# Delhi Technological University

## 2012 AUVSI Student UAS Competition

## Team UAS-DTU Journal Paper

## Abstract

The paper presents a description of the design rationale & deployment of Unmanned Aerial System developed by the students of Delhi Technological University, India. GARUDA, a modified Sig Rascal 110 R/C aircraft along with its Ground Control System is capable of performing autonomous flight & navigation, simultaneously gathering actionable surveillance data using optical sensors. The system includes commercially available autopilot system, Piccolo II for control & navigation with a customized imagery system capable of capturing & transmitting high definition images of the hostile territory simultaneously processing it to deliver actionable intelligence. The Ground Control Station (GCS) and the aircraft communicate in real time to provide situational awareness and safe and reliable flight. Modular in design the entire system can be brought to a flying state in less than 20 minutes.

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# 1 Introduction

## 1.1 Mission Requirement Analysis

In the 10th edition of the Student Unmanned Air Systems (SUAS) Competition, the team is tasked to patrol hostile area to provide intelligence, surveillance and reconnaissance (ISR) information to US Navy Seals. After a 40 minute setup period, the aircraft must takeoff, navigate autonomously through preset waypoints and provide imagery of targets on the ground. The flight and intelligence gathering must be completed within 40 minutes of takeoff. Additionally, the UAS has been tasked to relay information from a third party Simulated Remote Intelligence Center (SRIC).

According to the mission requirement analysis, a key performance chart was prepared to list down this year's threshold & objectives in order to efficiently allocate team's resources.

| Parameter | Threshold | Objective |
|---|---|---|
| **Airframe** | To make a more modular payload bay to reduce cycle time like replacement of batteries, easier switching of avionics without removing wings | Make tricycle gear for auto landing. Structural reinforcements based on previous years' experience and this year's flight tests |
| **Autonomy** | During way point navigation and area search. | Dynamic autonomy during all phases of flight, including takeoff and landing |
| **Imagery** | Identify any three target characteristics (shape, background color, orientation, alphanumeric, and alphanumeric color) | Identify all five target characteristics autonomously using onboard processing |
| **SRIC information Acquisition** | Acquiring the intelligence data within 5 min | Acquiring the intelligence data within 1 min |
| **Mission Execution** | Less than 40 minutes total<br>Imagery/location/identification provided at mission conclusion | 20 minutes<br>Imagery/location/identification provided in real time |
| **Communications** | Communication range up to 1 km | Communication up to 5 km with redundancy |

Tab1e 1: Key Performance Parameters Chart

## 1.2 Integrated Master Plan Integrated Master Schedule

According to the defined Key Performance Parameter's an **Integrated Master Plan-Integrated Master Schedule (IMP-IMS)** approach was followed to face SUAS 2012. A Master Plan was developed for the year followed by the formulation of a Master Schedule to efficiently allocate the team's budget & resources. The whole developmental process was divided into three stages.

**Analysis:** Shortcomings of the previous system were studied, and methods to overcome them were researched. New design improvements were explored. A Master Plan was prepared, catering to the KPP requirements and all developmental processes were clocked on the Master Schedule.

**Sub-System Development:** Each sub-system was extensively tested in lab separately in order to verify its performance. Ground testing was done to evaluate sub-system failure points which were subsequently rectified before integration.

**Integration & Flight test Evaluation:** Finally, each sub-system was integrated into the UAS as per the Master Schedule. Thorough flight testing was done to identify the behavior and performance of the complete system, and necessary improvements were made.

| Task | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May |
|---|---|---|---|---|---|---|---|---|
| **Aircraft** | Aircraft Fabrication | | | | | | | |
| **Autopilot Integration** | HILS Simulation | | In Flight Tuning | Waypoint Navigation | Auto Take Off & Landing | | Buffer Period | |
| **Imagery Development** | Code Shift | GPS Tagging | | Letter Recognition | | | | |
| **SRIC** | Peripheral Selection | Field Testing | | Deployment | | | | |

Table 2: Master Schedule

# 2 Airframe Design

## 2.1 Overview

The airframe being used is an overhauled Sig Rascal 110, modified to adapt to the system attributes and increased payload weight. The elliptical wings bear a strengthened spar and reinforced strut attachment point. The landing gear has been changed to tricycle configuration in contrast to the earlier used tail-dragger configuration for increased ground stability during take-offs and landings. The fuselage has been made wider and longer than the original to accommodate the batteries and increase payload bay accessibility. The propulsion system consists of a tractor configured Hacker A60 brushless DC out runner motor which is used in coalition with a 20x10 Nylon propeller. The motor is powered by two Thunder power 10-cell 5000mAh Li-Po batteries connected in parallel. The structural integrity of the new airframe has been verified through several ground tests and flight tests. The key Specifications of the air vehicle are listed below.

Figure 1: Modified Sig Rascal

| Parameter | Specification |
|---|---|
| Wing Span | 110in |
| Empty Weight | 18.7 lbs |
| GTOW | 24.2 lbs |
| Propulsion | Hacker A60 20x10 prop |
| Power | 10s 5000mAh Thunder Power Li-Po |
| Endurance | > 23 minutes |
| Stall: Cruise: Max Velocity | 21:29:60 knots |
| Payload Volume | 580 cu in |

Table 3: Key Specifications

## 2.2 Design Approach

The team assessed its performance in the last year's competition and locked down some key areas which needed to be worked upon. Since autonomous take-off and landing were the primary objectives for this year's competition, it was decided to shift to tricycle landing gear configuration for increased ground stability at the times of take-off and landing. As an inherent problem with the airframe, the wings had to be taken off each time the batteries had to be replaced. So, the battery compartment had to be made readily accessible to decrease the mean time between flights. To counter the aft C.G. issues which the team faced last year, the entire avionics system was planned to move forward to increase the static margin and increase the longitudinal stability of the aircraft. The avionics bay also had to be made more accessible for better system integration which would greatly reduce the setup time of the aircraft.

With the problems thus identified, the team marked some key system attributes specific to the mission requirements.

| Parameter | Objective |
|---|---|
| Payload volume | > 300 cu in |
| Payload weight | > 6lbs |
| Static Margin | 5% - 20% (positive) |
| Turnaround Time | < 5 minutes |
| Payload accessibility | Increased |

Table 4: Design Objectives

## 2.3 Airframe Development

The team considered other commercially available aerial platforms but none could closely meet the mission requirements. It was decided to stick to the Sig Rascal airframe as the team had a lot of experience with it and was satisfied with its stable aerodynamics. As it was very difficult to adapt the original fuselage to this year's objectives, it was decided to make a new airframe to suit the requirements.

Design modifications made to the original fuselage on the Solidworks CAD model were successfully incorporated in the fuselage during the fabrication phase. The wider semi-monocoque fuselage structure has been reinforced using advanced composites at the critical regions. The battery compartment has been enlarged and also made accessible with a lockable hinged top lid**.** Fiber glass has been used to strengthen the motor-mount wall and the battery compartment. The structural integrity of the airframe has been verified with over 8 hours of flight time.

