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Norfolk State University
Terrestrial Aircraft for Reconnaissance Applications
Department of Engineering
Department of Computer Science
Norfolk State University, Norfolk, Virginia, 23504

ABSTRACT

The purpose of this paper is to outline the design of Norfolk State University Team TARA's VTOL (vertical takeoff and landing) aircraft, as well as each measure taken to ensure each mission was successfully completed. This is Norfolk State University's second time competing in the AUVSI-SUAS competition. In the first competition, Team TARA's main goals were to operate the UAS autonomously with the capability to travel precise locations on Earth using an autopilot and global positioning system (GPS), installing two cameras (one for first person view and the other for target recognition), and incorporating an inertial measurement unit. This year, the team's main goals were to improve the aircraft's landing gear and ground station, stabilize the Pixhawk flight controller, and become more proficient at autonomous and manual operations, while demonstrating a compliance with the Academy of Aeronautics National Model Aircraft Safety Code.

TABLE OF CONTENTS

1. Systems Engineering Approach

The system engineering approach taken by team TARA included the following: mission analysis, design rationale, and a risk and mitigation review. The mission analysis was split into two categories: primary and secondary tasks. The design rationale summarized the reasons for selecting a VTOL aircraft. Finally, in the risk and mitigation review section, safety concerns were discussed along with the plans of action.

1.1 Mission Requirement Analysis

The major competition tasks were organized in two categories: planned primary and planned secondary tasks. This is shown in Table 1. The autonomous flight task is shown Table 2; this table describes each objective the team wants to accomplish for autonomous flight. The search area task is shown in Table 3; this table describes each action the UAS should be able to complete while performing the area searching mission.

Table 1: Task Organization

Planned Primary Tasks	Planned Secondary Tasks
Autonomous flight	**ADLC (auto detect, localize, and classify targets)**
Search area task	**Actionable intelligence**
	interoperability

Table 2: Autonomous Flight Task Breakdown

Parameter	Threshold	Objective
Autonomous Flight Task		
Takeoff	Achieve controlled takeoff. Properly transition to autonomous flight	Achieve controlled autonomous takeoff. Properly transition to autonomous flight.
Flight	Maximum of three minutes manual flight. Maximum of three manual takeovers from autonomous flight.	Achieve controlled autonomous flight with no manual flight, except for transition from manual takeoff.
Waypoint Navigation	Capture waypoint in sequence with ±50 ft. accuracy, and maintain navigation ±100 ft. along the planned flight path	Capture waypoint in sequence while in autopilot control with ±50 ft. accuracy, and maintain navigation ±100 ft. along the planned flight path
GCS display items	Accurately display "no-fly-zone boundaries" and shall accurately display current aircraft position with respect to the "no-fly-zone" boundary, display indicated airspeed (KIAS) and altitude (feet-MSL) to the operators and judges.	Display must be visible to the judges and must indicate the UAS speed in the KIAS or ground speed in knots, and MSL altitude in feet.
Landing	Achieve controlled landing, Properly transition from autonomous flight.	Achieve controlled landing. Properly transition from autonomous flight.

Table 3: Search Area Task Breakdown

Parameter	Threshold	Objective
Search Area Task		
Localization (each standard and QRC target)	Determine target location within 100 ft. Must be paired with at least a threshold classification.	Determine target location within 75 ft. Must be paired with at least a threshold classification.
Classification (each standard target)	Provide any two target characteristics, electronically.	Provide all five target characteristic, electronically.
Classification (QRC target)	Detection	Decode the message.
Imagery (each target)	n/a	Provide cropped target image (>25% of image frame)

Autonomous Search	n/a	Aircraft in autopilot control during search.
Secret message	n/a	Decipher the message anagram collected from the targets in the search area.

1.2 Design Rationale

Team TARA has chosen to build a VTOL UAV. This UAV design allows for the ability to operate as a helicopter or plane. Though this is an expensive and complex system to design and operate, the team has the personnel (upper and underclassmen as well as one graduate student) and budget (sponsored by Lockheed Martin).

The VTOL design will help the team complete the two planned primary tasks. During autonomous flight the VTOL aircraft will simplify the takeoff and landing procedures (because of the removal of other launch mechanisms and/or procedures). In addition to takeoff and landing procedures the VTOL design will assist in course completion time and waypoint accuracy. By transitioning from hover to forward flight mode the UAV speed and fuel efficiency are increased. When transitioning from forward flight to hover mode the UAV can more accurately arrive at the programmed waypoints.

