固定翼开源自主小型无人机（FOSAM-UAV）
团队的系统设计与开发：2011年AUVSI学生UAS竞赛

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图1. OSAM-UAV团队

本文描述了犹他州立大学（USU）中心智能家居与智能系统（CSOIS）的固定翼开源自主小型（FOSAM）无人航空系统（UAS），该系统专门为远程 sensing设计。飞机设计内装有自建导航硬件，坚固耐用，便于携带，且无需操作员参与。Boomtail飞机是一款独特的复合翼设计，机翼通过双翼撑杆和推进器配置进行扩展。滑块着陆、泡沫/复合材料结构、飞行稳定性、转弯半径小，使其成为2011年学生无人航空系统（SUAS）竞赛的优良选择。所有这些优势都增加了在SUAS竞赛中获胜的可能性。主要目标是在美海军陆战队进行巡逻时收集情报、监视与侦察（ISR）。UAS被分解为三个子系统：飞机、自动飞行系统和载荷系统。地面控制站（GCS）和飞机在实时通信来提供情况意识和安全可靠的飞行。
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I. Introduction

Team FOSAM has a rich legacy of in house aircraft designs and extensive field testing. Based on experience from previous SUAS competitions, the aircraft must be able to withstand abuses that most commercial RC planes would not survive. Thus CSOIS have developed an aircraft capable of withstanding hard take offs and landings as well as transportation abuses. Capable of launching autonomously with a bungee cord and skid landing on any smooth surface, the Boomtail is a robust and mature platform. Team FOSAM’s successes stem from the systems engineering approach to solving problems and a long history of testing. With an aircraft and system designed for remote sensing and now using Digital Single Lens Reflex (DSLR) cameras, Team FOSAM is capable of completing the mission requirements.

A. Team FOSAM

Utah State’s Team FOSAM is comprised of a group of Mechanical, Electrical and Computer Engineering, and Computer Science Students. Team Lead is Aaron Quitberg, who has been heavily involved with the development of the Boomtail design and is the safety pilot for the team. Joseph Montgomery leads the target recognition design and Patrick Ball, Brad Neumann, and Jeremy Frint continue airframe development. Previous team members have passed on a tradition of hard work, knowledge, and dedication to every new member. This continuation of effort has kept the momentum going with research and development of new and better ways to be successful in this competition.

B. Mission Requirements Analysis

The goal of the SUAS mission is to gather ISR as autonomously as possible in real time. After a 40 minute set-up period, the aircraft must takeoff, navigate autonomously through preset waypoints and provide imagery of targets on the ground. Points are awarded for autonomous takeoff and landing, actionable intelligence and in-flight retasking, as well as automatic target recognition of the alpha-numeric targets. The flight and intelligence gathering must be completed within 40 minutes of takeoff. Safety is a high priority; therefore a safe-fly zone and a no-fly zone is enforced. Since the safe-fly zone is rather small, a highly maneuverable yet stable aircraft is a must.

![Mission overview](image)

Figure 2. Mission overview

The mission must be accomplished in a safe manner while generating accurate information for the military. Throughout this document the mission requirements are further explored in correlation with the team’s design decisions.

C. System Overview

For the past several years, CSOIS has been developing UASs for civilian use. Many other applications of UASs remain undiscovered, or are currently in development. The following paper presents motivations, a system overview and implementation details of the newest version of the CSOIS AggieAir system.

AggieAir™ is the CSOIS Unmanned Aerial Vehicle platform. While the previous version documented in the IEEE MESA conference¹ has proved to be useful and robust, Version 3 introduces many new features required for safety and reliability, and improvements encapsulate advances in technology required for new payload and mission parameters.
The AggieAir system architecture can be seen represented in Figure 4. AggieAir builds upon the existing Paparazzi architecture, adding a much higher level of navigation and payload capability. Separation of payload and the core requirements to fly the airframe is designed into the architecture, such that if payloads encounter software errors or other problems, the likelihood of the airframe falling from the sky is minimized.

D. Mission Preview

When called, the teams entering the airfield are provided time to set up their UAS and support equipment before their flight. Judges help direct and ensure that when the safety pilot’s transmitter is turned on: the mission has started. At that time the aircraft is powered up and the mission commences. For Team FOSAM, the plane will be powered on and the system will be checked for proper function. During this time a team member inserts a bungee cord into the grass strip near the dedicated takeoff area and a GPS coordinate is taken at this position. This position is entered as the home position on the GCS. After systems check out the plane will be attached to the bungee and pulled back. The safety pilot will then radio to the GCS operator when proper tension is on the bungee. The GCS operator will radio that launch is a go and the safety pilot will turn on the motor kill switch and the plane will be released. After the plane has passed the home position the motor will turn on and the autonomous waypoint navigation will begin. Cameras will be on during this time and pictures will be processed on board for potential targets. Pictures with positive
identifications will be sent to the imaging station for verification. When the waypoints have been flown and all actionable intelligence or popup targets have been received the GCS operator will radio to the safety pilot that the plane will begin descent to land. All of this will be done without any inputs from the safety pilot. After touchdown the plane will be retrieved and when the last pictures are downloaded the mission ends when the pictures have been positively identified, turned into the judges, and the transmitter is turned off. At this point the UAS and support equipment is taken down and other teams can set up for their flight.