Figure 2: Fabrication

Figure 3: Battery Compartment

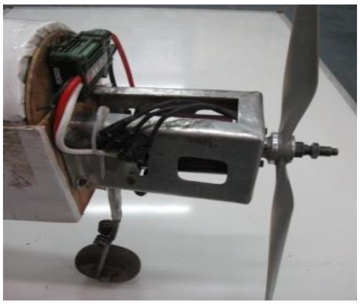


Figure 4: Motor Mount & Nose

Another major modification made to the airframe is the shift to tricycle landing gear configuration. The nose landing gear designed has a single wheel supported on both ends by a torsional spring suspension. The motor mount frame provided with the motor didn't allow much room on the front wall of the fuselage for mounting the nose gear. To address this, an aluminum bracket was custom made to accommodate the nose gear and the servo-driven steering mechanism.

The aft CG issue of the aircraft was successfully resolved by drawing the avionics systems closer to the front section of the fuselage. The placement of avionics systems was initially decided using CAD which helped in locating the CG of the aircraft and thus assisting in computing static margin and improving the longitudinal stability of the aircraft. The positioning of the camera housing was optimized to avoid blind zones due to the landing gear. Due to this gimbal was moved further forward. This further improved the static margin of the aircraft.

The externally accessible switch-board on the side wall of the fuselage is provided with separate switches for major avionics subsystems which aids in quick troubleshooting. The avionics bay aperture just aft of the wings provides an easy access to the system in case of minor issues, without opening the wings.

### 2.4 Propulsion System

The earlier used 1.9kW BLDC Hacker motor could not meet the increased thrust requirements of the air vehicle. As per the results obtained from Motocalc, a motor with a 2.4kW power rating was desired to propel the airplane. Based on past experience with the rugged built and stable performance characteristics of Hacker motors, the 2.6kW BLDC L series out-runner was selected. Using two 10S 5000mAh Li-Po batteries in parallel and a 20x10 nylon propeller, the tested endurance is more than 25 minutes. Low vibration levels and minimal acoustic signature were added advantage.

### 2.5 Developmental Tests and Modifications

The performance characteristics of different propellers were analyzed on a static Engine Test Rig. Thrust variations with throttle were studied for 19x10, 19x11, 20x10 and 20x11 propellers and the corresponding motor endurance was analyzed. Based on these studies, the 20x10 propeller was chosen.

The original Sig Rascal airframe suffered a crash due to the failure of the strut attachment point on the fuselage side wall, causing the left wing to snap in mid-air. To counter this problem, an aluminum strip was used to connect the strut attachment point, which effectively nullified the shearing force acting on the side walls of the fuselage.

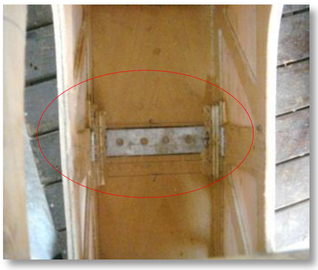


**Figure 5: Strut Attachment**

Drop Test was conducted on the new airframe by allowing the fully assembled plane to fall from a height of 6 inches, using dummy loads for simulating the payload. The airframe qualified the test with negligible main landing gear deflection.

The airplane can be assembled in less than 8 minutes. The underbelly and the wing tip section are painted with bright colors to increase mid-air visibility. With over 8 hours of flight time and 8 successful attempts at auto take-offs, the airframe is ready for the competition.

## 3 Flight Control Systems

### 3.1 Overview

Learning from previous year's system difficulties at achieving a fully autonomous mission, the team decided to upgrade the Flight Control System (FCS). This year, the team is using Cloud Cap Technologies's Piccolo II autopilot, owing to its better user interface, superior sensor integration capability and robust controller, vis-à-vis the previous FCS. An Integration process with timeline was devised, to enforce a systematic approach for incorporation of autopilot. This also helped in detailed description of all the tasks, thus improving the overall resource management.

### 3.2 Selection criteria

Last year's system presented a lot of problems due to the limited capabilities of the FCS. Some of the major problems faced in the previous year were:

1. Airspeed sensor integration: Default airspeed sensor was not giving reliable readings, so a workaround was designed to integrate an external sensor, which made the system complex and led to unstable performance.
2. Due to low processing power of the Ardupilot Mega Autopilot any improvement and modification in the source code was not possible.
3. The controller was not robust, and tuning of the autopilot was a tedious task.

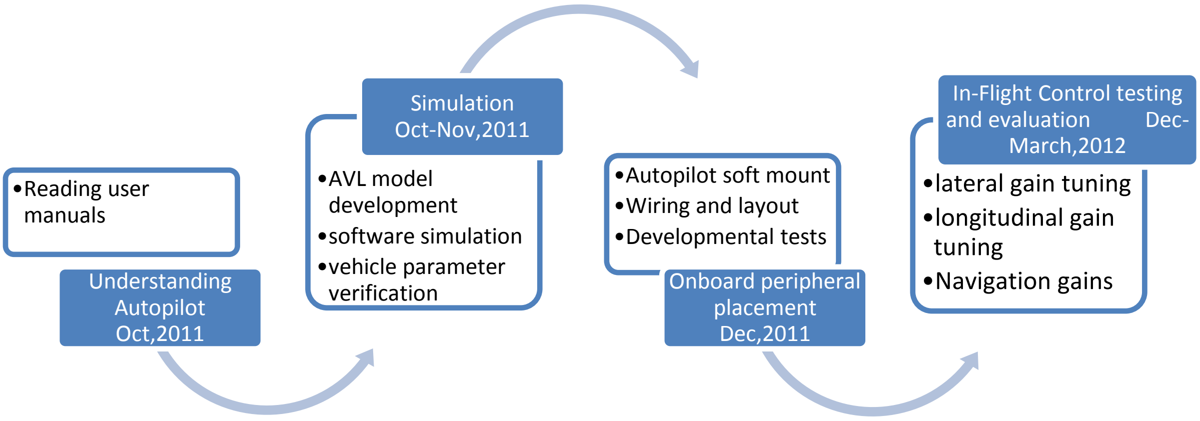
As per the IMP/IMS and budget status, a detailed market research was done to decide upon the best suited FCS for mission constraints. Cloud Cap's Piccolo II autopilot was found to have all the key features required with minimum integration time and robust controller. Easier integration of the FCS allowed the team to achieve improved flight characteristics, conduct more developmental tests and focus more on the information gathering aspect of the mission.

## 3.3 Sensors and Peripherals

Piccolo II uses a six-degree of freedom inertial measurement unit, global positioning system, and air pressure sensors to maintain a good reference of the aircraft’s attitude during flight. The autopilot system interfaces with the aircraft through the use of a wiring harness that allows a single plug to connect the autopilot to the aircraft. The antennas and pitot-static probe are connected separately. The GPS antenna is mounted in the front of the aircraft with maximum separation from the communication antennas. A combined Pitot-Static probe is mounted 24” out on the left wings and several inches away from the leading edge of the wing to avoid the slipstream of the propeller. Telemetry from the Piccolo is transmitted over the 2.4 GHz link to the Cloud Cap ground station. A half wave antenna is used over quarter wave antenna as telemetry antenna to improve its sensitivity.

## 3.4 Integration Timeline

The integration process was divided into steps as per the Master Plan and time was allocated as per the Master Schedule.



