

North Carolina State University  
**Aerial Robotics Club**

2007 AUVSI Student UAS Competition  
Journal Paper Entry

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by **Matthew Hazard (NCSU '08)**  
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Alan Stewart and James Scoggins



**Abstract:**

An unmanned aircraft system was designed and constructed to provide autonomous functionality, high quality aerial imagery, and precision target identification and location. An off the shelf autopilot was integrated with an embedded PC and a digital still camera, creating a system capable of generating a georeferenced images at least once every 3 seconds while flying a search pattern constructed with waypoints. Using high power 802.11g WiFi equipment, these pictures were transmitted to a ground computer station with custom imagery analysis software which automatically mosaicked images and handled target selection and measurement. The imagery system showed an average measurement precision of 125 feet. Improvements in georeferencing and the addition of automatic path planning, automatic target recognition, and lens distortion correction promise improvements in the total system accuracy.

## Crash Note

On Sunday, April 29, 2007, at 6:36 PM, the NCSU Aerial Robotics Club experienced its first crash in over three years of incident-free flying. The '12 Footer' went down in trees at our Butner, NC airfield. After a long day of autopilot tuning, the crash came as an unexpected blow to the team, just as we were making progress. Post-crash forensics indicated a servo battery discharged below a safe level during one of our longer flights, resulting in loss of servo power. Some of our most valuable pieces of equipment were totally lost, while others survived. Our Nikon D50 digital SLR survived the 500 foot crash with minimal damage. This picture, taken with the crashed camera, shows the extent of the debris field.



## System Overview

### Engineering Approach

The basic task of the AUVSI Student UAV competition presents a very difficult challenge for student teams. The competition scoring areas essentially boil down to autonomy, imagery collection, and imagery analysis. Achieving good performance in each of these areas requires its own set of equipment, personnel, and time. While each component of the system could operate on its own, the NCSU team has instead created a system architecture that links key systems together to achieve maximum performance. The complete Unmanned Aircraft System consists of vehicle, autopilot, and imagery subsystems that combine to create a tightly integrated solution for the whole mission.

### Autonomous Strategy

The aircraft system uses a navigator-pilot model to complete the mission goals. The onboard Piccolo LT autopilot handles the core responsibilities of autonomous flight, stabilization and waypoint navigation, but is ill equipped to generate its own flight plans. Thus an automatic mission planning program (the ‘navigator’) has been developed which uses flight parameters, camera specifications, and wind estimates to create waypoint paths the autopilot will fly during the course of the mission. The system thereby satisfies the mission autonomy requirements while increasing its utility for imagery acquisition. An additional imagery feature, camera stabilization, relies on the autopilot to control a gimbaled mount to point it straight down at the ground. This technique has been tested to reliably provide better results than similar manually controlled camera mounts.

### Expected Performance

The complete aircraft system has not been fully tested in its current configuration, due to circumstances involving the crash of our previous competition vehicle in late April. Most components of the system were tested in the old vehicle, so these performance estimates are still accurate for the replacement. The system will meet all minimum behaviors specified and quite a few of the optional goals, as listed below:

Table 1: Key Performance Parameters

<b>Mission Areas</b>	<b>Expected Performance</b>
Expected Autonomous Behaviors	Waypoint navigation, corridor flight, automatic flight path generation, in flight retasking, camera stabilization
Possible Autonomous Behaviors	Auto-takeoff and auto-landing may be added depending on test results and environmental conditions.
Imagery (Base)	Real-time transmission, high resolution color still imagery, automatic mosaic generation, targets fully identified (color, shape, alphanumeric), lens distortion corrected.
Imagery (Location)	Target locations accurate within 125 ft (tested). Target size and heading also available. Actionable intelligence available in less than 20 minutes.

## Vehicle Subsystem

### Summary

The host vehicle for the NCSU Unmanned Aircraft System is a high-wing conventional design: the .60 sized Senior Telemaster Trainer. This specific model is known throughout the R/C community for its stability and graceful flight. As a trainer aircraft, it is designed with features to make flying stress-free for a human pilot, including wing dihedral and large tail surfaces. These features are also important when an autopilot is added to the system, since the inherent stability of the aircraft makes tuning a simple matter.