Team TARA has equipped the UAV with a Canon S100 PowerShot digital camera. This camera will assist the team with the Search Area task. The Canon S100 has the ability to shoot and record video or still images in multiple formats, including NTSC and PAL. The camera is also able to record time, date, and GPS (global positioning coordinates) along with the video or image information. The Canon S100 PowerShot camera with 5x zoom capability will be used to monitor the ground area beneath the Team TARA UAV.

The other peripheral components that will assist with the planned primary tasks include: a Global Positioning System (GPS), autopilot system, inertial measurement unit (IMU) and a communication link between the UAS, remote control, and a surface laptop. Using a 2.4 GHz 9 channel RC radio link, manual flight control is provided. Flight controls are passed into a Pixhawk 4 autopilot system, which then provides the system with various autonomous flight capabilities. These capabilities include takeoff, landing, and waypoint navigation, with the ability to make in-flight adjustments. Sensor and control data is relayed to the payload subsystem by the Pixhawk 4. The Pixhawk 4 is also configured with a barometric altimeter, GPS, magnetometer, dual inertial measurement units (IMU), differential pressure airspeed sensor, safety buzzer, and safety switch. The dual IMUs provide redundant measurements; the barometric altimeter provides the autopilots altitude above ground level; the GPS provides 3D position; the compass/magnetometer provides heading; and the differential pressure sensor provides airspeed.

After comparing various UAVs (i.e. fixed-wing planes and copter designs), Team TARA chose the VTOL UAS because of its versatility. However, the major tradeoffs are cost and operational complexity. Team TARA believes the versatility benefit gives the team a better chance of achieving task goals.

1.3 Programmatic Risks and Mitigations

Risks can be inevitable at times, but with the right system in place, each risk can be mitigated. Below is a table entailing each risk, whether a permanent, essential, or characteristic attribute in building TARA, along with the impact, and method of mitigation.

Table 4: Programmatic Risk and Mitigations

Risk	Impact	Method of Mitigation
Property damage	**With an UAS at this size up to $2,000 of damage could occur with a 100 ft. drop**	**Team TARA has AMA insurance up to $20,000 to cover.**
Aircraft damage	**With a drop of 100 ft. the majority of the body will be destroyed**	**Team TARA can rebuild the UAS from the budget.**
Personnel damage	**With an UAS at this size personal injury could occur with a 100 ft. drop**	**Team TARA has AMA insurance up to $20,000 to cover.**
Exposed wires	**With exposed wires and resulting short circuit a fire could possibility occur**	**Team TARA has AMA insurance up to $20,000 to cover. Team TARA uses special insulting and crimping techniques.**

2. System Design

2.1 Aircraft

The VTOL UAS chosen is the FireFly6 (parts from BirdsEyeView Aerobotics). This aircraft encompasses simplicity, stress-free transitions, safety and reliability features, and compatibility as shown in Table 5. There are many key add-ons that alleviate any issues with flight control and compatibility. This aircraft has advanced VTOL autonomy (AVA), which is a flight control firmware. There are three different packages of AVA available. Each provides different functions, and is defined by the type of key as shown in Figure 1.

Table 5: FireFly6 Characteristics

FireFly6 Characteristics	
Stress-Free Transitions	AvA handles flight mode transition for the user. AvA allows the aircraft to transition from hover to ford flight, and from forward flight to hover mode.
Simplicity	Because of AvA, full VTOL flight control capabilities are brought to users by a single piece of hardware. The PX4hawk autopilot results in a clean and uncomplicated installation of electronics.
Safety and Reliability	Failure points are minimized using a single controller. If something goes wrong, AvA can step in. Return to Launch (RTL mode) is available on demand and as a loss-of-link failsafe, bringing the FireFLY6 safely home for an automated vertical landing.
Compatibility	AvA handles all complicated control mixing required to keep the FireFLY6 airborne. Special radio programming isn't required; any 7+ channel radio system will work.