## 3.5 Simulation

Simulation helped in basic understanding and acclimatization with the Piccolo Command Center. A CAD model of modified Sig Rascal 110 was developed on Solidworks, which was used to develop mathematical model of the aircraft using Athena Vortex Lattice. Using the mathematical model vehicle parameters were generated and analyzed in Piccolo Simulator. Software Simulation for mission was carried out to tune controller’s gains and to understand the autopilot behavior & limitations in a safe environment. Over 20 hours of software simulation was carried out to tune all of the loops, except the airspeed loop. However, these estimated gain values which showed damped response during simulation when tested in actual flight experiments showed unsatisfactory results. The mathematical model developed from the cad model was found out to be somewhat inaccurate resulting in different gain performance in flight situation than simulation.

## 3.6 Control Law Tuning

Dynamic tuning of control law involves severe risk, therefore all the parameters were chosen on the basis of software simulation and engineering estimate from flight experience. Time response graphs were carefully examined to calculate the error margins for gains in order to keep tuning process safe. An Iterative approach was followed in tuning of gains

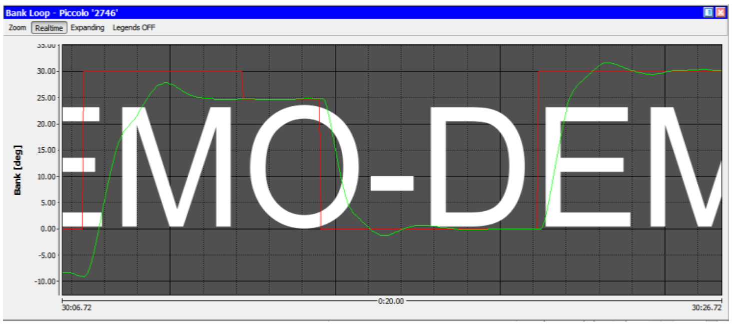


Figure 6: Closed Loop Control Tuning

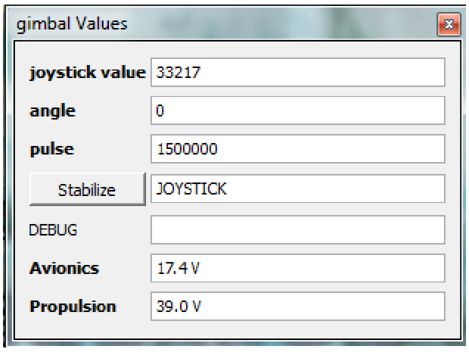
under its error margins. Time response parameters like rise time, steady state error, maximum overshoot and settling time for different control loops were computed from the graphs and a stochastic tuning approach was followed.

## 3.7 Gimbal Control and Battery Status Plugin

In order to detect the offset target a gimbal control plugin was developed to remotely control gimbal positioning. Gimbal could be operated in three modes:

1. Nadir
2. Joystick Control
3. Offset Angle

In Nadir mode gimbal is roll stabilized to point in downward direction. Joystick control mode provides control through remote joystick. The operation mode is easily switchable either from the buttons on the plugins or buttons on the Extreme 3d pro Joystick. The plugin's code was developed using Visual Studio 2005 and joystick interfacing was done using Microsoft's DirectX SDK. The graphical user interface was designed using Nokia's QT SDK.



| | |
|---|---|
| **joystick value** | 33217 |
| **angle** | 0 |
| **pulse** | 1500000 |
| Stabilize | JOYSTICK |
| DEBUG | |
| **Avionics** | 17.4 V |
| **Propulsion** | 39.0 V |

**Figure 7: Gimbal Control Plugin**

The Plugin also indicates real time battery voltage of the propulsion unit and avionics system. DANGER signal is displayed whenever the battery level falls below a safe level.

## 3.8 Search Area Planning

A thorough mathematical analysis has been done in order to ensure a minimum 15 % overlap between subsequent image captures and a complete traversal of search area in minimum time.

The focal length 'f' of camera is 28 mm and the size of the CCD sensor is 24mm (vertically) X 36 mm (horizontally). As the sensor size is less than 36 mm, a focal length multiplier 'k' of 1.3 was used.

$$Field\ of\ View = 2 \times \tan^{-1}(\frac{d}{2f}) \times k$$

*Where, d is size of the film in the direction measured = 36 mm in horizontal direction and 24 mm in vertical direction*
*F is the focal length = 28mm in case of Canon G10*
*Field Of View (in flight direction): 53.1*
*Field Of View (Horizontal): 36.9*

To perform search operations with overlapping images it was calculated that the minimum distance between adjacent flights paths should be less than 50 m with the nominal ground speed being 25 m/s at a capture rate of 1 image per 4 seconds. These values were calculated keeping in mind the FOV of the camera and altitude of the plane. To get overlapping images with maximum possible quality of targets captured, an altitude of 250 feet was chosen.

$$Minimum\ Distance\ between\ path\ lines = 2 \times altitude \times \tan\left(\frac{horizontal\ field\ of\ view}{2}\right)$$

$$Overlap\ (in\ metres) = 2 \times altitude \times \tan\left(\frac{vertical\ field\ of\ view}{2}\right) - Vg \times (capture\ time\ per\ image)$$

*Where Vg is ground speed*

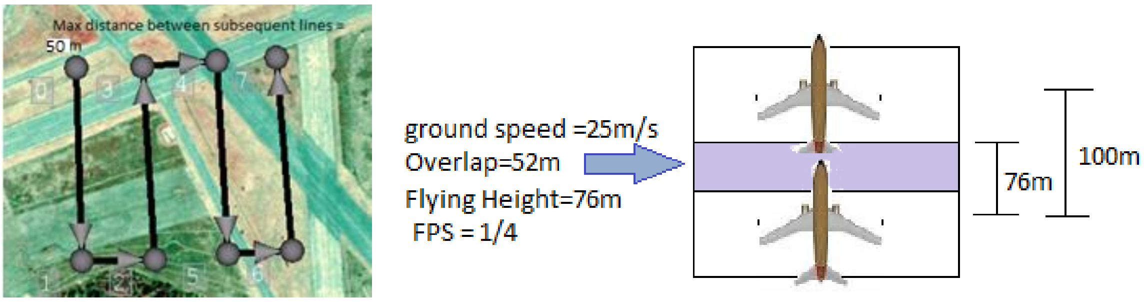


Figure 8: Sweep Pattern Analysis

Different sweep pattern were tried during the flight tests and were assessed on the basis of following parameters:

1. Time taken to cover the whole area(in minutes)
2. No. of images containing targets /total images captured
3. Different targets captured

After 3 flight tests an average was taken and continuous progressive wave pattern was found to be the best among all the patterns.

