North Carolina State University
Aerial Robotics Club

Journal Paper for the 2008 AUVSI Student UAS Competition

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Abstract

This paper details the North Carolina State University Aerial Robotics Club's entry into the 2008 Association for Unmanned Vehicle Systems International's Student UAS Competition. Students are required to develop a system that completes several tasks, involving autonomously flying a set of GPS waypoints, entering a search area, locating several targets and reporting their GPS positions and headings, among other bonus tasks. NCSU's unmanned system completes the above using mostly commercial-off-the-shelf components and integrates them together with software written by students. There are four main components to NCSU's unmanned system: the vehicle, autopilot, imagery, and ground station. In the event of a failure, several backups and fail safes can be imployed before having to initiate an in flight termination. This ensures safe operation and increases the longevity of the entire system.

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Mission Requirements

AUVSI has setup two basic requirements for the student UAS competition:

1) Autonomously fly a set of waypoints preceding entrance into a designated search area
2) Locate and provide the GPS position, heading, as well as shape and color information of targets within the search area

Several other tasks will be given mid-mission, such as dynamically uploading new waypoints and identifying a pop-up target. Points will be deducted for going over the mission-time of 40 minutes, but bonus points will be awarded for completing the task under 20. Above all, robust and safe operation is expected.

Overview of System

The aircraft is flown under manual control for the take-off, but once at a safe altitude, control is handed over to the autopilot subsystem. The maximum tested flight time is 35 minutes at a cruise speed of 35 knots, flying a generic “lawn mowing” search pattern. This is more than enough time for the competition’s tasks. The Piccolo, the aircraft’s autopilot package, guides the aircraft through the given GPS waypoints, and then enters the search area. This flight path is automatically generated using a custom-coded application dubbed the Path Planner. Radio modems allow full-duplex communication between the aircraft and the ground station, so that operators can monitor the subsystem’s health and also upload new waypoints. The entire time the aircraft is flying, the camera is orthogonally (with respect to the ground) stabilized, and taking pictures that are tagged with a GPS point and altitude of where they were taken. To save bandwidth, camera battery power, and hard drive space, a software trigger has been put in place that will only command the camera to take a picture when the aircraft has an altitude of 5ft or higher. These images are then loaded into a custom imagery program named the Imagery Viewer which displays the photos in a “Google Earth like” mosaic as they are downloaded in real time. An operator can then search this mosaic for targets of interest, and tag them to get the GPS positions, headings, and other required information. This target information can then be quickly printed off to a reference sheet that can be handed to the judges.

The system uses several wireless links. The frequency of each link is tabulated below for safety concerns.

Subsystem	Frequency
Manual R/C	72 MHz
Autopilot Control	900 MHz
Imagery Downlink	2.4 GHz

Systems Engineering

At the student UAS competition, the judges task each team with several items. The discrete actions conducted by judges are:

1) Distribute GPS waypoints and mission boundaries before the mission

2) Distribute dynamic re-tasking requirements during the mission
3) Receive a hardcopy of imagery results for post-mission assessment

The NCSU Aerial Robotics Club examined these requirements and based the developed system around them. Judges will hand a list of waypoints to the team, and the team will hand a copy of the reconnaissance results back to the judges, signifying the end of their round. The team's results will be confirmed by the judges.

NC State's system separates into four basic subsystems, which will be discussed below, to complete the above task. Each subsystem is critical. With a missing component, the rest of the subsystems simply turn into another off-the-shelf component. The network of subsystems is what defines NC State's entry into the competition. Below is a diagram showing the network of communication being performed at any one time during a mission:

