VCU School of Engineering
Virginia Commonwealth University

Autonomous Arial Vehicle and Ground Control System

Association for Unmanned Vehicle Systems International
Student UAS Competition 2012

Team:
Matt Battle
Joel Elmore
Sam Lanctot
Morgan Stuart
Jason Philips
Mike Elkins
Omar Youssef
Ben Young

Graduate Advisor:
Tim Bakker

Faculty Advisor:
Dr. Robert Klenke

Electrical and Computer Engineering Dept.
601 W. Main St.
Richmond, VA 23284

1 Abstract

The following paper describes the Virginia Commonwealth University (VCU) Student Unmanned Aerial Systems (SUAS) competition systems design and development for the year of 2012. Mission requirements analysis is included as well as the design rationale and development details for all aspects of the VCU air system. The flight system is broken down into subsystems consisting of the VCU developed Flight Control System (FCS) "*NexGen*" and ground control station (GCS) which are used to autonomously guide the UAV through user designated way points and execute search patterns. The payload consists of imaging and positioning devices allowing for target imaging and manual recognition/interpretation and geo-referencing. Redundant failsafe features ensure safe and reliable operation of the vehicle.

2 Table of Contents

3 Team Members

Jason Philips *Sam Lanctot* *Joel Elmore*

- **Joel Elmore** - Senior - Electrical Engineering
- **Sam Lanctot** - Senior - Computer Engineering
- **Morgan Stuart** – Senior – Computer Engineering
- **Jason Philips** - Senior - Electrical Engineering, Physics
- **Matt Battle** - Junior -Electrical Engineering
- **Mike Elkins –** Junior – Computer Engineering
- **Omar Youssef –** Junior – Computer Engineering
- **Ben Young –** Junior – Electrical Engineering

4 Mission and Requirements Analysis

In order to fulfill requirements for the SUAS competition the Unmanned Aerial System is designed to fly through designated way points while identifying targets that lay on the ground. The aircraft must also be capable of relaying accurate and sufficient real-time data to the ground control operators for assessment and action. Dynamic re-tasking of the flight path shall also be made possible. The aircraft must be able to complete all its tasks before 20 minutes in which the mission window will be over. Given a 58 mph cruise speed, the craft will be able to cover the equivalent area of a 4.5x4.5 mile box within 20 minutes. In addition, the aircraft has an average max flight time of 45 minutes, thus increasing the area of search by 220% of mission requirements. Application specific requirements will continue to be analyzed throughout the paper as they apply to each individual system.

5 Design overview

5.1 Systems overview

The autonomous flight system operates by utilizing a distinct modular design for flight control, payload management, communication, command system, and data analysis. The flight control contains manual RC controls for takeoffs, landing, and emergency takeover should the autonomous system fail. The autonomous flight system takes over after the UAV has been launched and is directed by the ground station which can dynamically re-task and/or re-direct the UAV by means of search parameters and GPS coordinates. The payload consists of a high definition camera controlled by a two axis gimbal with an independent inertial measurement unit (IMU) for control and target location. Communication with the UAV is provided over three different systems: payload control, manual RC control, and autonomous flight control modules. This separation of systems helps provide redundancy improving safety and reliability. Should any one system fail, flight control is still maintained. The flight control system and data analysis systems reside at the ground station with independent interfaces for flight control and target recognition. The command system is comprised of a server/client pair allowing the flexibility for multiple UAV's to be run simultaneously as well as multiple clients controlling a single or several UAV's.

5.2 Expected Performance

5.2.1 Preflight check

During the preflight check a complete systems check is performed providing operational capability and safety check. Way-points for flight can also be uploaded at this time. Systems are powered up and prepared for flight. In order to check all systems, we have created two checklists; one is for operational analysis and the other is for safety analysis. The operational checklist is as follows:

Trainer 50 Operations Checklist

Pre-Flight Assembly:

1. Assemble aircraft
2. Perform preflight checklist

First Flight of the Day:

1. Review safety procedures, set up barriers if needed, and locate fire extinguishers.
2. Verify that field operation procedures have been completed.
3. Perform safety briefing and establish flight agenda for the day.
4. FCS ON, Payload ON, RX, TX ON
5. Check control surface function with FCS in manual mode.
6. Check control surface function with FCS in auto mode.
7. Perform radio range check at 50 paces, TX in range check (low power) mode, all switches fwd and up.
8. Perform failsafe check, transmitter-OFF.
9. All equipment-OFF.