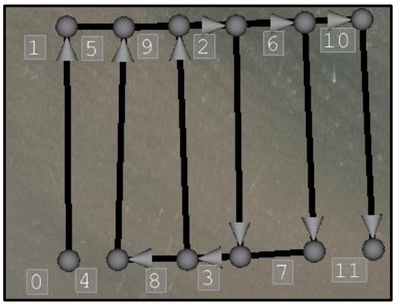


Figure 9: Progressive Wave

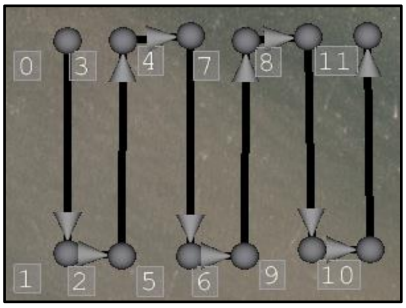


Figure 10: Regular Sweep

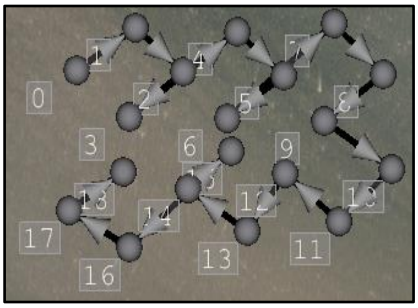


Figure 11: Progressive Circle

| Pattern | Time taken to cover the pattern (in min) (-10 points) | Images containing targets (5 points) | Different Targets Captured (10 points) | Total |
|---|---|---|---|---|
| **Progressive wave** | 5 | 14 | 5 | 70 |
| **Regular sweep** | 4 | 8 | 5 | 50 |
| **Progressive circle** | 7 | 14 | 5 | 50 |

Table 5 Test observations and evaluation

# 4 Payload

## 4.1 Imagery System Design

The mission objectives require autonomous detection of scattered targets on the ground in a specified search area. To achieve this, a roll stabilized camera continuously shoots images during the flight and stores these images on-board. These images are simultaneously transmitted to the ground station using a wireless link where these are processed through a series of algorithms to obtain useful information such as shape and its color, alphanumeric character and its color, the GPS coordinates of the image and the orientation of the target. The information obtained is finally displayed on the graphical user interface.

### 4.1.1 Design Approach

**Image Capture and Acquisition System**: The imagery payload of the aircraft consists of a digital camera, an onboard processor, and a wifi router. The digital camera is housed inside a single axis roll compensated gimbal which has been fabricated to provide inverse roll stabilization. Roll compensation was deemed necessary as during the flight tests, it was observed that aircraft sometime banked as much as 45 degrees. Thus an inverse roll command from the autopilot is used to control the gimbal.

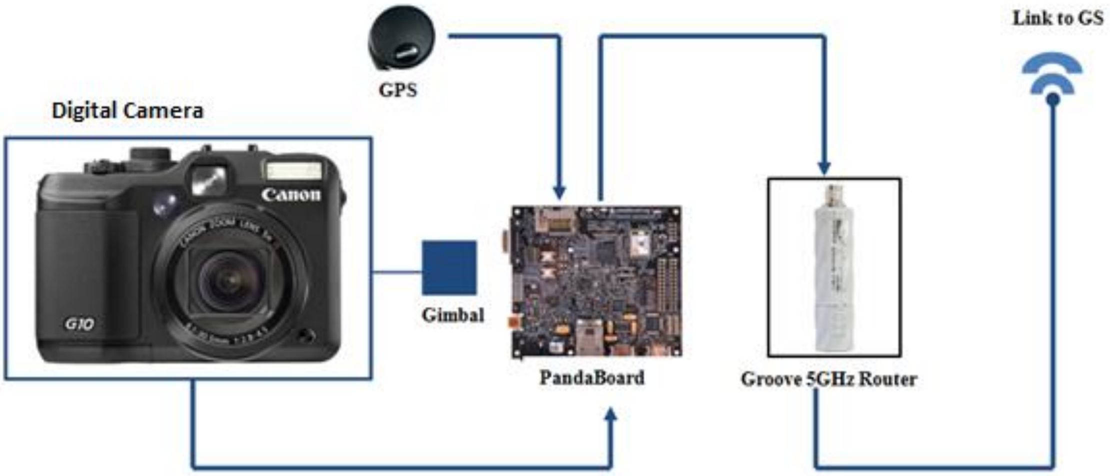


Figure 12 Onboard Imagery peripherals

**Canon G-10:** Canon G10, the digital camera used in the previous year system performed extremely well. The captured images had minimal blur, very good brightness. Satisfied by its performance, team decided to retain the same configuration this year.

| Camera Requirements | Threshold | Canon G-10 Properties |
|---|---|---|
| **Weight:** | 500 g | 390 g |
| **Field of view:** | ~45 Degree Horizontal Of View | 53.1 Degree Horizontal Field of View using a 28 mm lens |
| **Camera Parameters Control:** | Controlled through computer | Controlled By libgphoto Library |
| **Capture Speed:** | 1 Click Per Second | Approximately 1Click Every 3 Seconds |
| **Shutter Speed** | 1/ 2000 | Max: 1/4000 |

Table 6 Camera Specifications

**Image Acquisition**: The captured images are stored on to PandaBoard ES running a headless version of Ubuntu 11.04 which controls the camera parameters such as aperture, shutter speed, focus, and image quality etc. using libgphoto library. GPS coordinates acquired from Garmin 18x5hz GPS device are embedded in the image file as EXIF tags, so that the images acquired can be mapped on any generic interface using libexiv2 2.0 standard. These images are directly stored onto the SD Card and are simultaneously transmitted to the Ground Station using a secured 5 GHz Wi-Fi link created by Groove Routers.

The 2011 system used BeagleBoard xM as onboard processor which is very similar to PandaBoard but with lower hardware configuration. A comparison chart of the two single board computer is shown in Table 7.

| Parameters | PandaBoard | BeagleBoard xM |
|---|---|---|
| **Purpose:** | Image Acquisition with on-board image processing | Image Acquisition |
| **CPU:** | 1 GHz Dual Core ARM Cortex-A9 | 1GHz ARM Cortex –A8 |
| **GPU:** | 304 MHz PowerVR SGX540 GPU | None |
| **RAM:** | 1 Gb low power DDR2 RAM | 512 MB low power DDR RAM |
| **Communication:** | Ethernet and WiFi | Ethernet |

Table 7: Onboard Processor Comparison Chart

As clear from the chart PandaBoard has a much faster processor, hence a decision to upgrade to PandaBoard was taken.

### 4.1.2 Image Analysis System

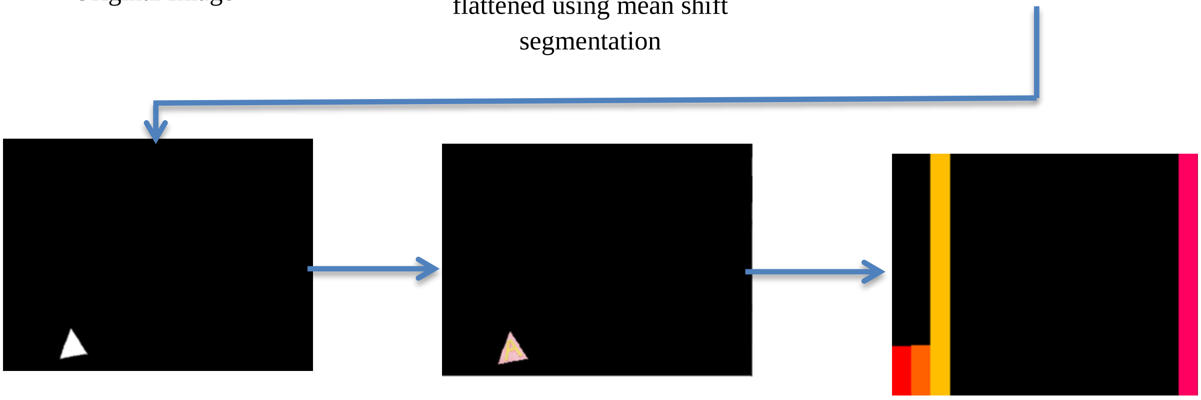
Once the images are acquired and transmitted to the ground station they need to be processed to provide actionable intelligence to the judges. The old code written using the C API of OpenCV, the open source image processing library did not have a good memory management system and hence resulted in an unstable code that crashed frequently. This year the whole code was ported to C++ which has more advanced features such as templates and automatic memory management routines, thus making the code more stable.