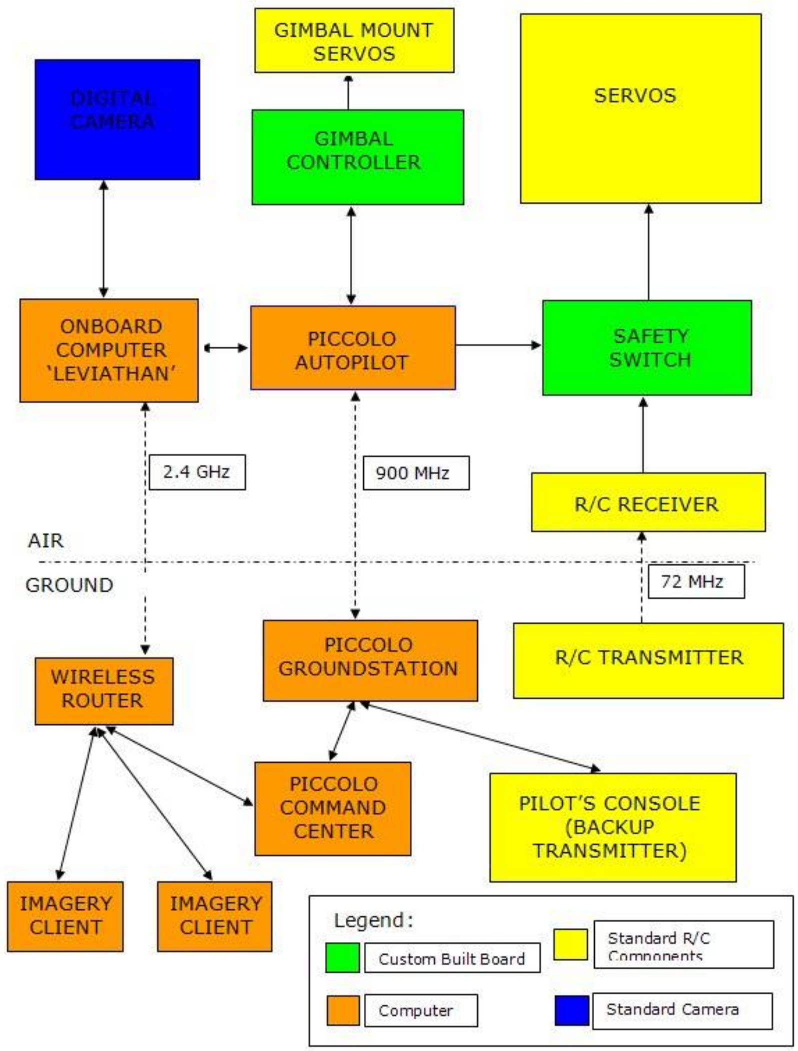

Figure 1: Communications Diagram

Vehicle Subsystem

The competition vehicle used by the NCSU Aerial Robotics Club is a modified 8 foot Senior Telemaster. The vehicle was modified from the original plans with two design goals in mind. One, the vehicle had to have a larger cargo area than last years competition vehicle, and two, the vehicle had to have a camera bay to house a Nikon D50 on a gimbaled mount. Using these two goals, the fuselage was widened to 6 inches, the height increased by 2 inches and the vehicle nose reshaped to provide more cargo space upfront. The 6 inch wide fuselage provides ample room for a computer, autopilot, safety switch and wiring. The vehicle has since been known as the "Superwide." The reshaped nose allowed for a separated battery and fuel tank compartment with a hatch for easy access. The vehicle empennage remained unchanged.

The vehicle wing is per plans with carbon fiber tape and fiberglass added to the main spar for increased strength under the higher wing loading. A pitot static tube mounted to the underside of the wing provides altitude and airspeed information. The center section of the wing contains a hole for the 2.4 GHz antenna from the onboard computer for ground communication. The Piccolo autopilot antenna is located underneath vehicle behind the landing gear.

Original plans call for a tail dragger landing gear configuration, however a tricycle style landing gear configuration was used instead to increase ground handling.

The ‘Superwide’ is powered by a OS .91FX 2-cycle engine using a 15% nitro-methane fuel. A 16 oz. fuel tank supplies the engine with approximately 35 minutes run time at 75% throttle. The engine is vibration mounted to the fuselage to protect the onboard electronics against vibration damage. A cowl was added to decrease aerodynamic drag. The onboard electrical systems are powered by two 11.1V lithium ion batteries and one 4.8V NiMH battery pack. The two lithium ion batteries are connected in parallel and power the onboard computer and autopilot while the NiMH pack powers the R/C receiver.

The vehicle is controlled using a 72Mhz JR 10X radio transmitter. Five channels are used to control the vehicle, four channels for aileron, rudder, elevator, and throttle, and one to switch control to the autopilot.

Figure 2: ‘Superwide’ Unmanned Aircraft System

Imagery Subsystem

The imagery subsystem itself is comprised of four individual components: the camera, gimbal controller, onboard computer, and ground station computers. The digital camera is the primary sensor for the entire subsystem, performing the basic reconnaissance. The onboard computer is able to communicate with the camera through USB. The onboard computer also takes telemetry data from the Piccolo LT and embeds it in the pictures before sending them down to the ground station computers. The gimbal controller also takes the telemetry data and stabilizes the two-axis mount, such that the camera is orthogonal to the ground. The last component of the imagery subsystem is the ground station computer. The computer displays hundreds of photos taken during the flight by organizing them spatially from the location they were taken. This eases the job the operator has to complete by displaying a lot of information in one location in manner that is suitable to the task at hand.

