Saint Louis University Unmanned Aerial Vehicle

2019 AUVSI SUAS Competition

Technical Design Paper

Abstract

Saint Louis University's AUVSI team SLUAV has iteratively designed, manufactured, and tested a fixed wing unmanned aerial system in preparation for the 2019 AUVSI SUAS competition. The team's main objective was to improve the performance and capabilities of the aircraft in addition to integrating an unmanned ground vehicle into the system, while meeting all of the mission requirements. The team consists of undergraduate students majoring in a spectrum of disciplines including aerospace engineering, mechanical engineering, electrical engineering, and computer science. The wide knowledgebase and skillset of the team provided a comprehensive toolset to improving the UAS. The aircraft is a 22-pound, 10-foot-wide, low-wing design with a modular payload that has been improved to drop a UGV, fly waypoints with greater accuracy while avoiding obstacles, and take pictures to be classified by a graphical user interface. The team has validated the ability of the UAS through both ground and air tests and is prepared for the competition in June.

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1 SYSTEMS ENGINEERING APPROACH

The SLUAV team utilized a systems engineering approach to develop a UAS capable of accurately and autonomously delivering a UGV, navigating around obstacles, and identifying targets on the ground. Through analysis of the competition rules, the team derived a set of requirements to meet each mission objective. The following sections describe these requirements and discuss how both these requirements and environmental factors influenced the design methodology.

1.1 MISSION REQUIREMENTS ANALYSIS

Table 1: Mission Requirements

Mission Objective	Mission Requirements
Timeline	The aircraft and ground support systems shall have a maximum set-up time of 15 minutes and tear down time of 10 minutes.
	The aircraft shall maintain a cruise for 20 $\pm$5 minutes at an altitude of 200 $\pm$ 100ft in 15 $\pm$ 5 knot wind.
	The aircraft and ground support system shall capture and process images in 15 $\pm$ 5 minutes.
Autonomous Flight	The aircraft shall autonomously take-off, fly and land within the mission flight boundaries in maximum wind gusts of 20 kts.
	The aircraft shall capture waypoints within a 100ft. radius in maximum wind gusts of 20 kts.
	The aircraft and ground system shall have the capability to alter the original flight plan while the aircraft is airborne, particularly for the obstacle avoidance mission task.
	The aircraft shall be able to sustain a turn radius of at least 30 ft.
Obstacle Avoidance	The ground system shall be able to receive information about the obstacles via the interoperability server and plot them on the flight plan map in 10 $\pm$ 5 minutes.
	The aircraft and ground system shall relay telemetry data to the interoperability server at an average of least 1 Hz
Object Detection, Classification, and Localization	The imaging system onboard the aircraft shall take pictures at an appropriate interval to cover a 0.1 square-mile area in less than 10 minutes and produce a ground sampling distance of 0.5 inches or better.
	The imaging system shall transmit the GPS coordinates of the aircraft when the camera is triggered.
	The ground system shall be able to manually send classified targets (in JSON format) and cropped images to the interoperability server
Air Drop	The aircraft shall carry a 48 oz. UGV to be dropped within 75 ft. of the target and continue to fly safely after the drop.
	The UGV shall be dropped from an altitude of 150 $\pm$ 25 ft while flying at 35 $\pm$5 kts and drive after contact with the ground.
	The UGV shall be able to autonomously drive over grassy terrain to within 10 ft. of the specified location
Safety	The aircraft shall be capable of manual pilot override.
	The aircraft shall terminate flight after 3 minutes of communication lost.
	The aircraft shall weigh less than 55 pounds.

To be successful with the mission, the team developed a set of mission requirements, shown in Table 1, that are both explicit and derived from the competitions rules. For the Timeline task, the airframe and ground station must be simple in organization, so the team has sufficient time to set-up and tear down the UAS, and also, the aircraft must be capable of completing the mission in a timely manner. The Object Detection, Classification, and Localization task calls for an imaging system to capture images of the entire search area, so to ensure the images cover the whole search area, the camera must take images at specified intervals based on the speed and altitude of the aircraft. When designing the aircraft and imaging system, the team must consider the tradeoff between image resolution, image capture capabilities on the camera, and cruise speed to optimize both time and quality of images. The Autonomous Flight and Obstacle Avoidance tasks requires a flight controller to be tuned so the aircraft is agile, but the Object Detection, Classification, and Localization task requires more stability to ensure better image quality. For the Air Drop task, an unmanned ground vehicle (UGV) must be dropped from the aircraft, as a result, the weight of the UAV will decrease the endurance of the aircraft and effect the possibility of completing other tasks. Also, after the UGV is dropped, the stability and control of the aircraft will change and alter the flight path, which will change how the aircraft completes other tasks. These tradeoffs will be discussed more in following sections.