The image processing algorithm has been described in the flowchart below:

Original Image

Texture of the ground flattened using mean shift segmentation

Saliency Map of the Image



Mask created using Graph Cut Segmentation

Segmented Image using the mask formed

Histogram of color distribution in image

Distance Theta curve for Shape Recognition

Letter Extracted from the image.

**Figure 13: Imagery Analysis Flowchart**

#### 4.1.2.1 Segmentation:

The image captured does not necessarily always contain targets. A novel approach to augment human based manual analysis for detection of salient objects in the image was used. To extract the target grab-cut segmentation technique is implemented which uses color contrast and edge information to efficiently segment foreground objects from the background.

#### 4.1.2.2 Color Recognition:

A color histogram is generated for each possible target. The highest peak in the histogram gives the color of the shape and the next highest peak in the histogram gives the color of the letter. Small bars representing the noise are ignored.

#### 4.1.2.3 Shape Recognition:

Shape recognition is performed using a ray-tracing approach wherein a ray is traced along the outer contour of the target and the corresponding distances from the centroid are noted for each angle. An r-theta graph is plotted where r is the distance of the point on the edge and theta is the angle. Based on the relative distances and angles between these characteristic points, shape classification is performed to robustly recognize polygons, circles, semicircles and shapes like stars and crosses. This algorithm has the advantage that firstly, it is invariant to scale, rotation, and skew and secondly, it does not give any false positives as a signature based approach might result in.

#### 4.1.2.4 Letter Recognition:

Letters are first segmented using the histogram information of the color. The implementation is based on scale and rotation invariant letter recognition based on Eigen spaces. A dataset was created using individual letters of different font and 36 images of the letter rotated by 10 degrees. Eigen space was generated using these images. The image of the unrecognized letter is then projected onto this eigen space and the shortest Euler distance is calculated between the point of projection to the locus of the Eigen vectors of all the letters. The Eigen vector which is nearest to the point of projection of the unrecognized letter gives us the letter in the target.

### 4.1.3 GUI

To provide all the data associated with the images transferred from the PandaBoard, an easy to use GUI was developed using QT, a cross platform library. The GUI displays the image taken from the PandaBoard and its GPS Coordinates. Using the bearing and the altitude values extracted from the GPS EXIF Tags, focal length and Field of View of the camera, change in GPS Coordinates between two pixels of the image can be calculated. The autonomously analyzed image opens a tab on the right side of the GUI which contains all the parameters such as Shape, Letter, and Color etc. The operator can manually overwrite this information to remove any false positives and submit the data. The submitted data is stored in an excel sheet which can later be shown to the judges. All the targets detected by the software are also printed as cue cards

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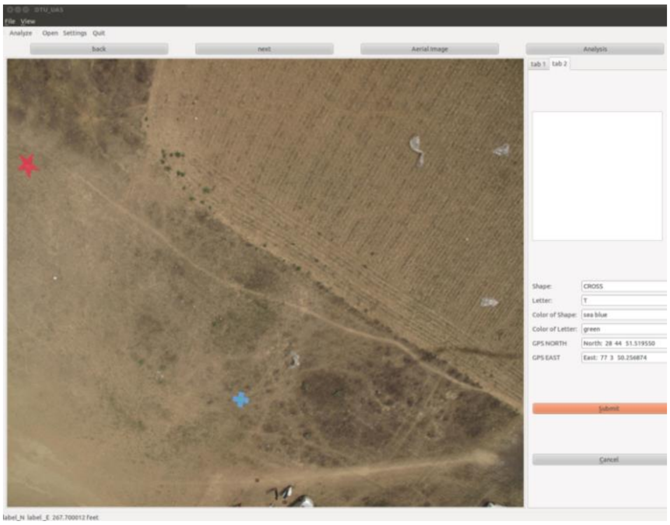

Shape: CROSS
Letter: T
Color of Shape: sea blue
Color of Letter: green
GPS NORTH North: 28 44 51.519550
GPS EAST East: 77 3 50.256874

label_N label_E 267.700012 Feet

Figure 14: Imagery GUI

## 4.2 Simulated Remote Intelligence Center

### 4.2.1 Overview

This year's mission statement entails the capability of relaying the information from the Simulated Remote Intelligence Center to the ground station. After going through the specifications and logon procedures described in the competition rules, it was inferred that this task could be accomplished using a Wi-Fi repeater or using wireless network adapter with a router. Wi-Fi repeaters being costly and heavier were discarded. Conventionally, one would use another router to make the systems independent of each other. However, a router is considerably heavy, and would add more traffic to the 2.4 GHz band. To side-step this problem, it was decided to add a network switch, that weighs less than a router, and use the same 5 GHz Imagery link to transmit the file to the Ground Station with minimum changes in the current system. The Wi-Fi adapter would connect to the SRIC's Linksys router during the mission and the data from the Wi-Fi adapter could be passed through the imagery router which would not be useful at that point of time as the target search would have been over. This solution actually proved appropriate and reliable during the flight experiments which are described in a separate section.

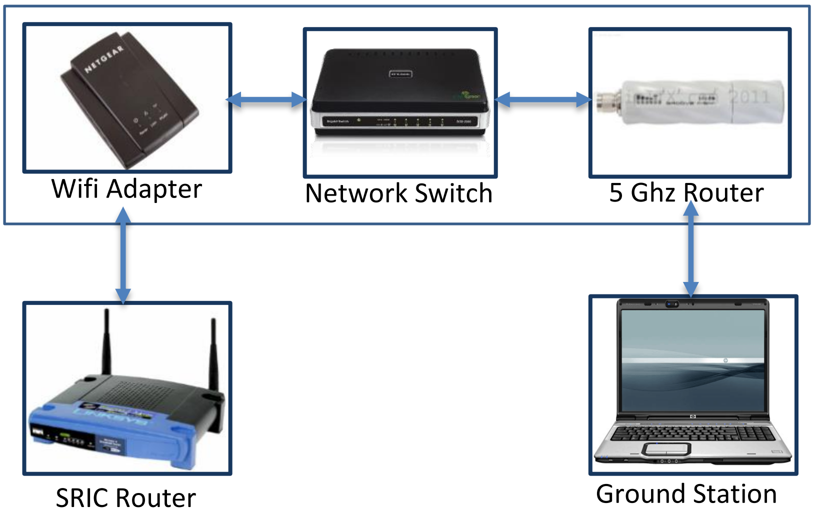

Figure 15: SRIC Information Flow Diagram

# 5 Power System Design and Layout of Avionics

The avionics power system has been designed to provide power to the avionics for multiple flights in order to reduce the turnaround time. A power requirements chart was prepared to study the power distribution and to calculate the total power required for the system.

| S.no. | Component | Voltage level (volts) | Quantity | Total Power Consumption (watts) |
|---|---|---|---|---|
| **1** | Piccolo II | 12 | 1 | 3.6 |
| **2** | Groove A5 Hn | 12 | 1 | 4.6 |
| **3** | Canon G10 | 7.5 | 1 | 5 |
| **4** | Panda board | 5 | 1 | 5 |
| **5** | Netgear | 5 | 1 | 2.5 |
| **6** | D-link 5 port switch | 5 | 1 | 2.5 |
| **7** | Rc receiver and multiplexer | 5 | 1 | 0.5 |
| **8** | Flight servos (idle) | 5 | 5 | 4.5 |
| | | | **Total Power Requirement** | 28.2 |

Table 8 Power Consumption Specifications

The endurance of the propulsion system is 25 minutes which meant that the avionics power system should sustain the load for at least 40 minutes, the target endurance being 60 minutes. The avionics is thus powered by a 4 cell, 3.7Ah Lithium Polymer battery that gives us an endurance of 60 minutes. This particular battery chemistry has been chosen for its high energy to weight ratio. The battery power is stepped down to 3 voltage levels: 12V, 5V and 7.5V using Castle Link's programmable BECs. A switchboard has been made to enable selective operation of various avionics systems and save power during setup.