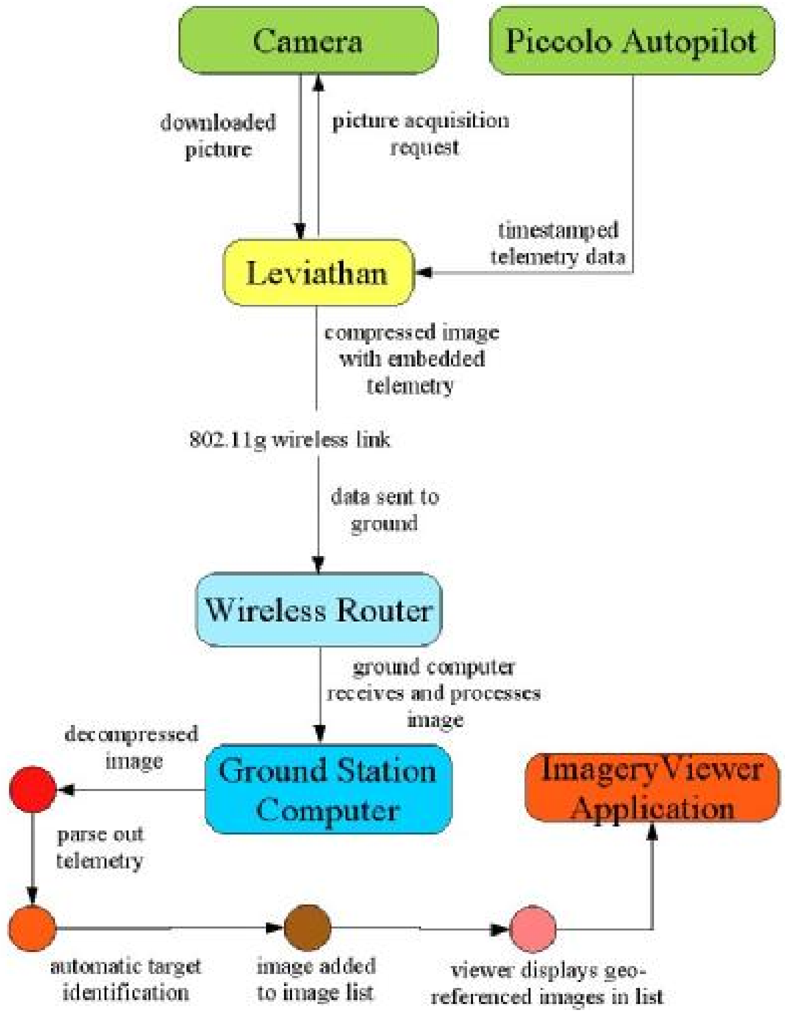

Figure 3: Imagery Communication Pipeline.

A. Digital Camera

The primary imagery sensor is a Nikon D50, an off-the-shelf digital SLR. The six-megapixel camera is mounted on a servo controlled two-axis mount in the camera bay of the fuselage. The autopilot streams telemetry data through its serial ports, which are read by the camera gimbal controller. The controller parses the data and commands the mount's servos to cancel out the aircraft's pitch and roll. This provides an orthogonal view from the camera to the ground.

Figure 4: Nikon D50 in Gimbal Mount

B. Onboard Computer

The onboard computer is the critical link between a normal camera and preventing useful information to an operator. The onboard computer, named ‘Leviathan’, controls the camera through the USB protocol. The computer is able to trigger a capture, download the image through USB, fuse the image with sensor data from the Piccolo LT in the images EXIF data, and transmit everything to ground station computers over a 802.11g wireless link.

A single board computer was chosen because of its 3.5” format, a 667 MHz processor PC/104+ expansion slot, and USB 2.0 connectivity. The computer runs a full Debian Linux operating system, installed on a vibration proof Compact Flash card. A separate flash card holds the startup scripts and applications for controlling the camera. A backup copy of each picture taken is also stored on the auxiliary card. This ensures that if the wireless link is temporarily lost, Leviathan can resume sending images without losing the images taken during the “blackout.” In case there is a complete loss of wireless transmission, the pictures can still be post-processed in the same manner when the aircraft has landed.