II. Airframe Systems Design and Implementation

A. Airframe

The first generation of aircraft used for this competition was Unicorn Delta Wings. While they provided the required maneuverability, turning could only be accomplished by banking which uselessly pointed the cameras toward the horizon. Gimbaled cameras were impractical since these wings belly-landed. Another problematic area was the low payload volume in the wing. Attempts were made to increase this volume; as a result the flight characteristics were compromised. An improved revision was needed. In 2009 a group of Mechanical and Aerospace students designed the first Boomtail aircraft using Expanded Polypropylene (EPP) foam. The Boomtail was designed for tight turning radii in coordinated turns, high payload capacity, and a large, accessible payload volume. Turn radii were based off the structural limit which was found to be about 1.5g shown by Equation 1.

\[ n_{\text{pl}} = \left( \frac{W}{W_{\text{max}}} \right) \sqrt{\frac{V^2}{g(R_{\text{minload}})^2} + 1} \]  

(1)

Where \( W \) is aircraft weight, \( W_{\text{max}} \) is aircraft maximum weight, \( V \) is instantaneous velocity, \( R_{\text{minload}} \), minimum turn radius under maximum load.

The desired turn radius was based on the field of view of the camera at 300 feet AGL, the structural limit of the foam, and the stall speed. This formula is below in Eq. 2.

\[ R_{\text{minstall}} = \left( \frac{1}{g} \right) \sqrt{\frac{\rho C_{L_{\text{max}}}}{2W/S_w} V^2} - \frac{1}{V^2} \]  

(2)

Where \( \rho \) is air density, \( W \) airframe weight, \( C_{L_{\text{max}}} \), maximum lift coefficient, \( S_w \) is wing surface area, \( V \) is instantaneous velocity.

From these parameters a turn radius of 110 feet was derived. Figure 6 shows how the fuselage volume was increased to allow more capacity and access to the payload.

After extensive testing the design was modified some to improve weight and balance issues and in 2010, Boomtail made its debut in the competition. The first launch provided more lift than anticipated which resulted in improper bungee hook release. The motor turned on full throttle, and then the bungee pulled the plane back down to the ground. After impact, the plane was still fully functional and took off and landed...
autonomously. Even with great performance, Team FOSAM has identified areas of improvement for the
airframe: decreased overall weight, increased strength of wing, tail spar connections, and modularity of the
empennage.

Various attempts were made to increase the strength while reducing the weight of the airframe. Originally
reinforced tape was used as a covering for the wings and fuselage but this tape was heavy and wore out easily.
Shrink wrap coverings are generally too hot for the foam but low temperature film from MonoKote called
Polycover adhered well with low heat. Removing the tape from the wings decreased the weight of the airframe
by a full pound.

The first idea to increase the strength of the wings was to cover them in fiberglass, but the wings
were heavier and far too brittle. If a small area of the fiberglass was damaged, it would cause stress
concentrations and resulted in delamination and failure. Previous attempts at covering the wings and
fuselage with reinforced tape resulted in excess weight yet superior impact resistance.

Due to the climate at Utah State University, the tape would quickly peel away and need to be replaced.
Finally, it was decided that fiberglassing the fuselage and only using reinforced tape on the LE and TE of the
wings would be ideal. MonoKote was used to cover the wings to give superior impact resistance and provide
the required strength for the fuselage. This has been the best compromise between weight and durability so
far.

The empennage was connected to the fuselage with pultruded carbon fiber spars that were inserted into
sleeves glued in the foam. This process caused cracking of the longitudinal fibers in the tube spar. A solution
to this was to insert the spars into special connectors that have been made to fit between the fuselage and
wings which transferred forces into the main and rear spar. These connectors were easily fabricated using
composite molding techniques, and are seen in Figure 7.

In past years, the vertical and horizontal stabilizers were permanently attached to the carbon fiber tail
spars which resulted in a larger shipping container than desired. Efforts to make the tail section strong
yet modular were very important to improve portability. In the new design, the horizontal and vertical
stabilizers detach from the tube spars. The rudder and elevator reconnect to the pushrods easily using quick
connect ball links. With this method there is no need to retune the UAS after assembly.