**Table 1: Aircraft Specifications**

Wingspan	96½ inches (8 feet nominal)
Wing area	9.0 square feet
Length	5.17 feet
Empty weight	11.5 pounds
Maximum tested takeoff weight	20 pounds
Competition weight without fuel	15.6 pounds
Gross / Takeoff weight	16.6 pounds
Engine displacement	0.912 cubic inches (15 cc)
Engine peak power	2.8 bhp @ 15,000 rpm
Typical propeller size	13x8 or 13x9
Cruise speed	40 mph
Payload volume	612 cubic inches
Fuel volume	16 oz
Flight time	30 min



**Figure 1: Senior Telemaster, '8 Footer'**

## Build Notes

The basic Eight foot Telemaster kit was modified to better fit the mission parameters and our payload. The fuselage was widened to 6", making room for the embedded computer systems, autopilot, radio gear, batteries, and a larger fuel tank. A larger engine was added to improve climb rate, especially on takeoff. The specified .60 size engine was replaced with a .91 glow fuel engine with a peak power output of 2.8 bhp. The fuel tank was enlarged to enable 30 minute flights without refueling, with a 20% safety factor. To accommodate the expected payload weight (far in excess of a typical R/C configuration), the wing structure was augmented with carbon fiber spar plates and completely boxed in with shear webs. The entire spar structure was wrapped with Kevlar thread to prevent delamination. The payload area was stiffened with plywood longerons which serve double-duty as convenient mounting rails. The stock tail-dragger landing gear was replaced with a tricycle configuration to improve taxiing performance and ensure ground clearance for the camera mount and antennas that protrude beneath the fuselage.

## Controls

The aircraft is controlled in a standard four-channel configuration. A safety switching circuit limits access to the ailerons, elevator, rudder, and throttle. With the safety switch, the R/C override will always have control authority unless the safety pilot 'clicks in' by switching the channel five 'gear switch' on the transmitter, which grants the autopilot control over the servos. Switching back cuts the autopilot out of the loop entirely, meaning the system *will not fail* as a result of an autopilot reset or complete failure, since the safety pilot can take control and operate the aircraft normally.

## System Power

Systems within the aircraft run on NiMh or lithium ion batteries. All of our systems use either a five or twelve volt supply. The majority of onboard electronics can tolerate nominal battery voltages. The R/C receiver, servos, and safety switch are all connected directly to a single high-capacity 6V nickel metal hydride battery. Similarly, the autopilot is powered directly from a 12 volt lithium-ion pack with a total capacity of 4.8 Ah. The embedded computer, 'Leviathan' also uses this battery pack, but is powered through an intermediate DC-DC converter which regulates the supply and provides all the necessary intermediate voltages required for accessory PC devices. Sharing batteries between devices has allowed us to reduce the number of switches, connectors, and the total number of batteries which need to be charged or replaced between flights, each of which could be a potential failure point. To maintain the integrity of the safety override, only R/C related equipment is connected to the 6V pack.

## Autopilot Subsystem

### (Time for a new Autopilot

After several years of working with the MicroPilot 2028g, the NCSU team decided to switch autopilots. While the MicroPilot served us well, we were pushing the envelope by expanding its role to stabilize our gimbaled camera mount in 2005 and 2006. Moreover, the 2028g has no facilities for connecting with higher-level devices, e.g., computers onboard the aircraft. During the crash in April 2007, the 2028g board was damaged. With the competition deadline looming, the team decided to purchase a new kind of autopilot rather than worry about repairing or replacing the MicroPilot.) Not sure about this section