> **NOTE:**
> **The following steps are to be repeated as needed for subsequent turn around flights**

10. Install payload and ready for flight.
11. Verify RX, FCS, ignition, and payload battery capacity OK.
12. Fuel model.
13. Verify transmitter frequency, program, and voltage.
14. FCS-ON, verify GCS link, GPS lock.
15. Verify Ignition-OFF
16. Prime engine if required.
17. Verify plugs and ignition wires secure.
18. Transmitter-ON, Receiver-ON.
19. Ignition-ON, perform engine start.
20. Perform full power (100% throttle) check.
21. Perform final control surface checks.
22. Perform final payload check - Verify GCS and FCS flight data logging is on and functioning.
23. Taxi into takeoff position.
24. Verify timer running.

Post Flight and Shutdown:

1. Taxi to shutdown area.
2. Throttle stick to closed, throttle cutoff – engine stopped.
3. Ignition OFF.
4. Payload-OFF, Receiver-OFF, TX-OFF, FCS-OFF.
5. Note timer value and complete logbook entry for flight.

In addition, the preflight checklist, which is mainly concerned with the safety of the aircraft, is as follows:

Preflight Checklist

Batteries

- ☐ Check and record servo battery voltages
  ________V ________V (8V nom.)
- ☐ Check and record ignition battery voltage
  ________V (8V nom.)
- ☐ Check and record FCS battery voltage
  ________V (12V nom.)
- ☐ Check and record payload battery voltage
  ________V (___V nom.)

Engine/Forward Fuselage

- ☐ Prop bolts (tighten)
- ☐ Spinner bolt (tighten)
- ☐ Engine mount bolts (check)
- ☐ Muffler bolts (tighten)
- ☐ Carburetor linkage secure
- ☐ Spark plugs tight
- ☐ Spark plug connections tight
- ☐ Fuel lines clear – condition OK
- ☐ Choke pushrod secure

Right Wing

- ☐ Strut secure, bolts tight
- ☐ Pitot tube secure, connected
- ☐ Aileron hinges secure
- ☐ Aileron servo hatch bolts tight
- ☐ Aileron horn tight
- ☐ Aileron linkage secure – keeper in place
- ☐ Flap hinges secure
- ☐ Flap servo hatch bolts tight
- ☐ Flap horn tight
- ☐ Flap linkage secure – keeper in place

Left Horizontal Stab/Elevator

- ☐ Elevator hinges secure
- ☐ Elevator bolt tight
- ☐ Elevator servo hatch bolts tight
- ☐ Elevator horn tight
- ☐ Elevator linkage secure – keeper in place
- ☐ Flying wire bolts tight
- ☐ Flying wires tight

Vertical Stab/rudder

- ☐ Rudder hinges tight
- ☐ Rudder cables tight
- ☐ Rudder horn tight
- ☐ Tail wheel bolts tight
- ☐ Tail wheel horns and linkage secure
- ☐ Flying wire bolts (bottom of fuselage) tight

Right Horizontal Stab/Elevator

- ☐ Elevator hinges secure
- ☐ Elevator bolt tight
- ☐ Elevator servo hatch bolts tight
- ☐ Elevator horn tight
- ☐ Elevator linkage secure – keeper in place
- ☐ Flying wire bolts tight
- ☐ Flying wires tight

Left Wing

- ☐ Strut secure, bolts tight
- ☐ FCS telemetry antenna secure, connected
- ☐ Aileron hinges secure
- ☐ Aileron servo hatch bolts tight
- ☐ Aileron horn tight
- ☐ Aileron linkage secure – keeper in place
- ☐ Flap hinges secure
- ☐ Flap servo hatch bolts tight
- ☐ Flap horn tight
- ☐ Flap linkage secure – keeper in place

