NORTH CAROLINA STATE UNIVERSITY

Aerial Robotics Club

Autonomous Reconnaissance System

Author: Joseph Moster

Contributors:
Sam Carter
Alex Kesling
Justin Pearson

Editors:
Dan Edwards
Matt Hazard
JB Scoggins

Submitted:
17th June 2009

This paper details the Unmanned Aerial System being entered into the 2009 Association for Unmanned Vehicle Systems International's Student UAS Competition by the North Carolina State University Aerial Robotics Club. The system is comprised of a fixed wing aircraft controlled by an autopilot. It carries an imagery payload for surveillance. The entire operation is controlled from a trailer based ground station and protected by safety procedures.

Table of Contents

Design Overview

The system is the result of an iterative design process that, starting with the previous year's system, makes changes on a sub-system level. The vehicle is a fixed wing aircraft that has evolved from a Senior Telemaster. The autopilot is a Piccolo LT that has been tuned for optimal performance by using a new set of flight cards. Imagery is provided by a Nikon D50 and a computer built from off the self parts. The ground station is based around NCSU's trailer which provides transportation and accommodation for every mission. Finally, well defined and rehearsed procedures keep missions safe for personnel and equipment alike.

Systems Engineering

To streamline the design process, the overall system is divided into five subsystems.

1. Vehicle
2. Autopilot
3. Imagery
4. Ground Station
5. Operations and Safety

These sub-systems are further divided into discrete components that interact with each other through specified interfaces. Standard parts are used when possible and interfaces are clearly defined and documented. A system schematic is included as appendix 2.

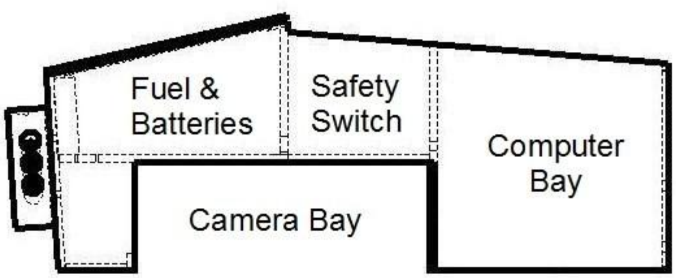
Vehicle

Competition requirements state that the aircraft must be Academy of Model Aeronautics (AMA) certified. For this year, NCSU has kept the same mindset with a similar platform from years in the past. The stability inherent in the design of the aircraft allows the autopilot to be integrated and tuned quickly.

Aircraft

The fuselage is significantly wider and taller than that of a stock Telemaster. The tail-dragger design was overthrown and upgraded to tricycle landing gear for improved ground handling. The wing's spar was highly reinforced to compensate for the increased mass due to the payload. The wing mounting was modified to use wing bolts instead of rubber bands for strength and accessibility. The engine was upgraded to an O.S. 1.20 AX.

- Wingspan – 94.5 in
- Length – 66.5 in
- Weight (no payload) – 16 lbs
- Weight (all payload) – 23 lbs
- Cruise Speed – 40 knots



- Flight Endurance – 35 min
- Fuel Type – 15% Omega Nitro (hobby grade)

Camera Bay

Dimensions: 5.5" x 11" x 4"

The camera bay is located on the lower half of the fuselage starting 3 inches behind the engine. This allows room for the camera be pointed as it remains tried to remain orthogonal to the ground. This location also brings the camera further away from the ground during landings and reduces drag by having the camera and gimbal out of the airstream.

Computer Vault

Dimensions: 5.5" x 8.5" x 8"

The onboard computer is mounted in space between the main landing gear. A layer of foam isolates the flight computer from the engine's vibrations. The ports face the empennage for easy access. The entire computer can be removed through the bottom for maintenance.

Autopilot Location

The autopilot mounts to a shelf in the tail of the aircraft approximately 6" aft of the flight computer. Foam rubber reduces vibrations being translated to the autopilot, which enhances performance of the inertial measurement unit.

Wing Mounting Plate

The wing mounting plate is standardized such that it is compatible with both wings currently used by NCSU. This allows wings to be changed out on both the competition aircraft and on a secondary test aircraft.

Center of Gravity

Heavy components, such as the camera and flight computer, are mounted close to the center of gravity. This configuration reduces the inertia of the aircraft which improves maneuverability performance. Additionally the distribution of weight is done such that no additional ballast is needed.

Electrical

The transfer of power throughout the aircraft is handled with a central Power Distribution Unit (PDU). The PDU is located on the top of the aircraft's empennage. The switches on the panel allow the operator to switch between ground power and batteries as well as switching power on to the other subsystems.

The cables running to and from the PDU are three pin locking connectors. All cables have the same voltage pin-out. This feature makes the cables interchangeable as well as insuring that wrong voltages are not sent to other subsystems.