	Transition	Stabilize	Altitude Hold (AltHold)	Land	Return to Launch (RTL)	Loiter	Guided (Fly to Here)	Auto	Camera Triggering
Mapping Key	X	X	X	X	X	X	X	X	X
Pro Key	X	X	X	X	X	X	X	X	
Sport Key	X	X	X	X	X				

Figure 1: Key Types for Software Package

Table 5: UAV Dimensions

UAV Dimensions	
Wingspan	60" (1524 mm)
Length	37.4" (950 mm)
Weight	6.6-9.0 lbs (3.0-4.1kg)
Flight Time	25 minutes average hybrid flight
Payload Capacity	2.5lbs (1.1kg)
Cruise Speed	30-35kts (34-40mph, 15-18m/s)
Max Speed	57kts (65mph, 29m/s)

Figure 2: Plane Airframe

The advantages of VTOL planes are that they can take off in small spaces just like a quadcopter, but also fly longer and faster like a plane. The FireFLY6 is technically an Y6 configuration. The two motors in the back of the plane are only for hovering and remain off during forward flight. The other four motors in the front of the plane also allow it to hover, with the exception that in forward flight mode, the motors rotate 90 degrees to produce forward thrust. Because the FireFLY6 is a plane, it has a relatively high flight time from 20 to over 30 minutes depending on your setup. In hover mode it gets 7 minutes of flight time.

The Power Distribution System requires 22.2 Vdc to launch the UAS. The original power system of the Firefly 6 is design with two 3s (11.1 Vdc) in series. This system does not allow for any redundancy. Once the batteries are drained to 20 Vdc (10 Vdc per battery) the UAS has to be landed and the batteries have to be changed. This is any average fly time of 20 minutes (70 minutes when doing bench testing). Team TARA's design will be used to increase the flight time and create redundancy. This will be achieved by taking two 6s (22.2 Vdc) batteries and putting them in parallel. This should double the flight time minus the increase in weight.

The two 5.8 GHz transmitters and the two cameras added required a separate battery, but requested the same voltages (5 Vdc or 11.1 Vdc). These different batteries add weight to the UAS and require upkeep. Our design will add two battery eliminating circuits (BEC) to the power distribution board. These extra components will be connected to the BECs, and all the required volts will be distributed from the power distribution board. The increase in voltage pull from the Power Distribution Board will decrease flight time, but the decrease in weight of the extra batteries will balance it back to almost twice the flight time we are trying to achieve.

2.2 Autopilot

The autopilot system for this aircraft design is supported by a Pixhawk PX4FMU autopilot flight controller. All peripheral devices are connected to this flight controller; in addition, the Pixhawk is configured and calibrated using the open source software Mission Planner. Mission Planner was configured for the aircraft into a software package called FireFLY6 Planner or AVA Planner (Advanced VTOL Autonomy) version 1.2.3. The benefit of using this software is that it is built directly for this aircraft and contains the same amount of abilities as the original Mission Planner. This software allows the user to calibrate the GPS, Accelerometers, and radio controller.

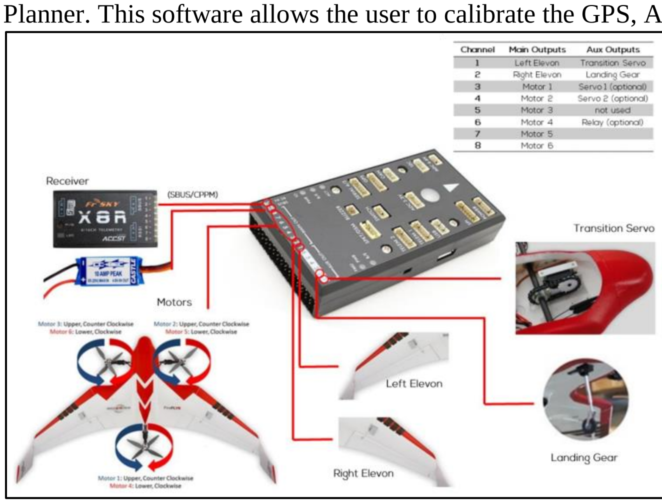


Figure 4: Pixhawk Connections (1)