Center Fuselage/Wheels

- ☐ Landing gear bolts (tighten)
- ☐ Wing strut bolts (tighten)
- ☐ Tires in good condition/hub bolts tight
- ☐ Axles tight
- ☐ Wheel collars secure
- ☐ Wing bolts tight

Avionics/Payload

- ☐ Avionics mounting board secure
- ☐ FCS enclosure secure
- ☐ MIDG mounting secure
- ☐ Servo batteries and connections secure
- ☐ Ignition battery and connections secure
- ☐ FCS battery and connections secure
- ☐ Payload battery and connections secure
- ☐ ON/OFF switches (4) and connections secure
- ☐ RC receiver secure
- ☐ RC receiver antennas properly installed
- ☐ RC receiver connections secure (tied)
- ☐ Powerexpander/servo connections secure
- ☐ Radio range check
- ☐ Fail safe check
- ☐ Payload check
- ☐ Fuel as required – amount__________

Dry A/C weight ______ Wet A/C weight ______

Dry CG ______ Wet CG ______

5.2.2 Launch

During launch phase, the navigation software if loaded and a connection to the FCS must be made. The aircraft's GPS coordinates are then gathered by means of the FCS's IMU, which contains a GPS receiver. Once the GPS coordinates are locked the navigator then enters the flight boundaries and no-fly zones, as well as a designated path that the aircraft will fly. Once this is done, the safety pilot is then signaled by the navigator that the FCS is calibrated and ready. Under manual control the engine is started by the safety pilot and the aircraft is guided to operational position and altitude, where the autonomous flight system is then activated. During the first few moments of autonomous flight the FCS is heavily monitored for any small changes in calibration needed due to ambient variables.

5.2.3 Flight

Way-points can be preloaded or given during flight. Existing way-points can also be manually modified at any time. Mission Flight is autonomous with a pilot monitoring flight during the entire mission as to ensure the correct operation of the vehicle and providing validation of safety. During flight the camera is controlled by ground control operators to scan for intended targets. Image and position data is relayed to ground control payload operators for manual identification. Intelligence is then manually gathered for submittal using telemetric, positional, and geo-referencing data provided by the aircraft.

5.2.4 Landing

Upon mission completion the UAV returns to a designated landing spot where manual control of the system is then obtained. At this point the vehicle is landed manually and shut down.

6 Design Descriptions and Rational

6.1 Air vehicle

The UAV is a fixed wing plane. The vehicle has a 100” wing span with an 84” body length and weighs approximately 30 pounds; this provides the capability for large payloads and better flight stability in non-ideal weather conditions. Propulsion is provided by a 55cc two stroke gas engine and a 22” propeller for an ideal power-to-weight ratio for multiply sized and weighted payload packages.