In hopes of achieving even more efficient aircraft Team FOSAM is continuously working on improving
their fixed-wing designs. The new design incorporates tapered wings for a more elliptical lift distribution,
as well as a thicker fuselage for more payload capabilities. The conceptual design was created by a group
of undergraduate mechanical and aerospace engineering students, and a preliminary design was done with
the help of aerospace graduate students. The preliminary design was done by writing a genetic algorithm
coupled with an aircraft design program, which was written by Utah States Warren Phillips. The design
looks extremely promising, with over an hour and a half flight time and up to 70 miles of flight. The aircraft
was built but unfortunately had some dynamic instability problems. During the last couple weeks of the
spring semester the team did a dynamic analysis on the aircraft, and discovered it was unstable in roll.
causing the aircraft to spiral. Although this should be easily fixed by adding more dihedral to the airframe, the team ran out of time to rebuild for this years competition.

The use of the DSLR camera requires the fuselage to be six inches thick. Increasing the volume of the fuselage changed the flight characteristics of the plane. Dynamic stability was also affected. To counteract the dynamic instability problem washout was built into the wings. Washout is twist built into the wings that forces a stall at the wing root leaving the wing tips and ailerons unaffected and also reducing the planes tendency to spin (Mechanics of Flight, Phillips\textsuperscript{2}). With the help of SolidWorks simulation (Figure 8) it was possible to verify that the increase of the fuselage volume was too extreme. Therefore an acceptable solution was to design a cover that increased the height of the fuselage only where the camera is located. This enabled the airframe to be able to carry larger payloads without adding excessive weight or drastically increasing the drag on the airframe. With the heavier payloads the wing loading needed to be decreased. The best way to do this was to extend the wingspan a few inches. Testing has verified that the increase in wingspan has helped expand the payload capability and 40 minute flights are still achievable.

B. Autopilot

The autopilot plays an indispensable role in autonomous UAV navigation. To choose an optimal solution for this mission, the team did a full investigation of small UAV autopilots including Procerus Kestrel, Micropilot MP 2028, CloudCap Piccolo LT, Paparazzi, and others. Decisions were made based on the size, weight, physical specifications, and functionality, details are provided in Table 1 and Table 2.

Tables 1 and 2 indicate the Kestrel and Piccolo autopilots are small, light-weight, and powerful. But their prices are relatively high and most of their onboard software is not accessible to users, which is a disadvantage for later orthorectification and camera equipment synchronization with the autopilot.\textsuperscript{4} The Paparazzi UAV project provides an inexpensive, robust and open source autopilot solution including both hardware and software. However, it uses infrared sensors for the attitude measurement. Infrared sensors are not as accurate as Inertial Measurement Units (IMUs) or Inertial Navigation Systems (INS), used by most commercial UAV autopilots to obtain better accuracy.
The autopilot system currently in use is from the Paparazzi project. Paparazzi consists of open source hardware and software for unmanned system development. The autopilot system includes two major components: the airborne system and the ground station. The airborne autopilot is called TWOG (Tiny With Out GPS) seen in Figure 10, and it has been modified to survive higher voltage for larger platforms. There is a software protocol so it can adopt sensor data from commercial IMUs for accurate attitude estimations. The ground station is based on a Linux computer which runs the Paparazzi Center, and it can be used to adjust different control parameters, modify the flight plans, monitor the flight status and control the UAS. Numerous autonomous flight tests have been accomplished to prove the robustness of this system.

To achieve both accurate image georeferencing and a fair price, the team chose to add an IMU to the Paparazzi autopilot replacing the IR sensors. Both an off-the-shelf IMU and an in-house developed IMU (called AggieNav) have been integrated with the Paparazzi autopilot, shown in Fig 9. The commercial Gx2 IMU from Microstrain was chosen for its relative low cost and high performance. The Paparazzi airborne

<table>
<thead>
<tr>
<th>Size (cm)</th>
<th>Weight (g) w/o radio</th>
<th>Power Consumption</th>
<th>Price DC In (k USD)</th>
<th>CPU</th>
<th>Memory (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kestrel 2.2</td>
<td>5.08<em>3.5</em>1.2</td>
<td>16.7</td>
<td>500mA</td>
<td>5</td>
<td>6-16.5</td>
</tr>
<tr>
<td>MP 2028(^9)</td>
<td>10<em>4</em>1.5</td>
<td>28</td>
<td><a href="mailto:140mA@6.5V">140mA@6.5V</a></td>
<td>5.5</td>
<td>4.2-26</td>
</tr>
<tr>
<td>Piccolo LT (w/modem)</td>
<td>11.94<em>5.72</em>1.78</td>
<td>45</td>
<td>5W</td>
<td>-</td>
<td>4.8-24</td>
</tr>
<tr>
<td>Paparazzi TwoG</td>
<td>4.02<em>3.05</em>0.95</td>
<td>8</td>
<td>N/A</td>
<td>0.125</td>
<td>6.1-18</td>
</tr>
</tbody>
</table>