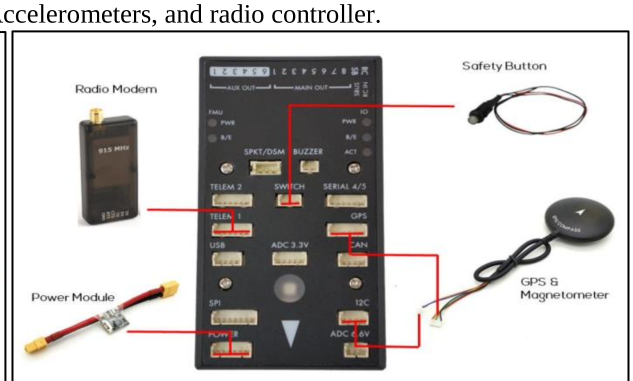


Figure 3: Pixhawk Connections (2)

Figure 5: Autopilot Mission Planner (AVA)

2.3 Interoperability

For simplicity, the interoperability server is written in python to allow for all interop client files to be accessed. This server is connected using MAVProxy to retain all information from the MAVLink connection to the aircraft. The connection is the exported from MAVProxy and sent to the python file that is connected to the interoperability server.

2.4 Imaging System

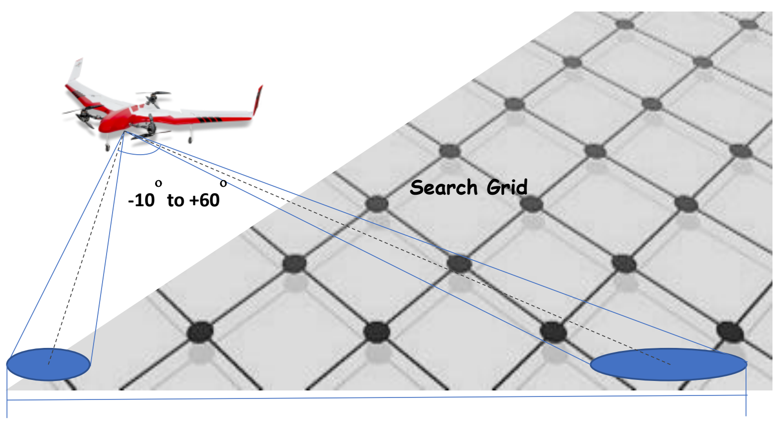


Figure 6: Camera FOV Diagram

The Canon S100 has the ability to shoot and record video or still images in multiple formats, including NTSC and PAL. The camera is also able to record time, date, and GPS (global positioning coordinates) along with the video or image information. Using an internal SD memory card, Team Tara will explore two alternatives for its object detection approach.

2.5 Object Detection, Classification, Localization

Team TARA will employ hybrid techniques to achieve object detection objectives. Standard object detection will be achieved through use of a digitally interfaced camera device and accompanying RF communication components. The Canon S100 PowerShot camera with 5x zoom capability will be used to monitor the ground area beneath the Firefly6 UAV. Using artificially created targets that mimic the minimum requirements for standard targets, we have confirmed the viability of the Canon S100 to render reasonable images for standard object identification. The challenge of also achieving an acceptable optical field of view (FOV) will be achieved using a rotating gimbal mount fixture. The fixture will be installed on the underbelly of the Firefly vehicle, and mount rotation will be controlled using a motorized actuating mechanism.

First, the team may choose to transfer live video information via the Flysight TX5804 A/V audio-video transmitter module. The Flysight 5804 board transmits over seven channels in the 5.8GHz F-band. The module will relay live or recorded video signal information to a Blackpearl RC801 FPV receiver. The Blackpearl will be located at the team base station. A base station monitor will then screen capture and crop the detected standard object, obtain the accompanying GPS information from the Firefly flight database, and prepare the appropriate information to meet submission requirements for standard object detection.

An alternative approach is to employ dual external links to the Flysight 5804 and the Pixhawk modules, and to activate the Canon S100 in a time-lapse mode during which images are captured at specified time intervals. The Flysight link will be used to monitor the ground environment as the Firefly transverses the assigned course path. As standard objects are identified by the base station monitor, selected image and GPS data will be captured at the Blackpearl and Pixhawk. While video image information is available via the Blackpearl, both video and GPS information is available at the Pixhawk. Once image and GPS capture is achieved, the base station monitor will prepare the digital image information for submission to the base station judges as required.

