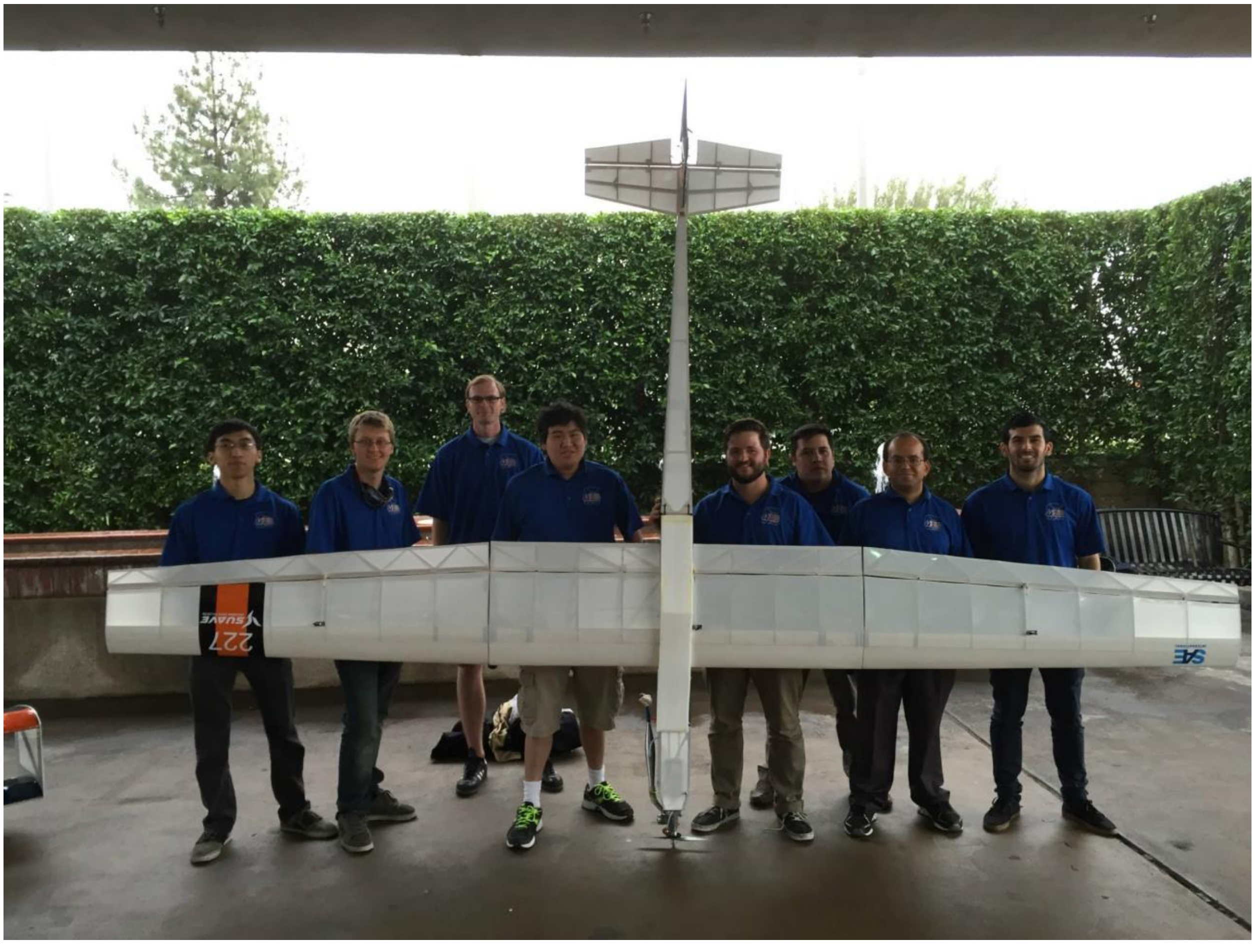
California State University, Fullerton Titan UAV

AUVSI Student Unmanned Aerial Systems

2015 Journal Paper



Following on the heels of a disastrous conclusion to the 2014 Titan UAV project, the 2015 team improved upon every aspect of the project. Despite a very small budget and a very aggressive project timeline, the Titan UAV team has come to adapt to every challenge it has faced. By designing and constructing a proven airframe nearly two months in advance of the competition and by including two highly capable computer science students onto a team of mechanical engineering students, the 2015 Titan UAV team aims to bring a highly capable and competitive UAS to this year's AUVSI Student Unmanned Aerial Systems competition.