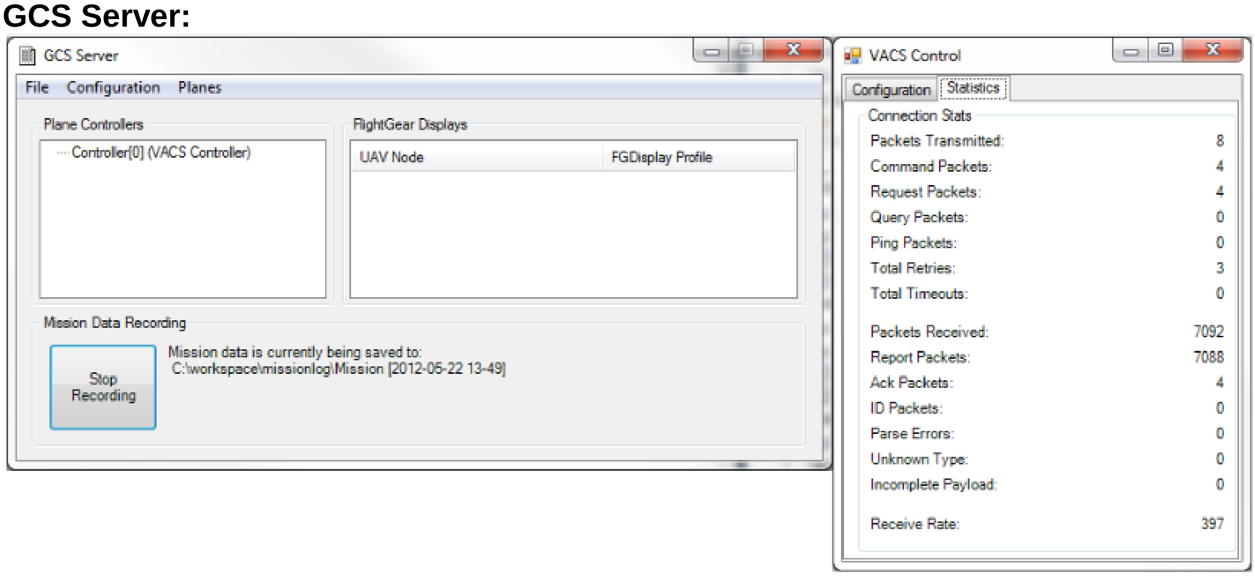
6.2 Ground control

The Ground Control Station (GCS) is the essential link to the aircraft. While the GCS is a flexible modular system, the standard configuration is comprised of at least 2 computers and 3 monitors. The distinct modules include the GCS server, GCS control client(s), video station, image analysis, and the camera control client. Shown below are the three main GUI’s (Graphical User Interface) that were created to yield full control over the craft.

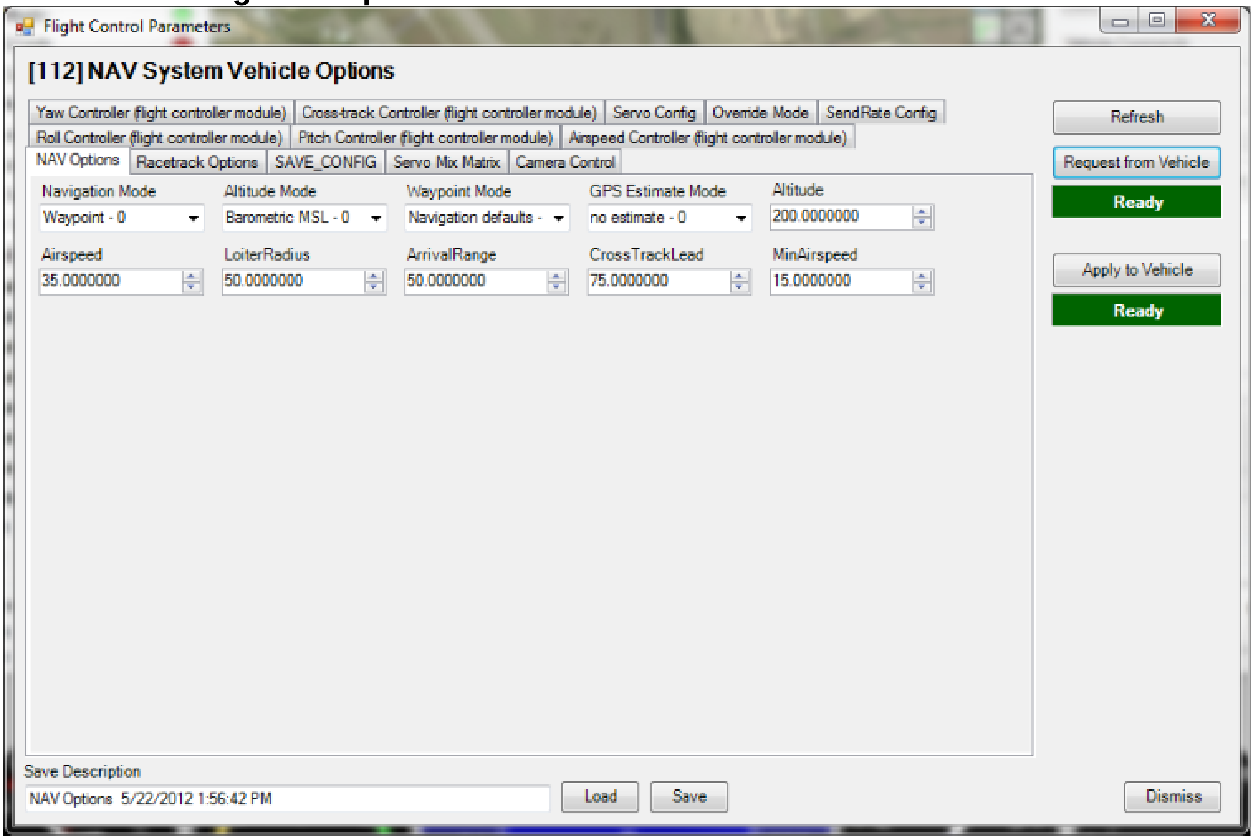
The Main Navigation window gives a visual third person view of the aircraft and the path it is flying fixed above a Google Maps image of its real time GPS coordinates. This is the GUI that allows the navigator to alternate the current flight path while the aircraft is in motion.. The GCS Server image shows the primary GUI that is used to monitor transmission of data from the payload. The images taken by the payload are then displayed on a secondary monitor so that both the image and the monitor GUI are visible at all times. Lastly, the Navigation Parameter and Options image is the primary GUI used by the navigator to adjust any variable in the FCS. This includes the pitch/roll/yaw rates of the craft, trim of the control surfaces, control over the airspeed, and various other freedoms over the behavior of the FCS.