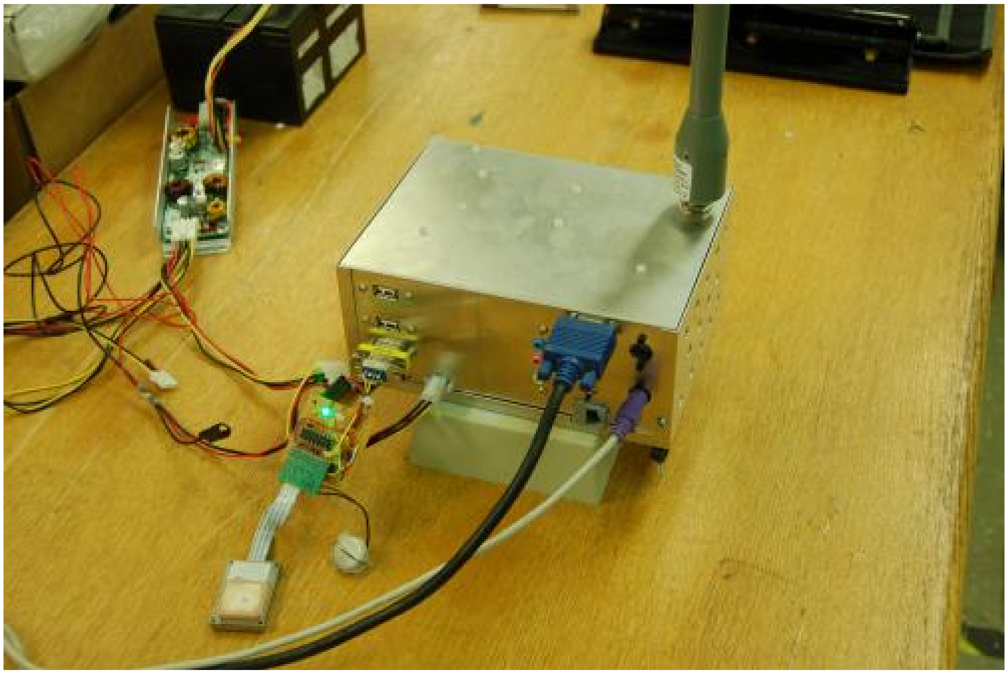

Figure 5: Onboard Computer, ‘Leviathan’

Autopilot Subsystem

The core of the autopilot subsystem is the autopilot itself. NCSU Aerial Robotics continues to use the Piccolo LT, manufactured by Cloud Cap Technologies. It is equipped with the ubiquitous set of three-axis accelerometers and gyros, which augment the onboard 4 Hz GPS receiver for fine control and navigation. The radio modem for communicating with the groundstation is built into the autopilot’s package, reducing the physical size of the subsystem, as well as the number of subsystems needed to complete the UAS.

Two onboard serial ports are available for payload controls or distribution of telemetry to onboard devices. The payload can also send messages back to the Piccolo, including additional waypoints or flight parameters. For the club, this means that the imagery and autopilot subsystems may be closely integrated.

In addition to flying a set of multiple waypoints, the Piccolo is able to orbit around a point at a specified radius and altitude. More advanced features include the ability to initiate a control surface doublet for analyzing the aircraft’s open loop stability, as well as autonomous-landing patterns.

This subsystem has been tested for over 60 hours this year alone. It has been put through its paces flying multiple aircraft, and serving telemetry while bench testing in the lab. Several attempts have been made at autonomous landings. This task has not been fully completed, yet, but more tests will be conducted before competition.