Table 2. Comparison of autopilot functions

<table>
<thead>
<tr>
<th>Waypoints Navigation</th>
<th>Kestrel</th>
<th>MP 2028(^9)</th>
<th>Piccolo LT</th>
<th>Paparazzi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto-takeoff &amp; landing</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Altitude Hold</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Air Speed Hold</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Multi-UAV Support</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Attitude Control Loop</td>
<td>-</td>
<td>30Hz</td>
<td>-</td>
<td>20/60 Hz</td>
</tr>
<tr>
<td>Servo Control Rate</td>
<td>-</td>
<td>50Hz</td>
<td>-</td>
<td>20/60 Hz</td>
</tr>
<tr>
<td>Telemetry Rate</td>
<td>-</td>
<td>5Hz</td>
<td>25Hz or faster</td>
<td>Configurable</td>
</tr>
<tr>
<td>Onboard Log Rate</td>
<td>&lt;100Hz</td>
<td>5Hz</td>
<td>-</td>
<td>N/A</td>
</tr>
</tbody>
</table>
code was modified to accept the sensor data stream from a gumstix microcomputer, which combines the data from both the IMU and GPS unit. It passes this data on to Paparazzi as well as binding this information with the aerial images created by the camera.

![Image](86x525 to 301x694)
![Image](311x525 to 526x687)

(a) AggieNav version 3 with associated GPS and Pitot tube (b) Microstrain Gx2 IMU

Figure 9. AggieNav3 and Backup Microstrain IMU

![Image](198x305 to 414x467)

Figure 10. Paparazzi TWOG autopilot board

With the new design of the OSAM Paparazzi autopilot, which implements an IMU, more accurate image registration can be achieved. Another advantage is that the image system is seamlessly integrated with the autopilot inexpensively (about $2500). The whole autopilot system has been fully tested at CSOIS and has been proven to be stable and robust.

C. Navigation

AggieNav, first introduced in earlier conference papers, is a full 6-DoF IMU that allows for high-performance and low-cost UAS navigation and control, in addition to providing high-accuracy attitude estimation for payloads with high pointing sensitivity. An improved AggieNav system block diagram can be found in Fig. 11. The improved version of AggieNav (pictured in Figure 9) has a 330Hz inertial system bandwidth to support attitude control of four and eight-rotor helicopter designs, and is mounted longitudinally to allow the IMU to be closer to the airframe center of gravity.
1. Sensors for Small UAS Navigation

In previous work,\textsuperscript{6} the hardware in AggieNav was introduced and examined. The system design has been updated to reflect both new requirements and changes in hardware availability (in the case of the pressure sensors).

Analog Devices has introduced an improved version of the ADIS 6-degree-of-freedom sensor with 3-D magnetometer capability, as well as a larger 18g accelerometer range. The larger acceleration range allows AggieNav to be used for many more applications, and the magnetometers allow the elimination of the previous compass module, to use the Magnetic Anomaly Map\textsuperscript{9} to more accurately navigate with the aid of the AggieAir GPS unit.

The pressure sensor selection for AggieNav has been made to allow for a high rate of measurements, as well as differential accuracy. The previous pressure sensors (VTi SCP series) have been discontinued, and were not able to sustain a 50+Hz sampling rate. Honeywell ASDX series sensors have been chosen to support the higher sampling speed demands for high navigation data rates, as well as the higher accuracy needed to do wind speed measurements. Both absolute and differential pressure sensors have been included for complete data about altitude and airspeed. The process of airspeed calculation from sensor data via Pitot tube remains the same for small and large aircraft.\textsuperscript{10}

2. Attitude Estimation Techniques

As previously published\textsuperscript{6, 11} AggieNav3 has onboard estimation algorithms that give the Paparazzi autopilot a very good estimation of the actual roll, pitch, and yaw. Figure 12 shows the close matching AggieNav estimation of roll vs. a Microstrain 3DM-GX2 commercial IMU during a typical UAV flight. In this flight, AggieNav3 was used for autonomous navigation while the 3DM-GX2 was merely used for monitoring and verification.

III. Payload design and implementation

The payload system is the central focus of the proposed mission, hence much effort has been put forth to enhance the design and capabilities of this part of the UAS. The payload system consists of a Nikon D90 DSLR camera as the sensor, a Pandaboard single-board computer that runs the payload control (AggieCap) and image processing (AggieID), and a Ubiquiti Networks Bullet BM5HP high-powered radio to network with the imaging station on the ground.