Batteries

The batteries are electrically separated based on voltage and the criticality of the sub-system they power. The flight batteries provide power only to the safety switch and the control surfaces. The flight computer and autopilot are powered by a pair of 11.1 volt batteries. The camera gimbal has its own battery due to its high power draw. All sub-systems are connected by a common ground. This layout is detailed in appendix 4.

Voltage	Quantity	Sub-system
4.8 V	2	Flight Control
11.1 V	2	Imagery & Autopilot
4.8 V	1	Gimbal

This combination of batteries results in an endurance of over an hour thus providing ample time for ground preparations, flight time, and post processing.

Autopilot

NCSU's autopilot is capable of the following:

- Navigating by GPS waypoints
- Receiving commands mid-flight
- Providing telemetry to peripherals
- Providing telemetry to ground station

To fulfill these criteria NCSU utilizes Cloud Cap Technology's Piccolo LT. Experience with the system has shown the Piccolo to be a reliable and rugged component

Flight Algorithm

The Piccolo LT uses sensors to continuously know its position, velocity, and acceleration in the airspace. To this end a six degrees of freedom inertial measurement unit, global positioning system, and air pressure sensors are included.

The Piccolo controls the aircraft based on aircraft properties and gains provided by the NCSU team. Measurement of those properties is done in the lab while gains are calibrated during flight tests. The process for tuning the gains is detailed in a set of flight cards.

The design of the aircraft produces stable flight characteristics that expedite the tuning of the Piccolo.

Flight Path

The Piccolo is controlled by the Piccolo Command Center. This software allows the operator to easily designate GPS waypoints as well as view telemetry from the aircraft. The Command Center software is run on a computer in the ground station trailer. This software allows for Software-in-the-Loop SIL and Hardware-in-the-Loop HIL. Both of the functions are valuable in the training of operators and the verification of the Piccolo.

Peripherals

The autopilot system interfaces with both the aircraft and imagery sub-systems. It also connects to external sensors and antennas. This interface is simplified through the use of a harness which allows a single plug to connect the autopilot to the aircraft. Only the antennas and pitot-static tubes need to be connected separately.

The GPS antenna is mounted on the rear of the aircraft separating it from interference. A ground plane increases the antenna's sensitivity and RFI resistance.

A pitot-static probe is mounted 22 inches out on the left wing to avoid the slipstream of the propeller.

A 900 Mhz antenna is directly connected to the Piccolo and exits the top of the aircraft. This half-wave antenna improves sensitivity over the previously used quarter-wave antenna.

A standard mounting interface allows the Piccolo to be transferred to other aircraft in the NCSU fleet.

Safety Switch

Servo commands coming from the autopilot are feed directly into a safety switch box. This box is controlled by the RC Link and switches control of the aircraft between the autopilot and the safety pilot. This allows the human pilot to take control of the plane regardless of the autopilot's status. A system schematic for this setup is located in appendix 2.

Telemetry

Telemetry from the Piccolo is transmitted over a built-in wireless modem to the Cloud Cap ground station. The ground station makes the telemetry available over a serial link. This link is further detailed in the ground station section.

Imagery

A still photography imagery payload transmits images and telemetry data to the ground over a wireless link. Images are then screened and processed using Google Earth.

- Rate: 1.3 seconds per photo
- Resolution: 3008 x 2000 pixels
- Exposure time: 1/1249 seconds
- Size: ~2.8 Mb
- Imaging Altitude: 500ft
    - 2.62 x 2.56 inches/pixel

Image Processing Methodology

Imagery operators process images making corrections and identifying target characteristics. To cope with the slower speed at which human operators are able to process images, the architecture of the processing system is such that multiple operators are able to be added dynamically. This multi-human-core structure is able to correct for errors in GPS, heading, altitude, pitch, and yaw.

Digital Camera

A Nikon D50 digital SLR camera provides high quality 6 megapixel images. As an SLR it is able to take pictures with a shorter exposure time than other cameras. This reduces the negative impact that velocity and vibrations have on imagery. The length of the exposure time means that the aircraft only moves about 16mm when at cruise speed. The camera's settings are also tuned to provide optimum performance by using manual zoom, high-res mode, and appropriate anti-blur and sharpness settings.

Camera Gimbal

The Nikon D50 is mounted on a two axis gimbal. By receiving telemetry from the autopilot the built-in micro-controller is able to command the servos to maintain the camera in an orthographic position relative to the ground. This eliminates distortions resulting from taking pictures at an angle.

Flight Computer

The on-board computer controls the settings of the camera and commands the taking of pictures. Those pictures are then merged with telemetry from the autopilot and transmitted to the ground station computer.

The computer is built from off the shelf consumer electronics. This allows the computer to be built cheaper and with greater compatibility with software and hardware. Our flight computer's hardware capabilities are summarized below.