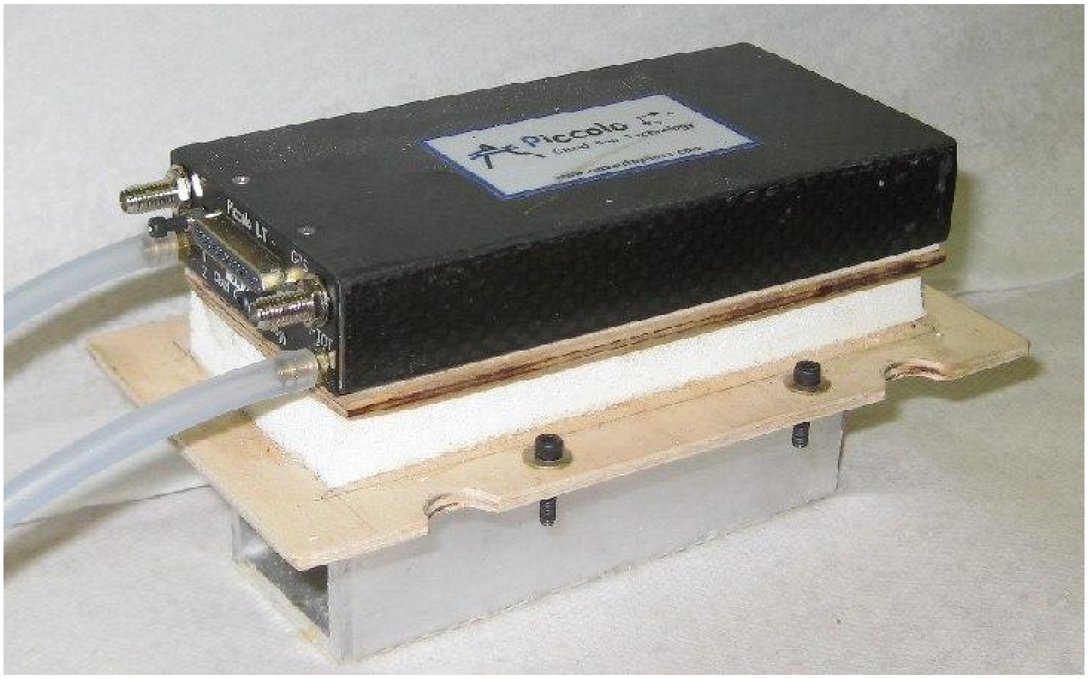

Figure 6: Piccolo LT from Cloud Cap Technologies

Trailer/Ground Station Subsystem

The NCSU Aerial Robotics' trailer is a six by ten foot enclosed trailer. It supports the entire setup for autopilot and imagery ground stations, aircraft, any extra payload, and all necessary equipment needed to repair or rebuild most components of the NCSU UAS. There are two main shelves inside the trailer custom built by students for the purpose of flight testing. The top shelf is used for storage while the main shelf becomes the "desktop" for the operators and the ground station computers once at the flight field.

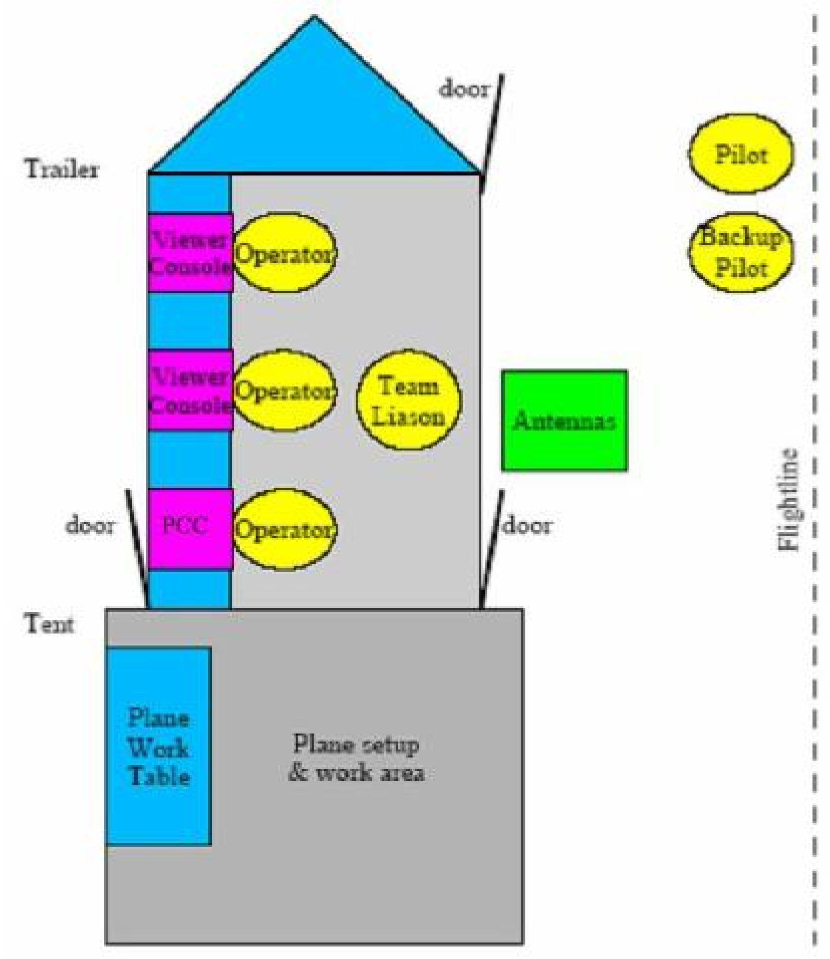

Figure 7: Typical Ground station Layout.

C. Imagery Viewer

The imagery analysis portion of the ground station consists of several desktop computers, running Debian Linux and custom software. One acts as the wireless base station for the remote vehicle and ground station server. It retrieves photos from the vehicle's onboard computer, and prepares them for viewing on one or more client computers. All of the imagery computers are networked with a gigabit network, enabling quick transfer of decompressed images between the server and clients. Each viewer station displays the entire set of collected imagery and is free to operate independently of the others. The system enables multiple analysts to work in parallel, increasing the likelihood that all targets will be identified correctly.

A unique feature of the ground station software is the ability to load hundreds of images into the viewer, while even the newest COTS graphics cards can only hold a couple dozen high-resolution images in accelerated memory. The NCSU system selectively pages images in and out of texture memory to optimize for a given hardware configuration, using a priority system based on where the user's viewing area and zoom level. Another key feature is real-time lens distortion correction, a pixel-by-pixel operation that is done entirely on the graphics card, leaving the CPU free for other computationally expensive operations.