Main Navigation Window:

GCS Server:



Parameter Navigation Options Screen:



6.2.1 GCS Server

The main GCS system runs the server in which the airplane data is stored. This server also functions as the radio link which transmits commands to the aircraft and also receives flight data. The server can be used to remotely update data on any number of ground control clients. This allows for a good deal of modular additions to the basic functionality of the GCS control module.

6.2.2 GCS Control Client Interfaces

The GCS Control client is the main station where commands are sent to the FCS on board the aircraft. It consists of several different control interfaces that together allow complete control of the air system.

6.2.2.1 Main Display Interface

The main display contains a map which allows for adding way-points to the flight path at any time during the mission. Featured prominently is a satellite image of the flight zone. This interface displays no-fly zones, search areas, flight path, identified targets as well as the current heading, position and actual flight path of the vehicle. Everything is modifiable using a simple point and click interface.

6.2.2.2 Telemetry Panel Interface

The telemetry panel contains the following information providing feedback in either English, Metric, or nautical units where appropriate.

- Mode of vehicle operation (Manual/Autonomous)
- Vehicle Altitude(above sea level and above ground level)

- Vehicle Position(Latitude, Longitude)
- Vehicle Orientation(Pitch, Roll, Yaw)
- Vehicle Velocity Info (Air Speed, Ground Speed, Ground Track)
- Vehicle Fuel Levels and approximate flight time remaining
- Status of wireless communications link
- Diagnostic information

6.2.2.3 Telemetry Gauges

Selected telemetry data is also shown in the form of graphical instrument gauges for easier reading by operators and judges. Gauge position, size, and units of measure can also be adjusted by the user. The following gauges are included:

- Altimeter: Displays both current altitude and target altitude
- Speedometer: Displays both current air speed and target air speed.
- Compass: Displays vehicle's current heading and ground track.
- Attitude: Displays vehicle's current pitch and roll

6.2.3 Parameter Control Forms

In addition to the various interfaces, the control client features collapsible parameter entry forms along the right hand side of the display. This allows for quick access to flight parameters without cluttering the display area. In addition to allowing adjustments to target air speed and altitude, the flight operator can make adjustments to the aircrafts persona Identification (PID) control parameters and server trim values if necessary.