1.2 DESIGN RATIONALE

As seen in Figure 1, the team translated the mission objectives and requirements into hardware and systems to be designed and developed.

The team analyzed choices for an airframe, and instead of spending time and resources on designing/fabricating/flight testing a new airframe, the team chose to use the previous year's airframe and flight controller as the starting point. The airframe is capable of carrying the payload, but the UGV was too wide to be dropped from inside the fuselage, so the UGV will be attached to the airframe externally. To minimize the change in static margin after the 48 ounce UGV is dropped, it will be dropped at the airframes center of gravity. The center of gravity of the airframe is located near the quarter chord ($.25\bar{c}$) of the wing, so the UGV will be mounted externally under the wing, but since the previous years' airframe utilized a pusher propeller, the team was concerned the UGV would hit the propeller upon release. As a result, the team made a decision to move the propeller to the nose of the aircraft.

To simplify construction in the future, the team thought about eliminating the nose gear and installing two tail draggers underneath the horizontal stabilizers, but in order for the wheels to be in contact with ground on take-off, the main gear needs to move ahead of the center gravity or closer to the nose. In years past, the main gear has been integrated with the midsection of the foam wing, and if it moved closer to nose, it would have to be installed through the fiberglass fuselage, and as a result, the fiberglass may tear during hard landings. Also, the tail dragger causes the flight controllers parameters to be altered, and since the Pixhawk 2.1 from the previous year provided multiple fully autonomous and successful missions, more time will be saved if the nose gear is constructed, because tuning and testing the flight controller with a new configuration will be far more time consuming.

The team had previous experience with the gphoto2 library, specifically on the raspberry pi computers, so the team looked for cameras that were compatible with gphoto2. Also, the camera needed to have an aspect ratio and focal length combination capable of capturing images at an interval that will cover the entire search area. The image quality needs to be taken from an altitude to give sufficient resolution to identify targets. As a result, the team chose the Canon PowerShot SX740 Camera.

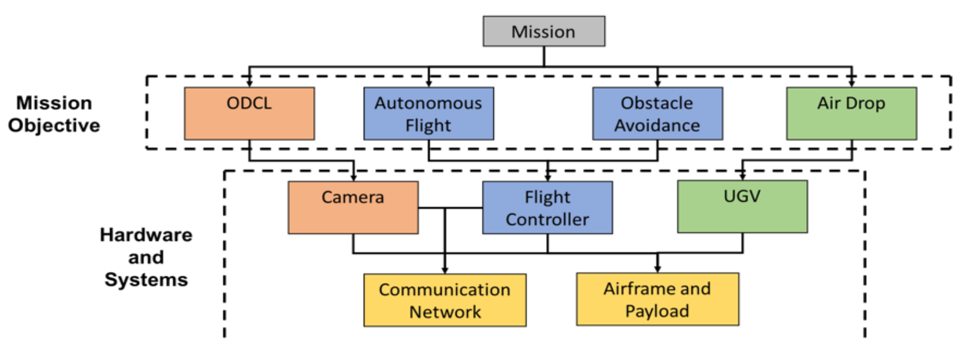

Figure 1: Flow of Decisions

In order to be eligible to complete the waypoint accuracy and obstacle avoidance task, the team has fine-tuned their communication network by replacing the 3DR robotics telemetry radio with the jDrones long Range telemetry radio to ensure telemetry is being sent to the ground station at an average of 1 Hz. Also, to be able to have actionable intelligence, the team is using Wi-Fi to transmit pictures in flight.

2 SYSTEM DESIGN

2.1 AIRCRAFT

SLUAV chose to keep the same airframe design from the previous year, but re-designed aspects of the UAV to fit the 2019 competition requirements. The modular design allowed the team to easily implement changes without re-building the entire airframe.