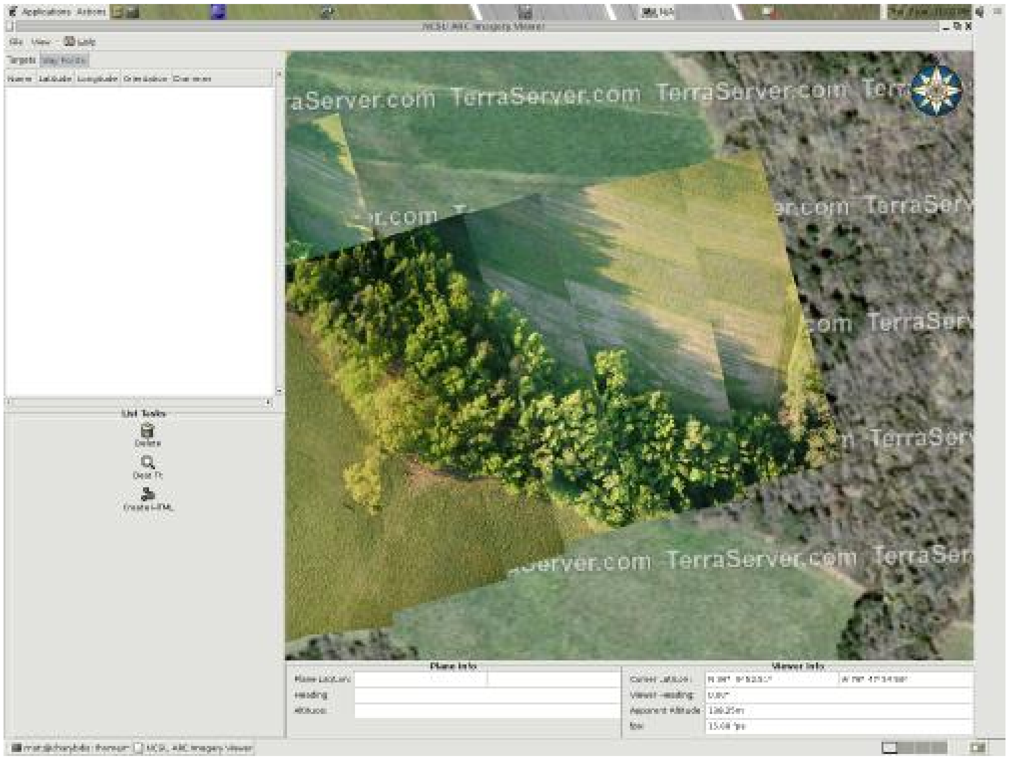

Figure 8: Screen shot of Imagery Viewer

D. Piccolo Ground Station

The Piccolo system from Cloud Cap Technologies is rather unique in that it has a specialized piece of hardware that houses the radio transceiver and GPS receiver for communicating with the aircraft and the host computer. It connects to the host computer through a serial connection. The operator can communicate with the aircraft through the Piccolo Command Center, sending navigation patterns and commands. This is done through a simple mapping screen.

The ground station hardware is also the link from the secondary transmitter to the aircraft. This is another of the system's redundant features. If the manual R/C link should fail, the "pilot's console", as described by Cloud Cap, will still be able to control the aircraft. This is discussed further in the section on Safety.

E. Path Planner

The Path Planner is an application which simplifies and automates the process of mission planning. Mission planning is the act of deciding which path the aircraft should take and calculating mission estimates such as flight duration and total distance traveled. While this task can be done by a human operator, the Path Planner allows this process to be done quickly and ensures that optimal plans are made for searching search areas.