Preliminary designs in the payload system included a Gumstix Computer-On-Module (COM)\textsuperscript{12} for payload control and on-board image processing. The Gumstix consists of a single 720 MHz OMAP 3530 processor with an ARM Cortex-A8 CPU and 256 MB of SDRAM. This was sufficient for simple payload control, however it proved ineffective for on-board target recognition because of its limited processing power. The Pandaboard, introduced to the public late last year, offers a dual-core 1 GHz OMAP 4430 processor.
II. COMPARISON OF ATTITUDE ESTIMATION: AGGIE NAV V. S. G. X 2

![Graph showing comparison of roll and pitch between AggieNav3 and Microstrain 3DM-GX2 IMU.]

Figure 2. Comparison of roll.

Figure 3. Comparison of pitch.

Figure 12. AggieNav3 roll data compared with Microstrain 3DM-GX2 IMU during autonomous flight

This upgrade has enabled us to vastly improve the payload software as well as enable the target recognition processing to be on-board the UAS during flight, providing more actionable intelligence for the mission.

The use of a dedicated on-board imaging computer (the Pandaboard) is also a safety feature to ensure that the CPU-intensive imagery operations do not interfere with the navigation or flight-control systems of the UAS. The navigation system communicates asynchronously with the imagery system to provide it with real-time positional data. This was done to prevent the unlikely event of the UAS failing due to the imagery system becoming unresponsive.

A. Choice of Camera

A camera’s maximum capture speed is the minimum time between shots that a camera can sustain for an indefinite period of time. Many cameras are advertised as having maximum capture speeds that are not sustainable over more than a few seconds.

In the past, the standard payload has included two Canon PowerShot SX100IS cameras. The motivation for having two cameras is that, in the tests, the SX100IS has a maximum capture speed of 3 seconds. It is required to capture photographs more frequently than this, so a second camera is used to capture a
photograph every 1.5 seconds.

This year, the quality of the imagery is improved by using a DSLR camera instead of a point-and-shoot camera. Two comparable alternatives are the Nikon D90 and Canon 450D. The most important difference between these two cameras is maximum capture speed, so the performance of these cameras was compared by timing 5,000 captures with each camera. While average capture speed is interesting, maximum capture speed is more important.

Figure 14 is a histogram comparing the performance of 5,000 captures per camera, the x-axis representing the time each capture took (capture speed), the y-axis representing the quantity of captures in each time range. After composing this histogram, two important facts became clear: the 450D has a shorter maximum capture time; the D90 has a more reliable capture speed (lower variance).

Due to the inconsistent Canon performance, the camera is reliably about 1.2 seconds per capture, it is not certain that every capture will be less than 1.2 seconds.

Due to the consistent Nikon performance, 1.4 seconds per capture is reliable. It is certain that the Nikon D90 will never take longer than 1.4 seconds to capture a photo. This year, team FOSAM will fly with the Nikon D90.

To ensure that the camera gets a wide enough field of view, the team uses a small array of two cameras, which is light enough for the UAV to carry, while doubling the system’s field of view. Calculations and testing show that even the smallest anticipated target can be identified at the UAS’s maximum mission altitude. To ensure that no targets will be missed, there must be overlap between the pictures. To determine the time needed between pictures for an appropriate amount of overlap Equation (3) was used. The time needed between pictures varies directly with the altitude and the speed of the UAV. It was determined that a period of three seconds between pictures leaves more than adequate overlap.

\[
t_{\text{min}} = \frac{(1 - p) \times F_y}{v}
\]  

(3)

where \(p\) is the fraction of overlap in the pictures, \(F_y\) is the vertical length of camera’s footprint, \(v\) is the speed of the plane. \(F_y\) is calculated using Equation (4).

\[
F_y = \frac{h \times P_y \times P_N}{f}
\]  

(4)

where \(h\) is the flight height, \(P_y\) is the pixel size and \(P_N\) is the number of pixels in the CMOS sensor. \(f\) is the focal length of the lens.

B. AggieCap Payload Control

In previous years, the payload control system, called GhostEye, was implemented in C, which is commonly used in embedded systems due to its relatively low CPU and memory usage.

This year, the payload control system has been re-written in Python, and given the name AggieCap. Switching from C to Python was a serious decision. The language was switched due to the following reasons:
• Requirements outside of the AUVSI competition demanded that GhostEye be expanded to support more than just visible light still cameras. GhostEye would need to be changed to be more modular, so this was a good time to make other big changes.

• Python is an intuitive and practical language that is easy to learn, so present and future undergraduate software developers can be more productive with their time. Because the team is composed of students, software developers often lack experience and time; Python places meaningful contributions within the reach of everyone.

• Python is an interpreted language with a garbage collector, so memory management issues are handled by the interpreter. Productivity improves because the possibility of memory-related bugs is mitigated. Furthermore, managing a project written in C for an embedded system is not trivial. Teaching a new, undergraduate developer how to properly use the embedded SDK is even less trivial.