Fabrication

The airframe has a fiberglass fuselage with aircraft plywood bulkheads throughout the interior. The team utilized a wet-layup, and to minimize weight, a vacuum bag approach was used to ensure excess epoxy was pulled from the fiber glass. The midsection of the wing is seam taped to the fuselage and is made of insulation foam. Two carbon fibers spars, a main and anti-torsion spar, were imbedded into the midsection. Now, in years past, the team implemented a 5-degree dihedral into the mid-section to promote greater aircraft stability, but in order to increase agility for the waypoint navigation and obstacle avoidance tasks and ease the manufacturing process, the team built a straight, no dihedral midsection.

The wings and tail are made of insulation foam. The carbon fiber tail booms are detachable and connect into two balsa blocks mounted on the midsection. The main and anti-torsion spars for the wings are interconnected into the same balsa blocks. A pin, starting at the leading edge of the airfoil, connects to the tail boom. This allows the wings, tail, and fuselage to be detached from each other, so implementing repairs and traveling for test flights is easier to accommodate.

The main gear is imbedded into the bottom of the mid-section, and four nylon bolts run through the midsection and secure the main gear. The nylon bolts provide a weak point for the aircraft, so when the aircraft experiences a hard landing, the main gear will break off, and the aircraft will slide on the belly of the fuselage. Now, if metal screw were used to hold the main gear in place, a hard landing may cause the aircraft to turn or flip in manner that could cause damage to the wings and/or tail, and in terms of manufacturing, replacing the wings and/or tail takes more time compared to the main gear. Figure 2 shows the main gear analyzed in Abaqus FEA.

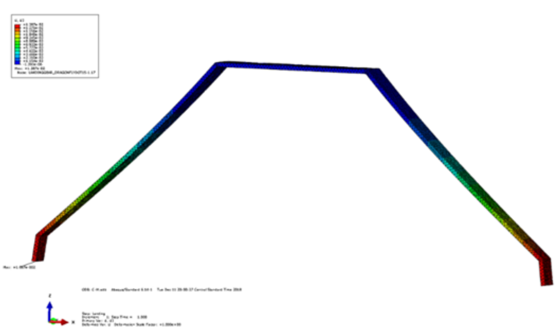

Figure 2: Abaqus FEA model

Internal Layout

Last year, the team utilized a pusher propeller with a twin boom tail configuration, but for this year and as previously mentioned, the team needed to drop the air delivery system from the airframe's center of gravity to maintain stability, but the team was worried the air delivery system would hit the propeller after being released from the UAV. As a result, the team moved the motor to the nose of the aircraft. With

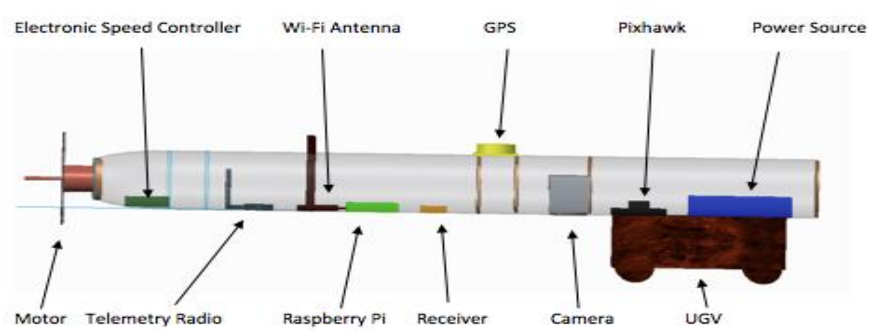

Figure 3: Fuselage Layout

the center of gravity designed to be near the quarter chord of the wing, the team was concerned there was not enough fuselage volume aft of the center of gravity to counter the pitching moment created by the motor and propeller at the nose. The team conducted a center of gravity analysis seen in Table 2.

Propulsion and Performance

A Hacker A60-5XS-V2 motor, 100A ESC, and 5-cell LiPo battery power the airframe. As part of the requirements in Table 1, the airframe needed to have a turn radius of at least 30 feet to avoid obstacles with a radius of 30 feet. With a cruise speed of 31 mph which is 10% greater than stall speed, Equation 1 was used to find that the minimum bank angle would need to be 65.41 degrees [2]. Now, as the UAVs bank angle increases, the load factor on the wings increases as seen in Equation 2. A bank angle of 65.41 degrees produces a load factor of 2.4, and with the plane weighing 19 pounds, the wings need to carry a load of 45.6 pounds. The team did a wing loading test as seen in Figure 4, and the wings successfully supported 50 pounds. As result, we conclude that the plane is capable of making a turn with a 30-ft. radius.