### Piccolo LT

NCSU's autopilot is the Piccolo LT, manufactured by Cloud Cap Technologies. The LT is CCT's newest and lightest autopilot and is equipped with the standard complement of three-axis accelerometers and gyros, which augment the onboard 4-Hz GPS receiver for fine control and navigation. The radio modem used for autopilot control is built into the autopilot package, reducing the total size of the system and the number of interconnected sub-systems required to create a viable autopilot system. The LT has two onboard serial ports available for payload control or distribution of telemetry to onboard devices. The payload can also send messages back to the autopilot, including additional waypoints or flight parameters. For the NCSU system, this means the payload and autopilot subsystems can be more tightly integrated, specifically removing the need to duplicate sensors for imagery georeferencing. See the **Payload** and **Autonomy** sections for more information. In addition to traditional waypoints, the Piccolo navigation algorithms can also create an orbit of specified radius and altitude around a point and create landing patterns while in flight. More advanced features include the ability to initiate a control surface doublet (a measured deflection held for a short period of time) to analyze the aircraft's open loop stability. Included software enables users to visualize aircraft motion *during* the tuning process rather than relying on visual perception of the aircraft response.



Figure 2: Piccolo LT Autopilot

## Autopilot Ground Control Station

The Piccolo system is unique in that it uses a separate piece of hardware similar to the avionics which contains the radio transceiver and a GPS receiver for generating differential GPS corrections. It connects to the autopilot operator's PC using a serial connection. The autopilot operator communicates with the onboard avionics using a specialized program known as the *Operator Interface*. This software package handles preflight configuration and displays telemetry and vehicle position during flight. A mapping and command screen is the primary interface for transmitting navigation commands to the autopilot.

## Intermediate Override

The Piccolo system also employs an R/C transmitter which connects to the ground station via the trainer cord system. In a typical installation, the safety pilot's commands would be formed into a data packet and sent to the airplane over the 900 MHz link or a redundant satellite link. In a military UAV system, this is highly desirable since the practical range of a typical R/C transmitter is much less than five miles. With high-gain antennas, the 900MHz link could extend much farther, and satellite radios have no line of sight restrictions. For the AUVSI competition, the NCSU team decided to integrate the autopilot system into the existing discrete safety switch architecture, enabling a unique crossover layer between autonomous flight and full manual override. Rather than sending actual servo positions to the aircraft, the avionics can continue to control the aircraft normally while the autopilot operator sends higher level commands like bank or pitch angle. The NCSU team foresees using this functionality to monitor the no-fly zones from the trailer (where the operator has a top-down view of the plane's location relative to the mission boundaries) and modify the aircraft's flight path if necessary. In our older systems, the safety pilots relied on voice communication from the autopilot operators to tell them which way to turn. With the new system, the safety pilot will only take control of the aircraft for takeoff and landing, in case of emergencies, or as requested by the system operators.

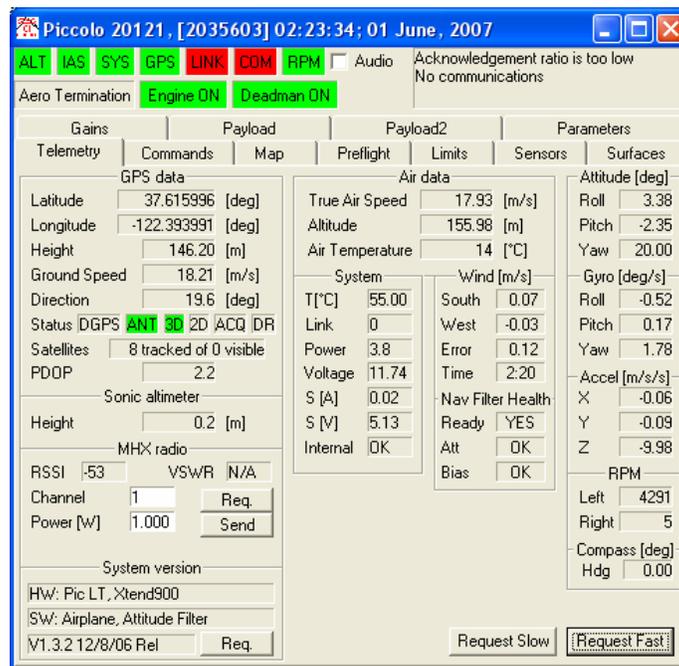


Figure 3: Piccolo Operator Interface Screenshot

## Imagery Subsystem

### Summary

The Imagery subsystem consists of three primary components: a digital camera, an onboard computer, and computers on the ground. The digital camera is the primary sensor for the imagery system and performs the basic reconnaissance function, imagery collection. The onboard computer controls the camera telling it when and how to take pictures and communicates with the aircraft's avionics. With telemetry from the Piccolo LT, the computer can embed up to date location and orientation information in each picture before sending the pictures to the ground for real-time processing. The ground station computers make real-time processing feasible by displaying hundreds of photos in a framework that spatially organizes each photo in the location it was actually taken.