- 1.6Ghz Dual Core Intel Atom CPU
- 802.11a Wifi @ 25 Dbi
- 2.5" SATA Solid State Drive; 32 Gb
- 2 Gb Memory
- Power Draw
    - Idle: 10 Watts
    - Full Power 30 Watts

Wireless Link

A standard 802.11a Wifi wireless connection is used to communicate between the flight and ground computers in the imagery subsystem. This allows for near-continuous transfer of images from the camera for real-time processing on the ground.

802.11a was chosen for the imagery subsystem's wireless link because it falls within the 5Ghz range and as such will not interfere with the 2.4Ghz Spektrum RC subsystem. The 2.4Ghz Spektrum radio link for the RC subsystem was chosen to replace the 72Mhz gear previously used. This change protects the RC system from radio hits or interference which could cause a communication loss with the aircraft.

An omnidirectional antenna on the bottom of the aircraft provides continuous connectivity regardless of the aircraft's heading in relation to the ground station.

Primary Imagery Computer

On the ground, a dedicated computer receives images over the wireless link. The hardware used in this computer is almost identical to the flight computer. This has greatly improved maintainability of the wireless link.

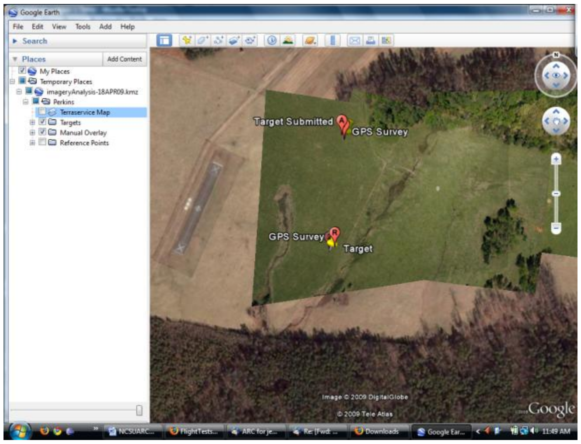
Received images are prescreened for targets by an operator. Images with targets are then made available to the secondary imagery clients. The distribution system is based around a simple web-server which capitalizes on the capabilities of Google Earth as a networkable product. The system is further designed to dynamically add clients on the fly.

Secondary Imagery Clients

The imagery clients receive images from the primary imagery computer. Images are automatically overlaid in Google Earth based on telemetry data embedded in the image. The operator then corrects for location, orientation, size, and skew. The operator then pin-points any targets. When all images have been processed the data is then returned to the primary imagery computer for compilation.

Previous imagery solutions have allowed for similar viewing ease as Google Earth, however this newest implementation allows the images to be corrected to a background map.

To generate this map, overlays with accurate GPS are imported and then detailed maps are referenced to them. This creates a highly accurate and detailed map onto which imagery from the aircraft can be overlaid onto.



When put to the test, the NCSU system showed repeatable accuracy to within 10 meters (32 feet) when compared against a handheld GPS unit.

Ground Station

The ground station is the base of operations for the competition and all flight tests. The centerpiece of this sub-system is the trailer which houses the ground portion of the autopilot and imagery systems. An array of antennas is crucial to maintaining this link.

Trailer

The trailer acts both as command center and as transportation vehicle. The large volume allows multiple fuselages and wings to be transported in addition to a full complement of field tools and spare parts.

During missions, the trailer takes on the role of a command center for the autopilot and imagery systems. The desk space allows the autopilot operator to have the Piccolo Command Center running on dual monitors to increase the ease with which to operator can receive and interpret telemetry.

The main imagery operator also has a seat in the trailer. From this location the network for imagery distribution is setup.

Antennas

Around the trailer a number of antennas will be positioned including GPS and 900 Mhz for the Cloud Cap ground station hardware. For connecting to the flight computer a 19DBi gain patch antenna is used. This antenna provides a greater reception area reducing the accuracy with which to antenna must be pointed.

The 5.8 Ghz antenna is further configured on a remote control gimbal that will allow it to be pointed autonomously during a mission. This capability reduces crew requirements and allows for greater flexibility in the location of the antenna.

Operations and Safety

The NCSU UAS is designed to maximize operator and spectator safety. As with any complex system, there are inherent risks associated with operating the aircraft. NCSU has minimized those risks by following standard procedures during flight test operations, selecting robust equipment, and eliminating single point failures.

NCSU also implements Crew Resource Management (CRM) for all flight tests, including the AUVSI competition. The focus of CRM is obtaining a wide range of knowledge. This includes communications, flight situational awareness, problem solving, decision making, and teamwork. CRM includes a technical understanding of how to operate the aircraft itself as well as maintaining an organized flight.

With CRM and Safety in mind the following was done:

- Defined Flight Line
- Defined Positions and Duties
- Defined Mission Procedures
- Testing of the UAS at flight tests
- Failure Mode Effects Analysis
- Hazard Analysis

Flight Line

The flight line is located immediately adjacent to the trailer and is the location that the aircraft will be prepared and then controlled from during the radio control phases of the mission. This area will be cordoned off during competition for the safety of spectators. Appendix 3 diagrams the flight line and its relationship to the trailer.