Equation 1

$$\phi = \tan^{-1}\frac{V^2}{R_t\, g}$$

Equation 2

$$n = \frac{1}{cos\phi}$$

Table 2: Center of Gravity Analysis

Component	**Mass (lb.)**	**Moment Arm (in.)**	**Pitching Moment (lb.-in.)**
Camera	0.917	32.94	30.2
Bottle	0.511	0.00	0.0
Prop + Motor	1.228	0.00	0.0
Pi board	0.085	23.58	2.0
Telemetry	0.055	39.30	2.1
GPS	0.099	19.65	1.9
Power Source	2.750	41.27	113.5
ESC	0.309	0.79	0.2
Wifi Emitter	0.113	31.44	3.6
Pixhawk 2.1	0.145	35.37	5.1
Receiver	0.036	35.37	1.3
Fuselage	1.700	26.00	44.2
Wing Port	2.250	39.14	88.1
Wing Starboard	2.250	39.14	88.1
UGV	3.000	39.14	117.4
Nose Gear	1.091	9.98	10.9
Servos	0.156	21.62	3.4
Tail	2.250	84.50	190.1
Total	*18.945*		*702.2*
C.G. Location (in,.)	**37.0627833**		

Table 3: Airframe Dimensions

	Wing	Horizontal Stabilizer	Vertical Stabilizer
Airfoil	FX 63-137	NACA 0015	NACA 0015
Span (ft.)	10	1.85	0.62
Area (ft^2)	22	3.04	2.05
Aspect Ratio	4.55	1.13	0.19
Chord (ft.)	1.04	0.876	0.876

Figure 4: Wing Loading Test

2.2 AUTOPILOT

Flight Computer

With autonomous flight at the core of the competition, the team chose 3-D Robotics' Pixhawk 2.1 flight controller as the auto pilot system for the UAS. The Pixhawk was very easy to install onto the airframe, which saved the team time, and at a reasonable price, the team did not have to sacrifice their budget. With power and sensor redundancies as well as manual pilot override, there are minimal developmental risks. There are multiple connectivity options for additional peripherals, like a telemetry radio which is required to complete the obstacle avoidance and waypoint capture task. The airframes connections to the Pixhawk are shown in Figure 5.

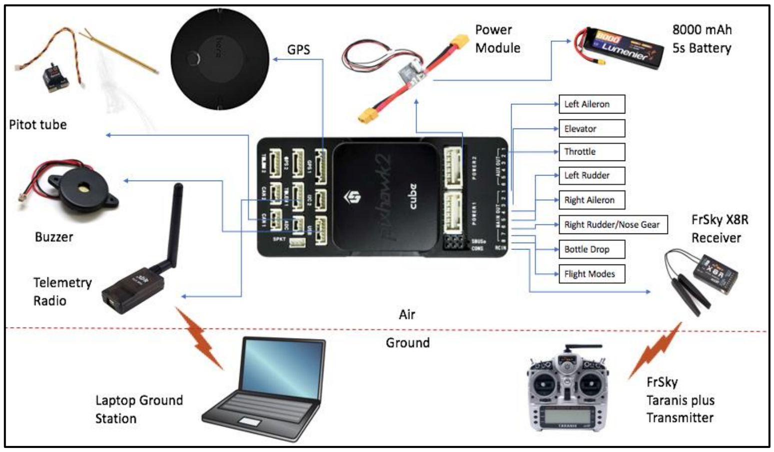

Figure 5: Pixhawk Schematic

On the Pixhawk, the team utilizes ArduPilot 3.8 firmware. The open source ArduPilot firmware has extensive documentation and provides the airframe with fully autonomous flight capabilities, like autonomous take-off, landing and level flight. Also, in the event of connection loss, the Pixhawk is able to terminate flight in a manner that meets the AUVSI failsafe requirements.

Ground Control Station

The team chose to use the open source Mission Planner software to interface with the flight controller [1]. With autonomous flight being one of the more critical tasks in terms of points, the team relied heavily on Mission Planner to plan the flight path of the UAS by designating waypoints for the UAS to capture. Also, the software has numerous options, such as sensor calibration, altering parameter value, in-flight visual displays, and servo control. In addition to the raw ArduPilot version, the team altered the interface to be able to forward telemetry to the judge's interoperability server and overlay circles onto the mission map for the obstacle avoidance task. Figure 6 displays the Mission Planner software on the team's ground control station.

