to keep the fuselage together should the carbon fiber fail.

A tricycle landing gear configuration was utilized for the UAV. The #674 Robostrut was used as the nose gear and steering was integrated with a servo. The rear gear was designed with 1/8" Aluminum 5052-H38 sheet metal and was water-jet cut and then rolled. Height and track were adjusted to account for wingspan, ground turning speeds, and take-off angles.

On-Board Electronics

The UAV is controlled by an extensive set of electronics. Figure 8 provides an overview of the on-board electrical system and how the individual components are connected.

3. Alternatives Considered

3.1. UGV Alternative

Alternative designs were the UGV were considered in the initial stages of its design, including a two-wheeled cylindrical configuration similar to a self-balancing scooter and store-bought remote-controlled cars, besides the tracked platform design. Each design was evaluated based on several criteria such as drivability, useful onboard volume, cost, ease of modification, and endurance against the impact during the airdrop. The cylindrical configuration would have little onboard volume since most of the space between the two wheels would be taken up by the drivetrain and the various electronic components; this means that mounting the bottle on the UGV would be very difficult. This configuration would also need a mechanism (such as a deployable "tail" with a third wheel) to ensure stability, which would have taken up even more space. Onboard volume was a major issue for store-bought remote-controlled cars as well if the original body of the car was

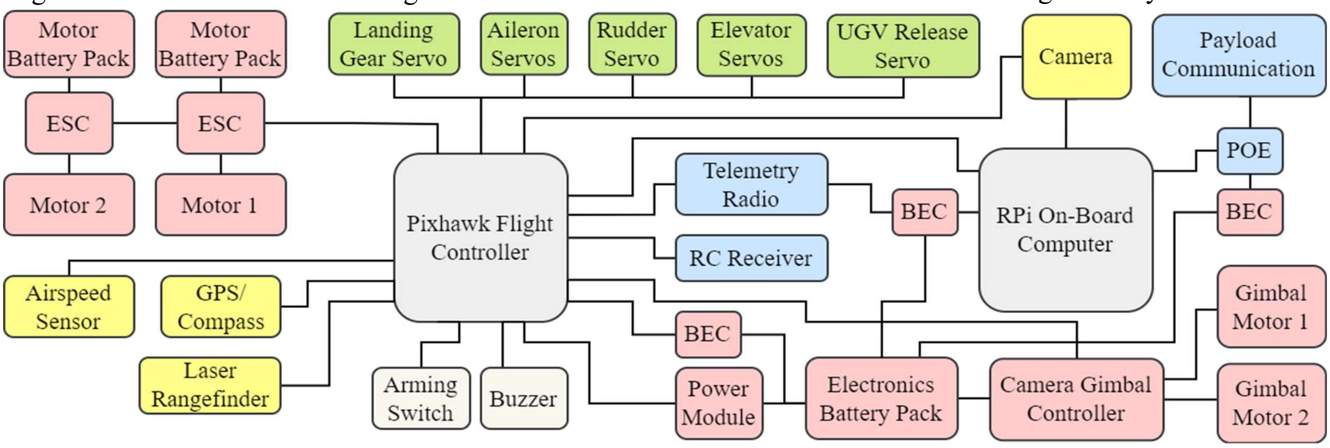

Figure 8. High-level diagram of UAV electronic components and interfaces

to be retained. Otherwise, a new car body, with an optimum amount of space for all electronic components and the bottle, would have to be designed from scratch, which would take a considerable amount of time. Instead, the store-bought tracked base used in the final design already had a large amount of space on top of the flat metal chassis. The holes on top of the chassis also allows the attachment of the various electronic components and their mounts, and a mount for the bottle, using fasteners. The tracks also allow the vehicle to be able to drive in a diverse range of terrains. The flat, fairly symmetrical design of the base also ensures that the landing orientation is upright during the airdrop.