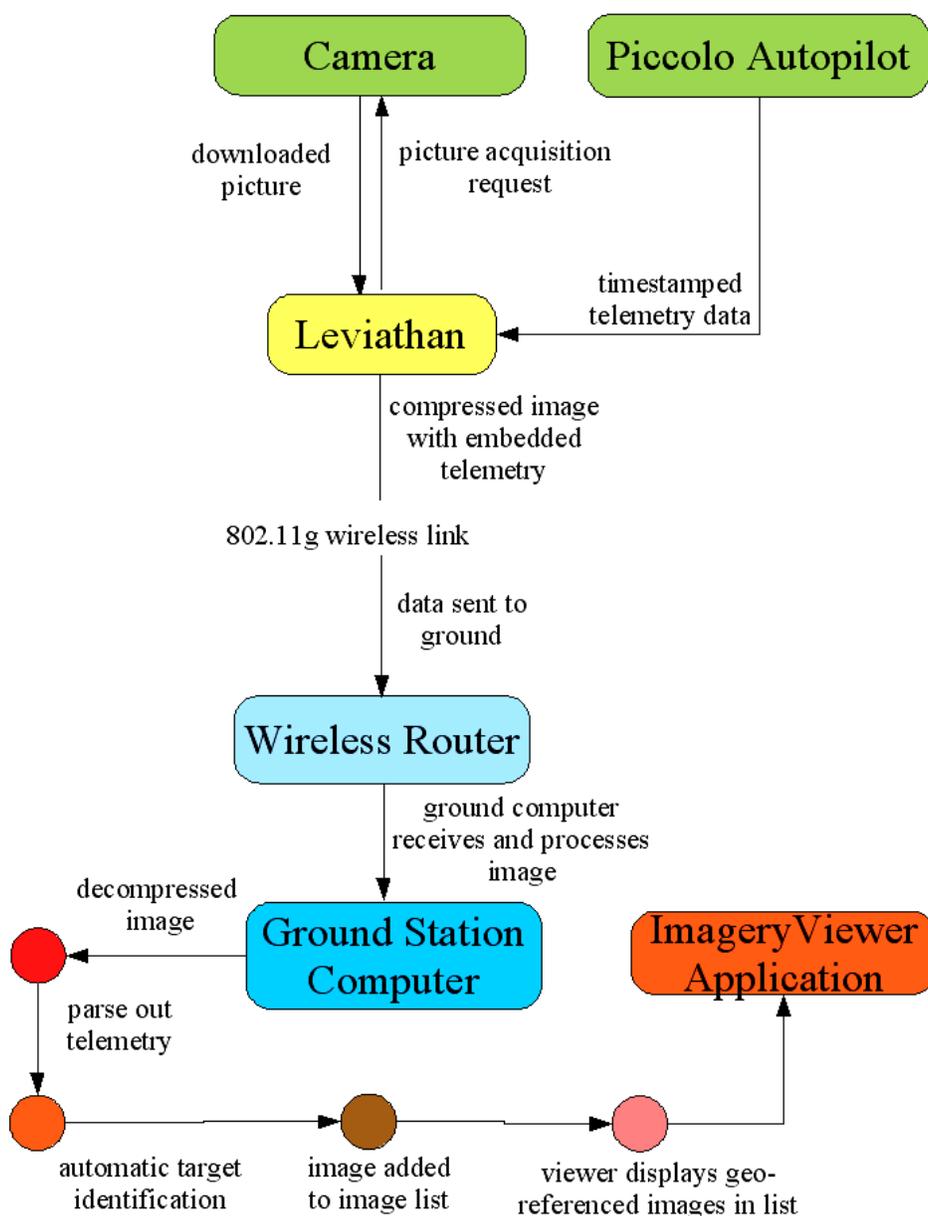


Figure 4: Imagery Workflow Diagram

## Camera

After the April 2007 crash, NCSU rebuilt its system in a smaller airframe. With the smaller payload volume, a smaller camera was necessary. The imagery team chose the Nikon P2. As a standard point and shoot digital camera, the P2 stands out by supporting USB 2.0 High Speed as well as a unique remote control mode that enables a host computer to acquire images from the camera without waiting for it to save them to the memory card first. It has a 36-126 (35mm equivalent) lens, and the zoom level is controllable from a software level. The P2 is capable of shutter speeds of up to 1/2000<sup>th</sup> of a second, an important feature for vibration reduction. The camera is mounted in a pitch-roll gimbaled mount to account for airplane deviations from horizontal flight. This strategy minimizes the perspective error induced by a camera that doesn't point straight down, since a camera fixed to the airplane will lose information whenever the airplane is banked to one side or the other. Given sufficient altitude, the system still has a very wide effective field of view, especially compared to low resolution analog video systems. Our testing (albeit with a slightly higher resolution camera) and competition experience has demonstrated that digital still photography is the best choice for reconnaissance purposes. A summary of the relevant camera features is listed below:

**Table 2: Nikon P2 Specifications**

Sensor Resolution	5.1 Megapixels / 2592x1944