Figure 6: Ground Control Station

2.3 OBSTACLE AVOIDANCE

For the obstacle avoidance task, the team has written a Python script capable of importing obstacles from the interoperability server utilizing a KML overlay to be displayed on the Mission Planner map. The waypoints can be

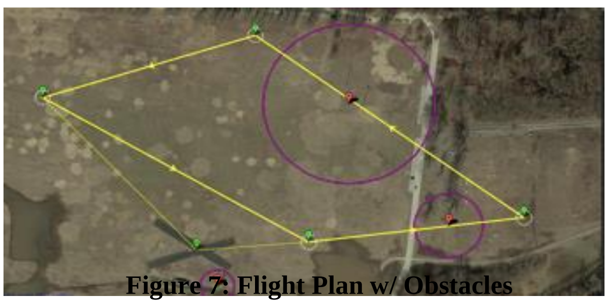

Figure 7: Flight Plan w/ Obstacles

Figure 8: Flight Plan w/ Altered Flight Path

adjusted to avoid the obstacles as seen in Figures 7 and 8. Now, the team will be primarily relying on altering the waypoints with inputs from a user, but the team has been developing an algorithm to autonomously alter the waypoints. Utilizing the DroneKit library [2], the algorithm will import the obstacles and the pre-defined waypoints, and where obstacle collision is eminent, the algorithm will initially insert a waypoint at the center of the obstacle, and then depending on the radius of the obstacle plus a factor of safety, the waypoint will move to the left right of the obstacle. Before the new mission waypoints are sent to the UAV, the altered waypoints and stationary obstacles will display on the Mission Planner map, so a user can alter waypoints if they deem necessary. Having the ability to alter waypoints was an important decision, because the height of the obstacle is displayed when cursor scrolls over it, so this gives the team to the chance to alter the waypoints to fly over short obstacles instead of avoiding them on the side

2.4 IMAGING SYSTEM

Two of the most critical aspects of the camera included having a resolution clear enough to identify targets and being capable of taking pictures at an interval that covered the whole search area. To define the requirements for the camera based on these aspects, first an altitude of 300 feet was assumed, since in flight testing, the aircraft rarely flew above this altitude, especially when capturing images. The team made the assumption that if image resolution was sufficient at 300 feet, it would also be sufficient for lower altitudes. Second, the camera needed to take photos at an interval that causes images to overlap in terms of ground coverage, so the team assumed the minimum altitude of 100 feet set by competition rules. Three cameras were analyzed for both situations: a Sony a6000, a Canon SX740, and a GoPro Hero.

Resolution

For the Object, Detection, Classification, and Localization task, the alphanumeric on the target are at least 1-inch wide as described by the competition rules, so in order to detect them, a ground sampling distance (GSD) of 0.5 inches is required.

$$GSD_{height} = \frac{Flight\ Height * Sensor\ Height}{Focal\ Length * Image\ Height} \qquad GSD_{width} = \frac{Flight\ Height * Sensor\ Width}{Focal\ Length * Image\ Width}$$

Table 3: Resolution Parameter Comparison

Camera	Focal Length (mm)	Sensor height (mm)	Sensor width (mm)	Image Width (pixels)	Image Height (pixels)	GSD height (in)	GSD width (in)
Sony a6000	24	3	2	6000	4000	0.113	0.050
Canon SX740	24	4	3	5184	3456	0.174	0.087
GoPro Hero	14	4	3	4000	3000	0.343	0.193

Utilizing the equations above, the GSD was calculated at 300 feet for each camera as seen in Table 3. The GSD for each camera meets the requirements with the Sony a6000 having a higher resolution and the GoPro Hero having the worst of the three.

Capture Interval

With the airframe cruising at 45 fps (31 mph) and assuming an altitude of 100 feet, each of the cameras were analyzed to find the slowest interval that will cover the entire search area.

$$Angle\ of\ View\ (AOV) = \frac{180}{\pi} 2\tan^{-1}\frac{sensor\ width}{2(Focal\ Length)} \qquad Ground\ Coverage\ (GC) = 2 * \frac{Altitude}{\tan\frac{AOV * \pi}{2 * 180}}$$

$$Minimum\ Capture\ Rate\ (MCR) = \frac{GC}{Velocity}$$

Table 4: Image Capture Capabilities

Camera	AOV (deg.)	GC at 100ft. (ft.)	MCR (sec/photo)
Sony a6000	72.2	274.3	6.03
Canon SX740	72.2	274.3	6.03
GoPro Hero	102.7	160.0	3.52

As seen in Table 4, the Sonya6000 and Canon SX740 were more than capable of meeting their respective capture rate requirements, but the GoPro's actual capture rate was too close to the requirement, so the team omitted it.