Positions

Each crew team member is able to contribute towards the successfully operation of the UAS. Well defined duties keep crew members focuses on their task and aids in the identification of weaknesses in the setup. These definitions also make communications brief and directed that the right member. The minimum crew requirement is three people, pilot, flight director, and auto-pilot operator.

Flight Line Crew

Flight Director – This duty requires an understanding of the communication needs of the other crew members. The director's duties include:

- Clearance for taxi and takeoff
- Manages handover procedures to and from autonomous mode
- Calls out checklist items
- Standard Operating Procedures

Pilot – The pilot's main concern at all times is maintaining the safety of the aircraft. If any error occurs during flight, the pilot is responsible for taking over manual control of the aircraft. In NCSU's operations, the pilot manually takes off and then listens for clearance so the autopilot can begin autonomy.

Safety Pilot/Scribe – The safety pilot is responsible for spotting the main pilot. This member stands beside the pilot, assisting with no-fly zones, speed, and altitude. The safety pilot is also there as a backup in case the pilot is unable to fulfill duties due to an emergency. This position can be covered by the flight director during minimum crew configuration.

Trailer Crew

Autopilot Operator – Creates flight plans, and monitors telemetry data in real time. Operator also communicates with the pilot and flight director for transferring control of the aircraft.

Imagery Operator – Screens images as they arrive from the aircraft. Also manages the wireless link and programs running on the flight computer. This position is not filled if post processing is used exclusively.

Antenna Operator – To optimize performance the ground station antenna for the imagery system needs to be pointed at the aircraft within a 30 degree cone. Precise aiming of the antenna improves the connection allowing faster transfer of images. This position is not filled if post processing is used exclusively or if the auto-targeting mode is used.

Team Liaison – The team liaison handles communication with the judges during the competition mission. Duties include:

- Receive search area and No-fly zones
- Receive re-tasking instructions during mission
- Provide telemetry to judges
- Provide observation areas to judges
- Answer questions during flight

Procedures

Prior to this season's flight testing, new operational procedures were written to cover mission critical systems. New checklists were written for the autopilot and imagery sub-systems, ensuring reliability and safe use. These procedures optimized startup time and minimized risk.

Testing and Evaluation

NCSU's UAS has been at 5 flight tests this year. During these flight tests, our safety procedures were tested and improved, the autopilot was properly tuned to the aircraft, and the imagery system was thoroughly tested.

Our detailed records show the aircraft has now spent 1 hour 27 minutes and 53 seconds aloft. Current data indicates our aircraft is capable of flying a complete mission in less than 15 minutes:

- 8 minutes – Collecting Imagery
- 2 minutes – Flying Waypoints
- 5 minutes – Takeoff & landing

The Piccolo LT autopilot is capable of flying the aircraft in winds with a crosswind component up to 11 kts. It is able to maintain course accuracy within 25 feet, and altitude within 50 feet.

Using imagery from our test flights we have been able to identify targets to within 10 meters. We have also been able to improve the quality of our imagery by tuning the settings of our camera. This improvement is evident when comparing the imagery from the different settings.

Pre-Tuning

Post-Tuning

Failure Analysis

A Failure Mode Effects Analysis was conducted based on known possible failures and the failures of years past. A copy of NCSU's FMEA is included as appendix 5.

With the FMEA in mind, single point failures within the critical sub-systems were minimized. The flight critical electronics, colored in yellow in appendix 2, were given special attention. The RC link was switched to 2.4Ghz to protect the connection from interference. All servos, power cables, and signal cables were fitted with locking connectors. Each connection was also considered to be a possible source of failure and were reduced in number as much as possible.

Hazard Analysis

A detailed Hazard Analysis was constructed for each flight test. The hazard analysis covers in-flight failures and real-time mission failures. Hazards classified as Level 1 hazards are the most dangerous, and include catastrophic structural failure. Hazards classified as Level 4 hazards are the least dangerous and include such failures as misalignment of the nose wheel steerage system. Any event on the Hazard Analysis checklist is considered reason to abort the mission. The flight director initiates the Hazard Analysis checklist, and briefs the team prior to each mission on the hazards associated with that mission. A copy of the hazard analysis is included as appendix 6.

No Fly Zone

The Piccolo command center will have no-fly zones marked in red. These zones are conveyed to the pilot and safety pilot prior to launching the mission. If the aircraft enters the no fly zone, manual control of the aircraft will be taken, and the aircraft will be forced to fly away from the no-fly zone boundaries. If the aircraft is out of control or has very limited manual control, it will be forced to crash.

Conclusion

The NCSU system can complete the AUVSI mission and within the given time limit while following all rules and regulations. Separating into five sub-systems (vehicle, autopilot, imagery, ground station, and procedures) helps NCSU be successful.