6.2.4 Target Geo-referencing and Image Client System

In order to meet the goals of the SUAS 2012 mission, the imagery analysis must be able to capture and display images to the judges during the conduct of the mission or when handing in the mission report sheet. The system must identify the target parameters from various altitudes and proved actionable intelligence including imagery, location, color and other parameters to the judges. In order to best achieve these goals the target recognition system was split into two parts, the video receiving station and the image analysis client.

6.2.4.1 Video receiving station

The video client provides real-time feedback of the aircrafts payload video camera. This allows for initial searching for targets as well as verification of the aircrafts performance and location. The video client is synchronized with the telemetry data as it is received. This resolves latency problems due to required buffering of the video stream for assisted target recognition and analysis. The video station includes a database of past values of certain flight parameters needed to perform geo-referencing of the obtained images.

Whenever the user selects a frame in the video feed that he/she believes contains a target, the history database provides the time, position, and camera angles at the time the image was taken. This image obtained from the video feed, along with the positioning data is saved on the computer to be used by the image analysis client.

6.2.4.2 Image Analysis Client

The image analysis client is run in concurrence with the video receiving station. The program allows the analysis operator to review the images captured from the high definition video camera and determine if there are targets within the image. If the suspected target is verified that there is a target within the image, the image analysis client saves the information pertaining to the target, and performs geo-referencing by calculating positioning information of the camera to determine the location of the target. Once all target parameters are determined the program then saves all the information into a single file.

6.2.4.3Geo-referencing

Geo-referencing is performed by taking the relative position data of the camera and calculating its field of vision. The positioning information is obtained from the onboard inertial measurement unit (IMU) attached to the camera. By knowing the altitude, latitude and longitude, pitch, role, and attack angles, the center of vision of the camera can accurately be determined. Utilizing this angle information it is also possible to calculate points off from the center of the field of view by calculating the ground angle with reference to the image taken.

6.2.5 Camera Control Client

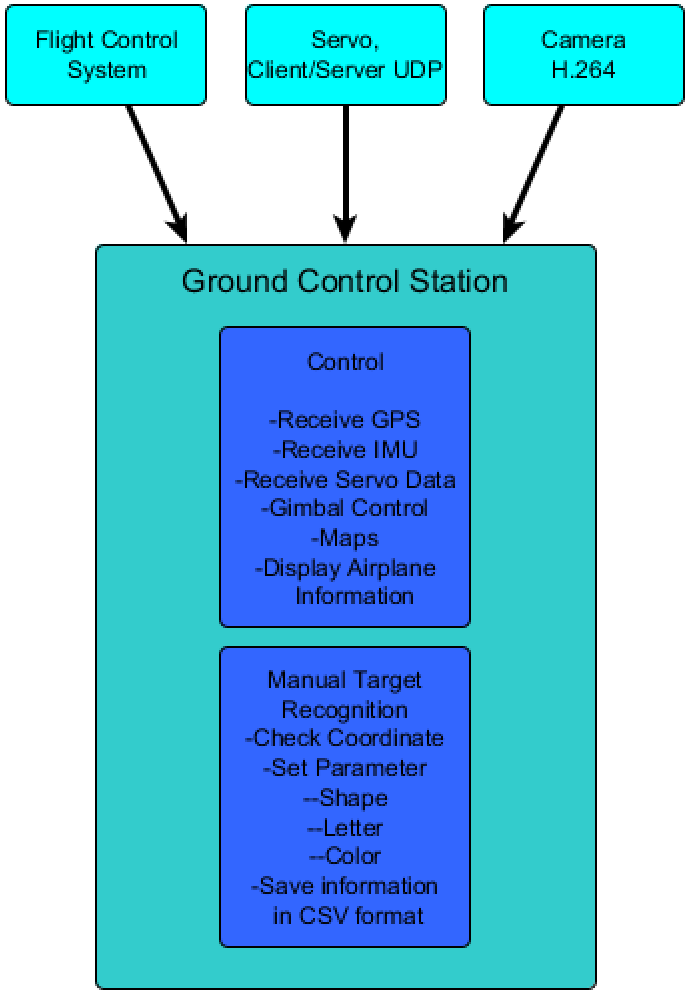
The position of the camera is controlled via a socket link to the FX12 on the aircraft's payload. The FX12 then controls the positional servos on the gimbal, even using telemetric data to compensate for intentional movement of the aircraft. The position commands for the gimbal are provided by a joystick at the ground control station. By using a joystick for control of the gimbal both the position and rate of change of the servos can accurately be adjusted. The ground server for the servo control also includes an interface to the camera to allow the adjustment of the zoom level which is also communicated to the main GCS server for use in the imaging client. Built in software limits assure that the gimbal never reaches a position in which it might damage itself or become jammed preventing damage to the camera or its mounting structures.