Camera Decision

While the Sony a6000 appears to have the best performance parameters, it was not fully compatible with the gphoto2 library [3], which the team has employed in the past on a raspberry pi computer for image capture. To avoid using time and resources for finding a new method of image capture using the Sony a6000, the team omitted it from the selection. As a result, the Canon SX740 was chosen due to its sufficient resolution, image capture interval, and gphoto2 compatibility.

2.5 Object Detection, Classification, Localization

For this year, the team focused on submitting targets manually, so the team will not be attempting to submit targets autonomously. With autonomous submission being 2-3 percent of the maximum allowable competition points, ignoring autonomous submission was not detrimental.

Detection

For this year, the team focused on submitting targets manually, so the team will not be attempting to submit targets autonomously. In order to detect potential targets, the UAS uses a Java graphical user interface (GUI) in order to visually and manually specify targets. Images, like the one in Figure 9, taken from the UAV are sent to the ground station and saved to a folder, so once the images are saved to the specific folder, the graphical interface can be started and the detection process can begin. The detection process begins with a user finding targets in an image, and once a region is detected, the user clicks the top left corner followed by the bottom right corner of the region to form an encapsulating rectangle around the target. This region is then saved as an image file to a separate directory on the computer system for classification at a later time.

Classification

The classification phase of a region of interest is done through a different Java GUI. The images from the detection phase are saved to a specific directory and loaded one at a time into the interface. The user is allowed to type into a textbox the different characteristics that are visible in the picture, as seen in Figure 10. The characteristics that the user can type into this text field are if the target is emergent or standard, the shape and color of the target, as well as the alphanumeric and its color. This text is then saved into a JSON format with the same file name as the image file to be submitted to the judges. The images that are loaded into the interface sometimes need to be scaled up in order to see the full scope of the region. In order to do this, the interface makes use of the java.awt.Image library. This library contains functions that are useful in translating and representing images without the loss of quality. It is important that the loss of quality is reduced as much as possible because this entire process relies on the image of the region being visible to the user.

Figure 9: Image from UAV

Figure 10: Image in JAVA GUI

Localization

The camera will be pointed straight down throughout flight in the search area, so for each image, the team is assuming the GPS coordinates of the aircraft at image capture will correlate to the center of the image. The team will be receiving data (latitude, longitude, altitude, and compass heading) in flight, and this data is synchronized with each image through time-stamp comparison on the Pixhawk and the camera. The altitude is utilized to determine the distance per pixel within the image. The compass heading is used to rotate the image, so the respective x and y displacement can be added/subtracted to the latitude and longitude of the center of the image. This process is done when the user selects a target and is outputted automatically.

2.6 COMMUNICATIONS

The three types of wireless links for communication are telemetry, Radio Controlled (RC), and Wi-Fi. Three ground station computers are connected wirelessly to a TP Link router, which is connected to the judges' server via an Ethernet cable. Figure 11 displays the communication between the air and ground.