2.6 Communications

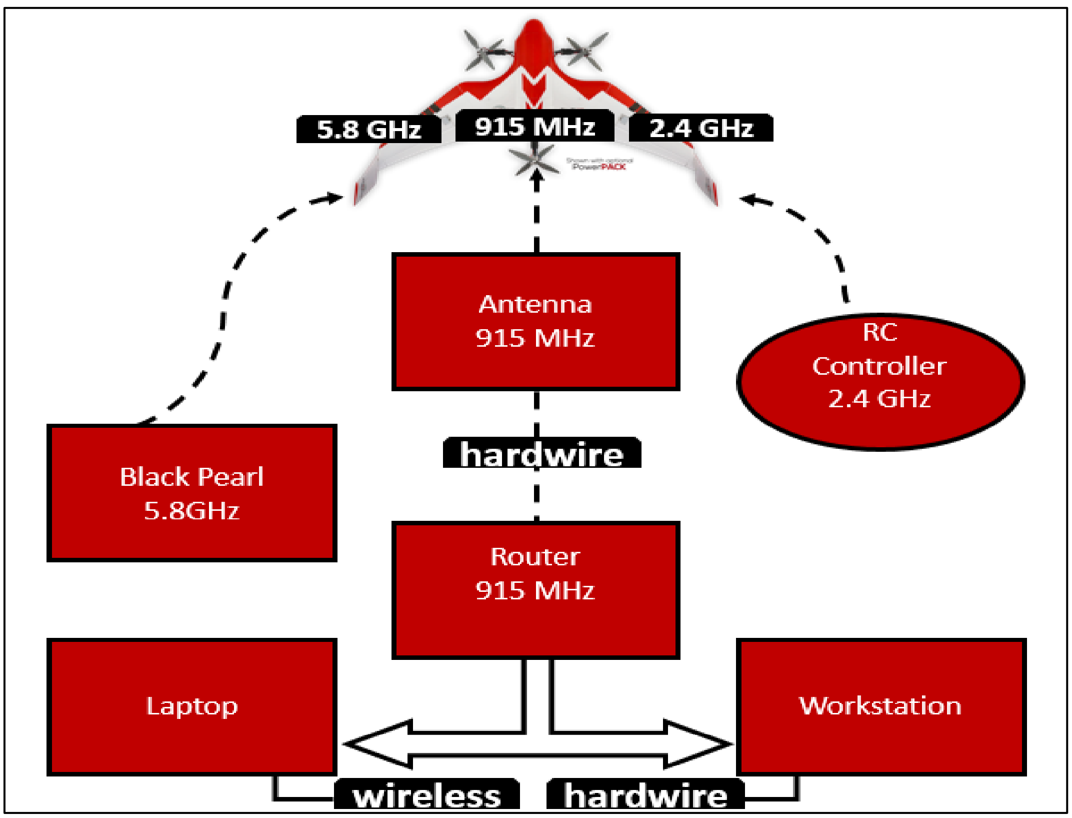


Figure 7: Ground Station Block Diagram

Maintaining connection with the aircraft is the main concern for the software team; this includes connections between the radio controller, the flight controller, and the flight and image computers. The radio controller connects directly through a 2.4 GHz telemetry channel. The aircraft camera connects to the imaging computer via a 5.8 GHz video transmitter. The flight controller is connected to the autopilot software using a 915 MHz telemetry transceiver.