The use of sub-systems allows for modularity easing future modifications. The marked judges' observation spots in the trailer gives excellent access to real-time target information and more detailed high-resolution images after landing. Dynamic re-tasking is accomplished through a wireless link between the autopilot and the ground station. It gives unparalleled speed to acquire, identify, and track targets while strengthening situational awareness.

Finally, the ground station trailer setup makes information easily accessible to an audience and keeps team members focused. This level of operation encourages professionalism and maintains focus on a common goal.

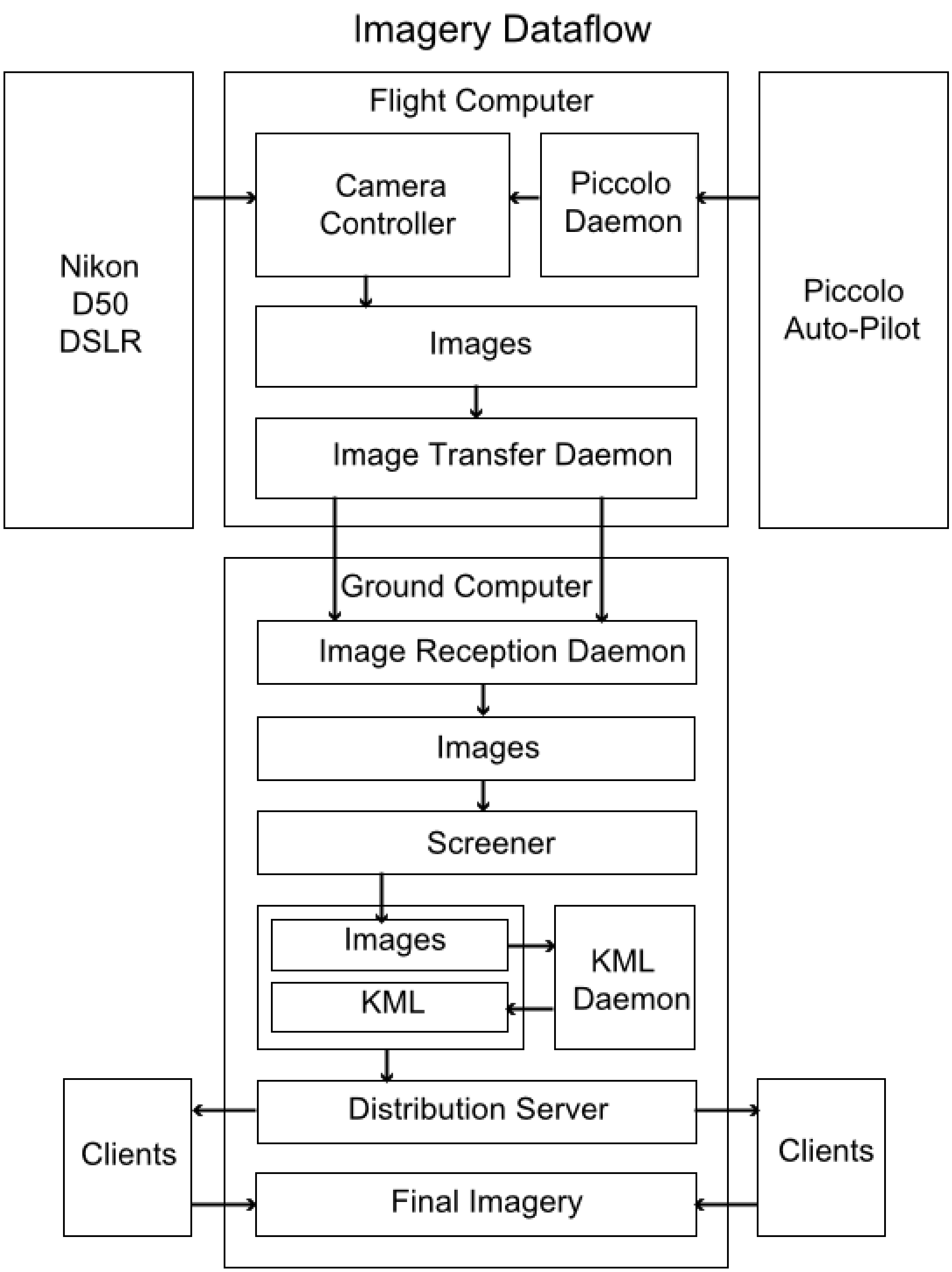
North Carolina State University is prepared to compete at the 2009 AUVSI Student UAS Competition mission.