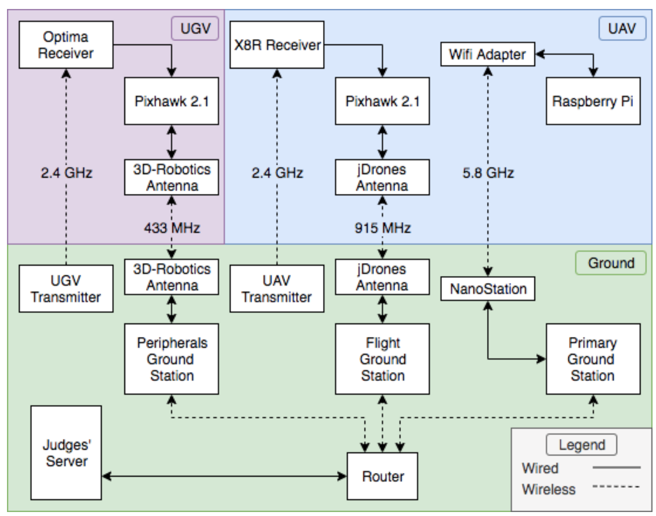

Figure 11: UAS Communication

A set of long-range jDrones 915 MHz telemetry antennas link the flight ground station to the UAV. The flight ground station runs Mission Planner and is dedicated to the flight plan and status monitoring of the UAV. The telemetry antennas continuously transmit data to Mission Planner, and a python script downloads the altitude and GPS location of the UAV via Mavlink. The data is parsed through by a second python script that formats the information as it is downloaded and submits it to the judges' server at a rate of 2.5 Hz, which is above the required rate of 1 Hz. The FrSky X8R receiver, connected to the Pixhawk 2.1 UAV flight controller, establishes an RC link over the 2.4 GHz frequency band between the platform and the transmitter on the ground.

A second set of 3DR Robotics 433 MHz telemetry antennas link the peripherals ground station with the UGV. The peripherals ground station computer runs Mission Planner for the UGV, in addition to serving as an additional platform for image processing if necessary. An Optima Receiver is connected to the Pixhawk 2.1 flight controller aboard the UGV, establishing an RC link between that platform and the second transmitter on the ground.

An Ubiquiti NanoStation [4] is connected via an Ethernet cord to the primary ground station, which serves as the main link to the interoperability server. A USB wireless adapter aboard the raspberry pi establishes a Wi-Fi link between the NanoStation and the raspberry pi for images to be downloaded to the ground station. Since the NanoStation is a very powerful antenna, it is mounted on a pole to reduce exposure risks.

2.7 AIR DROP

The team has already discussed the changes to the airframe as a result of the air delivery mechanism. The team began the task by purchasing a 1/18 Scale RC car and integrated a Pixhawk 2.1 controller onto the frame. The Pixhawk is running ArduRover3.4, and since the team has expertise in term of interfacing a Pixhawk onto vehicles, the team saved time. After ensuring the rover could drive autonomously, the team began looking into how the rover would be released and descend from the aircraft.

The team decided to mount the rover external from the fuselage, because with the center of gravity at the quarter-chord of the wing, the team did not want to put a big hole through the midsection of the foam wing and compromise the structural integrity of the wing. The rover will be held by six servos embedded into the bottom of the midsection, and the servos will be connected to one RC channel to ensure release occurs at the same time. In order for the rover to land safely, there must be an increase in drag during the drop, so the team utilized a parachute. The parachute will be folded and pressed between the rover and the mid-section, so when the servos release, the parachute will begin to unravel and deploy shortly afterward. Further tests are planned to ensure the viability of this design and improvements will be made to ensure the safe landing of the rover, during the competition.

Now, picking the size of the parachute will dictate how the rover descends. If the parachute is oversized, it will ensure the rover will impact the ground safely and be able to drive safely, but the parachute will be more susceptible to the wind, and it will be harder to control the accuracy of the drop. With a smaller parachute, the rover will drop more like a projectile and will not be effected by the wind as much, but the impact force of the rover will be greater and may compromise the rover's ability to drive.

The team needed a parachute size big enough to survive the impact but small enough to fall more like a projectile. The team tested and found that 20 fps was the best impact speed, so the team sought out for a parachute that will slow the rover to 20 fps.

$$Parachute\ Diameter = \sqrt{\frac{8mg}{\pi \rho C_D V}}$$

Cd = coefficient of drag of parachute

ρ = density of air

V = Velocity of descent

Using the equation for parachute diameter and assuming a Cd of 0.97, density of 0.0765 lb./ft^3, and mass of 3 pounds, a parachute diameter of 34.5 inches was determined, so since the parachutes are cheaper to buy by a foot diameter, the team purchased a 36-inch diameter parachute. Also, after the rover settles upon landing, it will drive with the parachute attached so the parachute does not blow away.

2.8 CYBER SECURITY

Cybersecurity is achieved through the comprehensive enumeration and mitigation of potential threats to and vulnerabilities within a technological system. Identifying, understanding, and addressing these threats and vulnerabilities is critical for cyber-physical systems such as unmanned aircraft, which have the potential to cause significant material damage and physical harm if compromised.

Vulnerabilities and Threats

The primary cybersecurity vulnerabilities of a UAS are the connectors (e.g., endpoints) and connections (e.g., communication links) of different system components. Communication between UAS components via radio waves can be subject to security threats of interference, jamming, and spoofing. Secondary UAS cybersecurity vulnerabilities include firmware exploits, network exploits, eavesdropping, and component hijacking [5]. Threats can occur through attacks on sensor signals (GPS, ADS-B), actuator signals (elevators, throttle), the flight controller and related software, the UAS control network, the ground control station and mission computer network, and even the competition-specific mission communication system (e.g., interoperability protocol) [6] [7]. The team's cybersecurity mitigation techniques have been developed to directly address and resolve these threats.