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1.0 Introduction

The 2015 edition of the Student Unmanned Aerial Systems (SUAS) competition marks the third year of Titan UAV's participation. This year, the team is composed of nine mechanical engineering students and two computer science students. An additional challenge was posed by the aggressive schedule set forth for participation in two competitions: SAE Aero Design West and AUVSI SUAS. Due to budgetary constraints, the team plans to use the same airframe for both competitions.

The airframe, *The Balsa Buzzard*, or *Buzz*, was proven flight worthy at Aero Design West by lifting 15 lb. of payload, providing live telemetry and digital video feed, and attempted to drop a 3 lb. sandbag onto a target from 100 ft. MSL. After completion of the Aero Design West competition, the team set to work on repairing the airframe and adapting it to fit a new mission profile. For the first time in the history of Titan UAV's participation, the team will have a proven custom airframe ready to fly weeks ahead of the competition date.

2.0 Systems Engineering Approach

2.1 Mission Requirements Analysis

With the absence of any returning team members from the previous year, Titan UAV worked tirelessly to research many different approaches to achieving as many mission tasks as possible. The mission tasks were outlined in **Table 1** and thoroughly analyzed to determine which tasks the team would attempt.

Table 1: *Analysis of mission requirements for 2015 SUAS.*

Task	Threshold	Objective	Task Goal
Autonomous Flight	Controlled takeoff/flight/landing, waypoint navigation, no-fly-zone.	Autonomous takeoff/flight/landing, waypoint navigation, no-fly-zone.	Objective.
Search Area	Target identification within 150ft and classification.	Target identification within 75ft and classification.	Objective.
ADLC	N/A	Autonomous target detection, localization, classification.	Objective.
Actionable Intelligence	In-flight completion of search area task threshold.	In-flight completion of search area task objective.	Objective.
Off-Axis Standard Target	Identify two target characteristics.	Identify all five target characteristics.	Not attempting.
Emergent Target	Provide image of emergent target.	Provide image of emergent target, autonomous re-tasking.	Objective
SRIC	Upload file.	Autonomous upload and download.	Not attempting.
IR Target	Identify static IR target.	Autonomous identification of static and active targets.	Not attempting.
Air Drop	Manual release and impact within 100ft of target.	Autonomous release and impact within 30ft of target.	Threshold.
Interoperability	Integrate with provided server, 1Hz update rate.	Integrate with provided server, 10Hz update rate.	Objective.
SDA	Avoid virtual obstacles.	Autonomous avoidance of virtual obstacles.	Objective.

2.2 Design Rationale

The airframe being used for the 2015 SUAS competition, *The Balsa Buzzard*, is a modified version of an airframe used in the 2015 Aero Design West competition. Several of the objectives for Aero Design matched closely with SUAS tasks: autonomous flight, target search, actionable intelligence, and air drop. These similarities allowed for a straightforward adaptation. A $0.49\ in^3$ displacement nitro engine was replaced with an E-Flite Power 90 electric motor, driving a $20 \times 10"$ propeller to produce significantly more thrust. The fuselage design of *Buzz* allows for the full enclosure of all electronics internally. Additionally, *Buzz* was designed to maintain steady flight at higher altitudes, allowing for a greater field of view of the target search area.

The payload system is mainly composed of a Pixhawk flight controller and a Raspberry Pi 2 for onboard processing. The live image feed comes from a Raspberry Pi Camera, which is transmitted by a Ubiquiti Bullet M5 and received by a Ubiquiti Airgrid.

2.3 Expected Task Performance

Since the design of the system for Aero Design West already included an autopilot, live video/image link, and onboard processing, the team aims to achieve objective-level completion of the autonomous flight, search area, actionable intelligence, and emergent target tasks. Additionally, the air drop system was modified to accommodate the smaller payload for SUAS, where the team aims to achieve a threshold completion of the air drop task.