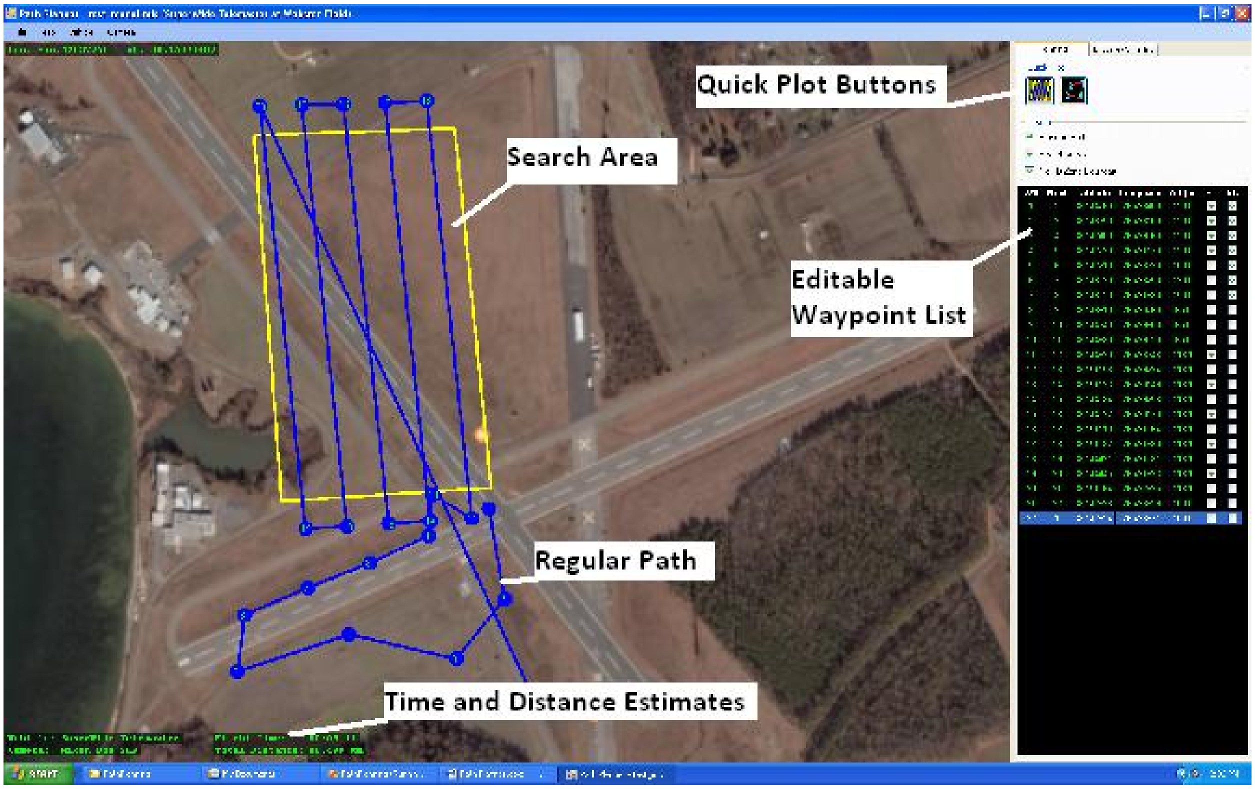

Figure 9: Overview of Path Planner Screenshot.

The Path Planner is primarily used during preflight planning, however it has a significant impact on the performance of the flight. This is done in two ways. The first is the way in which it plans search areas. The judges for the AUVSI Student UAS Competition hand out GPS waypoints marking the vertices of the polygon that bounds a search area before the mission. By giving this information directly to the Path Planner, an initial plan can quickly be determined with no other intervention by the user. This increases the flight performance because the algorithm that builds this initial path takes into consideration many specifications of the aircraft and camera. For instance, camera information such as sensor size and field of view are given to the planner in a configuration file. From this, and a user specified desired camera resolution, the planner can find the optimal altitude to search the search area. Once the optimal altitude is calculated, the field of view of the camera is used to calculate the spacing between individual search lines.

A configuration file can also be given specifying the aircraft parameters. This is done so the planner can make sure that search lines are not closer then is physically possibly for the aircraft to turn to. With all of this taken care of by the Path Planner, it is ensured that search areas are flown as quickly as possible with optimal imagery coverage well before the aircraft is ever wheeled onto the runway.

Testing and Evaluation

NCSU's UAS has had well over 30 hours of flying time this year. In this time, all of the subsystems have been adequately tested and improved. The autopilot subsystem is able to fly patterns generated by the Path Planner. The autopilot is able to fly a pattern covering the approximate search area, from a previous year, in approximately 7.5 minutes. Startup time for all of the computers in the trailer is approximately 3.5 minutes. The aircraft takes less time to start than the computers in the trailer, so everything should be ready to fly after the ground station computers have booted. Given an approximate take-off time of 1 minute and a landing approach of 3 minutes, the complete mission should take no longer than 15 minutes.

The imagery subsystem has had its kinks worked out. An operator at the controls of the imagery system is able to locate a 1.5 foot wide target while flying at an altitude of 750 feet.

In the time before competition, the club hopes to measure the accuracy of the imagery system. A handheld GPS unit will be used to tag the targets and compare against the coordinates that the Imagery Viewer gives. Also, more testing will be performed on autonomous landings.

Safety

Operator and spectator safety is of paramount importance with any complex aircraft, model or otherwise. To this end, NCSU has chosen systems that are very robust, and eliminated single point failures wherever possible.

F. Failure Analysis

In order to understand and evaluate the failure points in the system, NCSU conducted a detailed failure mode event analysis (FMEA). Autonomous, recoverable failures are best, where on board backup systems supersede the primary system. Mission critical failures result in the recovery of the aircraft, but a failure in the mission. Catastrophic failures result in a complete loss of the aircraft.

The FMEA in the appendix shows that the NCSU system is single fault tolerant across the board, with the exception of the Nikon D50 digital camera and battery. A loss in any other system component is fault tolerant, to the extent that the mission can still be successfully completed, or at worst case, the aircraft can be successfully recovered.