Considering that midflight electrical failure can render the aircraft uncontrollable, wire gauges has been carefully selected after studying the loads on various conductors. All wires have been now color coded, labeled and laid out in an organized manner. The wire gauges have been selected as per the 100 circular mils per amp thumb rule. The area obtained in circular mils was then converted to AWG values using conversion tables and the next lower value of the wire gauge was selected.

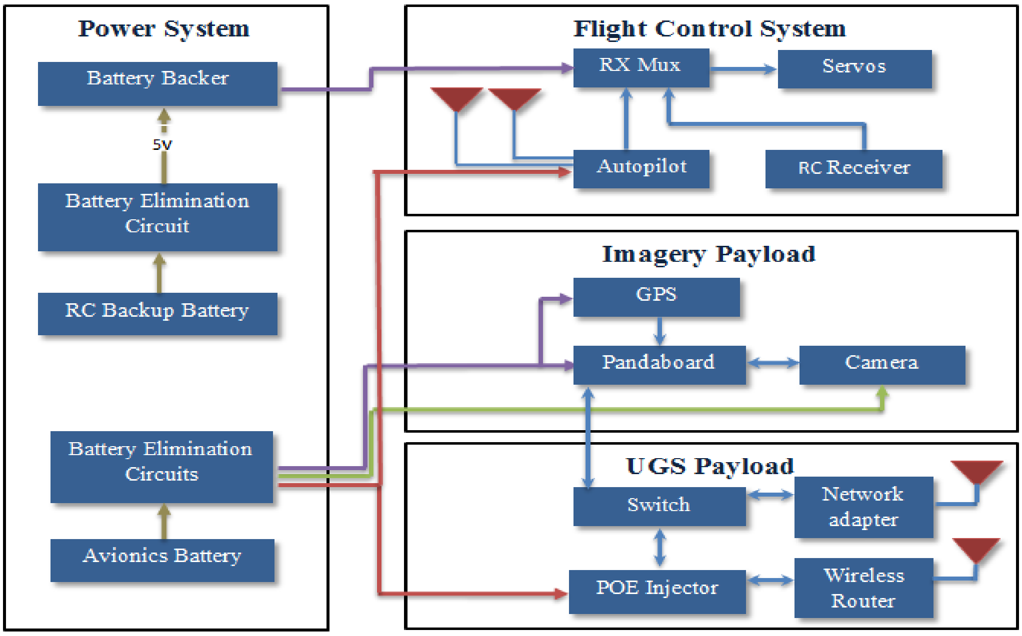

Figure 16: System Description

This year, there is added redundancy in actuator power. This helps the safety pilot to land the aircraft in the event of in-flight avionics power loss. The actuator power is switches automatically to a backup source, when the main battery fails.

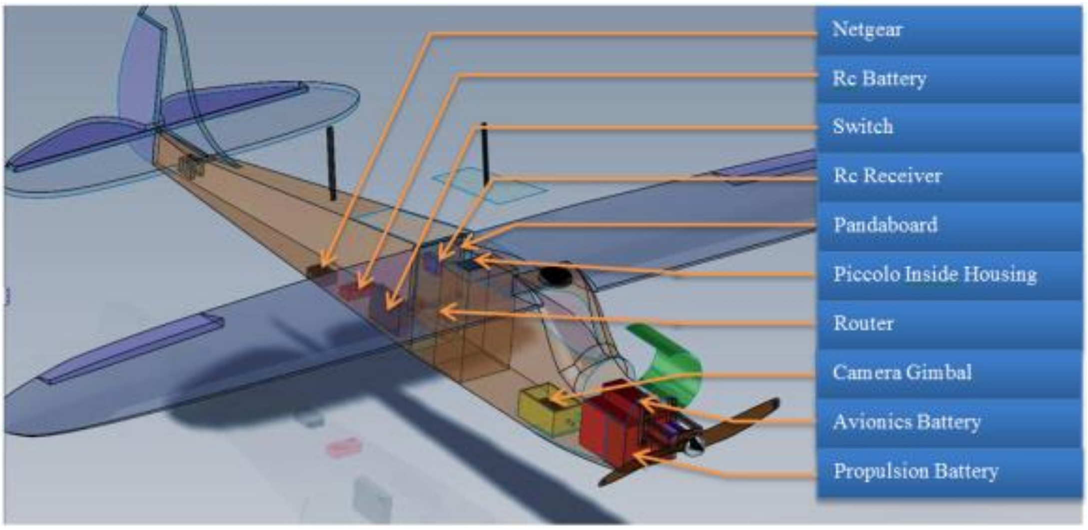

Figure 17: System Layout Using CAD

Component layout has been changed in view of the static margin of the aircraft and the feedback of last year's team. All the components that need to be accessed frequently are now moved under the avionics hatch, so that the need to remove the wings periodically is eliminated and the setup time is reduced.

# 6 Communication Systems

Last year's communication system consisted of two 2.4 GHz Wi-Fi routers that transmitted telemetry and imagery respectively. Since the RC link was also at the same band, the increased traffic in the 2.4 GHz band caused a lot of problems with the imagery channel, which was the link carrying the most data.

To correct this, this year Imagery link has been moved to the 5 GHz band. Not only does this reduce interference, but it also gives the imagery link a greater bandwidth .This has reduced the image acquisition time to 3 seconds. Since the Piccolo II has its own Communication link, the need for a separate Wi-Fi router has also been eliminated, thus saving a lot of weight.

# 7 Ground Station

## 7.1 Mission Control Centre

MCC consists of a laptop running Piccolo Command Center and other electronic equipment, all retrofitted into a single case called Portable Ground Station. Development of Portable ground station greatly reduced the setup time from 30 min with the previous system to less than 5 min with the added advantage of avoiding wire clutter around Ground Station. The modularity of the portable GS ensures that all the components stay together, and are not left out during transportation. An additional display screen installed allows real time mission and flight characteristics display for spectators and also works as extended workspace in case required. This station is also used to acquire information from SRIC during the mission.

**Figure 18: Ground Station Case**

## 7.2 Information Gathering station

IGS consists of two high performance laptops running image processing software developed in house. Alternate images are processed on each laptop which was done to reduce the overall processing time to achieve the whole mission in 20 min flight time. The images are autonomously analyzed to present actionable intelligence to the US Navy Seals.