• The payload control system is I/O bound, not CPU bound, so the CPU performance characteristics of C are not important. Moreover, the payload control hardware platform has more than enough RAM to make the memory requirements of Python a non-issue.

AggieCap uses Python’s Object-Oriented features. Each sensor type (still cameras, video cameras, IMU/GPS, wildlife trackers, etc) is represented with a class; all sensor classes inherit from one base sensor class. AggieCap manages parallelism outside of the sensors classes, so sensor classes need not consider thread-safety. This architecture implies that adding different types of sensors in the future should be relatively easy. Indeed, the sensor classes created thus far has proven this principle.

In tests, AggieCap has proven to work as well as GhostEye did. In the future, AggieCap will be easier to manage and expand.

C. AggieID Target Recognition

As the mission progresses (Fig. 15), the following attributes must to be known about each target, as seen in Figure 16.

![Figure 15. FOSAM in-air and ground-based GUI image acquisition and classification flow. gRAID is described below in Section IV.C](image)

• Geometric Shape
• Color
• Orientation
• Alphanumeric
• Alphanumeric color

It was the goal of this team to autonomously identify as many of these attributes and do so as quickly as possible to provide truly actionable intelligence during the mission.

The UAS is capable of autonomously identifying the specified targets on the ground in-flight independently of the imaging station operator with AggieID. AggieID runs on the Pandaboard payload computer.
and receives the images acquired by AggieCap. It is written in C++ and utilizes the open-source image-processing library OpenCV. OpenCV provides effective and proven functions for image-processing that are particularly useful to this mission.

The outline of the target recognition process is:

1. AggieID receives RGB images from AggieCap
2. RGB image is converted to grayscale and HSV for processing
3. The Saturation plane (of HSV) and the grayscale image are filtered for preparation
4. Contours are found in filtered grayscale and Saturation plane images
5. Contours within certain length thresholds are compared against contours of known shapes for identification

The images taken from the camera with AggieCap are in 2256x1504 resolution, the smallest resolution possible with the camera being flown. Testing showed that reducing the resolution of the images by about 50% in each axis significantly reduced the time required to process each image (about 10-15%) without significantly affecting the accuracy of target recognition. This reduction can be done with OpenCV functions in AggieID in minimal time.

Once the current image has been resized, it is converted into two different color spaces for further processing. The first conversion is into grayscale as this is relatively quick and allows easy identification of most targets. The second conversion is into the Hue Saturation and Value (HSV) color space. Testing showed that targets that are difficult to identify in RGB or grayscale images due to low contrast with the ground are easier to identify in the Saturation plane of the HSV color space.

After the image is converted, each resulting image is processed to find the contours or edges in the picture using Canny edge detection. OpenCV provides built-in functions to easily find and subsequently manage these contours in an image. Each contour found is saved as a list of two-dimensional points representing each pixel that makes up the contour.

Contours that are within the known size constraints of the target are then processed further to be compared to contours of known shapes. Two methods are used to compare these contours:

- **Hu Moments**
- **Perimeter Signatures**

A contour moment in OpenCV is a gross characteristic of the contour computed by integrating over all pixels of the contour. These moments are made translationally invariant by displacing the x and y values in the equations by the center of the contour. These are then made scale-invariant by normalizing the equations with the length of the contour. Finally, Hu Moments are linear combination of these normalized central moments. This creates invariant functions representing different aspects of the image in a way that is invariant to scale, rotation and reflection.

OpenCV provides optimized functions for computing and subsequently comparing Hu Moments of different contours. The function cvGetHuMoments() computes several Hu Moments for a given contour. Once
these Hu Moments are obtained, the function cvMatchShapes() returns a value corresponding to the similarity of two contours. The smaller this value is, the more similar are the two contours. This method was chosen for its quickness and is augmented with the use of perimeter signatures for added accuracy.

Perimeter signatures are also rotation- and scale-independent representations of contours useful for comparison to other contours. They are calculated by first finding the centroid of the contour and the pixel that is furthest away from the centroid. Then, for each pixel in the contour, its distance from the centroid is calculated and normalized with the furthest pixels distance. This normalized distance is then plotted against the angular distance between the line formed by the current pixel and the centroid and the line between the furthest pixel and the centroid. As an example, this is the two-dimensional plot of the perimeter signature of a square in Figure 17.

![Perimeter signature example](image)

Figure 17. Perimeter signature example

OpenCV does not include any functions to compute or compare perimeter signatures natively, so these functions were developed in-house and tested extensively. The perimeter signature approach showed to be more accurate generally than the Hu Moment approach. However, there are cases that favor each approach, so it was decided that they would be used in unison to identify potential targets.

This process is done to determine a target’s shape and alphanumeric. To determine the colors of each of those, the pixels inside the shape and alphanumeric contours are analyzed in the Hue plane of the HSV colorspace. This leaves only the orientation to be determined. Unfortunately, this capability has not been successfully automated and must be determined by the image station operator.