G. No-Fly Zones

NCSU will designate no-fly zones the day prior to competition. These zones will be marked in red on the Piccolo Command Center, and all waypoints will be set outside these zones. If at any time the aircraft is seen to be entering a no-fly zone, the autopilot will be redirected via the PCC to fly away from the no-fly zone. If the autopilot is unresponsive to waypoint adjustments, manual control of the aircraft will be taken and the aircraft will be forced away from the no-fly zone or forced to crash if out of control.

H. RC Safety Switch
As a result of an earlier FMEA and previous safety experience, NCSU includes a safety switch that is wired between the manual RC receiver, the autopilot and the servos. The safety switch provides common power to the manual RC receiver, and gives the ability to manually override the autopilot at any time. This separation of the servos from the autopilot allows the autopilot to fail without affecting manual control, while still utilizing the redundancy that the autopilot control system gives us, should the manual RC transmitter fail.

I. Loss of Communications
AUVSI rules state that a manual control system must be in place should the autopilot system fail. In addition, in the event of a manual control loss, the system should execute a hard over. NCSU utilizes a PCM RC receiver with a programmable "fail-safe" set to default the RC Safety Switch to manual and execute a right-handed hard over.

J. Radio Frequency Interference
Radio Frequency Interference is very important, since the loss of RC communication triggers a fail-safe and thus a hard-over, likely destroying the aircraft. To limit RF emissions from onboard equipment, the camera computer and autopilot system are located in aluminum cages that act as faraday cages which limit incoming and outgoing RF noise.

All communication antennas are located as far away from each other as possible, and grounding plates are used wherever possible in order to reduce interference and increase antennae gain. Additionally, all servos located aft of the firewall are shielded and installed with shielded wire in order to reduce RF interference on the primary control surfaces channels.

K. Battery/Power System
During extensive ground testing of the system, an external power supply provides primary power. This reduces the overall operator workload and increases system longevity by reducing the number of charge cycles on the batteries. The only system that does not receive external power is the camera, which is not turned on until the system is flight ready. When the system is flight ready, external power is switched off and the system is rebooted on battery power.

In-flight, all flight critical voltages are monitored via the Piccolo Command Station. During flight, the PCC will throw a red flag on the appropriate voltage, the operator will reference the FMEA and an appropriate action will be taken by the crew. Battery life and fuel life have both been measured in excess of 30 minutes, which is nearly double the time required by NCSU to take-off, photograph the target area and land.

Appendix

Failure Mode Event Analysis			
Failure	**Symptom**	**Action**	**Status**
RC Receiver malfunction	erratic behavior	1. pilot defaults to manual control	mission failure, recoverable
		2. if problem persists, pilot turns off transmitter, initiating hard-over	catastrophic
Autopilot malfunction	erratic behavior	1. pilot defaults to manual control	mission failure, recoverable
Loss of camera uplink	real-time image transmission stops	1. NCSU relies on onboard images	mission continues
Loss of autopilot uplink	indicated on PCC screen	1. if less than thirty seconds, aircraft continues previous flight path	mission continues
		2. if greater than thirty seconds, aircraft goes to lost comms waypoint	mission continues
		3. if after 1 minute link does not return, pilot takes manual control	mission failure, recoverable
Loss of GPS signal	indicated on PCC screen	1. aircraft initiates ?	mission continues
		2. if after 1 minute signal doesn't return, pilot takes control	mission failure, recoverable
12v system battery low	1. loss of camera uplink computer	1. NCSU relies on onboard images	mission continues
	2. indicated on PCC screen	2. pilot defaults to manual control	mission failure, recoverable
4.8v servo battery low	indicated on PCC screen	1. pilot defaults to manual control and lands immediately	mission failure, recoverable
3.3v camera battery low	indicated on PCC screen	1. auto land initiated as no more images can be captured	mission continues
Vehicle breaks	erratic behavior,	1. switch to manual	mission failure,

in flight	falling debris	mode	recoverable
		2. pilot attempts to fly damaged aircraft	mission failure, recoverable
		3. turn off transmitter to initiate hard-over	catastrophic
One servo dies	erratic behavior	1. autopilot attempts to fly without servo	recoverable
		2. if flight appears erratic, switch to manual control	mission failure, recoverable
		3. pilot attempts to fly aircraft and land	mission failure, recoverable
		4. turn off transmitter to initiate hard-over	catastrophic
Loss of sight of vehicle	pilot calls "out of visual range"	1. pilot flies via HSI and map on GCS	recoverable
		2. backup pilot watches sky for aircraft	recoverable
		3. pilot resumes watching aircraft in sky	recoverable
Engine dies in flight	perceptible change in aircraft sound, noticeable drop in airspeed	1. pilot switches to manual mode	mission failure, recoverable
		2.emergency landing procedure	mission failure, recoverable