Mitigation and Solutions

The team has implemented a safe and secure UAS by employing the common cybersecurity principles of least privilege and defense in depth and has focused on cybersecurity education and awareness for the entirety of the SLUAV team. All team members receive cybersecurity awareness training as an integrated component of flight safety briefings and competition testing. The team has implemented a cybersecure UAS for the SLUAV team to address the threats and vulnerabilities outlined above through the following measures:

- The team will establish and maintain redundant radio links and failover measures at the competition flight-line to mitigate consequences of potential interference, jamming, and/or spoofing attacks. The team will also generate and utilize immutable mission telemetry logs for active team review at runtime on a separate, dedicated flight-line workstation to ensure verified performance integrity of cyber-physical components. This will significantly reduce threats from radio-based attacks.
- The team has enabled cryptographic signing between UAS components using the newer MAVLink 2 protocol. This signing feature ensures messages received by various UAS components (e.g., to arm the plane for take-off) are verified as having been sent from confirmed, trusted sources (e.g., only the team's ground control station.) [8].
- The team's flight-line workstations and UAS components will utilize the dedicated subnet provided at competition. The team will utilize a router access control list to restrict UAS network access to and from the interoperability server and team workstations and will employ MAC filtering, WPA2, and updated complex passwords on the team router at competition.
- The team has regularly updated firmware and implement updated, secure login credentials on all mission hardware, including flight controllers (UAV and UGV), companion computers, cameras, routers and networking hardware, and flight-line workstations. The team will utilize multi-factor authentication for workstation user accounts where applicable.

Through these preventive steps and measures, the team is confident that the SLUAV team UAS has been established as a flexible, safe, and secure cyber-physical system. The team will continue to remain vigilant to additional potential threats and adapt to mitigate these threats in an informed and collaborative way.

3 Safety, Risks, and Mitigation Strategies

Safety is a primary concern throughout the development and testing phases of the UAS. The team took appropriate precautions by following proper procedures to ensure the safety of the UAS and surrounding personnel.

3.1 Developmental Risks and Mitigation Strategies

Developing a new aircraft poses a lot of risks, so primarily, the team prioritized the safety of the team member and secondarily, mitigated both timeline and structural setback on the airframe. Table 5 shows the most common risk and associated mitigation strategies.

Table 5: Developmental Risks

Risk	Mitigation Strategy	Likelihood	Severity
Exposure to toxic Fumes and Dust Particles	Fabrication and sanding are performed in a separate room in the lab. Team members always wear a respirator when sanding or working with fumes. Team members wet sand when working with carbon fiber.	Medium	Medium
Injury due to Insufficient Training	All team members are taught how to safely use all power tools and chemicals.	Low	High
Not utilizing team members effectively	The leaders meet weekly to discuss the tasks that need to be accomplished and assign tasks to team members based on their skills.	Medium	Medium

3.2 Mission Risks and Mitigation Strategies

Whenever testing it done on the UAS, there are risks both to the people nearby and the structure itself, so Table 6 shows some risks and their respective mitigation strategy.

Table 6: Mission Risks

Risk	Mitigation Strategy	Likelihood	Severity
Losing RC Connection	Fail-safes have been established in the Pixhawk and the receiver	High	Medium- High
Battery Depletion During Flight	Endurance tests are performed on each of the flight batteries regularly and records are kept for each flight	Medium	High
High Winds	The weather is monitored and flight testing is never conducted during unsafe weather conditions	Medium	High
Structural Failure	The aircraft was carefully designed, tested, and maintained to operate as designed	Low	High
Battery Fire	Batteries are always charged and transported in battery safe bags.	Medium	High
Air Delivery Malfunction	The air delivery mechanism was carefully designed and tested	Medium	High

4 CONCLUSION

Over the past year, the team has developed a UAS able to compete at the AUVSI Competition in June 2019. The team has altered their design from the previous year by changing the plane from a pusher to at tracker propulsion system. Also, the team has implemented and tested various software to complete mission tasks. The UAS meets all the specifications deemed by the completion rules, and the team is ready to fly in June.

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