3. Test and Evaluation Plan

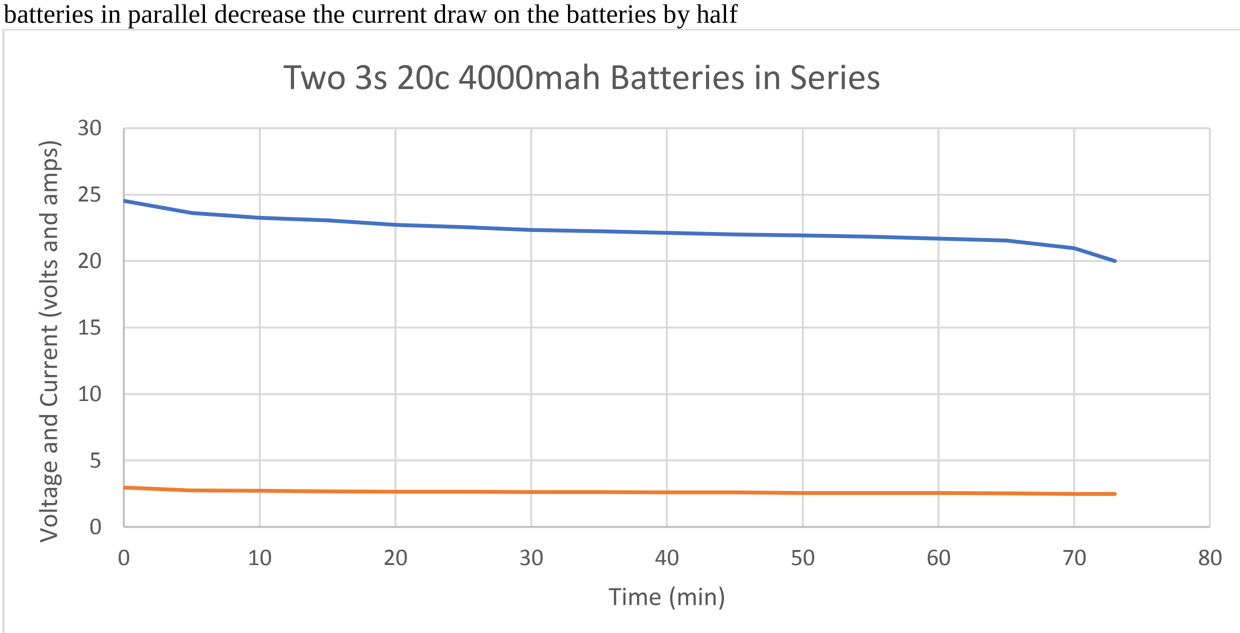
3.1 Developmental Testing

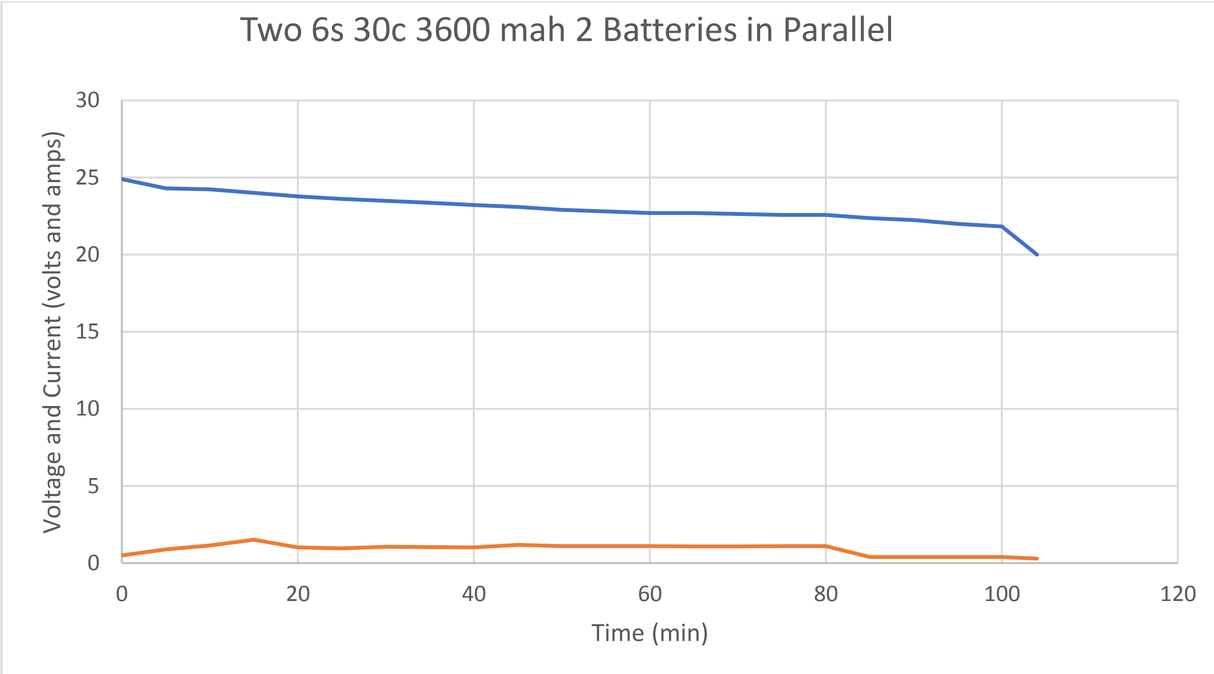
The detection team has observed working operation of the Canon S100 using the Flysight transmitter, and reception of signals at the Blackpearl RC801 has also been observed. The team will now verify the signal range for the transmission, and the formal procedures for appropriate submission of standard object information to the judges. The team must also investigate the image data quality for in-flight data, as compared to data taken by grounded vehicles. It is expected that some steps may need to be taken to dampen vibration or other noise-generation mechanisms that accompany in-flight data.