# 8 Mission Planning

Mission planning is crucial for a safe and successful flight test day. Detailed and careful planning is necessary for smooth & comfortable running of flight test.
Flight Mission planning & execution is divided into 4 stages according:

| | | | |
|---|---|---|---|
| Setting up Flight goals | Ground Station Set up | Attaining flight goals | Post flight checklist |
| Detailing of flight plans | Assembling Airframe | Monitoring flight characteristics | Airframe structural verification |
| Flight Simulation | Performing Pre-flight Checklist | Analyzing telemetry data | Post flight De-Briefing |
| Role Briefing & In Lab Checklist | Safety check-up by safety officer | | Data analysis |

**Table 9: Mission Planning**

A detailed role allocation & communication protocol amongst the members is imperative for any successful and safe mission execution with minimum time expenditure. With a lot of flight tests observations and proper risk assessment, role of each crew member was locked down and improved upon with further flight experience.

## 8.1 Role Allocation

### 8.1.1 Flight Director

Being the core decision maker, his responsibility encompasses developing flight plan, ensuring mission completion with least amount of risk to personnel and property, and smooth flight operations. The flight director is regularly updated by MCC operator about flight characteristics and diagnostic telemetry data and he commands MCC operator for any changes in flight plans. He confirms with safety officer and wingman before taking flight critical decisions like takeoff, landing or switching to autopilot.

### 8.1.2 Mission Control Center Operator

The MCC operator plans and deploys the aircraft for a specific navigation plan and constantly observes the flight characteristics for any possible risk which may lead to crash. He is also responsible for analyzing all the diagnostic telemetry data and monitoring all the flight characteristics simultaneously conveying the same to the flight director at regular intervals of time.

### 8.1.3 Imagery Operator

Interacts only with MCC operator for any kind of setup or troubleshooting issues and notify him after setup completion. His primary task is to analyze all the images for information and check for false positives. Another important routine task is to retract the lens before landing and notify MCC operator after all the images are retrieved from panda board.

### 8.1.4 Avionics technician

The avionics technician switches all the avionics and communicates with mission control center operator for preflight tests and troubleshooting. He checks for any loose connections and excessive heating in the components.

### 8.1.5 Airframe technician

The airframe technician is responsible for integration of the air vehicle, structural integrity and ensuring that everything is tightly fastened to the frame. He also notes down the velocity and direction of wind and conveys the information to wingman. He also performs all the preflight checks from airframe end.

### 8.1.6 Wingman

Wingman stays with the pilot during the flight and interacts with him regarding the flight. He has the authority to call off the mission in case of an emergency from visual observation of aircraft's attitude or a call from flight director. Wingman closely monitors airplane's behavior throughout the flight, and commands the safety pilot to shift to R/C control as soon as any erroneous behavior is observed which may lead to crash. He also disconnects battery after landing.

### 8.1.7 Antenna operator

He points the antenna to aircraft during flight.

### 8.1.8 Safety Officer:

The primary role of the Safety Officer is to ensure the safety of the crew, aircraft and the spectators. Considering that the job entails a rigorous sequence of safety checkpoints, a detailed account of the job is given under the "Safety".

# 9 Flight Testing & Evaluation

Flight testing is very crucial and the most time consuming phase of the IMP/IMS. With progressively more flight testing experience team was able to improve upon the safety routines, identify and mitigate hidden risks, optimize the communication protocol and professionalize the whole mission execution process. A series of developmental tests were carried out to verify the calculated flight plan parameters, ascertain communication system robustness and determine image acquisition and processing code's real time performance. A rigorous flight testing schedule was developed after studying each sub-system integration plan & master schedule.

| Tasks | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Control Tuning** | Lateral Tuning | | Longitudinal Tuning | | Waypoint Navigation | | Auto-takeoff | Auto Landing | Buffer Flights | |
| **Imagery** | Camera parameters selection | | Optimum Altitude selection | | Real time code run<br>Sweep pattern analysis | | | | | |
| **SRIC** | Altitude estimation | | | Testing and evaluation | | | | | | |

**F- Flight Day**

**Table 10: Flight Testing Schedule**

## 9.1 Autonomous Navigation

Keeping in mind all the risks associated with autonomous flight, proper flight test cards were developed that outlined the procedure to tune the given control loop. Such a procedure was rigorously followed for all the control loops. For example, a closed loop bank tuning test card is shown below:

- Take-Off and climb to approximately 300 feet altitude
- Remain in race track pattern and verify avionics functionality
- Disable all control loops except Bank Loop
- Set Bank angle command to 0 degree & Engage autopilot ON for 5 seconds
- Disengage autopilot & bring plane in upward wind position
- Set Bank angle command to +10 degree & Engage autopilot ON for 5 seconds
- Disengage autopilot & bring plane in upward wind position
- Set Bank angle command to +20 degree & Engage autopilot ON for 5 seconds
- Disengage autopilot & bring plane in upward wind position
- Set Bank angle command to -10 degree & Engage autopilot ON for 5 seconds
- Disengage autopilot & bring plane in upward wind position
- Set Bank angle command to -20 degree & Engage autopilot ON for 5 seconds
- Disengage autopilot & land the plane

A total of 330 minutes of autonomous flight has been achieved so far. Aircraft has been flown autonomously in winds of up to 12 knots.
A comparison chart between previous year system & this year system has been shown below:

| Control System | 2011 System | 2012 System |
|---|---|---|
| **Bank Angle Tolerance** | 10 deg | 5 deg |
| **Altitude Tolerance** | 30 m | 2 m |
| **Waypoint Tracking Tolerance** | Not defined | 5 m |
| **Airspeed Tolerance** | Not defined | 3 m/s |
| **Auto- Take Off** | Not defined | 8 successful attempts |

**Table 11: FCS Parameter Statistics**

## 9.2 Autonomous Takeoff

Autonomous takeoffs has been one of the most challenging tasks according to the fight test crash records because the chances of failure are higher, and failures from this part of the mission have caused the most damages. A total of 8 autonomous take-offs have been successfully attempted. Initially due to rough airstrip, ground tracking was inadequate which led to take-off abortion. Subsequent tuning mitigated the error in tracking. Data from R/C controlled takeoffs was examined in order to get correct elevator deflection & air speed at take offs. The analysis proved instrumental in determining correct rotation angles.

## 9.3 Optimum Altitude for SRIC Objective

The optimum altitude of loitering over the UGS enables quick link establishment and loiter radius ensures a reliable communications link with the SRIC. The minimum flying altitude was first calculated as follows to give a starting point for experimentation.

The minimum radius of turn with adequate factor of safety calculated was 50m.Using the GPS coordinate of the SRIC, and the stated antenna beam width (30 degrees), the minimum height to be inside the beam cone at all times during the orbit was:

$$Minimum\ Altitude = \frac{minimum\ turning\ radius}{tan(beam\ width\ angle/2)} = 186.60\ m$$

To find out the best height a test was conducted in which the orbit over the simulated UGS was done at different heights and the time taken to transfer a file was noted each time. After the test it was found out that the flying at 240 feet yielded best results.