6.3 Data link

Communication to the payload controller is provided over an 802.11n wireless bridge. This provides a direct Ethernet connection to link the FX12 to the ground station software as well as a link to the high definition camera. The Flight Control System (FCS) communicates over a dedicated and separate 900MHz wireless link. The manual flight mode communicates separately over a 2.4GHz link. The wireless bridge payload link and the FCS link operate over a self pointing directional dish antenna assembly providing a stable signal to the ground control system.

6.4 Data Flow Structure

The Data flow structure of the flight system is demonstrated in the diagram below. It summarizes communication between the ground station and the various components of the UAV.



6.5 Payload

The payload consists of a high resolution camera, a two axis gimbal, an inertial measurement unit (IMU), and an embedded computer system for control (FX12). This system allows for stabilized remote target locating. In addition, we have added an embedded system, the Pandaboard ES, to handle image analysis and documentation to effectively transfer as little data wirelessly to the GCS as possible. This will allow for faster image streaming.

6.5.1 Camera

We found that the Sanyo Ethernet camera that has been used in previous years, while it provided a usable high definition video stream to the ground, did not have the stability, mod-ability, and usefulness that we required from a vision system. We weighed the options of using a DSLR based camera system, or a machine vision type camera like Point Grey cameras.

In the end we decided on a dual camera system utilizing a Canon Powershot Point and Shoot camera and a PSEYE webcam. The camera stream is fast video stream that is used by the camera operator to control the operation of the camera gimbal, giving the operator the fastest possible feedback to his actions. The point and shoot camera is used to take wide angle snapshots that are of high definition and high quality. Through the use of custom firmware we are able to remotely control the camera and transfer images as fast as possible. The high quality of the images will pave the way for future projects in target recognition for the ground station and possibly on the on board computer systems. The PSEYE was chosen for the low cost and the relatively fast frame rate compared to similar cost cameras, which allows us to have more clear images from the video stream

Canon was the obvious choice for us for a point and shoot camera because of the community support for custom firmware through the Canon Hackers Developer Kit. This gives us some of the features of a DSLR (remote control, file access during operation, complete control of camera parameters) without the extra weight and cost that such a camera brings.

6.5.2 Gimbal

The gimbal allows for over 360 degrees of rotation and over 90 degrees of tilt providing complete coverage of the field of view from underneath the UAV. The gimbal utilizes high torque servos with bearings and all mettle gearing creating a strong and stable platform capable of more than five pounds of payload. The servos were modified for continuous operation to allow for additional gearing to be used to control the platforms. External potentiometers provide feedback to the servo control board allowing the position of the platforms to be directly read and any play in gearing automatically compensated for. In addition, the gimbal servos are automatically tweaked by the FX12 to compensate for intentional movement of the aircraft by reading the telemetric data and using a custom adjustment algorithm to keep the camera focused at a specific angle.

6.5.3 IMU

The Microbotics MIDG I is used to provide feedback of the cameras position and orientation allowing for the calculation of targets in the cameras field of vision. The MIDG I utilizes GPS, three axis accelerometers, three axis gyroscopes, and three axis manometers with built in filtering and sensor integration. This provides reliable readings without drifting over time or errors due to constant acceleration due to effects such as long term banking of the vehicle.