Due to time constraints on the two computer science students on Titan UAV, heavily programming-based tasks that comprised a higher percentage of the flight mission demonstration score were given priority. An overview of the scoring breakdown of secondary objectives showed that the ADLC and interoperability and SDA tasks should be prioritized over SRIC. Each of the two respective computer science students worked on their area of expertise. An image processing algorithm is under development to autonomously classify target characteristics, which will allow for objective-level completion of the ADLC task. Additionally, a custom script that communicates data between the ground station and the autopilot and onboard processor will allow for objective-level completion of the interoperability and SDA tasks.

The remaining two objectives, off-axis target and the IR target, are not being attempted due to budgetary constraints. The options for completion of the off-axis target involved the inclusion of a gimbal system and an algorithm to estimate the location of the target from visual and physical data. Both monetary and time constraints prohibit the team from attempting the off-axis target task. Finally, completion of the IR target task requires a very expensive thermal camera and the purchase of one would have consumed a majority of the team's project budget. Thus, the IR target task is not being attempted.

3.0 UAS Design

3.1 Airframe Design

This year's airframe was first used in the 2015 Aero Design West competition, hosted by SAE International. Early in the conceptualization stage, a basic study was performed in order to assess the imaging and airframe performance demands and how they related to one-another. The results suggested that, with a leisurely 20-knot cruise speed, the area could easily be surveyed in a fraction of the available time and at acceptable resolution using even a modest, low-definition camera. Efficiency and payload were then the next highest flight performance requirements, and it was realized that the airframes that were being designed by Titan UAV for the SAE Aero Design competition would be suitable for SUAS as well. Furthermore, an off-the-shelf backup airframe was procured as well in case the SAE aircraft were damaged or destroyed.

Titan UAV's Advanced Class entry to the SAE competition, "the Balsa Buzzard," was selected as the primary airframe for SUAS. As "Buzz" was already required by the SAE competition to carry an imaging system and telemetry, it was a logical choice. In the original configuration, Buzz has the following specifications:

- Empty Weight: 10 lbs
- MTOW: 26 lbs
- Wingspan: 14.7 ft
- Length: 10 ft
- Wing area: 22 ft^2
- Maximum speed: 29 kts
- Lift-to-drag ratio (max): 12:1

Buzz suffered damage during and after the SAE competition, and is being rebuilt to better-suit the new role. Modifications being made include shortening the wingspan to 10.2 ft, and conversion to electric power. The modifications should improve the endurance, maximum speed and cruise speed of the aircraft.

In addition, a *RMRC Skyhunter* will be used as a backup airframe in the event that *Buzz* is again damaged or destroyed. The *RMRC Skyhunter* is known to be a highly durable airframe capable of flight times of nearly two hours.

3.2 Autopilot System

The 3D-Robotics Pixhawk flight controller was chosen as the autopilot due to its low cost-to-performance ratio when compared to other similar options that are available to civilians. Due to its open source nature, there is a large online community that uses and supports its use. Several different modes, including auto, guided, and manual are available within the programming onboard the Pixhawk.

- Auto mode allows the UAS to follow a predetermined set of waypoints and is the basis for the autonomous flight that the system will be achieving.
- Guided mode functions as an interruption to auto mode, where the user is allowed to set a single waypoint that the aircraft will go to directly. The guided mode is the basis for the SDA system that will be implemented.
- Manual mode is entered by flipping a switch on the transmitter and gives the safety pilot full control of the aircraft.

An additional perk of using the Pixhawk is that it can communicate with other units by sending and receiving MAVlink packages. The flight mode, waypoints, and other parameters can be changed by sending the appropriate MAVlink package to the flight controller.

3.3 Imaging System

Electro-optical (EO) imaging is provided by a Raspberry Pi camera module. The camera is capable of capturing five megapixel still images as well as 1080p video at 30 frames per second (FPS). The camera was chosen for its extensive support with the Raspberry Pi single board computer and has readily available libraries. The camera module also had a very reasonable price of $20 that fit within the project budget. Preliminary testing of the camera's imaging resolution on ground level tests, as well as aerial tests, have shown that the quality of images from the camera are sufficient for both manual and automatic identification of targets. Test results of the camera module are further explained in 4.2.1 Electro-Optical Imagery.