D. Bullet Wi-Fi Link

The payload system is connected to the imaging station on the ground via a 5.8 GHz link provided by the Ubiquiti Networks Bullet radio. The BM5HP model was chosen partly because it is a completely integrated radio that has a robust weatherproof and minimal design. Also, it offers an effective range of up to 2 miles while its max power consumption is only 6 Watts. It is powered over Ethernet, reducing the number of connections necessary on the airframe.

IV. Ground Control and Imaging

A. Mission Planning

Every mission has its general procedures and special purposes, and the biggest difference for each mission is its fight plan. The tasks of every mission need to be divided into required parts and optional parts. Required parts always have higher priorities. Once each task is defined clearly, it can be added in the fight plan. All required and optional tasks should be included in the mission fight plan. After that, each part of the mission will be tested in the simulator to validate the feasibility and find as many potential problems as possible in order to improve the plan and reduce the risks of real fight failure. There are four major missions for the 2010 AUVSI Student UAS Competition: takeoff, way point navigation, search area, and landing. For the team, autonomous takeoff and landing, autonomous way point navigation and search area, real-time target
recognition are standard tasks. Pop-up way point and search are optional tasks, executed when mission time allows.

Prioritized mission list:

1. Autonomous Takeoff
2. Waypoint Navigation
3. Area Search
4. Autonomous Landing
5. Pop-up Waypoints
6. Pop-up Search Area

The user interface for the Paparazzi GCS can be seen in Figure 18.

Figure 18. Paparazzi Ground Control System

Autonomous takeoffs and landings are the two most challenging tasks according to the flight test records because the chances of failure are higher, and failures from both of these parts of the mission have caused the most damages. Therefore, an experienced safety pilot and a launcher who have practiced more than twenty times are dedicated for the job.

A procedure was devised in order to allow for safe landings and takeoffs. In order to increase the safety, a bungee launch system is devised which keeps the launcher’s hands away from a spinning propeller.

The next task on the list to be completed was to enable the aircraft to be able to search an area. This task required an update to the autopilot software in order to complete it to the team’s satisfaction. The team updated the software so that the aircraft could be told to search an area defined by any convex polygon, see Figure 20. It could also be searched in user defined degrees of sweep orientations or distance between sweeps. Finally the user can define an entry point into the polygon which tells the aircraft where to start its sweeps.

An automatic takeoff function has been written to work with the autopilot system. Takeoff and landing procedures are detailed below.

Autonomous Takeoff Procedure:

1. Set position of bungee.
2. Pull aircraft back
3. Release aircraft
4. Once aircraft passes over bungee position turn on motor
5. Continue to climb with no bank angle until height and ground speed are reached.
6. Go to next block.

Landing Procedure:
1. Circle around waypoint at a set radius and height.
2. Depart circle heading towards landing waypoint.
3. Descend with minimal throttle until within 10 meters of the ground.
4. Cut throttle and glide at computer calculated angle between current position and landing way point.
5. Touch down at landing way point.

To effectively achieve waypoint navigation, it is necessary to use the built-in functions included in the autopilot software, Figure 19 illustrates how this task is completed. The next task on the prioritized mission list is to let the UAS fly above an area of interest and stay in that area for search purposes until a new command is issued. This task requires an update to the autopilot software in order to satisfy the original expectations such as all the targets are found. A typical search area routine is shown in Figure 20. It could also be searched in degrees of sweep orientations or distance between sweeps defined by the GCS operator. Additionally, the GCS operator can define an entry point into the search area which tells the aircraft where to start its sweeps.

B. Ground Control Station

The Ground Control Station (GCS) is based on the COTS software Paparazzi. The Graphical User Interface (GUI) displays aircraft attitude, altitude, location, and other pertinent information like battery voltage, throttle percentage, airspeed, and general wind direction. This allows complete situational awareness and helps the GCS operator communicate with the safety pilot to ensure the safety of the system. When new commands are sent to the plane, it will display them in the console box and generate a voice message notifying the user.

The 2D map on the GUI screen is another important feature. If connected to the Internet it fills the window with satellite images of the area, giving the user a way to see where the UAS is based on landmarks. The map also displays the way points and the flight track of the plane. The window can be zoomed in to a suitable level to show the UAS’s entire mission or any part of the mission. The user is able to change the way point locations on the 2D map directly. This is necessary in the event that a new sub-mission is identified while the UAV is in flight. The flight plan can be adjusted to meet the new mission requirements.
Alternatively, the UAS can be called back from its mission early if an unforeseen problem occurs. The Paparazzi GCS provides the user with a high level of control over the airframe while it is in the air as well as produces a log of data that can easily be used to analyze the different aspects of the flight. On this screen is where the no-fly boundaries are created and are displayed with relation to the position of the UAS. If actionable intelligence is received it is easy to update the plane’s flight path to the new waypoint.