Shutter Speeds	8 seconds to 1/2000 <sup>th</sup> of a second
Aperture Range	f2.7 to f7.6 (at wide angle)
Nikkor Lens Zoom Range	36-126mm 35mm equivalent or 3.5x
Size	3.6x2.4x1.5 in (91x60x39 mm)



**Figure 5: Nikon P2 in two-axis camera mount**

## Onboard Imagery Computer, 'Leviathan'

The camera is only a small part of the complete imagery system; images must be combined with geographical data for them to carry enough information to allow quick interpretation. The NCSU software team developed software for the 2006 AUVSI competition that triggers the camera to take a picture, downloads the picture from the camera, fuses the image with sensor data from the Piccolo LT autopilot, and transmits it to ground station computers over the 802.11g link. The software runs on an embedded PC, nicknamed 'Leviathan.' Leviathan is a 3.5" format single

board computer that, although small, has a 667 MHz processor, USB 2.0 High Speed, a PC/104+ expansion slot, and other features. The computer runs a full Debian Linux operating system, installed on a vibration-proof Compact Flash card. The application code is stored on a separate flash card inserted before startup. When the computer boots, it runs the scripts and programs stored on the auxiliary flash card. A backup copy of each picture taken (with GPS and heading information) is stored on the auxiliary card. In case of complete wireless transmission failure, the pictures can be retrieved from the card for post processing.