3.4 Onboard Processing

The onboard computer is required to communicate with the autopilot system and relay information to the ground station through a wireless network connection. Additionally, the processor must control the program used for the interoperability and SDA task. The important criteria for the computer were price, form factor, and processing power. Out of the options considered, the Raspberry Pi 2 had the best combination of the aforementioned criteria, in addition to having a camera module that already had excellent documentation.

The Raspberry Pi 2 performs several tasks. Firstly, it runs MAVproxy, which communicates with the Pixhawk autopilot through GPIO pins on the Pi. MAVlink packages are then relayed from the Pixhawk to the ground station using UDP protocols through a wireless network connection. In addition to acting as a relay for MAVlink messages, MAVproxy can run custom modules written in Python. These modules receive a copy of each MAVlink package and are able to act, upon receiving them. A custom module was written that stores data about the current location of the aircraft and activates the camera system at a specific time interval. The image is then saved with the pertinent information that describes the aircraft's position and orientation when the image was taken.

3.5 Connections and Data Link

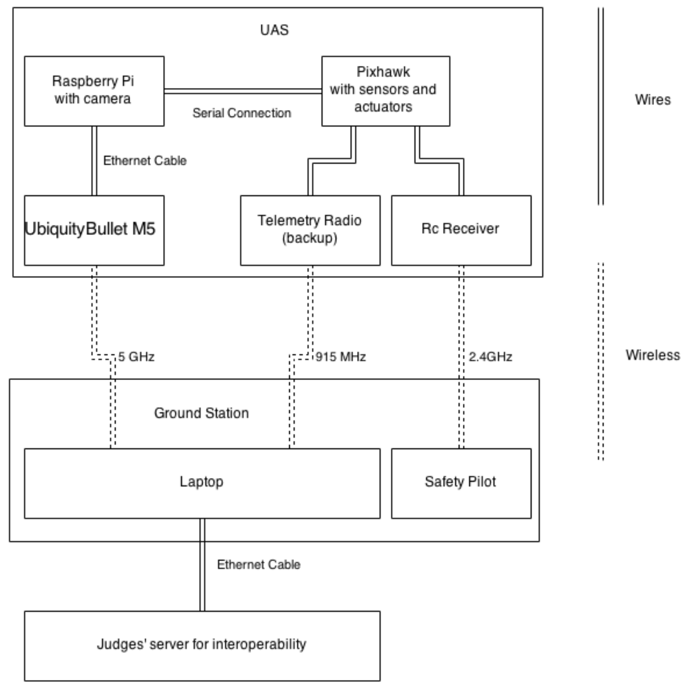

Figure 1: *Diagram of connections, wired and wireless.*

The data links between the systems can be described as follows:

- The Pixhawk communicates with the R/C transmitter through the 2.4 GHz band on an R/C receiver on the aircraft. It also communicates with the Raspberry Pi using a serial protocol that sends MAVlink packages.
- A wireless network connection on the 5.8GHz band exists between the Raspberry Pi and the ground station. This connection is established through the Ubiquiti Bullet on the airplane and a Ubiquiti Airgrid.
- The telemetry radio serves as a backup for the link between Mission Planner and the Pixhawk. In the event that the wireless network connection is lost, control of the aircraft will still be maintained through the 915MHz band.