The team has also determined that the S100 FOV with maximum zoom engaged is approximately +/- 8°. This translates to a physical circle of radius 16ft at the expected UAV cruising height of 110 – 120ft. The design team will seek to increase the effective FOV to +/- 60°, corresponding to a 250ft radius circle through rotation of the gimbal-mounted camera over a predetermined angle. The diagram illustrates this approach. Note that the increased viewing capacity is sought within the defined target grid area. Objects located outside the grid area by more than 40-45ft may not be detected.

3.2 Individual Component Testing

Increasing flight time is any important aspect to this project. So to gain more flight time the power distribution system was improved to allow two 6s batteries to operate in parallel. This almost doubted the flight time, but adds about .8 lbs. to the UAV. The .8lbs is the reason the UAV flight time did not completely doubt even though the batteries in parallel decrease the current draw on the batteries by half





3.3 Mission Testing Plan

Mission Test	Requirement	Evaluation
Hover Test	Hover for 3 continuous minutes autonomous and manual	Completed a successful hover for 3 minutes with and without autopilot
Auto Takeoff and Landing Test	Autopilot triggered takeoff and landing events	Completed autopilot triggered takeoff and triggered landing
Transition Test	Transition from hover mode to forward flight mode and back into hover mode	Completed a successful transition from hover to forward flight
Manual Takeover Test	Manual takeover from autonomous mode	Completed a manual takeover using radio controller
Interoperability (Scoring)	Test scoring system and waypoint accuracy	Completed multiple tests of the interop server scoring system
Failsafes	Test boundary conditions and flight controller disconnection failsafe	Completed landing when boundary conditions were met or controller disconnected

4. Safety Risks and Mitigations

4.1 Developmental Risks and Mitigations

The team has taken a number of steps in order to reduce the risks to both bystanders and the UAS. The most fundamental safety precaution taken was the inclusion of a safety person on the team. The Safety person is required to maintain constant view while on the flight line to ensure every team member conducts their jobs safely. The team has implemented failsafes to ensure that the UAS complies with section 9.3.6 of the AUVSI SUAS rules.

4.2 Mission Risks and Mitigations

The team requires that all pilots be AMA-licensed. All flights are logged and failures are noted. Flight logs assist with improvements to the systems and expand our safety checklists. The use of lithium batteries has many inherent risks. To mitigate these risks, all team members are trained on safe battery handling and usage. Also, all batteries are transported and charged in fiberglass LiPo-safe bags. For permanent storage, the batteries are stored in a flammable liquids cabinet.

4.3 Operational Risks and Mitigations

Safety is an important factor in the development and operation of autonomous systems. Safety begins at the preflight brief when the team's Safety person reviews the safety protocols and reminds the team of the risk, especially those specific to each mission. During the mission, individual checklists help to ensure every team member conducts their jobs safely. The checklist specifically checks to ensure each member meets all of their assigned safety goals. The Safety goals are specific points on the checklist which must be passed. At these points the team member reviews all the safety points they have passed, and reports these to the team lead and Safety person. These Safety goals help to ensure team communication and safe operation after the mission, team member meet to discuss lessons learned in the systems, navigation, area, navigation, and sensors (S.C.A.N.S) format. An excerpt from the pre-flight checklist is presented below.

PRE-FLIGHT CHECKLIST

This checklist is always completed immediately before each flight. This checklist ensures the safety of both the aircraft and any personnel.

Prep Plane:

1. Ensure the ESC is not connected to the power module
2. Connect flight batteries to UAS
3. Turn on power switches wait for Autopilot to start up
4. Verify autopilot boot
    a. Main LED = Blue or Green
    b. One long tone
5. Turn on camera
6. Turn on controller
7. Visually verify Datalink connection via status LEDs
8. When prepared for take-off, check motors to see if functioning fully
9. SAFETY QUALITY GATE: Report to SO and MC
    a. Batteries connected securely
    b. Autopilot boot successful
    c. Payload boot
    d. Datalink Boot
    e. ESC startup