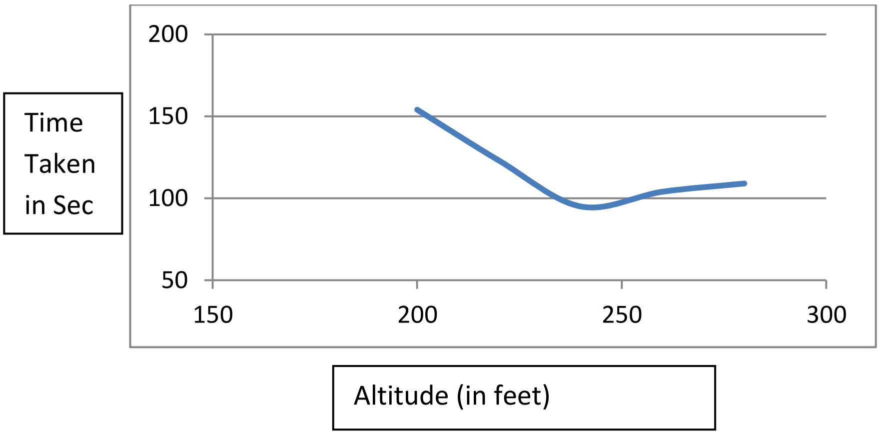

Figure 19: SRIC Altitude Estimation

# 10 Safety

Safety is of paramount importance for any UAS operation. The team strictly follows a set of rules to ensure the safety during operations of the mission. The established safety measures have been a result of crash analysis and learning from the 21 flight tests conducted this year. The safety officer plays a key role and is in-charge of overall safety of the flight crew members, spectators and the complete mission execution.

## 10.1 Crash Analysis

Learning the hard way is heart wrenching but it has taught the team a crucial aspect of flight i.e. importance of safety. As with any other aviation sector, crashes have led us to find the obscure loopholes in system & devise ways to plug them. The team has suffered 3 major crashes. The first one was a mid-flight wing fold due to a heavy gust. Post flight analysis revealed weakening of the strut-fuselage joint due to modification in the aircraft to accommodate the gimbal. Second crash was on the fourth auto take-off attempt. In this attempt the elevator deflection, during take-off, was increased as a result of which the aircraft pitched heavily beyond its stall angle. As a consequence, the aircraft crash landed before regaining RC control. Thus the stall angle and maximum elevator deflection was practically confirmed. In the third crash, pilot experienced a momentary loss of control surface effectiveness which took the plane into a spin. However at last minute pilot was able to just balance the aircraft thereby reducing the damage. Post flight analysis showed a loose throttle connection which was held responsible for loss of airspeed thereby rendering the control surfaces ineffective. The team’s experience with crashes has been a ‘Successful Failure’ enriching its knowledge about safety practices, safety checks and inspections.

## 10.2 Role of Safety Officer

Safety officer maintains a checklist to make sure that all the safety checks have been performed. All the safety procedures are devised as follows:

### Check # 1

The safety officer performs Air Worthiness Test Procedure (AWTP) as follows:

He confirms that the respective departments have completed their preflight safety checks.

| | |
|---|---|
| **Airframe** | Checking of all the mechanical fasteners of the aircraft, inspection of the surface of wings and fuselage for puncture or other damage, movement of control surfaces, smooth running of motor. |
| **Avionics** | Checking of RC control test, control surface trims & deflection test, battery voltages, loose connections and components, working of individual components. |
| **Flight Control** | Working of autopilot bypass switch, pre-flight control surface test, GPS health, communication strength, inertial sensors verification, airspeed and altitude verification. |

### Check # 2

**Flight Critical Tests:**

| | |
|---|---|
| Wing Tip Test | The aircraft is lifted from the wing tips as a structural test and to check the CG. |
| Range Test | The range of the transmitter is checked on the ground which should be atleast 300ft. |

### Check # 3

The Go/No-Go criteria are checked to ensure safe flying environment. GARUDA shall not fly under the following circumstances:

- If there is any precipitation
- If there is an approaching thunderstorm.
- If the visibility is less than 2 miles.
- If GPS lock fails or communication link strength is less than 80 percent during initial setup.
- If there is any perceptible damage during taxiing or other ground operations.
- If range test fails before 700 feet on the primary R/C link with full system operational.
- If control surfaces show glitches.
- If winds exceed 13.5 knots.
- If another vehicle is in air above the runway

### Check # 4

Once the all the above three checks have been performed, the safety officer informs the flight director for readiness for take-off. On clearance for takeoff from flight director he then clears the runway for take-off.
His role during the flight is to observe and ensure safety on ground. Post flight, he runs his safety checks which includes check for any structural damage incurred and avionics shutdown. Safety officer is also responsible to carry a first aid kit and fire extinguisher.

## 10.3 Failure Mode Effect Analysis

Based on past failures and possible risks experienced from several flight tests, a detailed Failure Modes and Effects Analysis (FMEA) approach was employed to devise Risk Mitigation Protocol to be followed by flight crew during flight tests.

Code Blue : Mission continues; Fully autonomous
Code Yellow: Mission continues; Manual override
Code Red : Mission failure; Emergency Landing/ Spiral drive

| Failure Mode | Indication | Step 1 | Step 2 | Step 3 |
|---|---|---|---|---|
| Telemetry link loss | Link indicator turns red on MCC | If link between 60% and 80%, mission continued | If link less than 60% , switch to manual and troubleshoot communication system | N/A |
| Image acquisition system fails | Communication Link failure or panda board malfunction | Recycle the router power, if link establishes within 3 min, mission continued | Emergency landing for imagery troubleshooting | N/A |
| R/C link failure | Actuator response time increases | Automatically shifted to RPV using autopilot link, mission continues | R/C link established , mission continues | Telemetry link unreliable , emergency landing, mission stops for troubleshooting |
| Mission control computer crashes | Computer hangs or shuts down | Shift to R/C meanwhile backup computer brought in, mission continues | Mission control computer ready, switch to auto, mission continues | |
| Avionics or propulsion battery level unsafe | Indicated on PCC plugin | Battery level below unsafe level, approximate flight time 4 min left | Battery level below danger level, Shift to Manual and emergency landing | |
| Motor cutoff/battery voltage low | Continuously falling airspeed and/ or altitude | Chances of motor cutoff, switch to manual emergency landing | N/A | |
| Component disintegration | Falling debris, erratic behavior | Emergency Landing; Mission Call-off | N/A | N/A |
| Imagery Terminal Crashes | No output on screen | Flight continues; Backup terminal brought in | N/A | N/A |
| Unable to hold altitude/enters in no fly zone | Altitude or position error observed on MCC | Switch to manual, mission continues Adjust the control law gains | Switch to autopilot and observe , problem rectified, mission continues | Problem persists, manual override mission continues |

Table 12: Failure Mode and Effect Analysis Chart

# 11 Conclusion

The 2012 competition entry marks the implementation of fully autonomous system in the team’s UAS for the first time in 3 years. Safety, reliability and modularity were the main focus of team’s design approach.

Through extensive flight tests and mock drills, GARUDA has been shown to be a reliable system capable of flying an autonomous surveillance mission that is both safe and high-performance. Safety and reliability has been of paramount importance which has been ensured in every aspect of the mission.

Validated with successful flight tests and over 330 minutes of autonomous flight time, “GARUDA” is capable of successfully achieving all the mission requirements.

The team is confident about the system’s performance and its competition readiness.

# 12 Acknowledgement

The team UAS-DTU would like to immensely thank Lockheed Martin Aeronautics Company for their mentorship and support in the project. The team also acclaims the support of the former team members who helped the team in preparing flight plans and execution of mission.

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