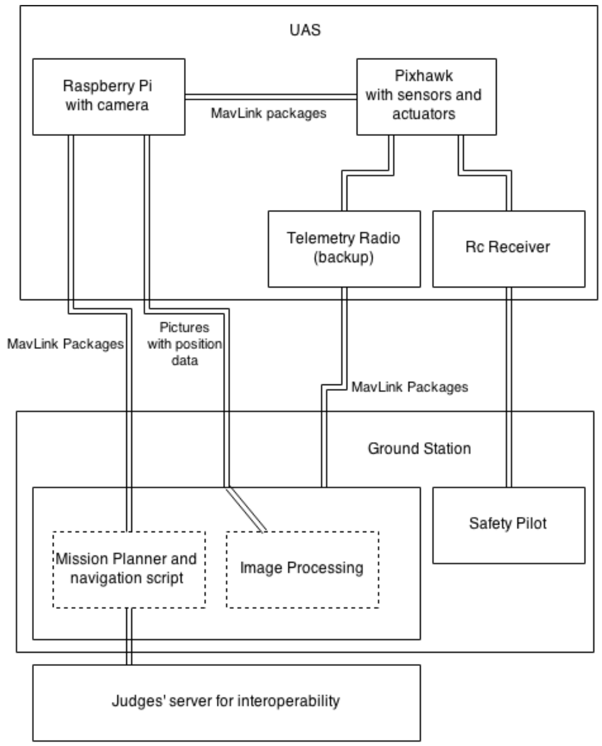

Figure 2: *Diagram showing flow of data packages between various components of the UAS.*

3.6 Ground Station

The ground station is composed of laptops running Mission Planner and various custom software, as well as a safety pilot using a standard 2.4 GHz R/C controller. One laptop running Mission Planner allows the user a GUI for mission planning. Additionally, it allows for scripting using IronPython, which then has access to variables within Mission Planner, such as aircraft position, airspeed, orientation, and many more. The IronPython script can issue new waypoints and change the flight mode of the aircraft. The IronPython script can also act as a server and accept new waypoints and relay them to Mission Planner and the aircraft, with the capability to respond with current information regarding position, airspeed, and orientation.

Flight controller telemetry is displayed through the Mission Planner interface, shown in **Figure 3**. The interface's flight data window shows aircraft attitude, altitude, ground speed, heading, flight mode, and relevant waypoint information. A map overlay that shows satellite imagery of the flight area also updates with the aircraft's position, waypoint plans, and flight boundaries.

Figure 3: *The Mission Planner interface, showing map overlay, aircraft telemetry and home waypoint information.*

A second Python script on the ground station is responsible for all navigation decisions, communication with the judges' sever, and displaying required information for the interoperability task. It communicates with the IronPython script to receive data from the aircraft and to issue new waypoints and commands when necessary.

Finally, the ground station runs a program that fetches images and relevant information from the aircraft using FTP or SCP over the wireless network connection. This program is then responsible for locating the targets and showing them to the operator.

3.7 Mission Planning

The mission can be divided into two parts: one with static waypoints and one with dynamically changing waypoints.

During the static waypoint section of the mission, takeoff and landing will use predetermined waypoints. The route to and from the search area will also use predetermined waypoints in order to comply with the competition rules. During the air drop task, the aircraft will also be following a set of predetermined waypoints to drop the package at the appropriate location based on the aircraft's position and airspeed. Thus, while the path is to the target is predetermined, the actual drop point will be calculated in flight.

For the dynamic waypoint section of the mission, an algorithm based on stochastic optimization methods will be used, namely for the search area and SDA tasks. The control system will generate random waypoints and give each point a fitness value based on distance and if the waypoint goes over previously photographed areas. Lesser distance and lesser photographed areas will give a higher fitness value. Paths through or very near obstacles presented by the SDA task will have a fitness value of zero. The script will then pick the best waypoint and give it to the aircraft as an order.

Before sending any waypoint commands to the aircraft, the script will ensure that the waypoint does not take the UAS outside the allowed fly zone. If going towards the waypoint involves a risk of leaving the allowed flight zone, it will be replaced by a predetermined waypoint inside the allowed flight zone.

4.0 System Testing and Results

4.1 Mission Task Performance

Physical testing of the system at the time of writing included two full flights, one of which was performed at the 2015 SAE Aero Design West competition. During the competition flight, the autonomous stabilization, wireless data transmission, video imaging system, and air drop mechanism were put to test. At the time, the aircraft was powered by a $0.49in^3$ displacement nitro engine, which made the aircraft difficult to handle in high wind conditions. As a result, the air drop mechanism did not achieve an accurate hit on target. The stabilization, data transmission, and imaging system successfully achieved their goals.