Acknowledgements

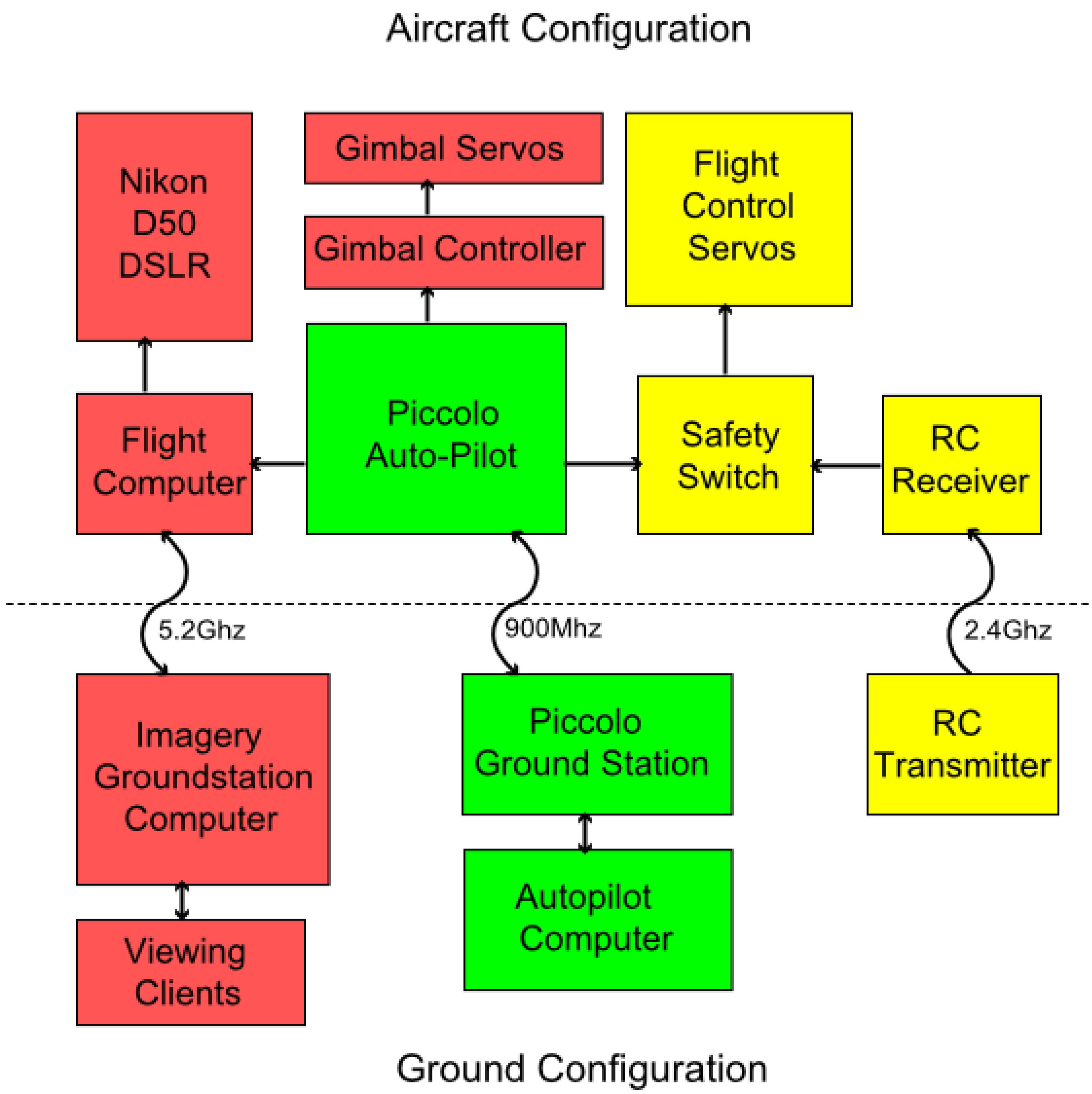
North Carolina State University's Aerial Robotics Club is proud and honored to compete in the 2009 AUVSI Student Unmanned Aerial Vehicle Competition and would like to thank the following sponsors, who made our participation possible:

- Jeff Foley of Foley Manufacturing
- JR Spread Spektrum Technology
- NCSU MAE Department
- Cloud Cap Technology
- NCSU Flight Research
- NCSU E-Council
- NCSU SGA