3.2. Propulsion Alternative

The alternative propulsion system that was considered was a single puller propeller configuration at the front of the fuselage. This was a more simplistic design because there wouldn't be a necessity for such an in-depth analysis of the wing structure and it's mounting system to the fuselage would be easier to design. However, the twin propeller system on the wings provides with increased stability due to a single propeller providing asymmetric thrust. Also, not having to account for the large battery and mounting system inside the fuselage allows for a reduced size. The drawback to this design was the added structure required on the wings. This was deemed an appropriate tradeoff for the space reduced in the fuselage and the added stability. The FEA study confirmed the structural integrity of the wing with the propulsion system, without having to add any extra structure.

3.3. Imaging System Alternative

Multiple alternatives are available for the imaging system hardware and interfaces to maximize the camera's capabilities. The on-board computer was upgraded to the Raspberry Pi 4 to meet the camera manufacturer recommended specification and utilize the USB3.0 connection on the camera. Alternative on-board computers provide lower costs but exclude the key features listed previously. Another alternative considered involved using the on-board computer to perform processing on the acquired images. This was decided against, consolidating all image process software to the significantly more powerful ground station computer. Lastly, the exact protocol used to send the images over the LAN provided by the payload communication system had several alternatives. Using a TCP socket directly would require minimal overhead but require more software complexity to handle errors such as loss of communication. A web server system was chosen because it is a well-established protocol with little overhead and interfaces well with the image processing structure.

3.4. Mapping Alternative

An alternative solution considered for mapping was to use OpenDroneMap, an open-sourced software used for creating map orthophotos and terrain models. Compared to pure image stitching, it is more robust and provides many more features for analyzing the area surveyed. For example, it computes a detailed 3D model of the terrain using the images taken. However, having an abundance of features such as terrain modelling added too much overhead for computing a simple orthophoto, which leads to unacceptably long processing times. Thus, OpenDroneMap was not used for this competition.

4. Testing and Evaluation Plan

4.1. Developmental Testing

Table contains the test plans that are used to verify the functionality of major components of the UAV system. These tests are used during development to evaluate component performance in isolation and ensure successful completion of mission tasks.

4.2. Mission Testing

Table describes the tests that are used to verify mission performance and provide feedback on complete system performance.

4.3. UGV Testing

For the purposes of testing, three of the aforementioned tank bases were purchased at low cost. This is to ensure that the in the event of a failed drop, the other copies can serve as a source of space parts or as complete replacements. Additionally, in order to optimize for the fastest terminal drop velocity that leaves the vehicle unharmed, multiple sizes of parachutes were purchased, ranging from 3ft to 6ft. The testing plan relies on iterative steps that slowly get closer to the final configuration. First, the parachutes are tested with a mock payload to ensure that all deploy as intended. Then, the tank base with minimal added weight is attach to the parachute ensuring that the bare base can survive the impact. Then, more weight is added in the form of mock weights and 3D prints, until the final estimated weight is reached. Lastly, the electronics are integrated into the design, and a full systems test is conducted. This approach to the testing allows for problems with the design to be dealt as they appear, without the loss of components.

5. Safety, Risks and Mitigation

5.1. Developmental Risks & Mitigations

All members of SUAV followed appropriate safety protocols as laid out by the University of Calgary during manufacturing and testing. Assembly plans were made for each component to be manufactured or tested and included a list of the personal protective gear that must be worn when carrying out the plan. Table 7 summarizes the developmental risks and hazards that were recognized by the team and the safety management plans to mitigate them.

5.2. Mission Risks & Mitigations

Risks were evaluated using a failure modes and effects analysis (FMEA) to anticipate potential in flight failures. The effect and probability of each subcomponent failure on the mission status was examined and a severity class was defined accordingly. Failure detection and compensating provisions were then considered to prevent foreseeable critical failures. Part of the full FMEA table is shown in Table below.