Figure 4: The Balsa Buzzard, *awaiting its flight run at Aero Design West.*

Figure 5: Buzz *takes flight in tricky wind conditions.*

4.2 Payload System Performance

4.2.1 Electro-Optical Imagery

The Raspberry Pi camera was set up with two different focal length cameras, 3.6mm and 6mm. These two different focal lengths were tested on targets at different distances for image quality. The experimental setup is as follows:

Imaging Equipment Test Comparison:
Camera #1: Regular HD Pi camera with 3.6 mm focal length
Camera #2: Larger HD Pi camera with 6mm focal length

Fixed Parameters:
Resolution of 1920x1080p
Transmission system: Airmax Bullet paired with Air Grid Antenna

Varying Parameters:
Frames per Second: 5, 15, 30
Bit Rate: 2, 5, 8
Distance: 225 Feet, 350 Feet
*Outdoor lighting is also a variable outside of our control and will be a variable during the competition as well.

Figure 6 and **Figure 7** show the results for images from 225 feet:

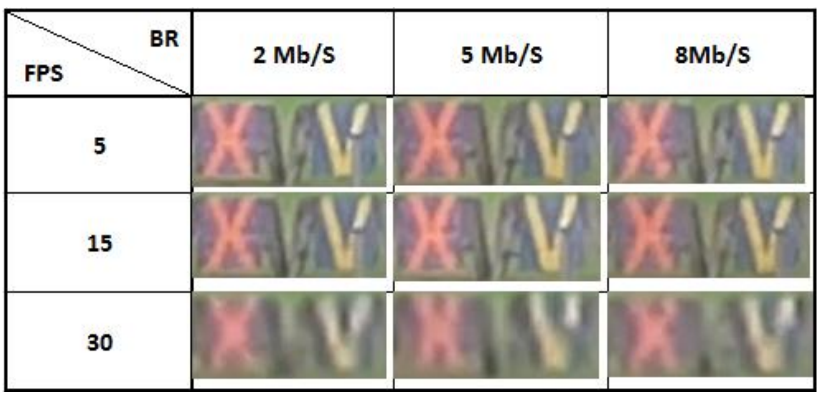

Figure 6 *3.6mm focal length camera viewing targets from 225 feet.*

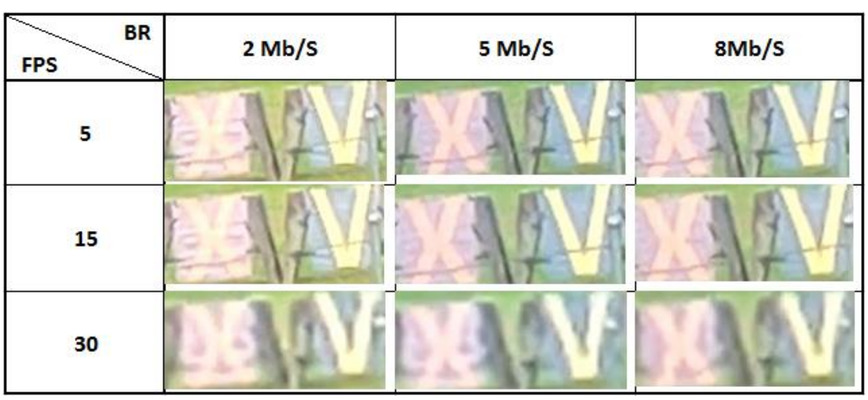

Figure 7: *6mm camera viewing targets from 225 feet.*

Figure 8 and **Figure 9** show the results for images from 350 feet:

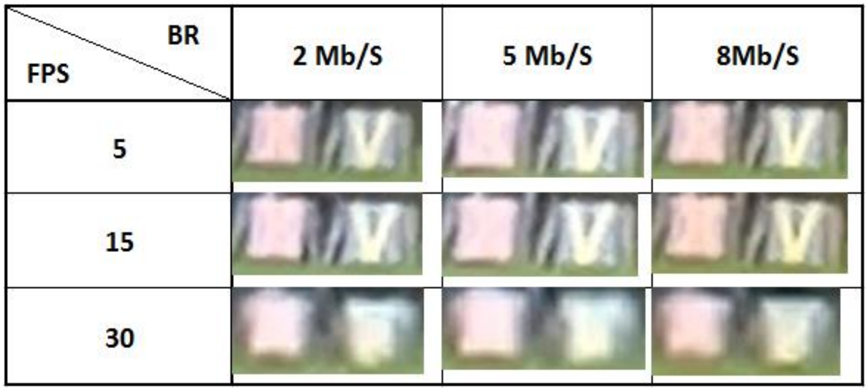

Figure 8: *3.6mm camera viewing targets from 350 feet.*

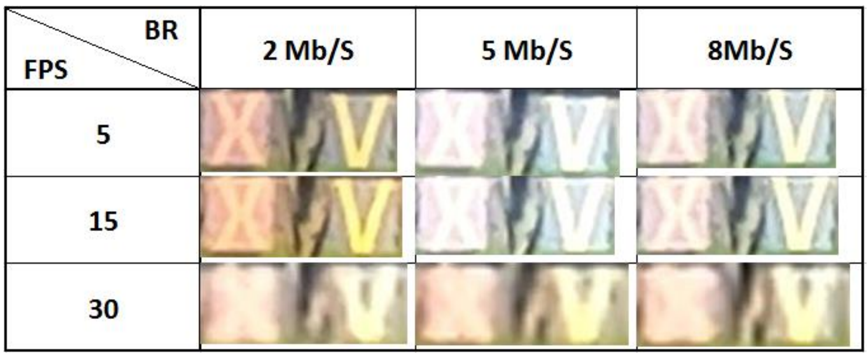

Figure 9: *6mm camera viewing targets from 350 feet.*

Note that BR is bitrate and FPS is frames per second.

Based on the results of the 225 foot test, it can be observed that on both cameras the image becomes more unclear above 15 frames per second for FPS. This same trend can be observed in the 350 foot test as well. The best frame rate is between 5 and 15 frames per second. At the 225 foot distance, both cameras provide image quality that can allow manual recognition of the colors and letters on the target posters. However, at the 350 foot distance, the 3.6mm camera begins to become very unclear. Thus, the best choice for imaging is the 6mm camera.

4.2.2 Autonomous Target Detection, Localization, and Classification

For the target recognition system, each image is analyzed on the ground station computer while the airplane continually takes photographs of the search area. The system is written in Python and uses the OpenCV library for image analysis. Each image is converted into the HSV color space which is a three channel image with each channel being a binary image for hue, saturation, and brightness. Once the image is converted the entire image is analyzed and the average hue value is removed leaving only some noise and any targets in the image. To remove the noise we used OpenCV's erode and dilate functions. After this last step we are left with a blank image only containing the targets.

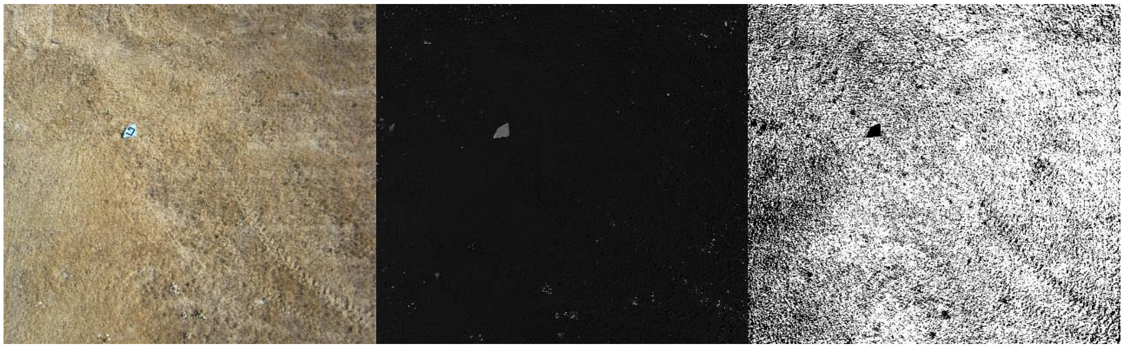

Figure 10: *OpenCV HSV conversion of test images.*

To isolate each target, OpenCV's contour functions were used. We found the targets center and dimensions. These were used to crop each target into its own separate image. Each target in the image becomes its own object which allows us to store the characteristics of each target and also check for duplicate detections of the same target. Once each target is isolated the cropped image and contour data is passed to custom written functions and filters written in python to get characteristics such as color and shape. The background color was found by finding the most abundant color in the image. To find the shape the program searched for lines in the image and the angles between each line. Each shape has a different number of edge lines and the appropriate angles between the lines to make up that shape. The program also pulls recorded position data from the flight at the position each photo was taken and uses it to calculate the location of each target.