6.5.4 Computer Controller

The FX12 embedded computer system utilized for the payload control was designed and built by VCU. It provides a power PC core running Linux on an FPGA creating an enormous amount of flexibility for peripheral control. The FX12 communicates over Ethernet reporting camera positioning information to, and receiving commands from, the ground station. The FX12 also manages communication with the IMU and controls the servo's providing a feedback loop for stabilizing and absolute position pointing. Calculation for the location in the center of the camera's field of vision is also calculated on the FX12 while the targets absolution is calculated at the ground station using this point as a reference.

Also included in the payload package is a “Pandaboard” revision A3 Single Board Computer (SBC). The Pandaboard contains all the necessary components of a computer and runs a full version of the Ubuntu operating system. This allows the Pandaboard to serve multiple tasks at once.

The vision system connects directly to the Pandaboard, where the video stream is compressed into a H.264 MPEG 4 video stream for transfer to the ground, and the photos are tagged with real time data from the IMU and GPS sensors, allowing us to make the best assessment of not only where the plane was when the photo was taken, but also what direction the camera and plane was pointed and where the targets are in relation to the plane. The Pandaboard maintains a FTP server client connection with the ground station which it uses to handle requests for photos and data and transfer them to the GCS.

The Pandaboard also implements our solution to the retrieval of intelligence on the field. Through a script the board refreshes a USB wireless adapter which is on the outside of the plane.

If this wireless adapter finds the designated wireless signal from the intelligence network, it automatically logs in and downloads the pass code from that network and makes it available to the ground station to download.

7 Safety Considerations and Approach

7.1 Failsafe flight modes

The flight control system incorporates additional flight modes that ensure maximum safety in the event of a system failure. These flight modes can also be activated by the safety pilot or the Flight Control Operator.

7.2 Return Home (4.1.5 in rules)

The return home system is built into the FCS with its own dedicated components. In the event of failure of the radio link for more than 30 seconds the system will first attempt to return to the home coordinates that were preset before the beginning of the mission.

7.3 Flight Terminate

In the event that not only does the autopilot lose contact, but the separate safety pilot receiver loses its link the aircraft will automatically return to manual control mode, turn off the engine and engage in a low energy spiral as specified in the mission requirements. In this way the mission flight can be terminated at any time by turning off the safety pilot transmitter and the aircraft will terminate. In the same way if the aircraft travels too far from the ground control station and is unable to return within range within 30 seconds the aircraft will self terminate flight.

7.4 Batteries

Battery voltages are continuously monitored by the FCS (and transmitted to the GCS) to ensure they remain in safe operating regions. Safe operating thresholds are calculated based upon the current aircraft distance from the home location, with an additional safety margin. If any battery voltage drops below this safety threshold, the FCS enters Return Home mode. In the event that the flight critical motor batteries become depleted before the aircraft is able to return home, the aircraft will perform a minimum energy landing.

7.5 Failure Modes Analysis

Failure	Response
Loss of RC Communication (Initial)	Ground operators are notified and FCS enters return home mode.
Loss of RC Communication (30 sec)	Aircraft will execute flight termination procedure.
Loss of GCS Communication (30 sec)	Ground operators are notified and FCS enters return home mode.
Loss of GPS Link (Initial)	Aircraft will hold course and minimum safe speed, if the aircraft approaches a no fly zone or otherwise unsafe conditions manual control will be activated by the ground control team and the RC Safety Pilot will take control.
Loss of GPS Link (1 min)	RC Safety Pilot will take manual control.

FCS or Receiver battery or fuel level for aircraft falls below minimum level	Ground operators are notified and FCS enters Return Home Mode. Additionally RC Pilot might assume control.
FCS or Receiver batteries or fuel levels fall below critical levels	Aircraft Will Execute flight termination procedure.
FCS battery dies	RC Safety Pilot will take manual control.

8 Acknowledgements

The VCU SUAS 2012 competition team would like to thank the following individuals and organizations for their guidance and support throughout this project. Each has unselfishly contributed to make this project a possibility. We would like to extend our sincerest gratitude.

- Dr. Robert H. Klenke
- Tim Bakker
- Garret Ward
- Mark Sternheimer
- VCU School of Engineering