C. Imaging Station

The imaging operator station receives the images from the airborne payload via the wifi connection discussed previously, and presents the data to the user via the GUI seen in Figure 21. From here, an image operator can view the data provided by the airborne target recognition system, and collaborate with other image stations to discover more targets and reduce the number of duplicate targets presented to the AUVSI judges.
V. Testing and Airworthiness

Testing was performed through simulation, followed by in lab component testing and subsequent in-field testing. Every component has undergone several hours of testing several times a week. An iterative/incremental design process gave opportunities for many systems to be developed simultaneously. Completion of the Boomtail airframe and the revised design has provided the team with more possibilities for payload in the future.

A. Safety

There are many inherent risks with the use of unmanned aircraft including: complexity of the system, use in national airspace, component failure, and negligence. Precautions have been identified to reduce these risks. Every flight test is confirmed with university personnel and weather is checked regularly. Risks can be mitigated most with focus on two identified criteria: airworthiness and checklists.

B. Airworthiness

Before expensive navigation hardware is installed in any new aircraft, Team FOSAM conducts a thorough radio control test flight. If the safety pilot judges that the aircraft is stable and responds correctly to inputs, the autopilot is then installed. Manual take-off is always used after autopilot integration because tuning gains have not been adjusted. When the safety pilot trims the aircraft for straight and level flight the autonomous mode is activated. Careful observation of the aircraft responses indicate if it is tuned properly. When satisfactory tuning is finished autonomous takeoff and landing are tested. At this point the aircraft is considered airworthy. Costs and damage to property can be reduced by following this approach.

In the event that a problem should occur to the UAV while it is in flight in may need to make decisions about what the best course of action would be. This ensures the UAV is always flown as safely as possible. A plan for how the UAS should react to different situations is outlined in Figure 22.

![Figure 22. Autonomous navigation flowchart, blue means the UAV continues autonomous flight based on the flight plan, red means the aircraft will use an alternate form of guidance whether it is direct human guidance or an embedded routine](image)

Using the above procedure codes the necessary code was written for these tasks to be achieved successfully. The code was then simulated using the Paparazzi GCS, after which it was tested with the full system. All of these procedures have been tested and shown to work with a real UAV and have undergone extensive testing during which they have proved reliable.
C. Checklists

Before any test flight multiple comprehensive checklists were used to make sure everything needed was in proper order. These same checklists will be used during the competition. A basic overview of the checklists include: AggieNav equipment, modems, safety equipment, UAS and parts, GCS, Imaging computer, and backups of all of these. An additional checklist is reviewed before the UAS is put into flight. This includes, but is not limited to, checking power to all components, making sure everything is connected and set up appropriately, and all required electronics are working with GCS equipment. Sample checklists can be viewed in Figure 23.

![Sample FOSAM team checklists](image)

**Figure 23. Sample FOSAM team checklists**

VI. Data Links

Team FOSAM uses these frequencies for command and control of the UAS and the payload:

- The Telemetry/Ground Control Data Link is run on the **900 MHz band**. It is used to transmit UAV sensor data such as location, battery level, angular position, and wind speed to the ground control station. Using this link the Paparazzi Autopilot can be given new flight instructions, be advanced to later parts in the mission, or be commanded to repeat aspects of the mission.

- CSOIS has developed a high-bandwidth **2.4GHz or 5.8GHz** WiFi communications link for use with the UAV’s camera payload, transmitting images from the air to the Imaging station. For the 2011 SUAS, 5.8Ghz shall be the primary frequency for the mission, while 2.4GHz shall be reserved for a backup frequency.

- The Safety Link is used to take control of the aircraft using a remote control on the **72 MHz band** in case of an emergency. A switch on the remote control determines whether the UAV should follow the remote control’s guidance or its own autonomous navigation plan. A seasoned remote control airplane pilot in this way can take control of the UAV if it appears the autopilot has lost control or if the pilot wants to navigate the aircraft through a delicate procedure such as takeoff or landing. In practice, the Safety Pilot generally does nothing more than watch the UAS while in flight.

VII. Conclusions

This paper has shown that the FOSAM team has thoroughly analyzed the system requirements for the 2011 AUVSI Student UAS Competition. Based on these requirements and previous experience, they have designed a UAS solution to successfully accomplish the mission at hand. This UAS solution includes an
improved airframe, updated hardware for the flight control and payload systems, and stable and efficient ground stations.

This paper also shows that safety has been a foremost priority through the design and implementation process. Hours of testing have been done on all systems to ensure that problems will not affect the safety of the ground personnel.

The FOSAM team looks forward to participation in this years AUVSI Student UAS Competition. The team is confident in their entry and looks forward to seeing the results of the competition.

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