Figure 11: *Isolation of target from full image.*

Once the characteristics are found the target object saves the cropped image and updates the output text file with the new information. The final data is stored on a flash drive to be presented to the judges.

4.2.3 Actionable Intelligence and Emergent Target

At the 2015 Aero Design West competition, the wireless data connection was proven worthy by streaming live digital video from an onboard Raspberry Pi camera. The same wireless data connection has been used to send and receive data on later ground tests. Live imagery transmitted to the ground station can be used for identification of the emergent target, as well.

4.2.4 Air Drop Task

The mechanical part of this task has been tested during the 2015 Aero Design West competition. It worked well for a three pound sandbag and is expected work well for this task, with some modification for the difference in size and weight. Navigation and control software on the ground would navigate the UAS towards the target and send an R/C override signal through mission planner to drop the package at the appropriate position. The appropriate position will be determined based on basic dynamic equations and might consider drag acting on the egg. There are currently plans to test the dynamic properties of the egg in the wind tunnel located on the Cal State Fullerton campus.

4.2.6 Interoperability

The python code that runs on the ground station includes an object that is responsible for commutation with the judges. This object has been tested with an Ubuntu server running on a virtual machine on the same computer as the python script. A network connection was established and communication was running at 20Hz, twice the necessary speed of 10Hz for objective-level completion of the task.

4.2.7 Sense, Detect, Avoid

Currently, the avoidance algorithm has not been physically tested. Simple navigation tests have been performed and the test platform did receive the correct waypoint. The code for waypoint communication and obstacle communication has been tested separately. Algorithm for “intelligent” decision making is still being developed. Testing will include a hardware in the loop simulation on mission planner and after field testing.

5.0 Safety Considerations

Although the ultimate intent of any UAS operation is to accomplish its mission, safety must always remain the highest priority. As such, it is critical that precautions and safeguards be implemented both in the design and operation of any UAS. Baseline safety requirements for the SUAS competition are outlined in section 9 of the SUAS rules, and additional safety measures are taken at the discretion of the Titan UAV team.

5.1. Specific Safety Criteria

Specific design requirements were mostly drawn from codified sources including the SUAS rules, the Academy of Model Aeronautics safety code, federal aviation regulations commonly used for certified aircraft, and other sources. Such requirements include:

- Design aircraft to withstand aerodynamic load factors ranging from +4 G to -2 G at maximum design weight
- UAS must feature a datalink transmitting flight telemetry, including altitude and position, to the ground station

- Aircraft must feature an automatic flight termination protocol commanding hard-over of all control surfaces in the event that signal is lost for more than 3 minutes

5.2. Safety risks and mitigation methods

During the design process, efforts were made to consider every possible mode of failure, and mitigate the probability and severity of each failure mode.

- Structural problem or problems with control surfaces in flight
    - Prevention: Design airframe and actuators with ample engineering margins beyond the expected flight loads
    - Mitigation: Switch to manual and land safely if possible, otherwise terminate flight a safe distance away.
- Loss of RC signal
    - Prevention: Avoid in-band interference. Locate RC receiver in tail away from onboard interference sources.
    - Mitigation (primary): Return to home (RTH) for 30 seconds or until signal is reacquired. Land under datalink control if connection cannot be reestablished.
    - Mitigation (contingency): Terminate flight after three minutes without communications.
- Loss of primary datalink
    - Prevention: Utilize proven Ubiquiti Airmax M5 connection with long-range configuration.
    - Mitigation: RTH and troubleshoot until connection is reestablished. Land under RC control if connection cannot be reestablished.

Additionally, common practices were followed wherever they were deemed not to conflict with performance, in order to minimize the likelihood of unforseen failures.

6.0 Conclusion

With the presence of a proven airframe and two very capable computer science students, the 2015 Titan UAV team expects to bring a robust UAS to the Student Unmanned Aerial Systems competition. The objective-level achievement of all primary tasks as well as threshold and objective level achievement of most secondary tasks is well within reach of the team. A significant amount of testing on operational procedures and safety have been taken to ensure that the team performs to its fullest potential.