Table 5: Development Testing Plan

Component	Test	Description
Imaging System	Image capture and transmission to ground station server	Setup all image system equipment including camera, on-board computer, Wi-Fi bridge, and ground station server. Set camera to high frame rate and verify all images arrive at ground station server. Verifies the on-board computer successfully interfaces with the camera and forwards the image to the ground station through the Wi-Fi bridge.
	Camera gimbal	Setup camera gimbal on sturdy frame with the camera attached. First, test the gimbal's performance using the gimbal controllers built in inertial measurement unit. Verify that the camera responds to the controller input. Second, use the Pixhawk gimbal output to control the camera. Verify that the camera responds to the controller input.
Object Detection/ Classification	Shape, letter, color, and rotation detection	Provide sample images to the respective detection algorithms. Verify that the algorithm outputs match with the expected results.
Localization	Determining object location	Provide sample images to the localization algorithm. Verify that the output matches the locations of the objects in the sample image.
Mapping	Map generation	During a test flight, take several images of the area. Verify that the images are properly stitched together in the resulting map.
Airdrop	Drop algorithm	During a test flight, attempt a payload drop using a substitute UGV object. This verifies that the drop algorithm can initiate a drop and risks no damage to the UGV. Proceed with UGV testing.
Aircraft Electronics	Control electronics test	Connect flight controller to all peripherals. Perform taxi test to verify all components successfully connect.
Obstacle Avoidance	Interop entity retrieval	During a test flight, retrieve sample obstacles from interop system and upload into Mission Planner. Verify aircraft autopilot avoids obstacles.
Communication System	Telemetry, Image, and RC	Verify all communication links provide adequate strength and continuity. Test connection distance in open field.
	Antenna tracker	Setup antenna tracker and move the plane electronics around an open field to test tracking abilities.
Web Server	Object clustering	Provide sets of sample data to the web server. Verify that the object clustering removes redundant data entries.
	Object submission	Provide sample images and verify manual selection and submission of images. Verify and test automatic submission of detections. Verify interop interactions properly submit using interop repo.

Table 6: Mission Testing Plan

Mission	Test	Description
Image Capture, Analysis and Upload	Imaging system, ground station image processing, and map image programs	Flight test with full imaging system and components. Place test objects in the flight area and verify all objects can be successfully detected and reported to a local instance of the interoperability system. Test manual object selection and upload. Verify map image generation and submission.
UGV	Airdrop and UGV activation/movement	Flight test with UGV airdrop at test location. Verify UGV's activation and drive to target location.
UAV Autonomous Flight	Autonomous flight and object avoidance	Flight test using the autopilot provided by flight controller. Test performance updating flight path to new waypoint boundaries.

Table 7: Developmental Risks and Mitigation Measures

Developmental Risk	Probability	Severity	Mitigation
Risk of injury when operating power tools	LOW	LOW	All members must complete mandatory university training before operation of power tools. Safety googles and close toed shoes must be always worn.
Risk of miscommunication between members when assembling/ manufacturing complicated components	LOW	LOW	Assembly plans were created for each manufacturing session all participating members were instructed to review and understand the plan before the session.
Time constraints in project completion	LOW	LOW	Effective project management delegation that prioritizes tasks to maximize mission points.
Improper storage and use of batteries	LOW	LOW	Use best battery handling practices. Store batteries at nominal voltage in protected container. Inspect batteries for damage. In-circuit protection devices to prevent excessive power draw.

Table 8: Recognized Mission Risks and Mitigation Measures

Mission Risk Statement	Detection	Probability	Severity	Mitigation
Pilot error	Operators	LOW	HIGH	Ensure two pilots are available and both have trained and logged 25+ hours of flying time
Crash	Operators	LOW	HIGH	All components were made modular for ease of replacement
Telemetry Communication Failure	Operators	LOW	MEDIUM	Backup telemetry link through Wi-Fi bridge. Safety pilot takeover.
Image Communication Failure	Operators, On-Board Computer	MEDIUM	LOW	Save images locally for processing after mission. Manual operation of the antenna tracker.
UGV Communication Failure	Operators, UGV PixHawk	MEDIUM	LOW	UGV autonomously detects drop and does not require communication to complete objective.
UGV Power Failure	Operators, GCS	LOW	LOW	Do not release UGV if power failure is detected before air drop.
Motor Power Failure	Operators, UAV PixHawk	LOW	HIGH	Safety pilot takeover and manually glide UAV to safe landing.
Web Server Failure	Operators	LOW	MEDIUM	Secondary computer with identical copy of server software, intense testing of server software

6. References

[1] AUVSI Seafarer Chapter, "SUAS 2022 Rules," 2022. [Online]. Available: www.auvsi-suas.org. [Accessed 2021].

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7. Acknowledgements

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