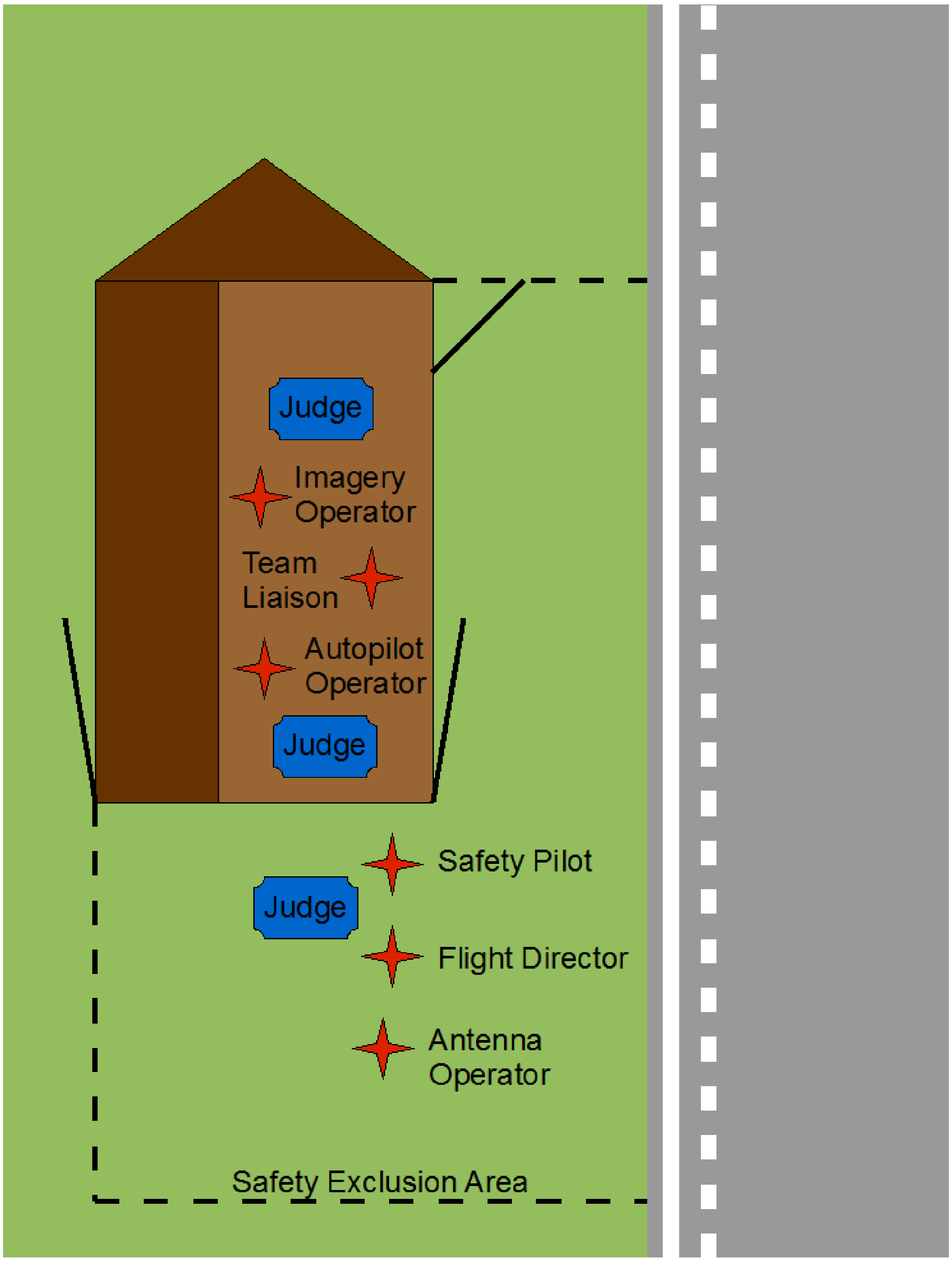
Appendix 1 – Imagery System Diagram



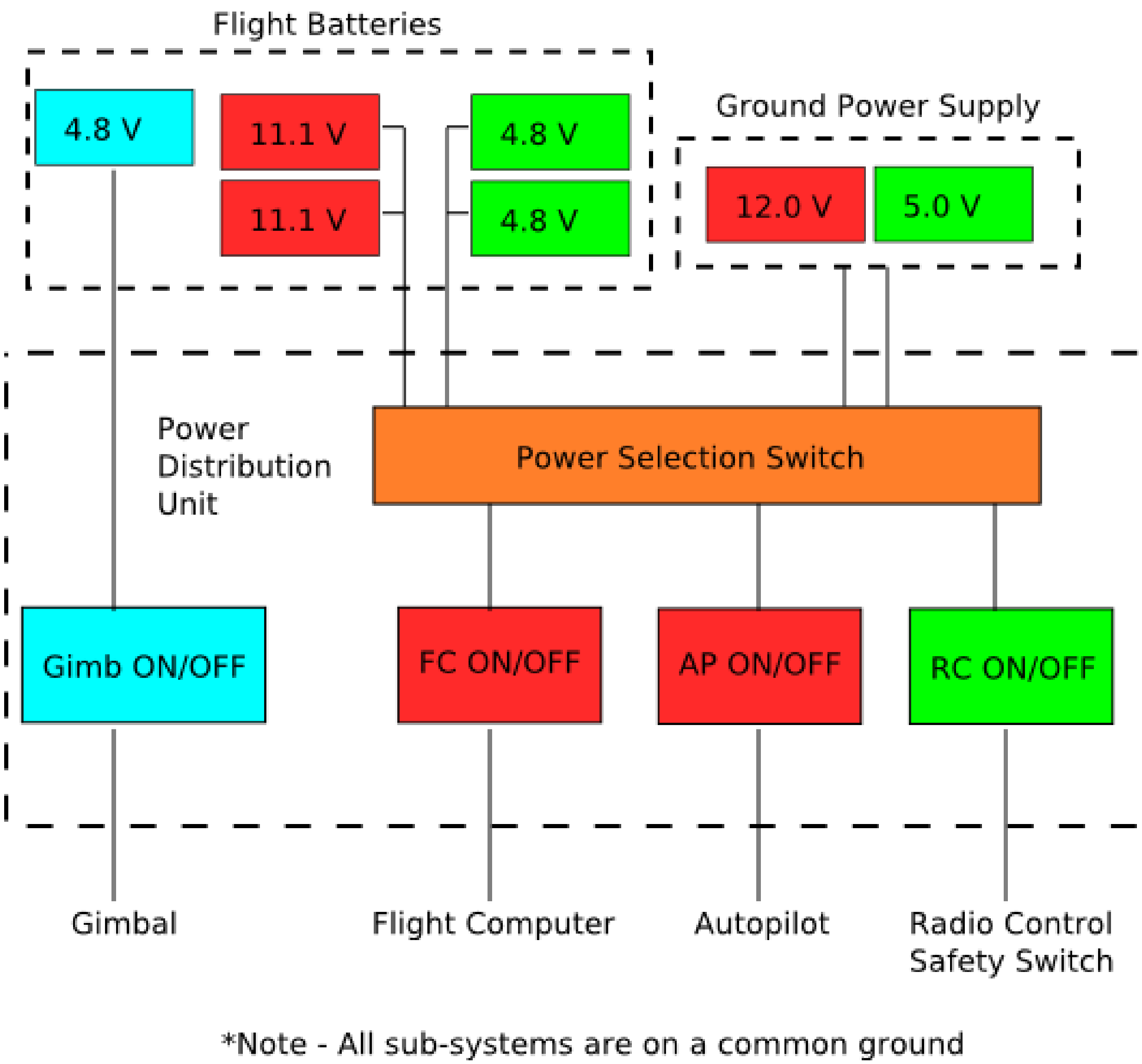
Appendix 2 – Sub-system Connectivity



Appendix 3 – Flight Line Configuration



Appendix 4 – Power Distribution



Appendix 5 - FMEA

Loss of Camera Uplink	Real-time image transmission stops	1. NCSU relies on onboard data storage	Mission Continues
4.8v Servo Battery Low	Indicated on Command Center	1. Safety pilot defaults to manual control and lands immediately	Mission Failure, Recoverable
12v System Battery Low	Indicated on Command Center	1. Safety pilot defaults to manual control	Mission Failure, Recoverable
Vehicle breaks in-flight	Falling debris, erratic behavior	1. Safety pilot defaults to manual control	Mission Failure, Recoverable
		2. Safety pilot attempts to fly damaged aircraft	Mission Failure, Recoverable
		3. Turn off transmitter, initiating hard-over	Catastrophic
One servo dies	Erratic aircraft behavior	1. Autopilot attempts to fly aircraft without servo	Mission Continues
		2. If flight unstable, manual control is resumed, and aircraft attempts landing	Mission Failure, Recoverable
		3. Turn of transmitter, initiating hard-over	Catastrophic
Engine dies	change in aircraft sound, loss of airspeed	1. Safety pilot defaults to manual control, initiates emergency landing procedure	Mission Failure, Recoverable

Appendix 6 – Hazard Level Analysis

Hazard Level 1	
Hazard	**Procedure**
Catastrophic Wing Failure	None
Catastrophic Fueselage Failure	None
Control Surface Failure	Pilot clicks out of autopilot and attempts to land. Notify ground station coordinator when possible.

Hazard Level 2	
Hazard	**Procedure**
Engine Failure on takeoff before runway midpoint	Pilot aborts takeoff on runway. Notify ground station coordinator when possible.
Engine Failure on takeoff after runway midpoint	Pilot aborts takeoff straight ahead. Notify ground station coordinator when possible.
Engine failure in flight	Pilot clicks out of autopilot and attempts to land. Notify ground station coordinator when possible.
Autopilot Failure in any flight condition	Pilot clicks out of autopilot and lands. Pilot notifies ground station coordinator of failure.
Pieces fall off aircraft	Pilot aborts mission and lands immediately

Hazard Level 3	
Hazard	**Procedure**
Sporadic Autopilot Behavior in cruise	Pilot clicks out of autopilot and notifies ground station coordinator. Ground station coordinator alerts the pilot to status of continuing mission autonomously or under R/C control.
Sporadic Autopilot Behavior in landing	Pilot clicks out of autopilot and lands or attempts a go around.
Sporadic engine behavior	Pilot aborts mission and lands immediately

Hazard Level 4	
Hazard	**Procedure**
Nose wheel not aligned on takeoff	Pilot aborts takeoff and vehicle team corrects.