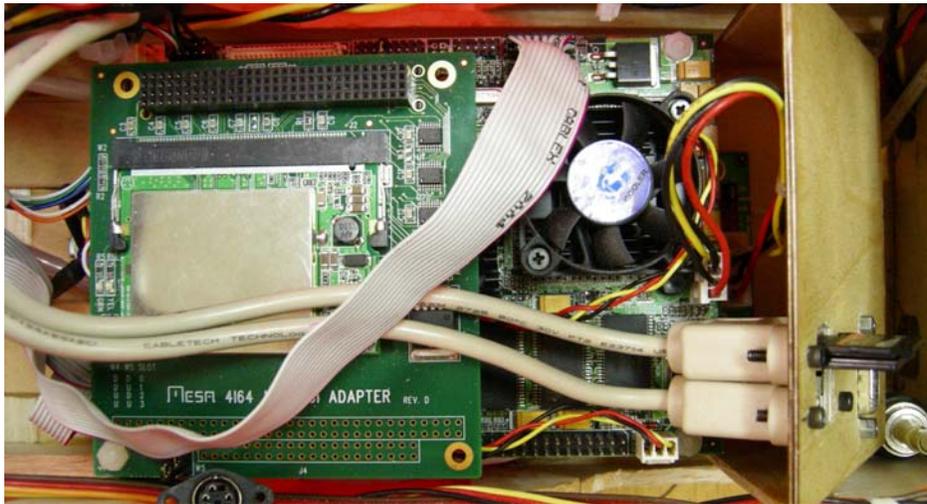
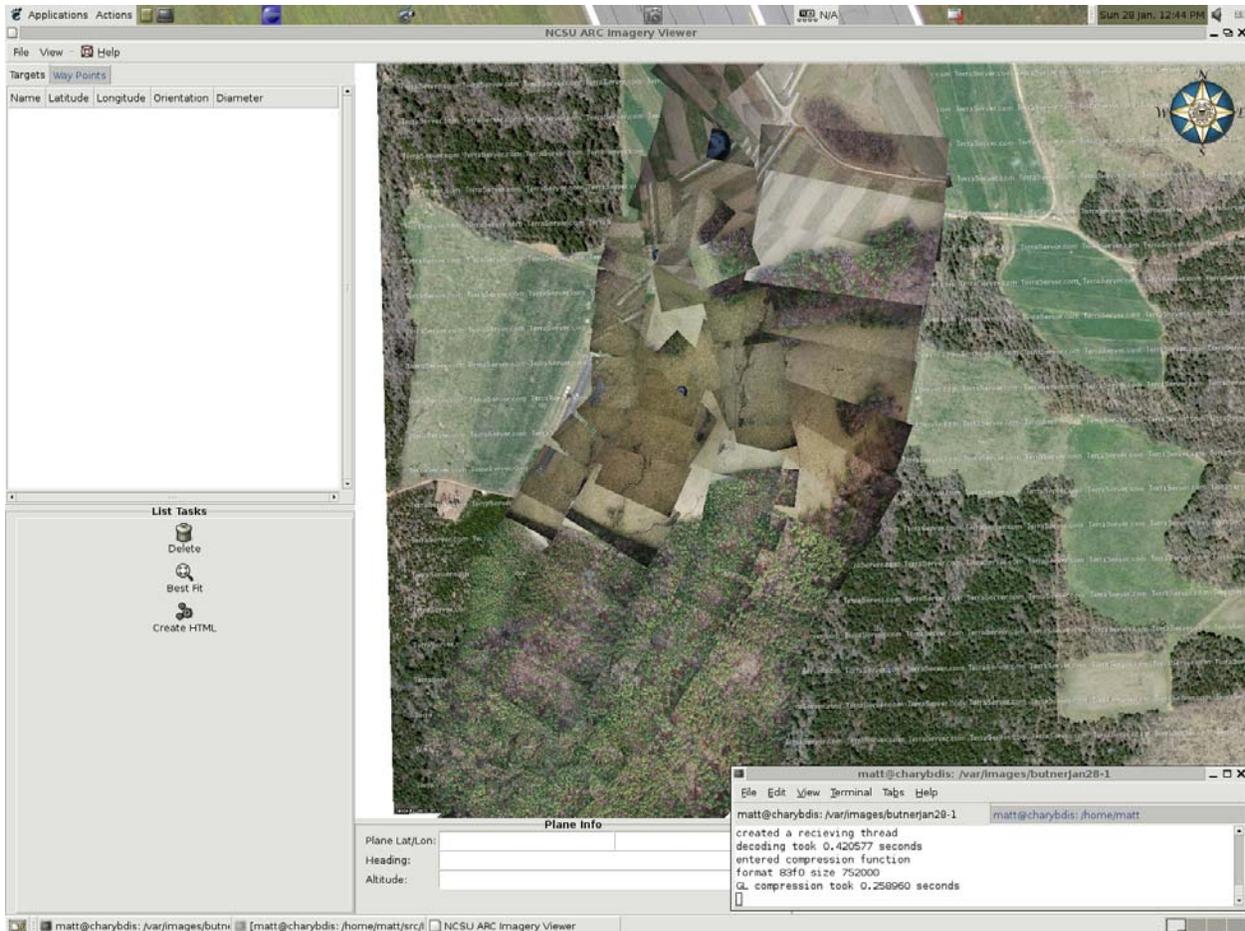


Figure 6: 'Leviathan' Embedded PC

### Ground Station Imagery Computing

The core of the imagery system is the real time analysis performed on the transmitted digital still images. The software developed for AUVSI 2006 has matured and undergone significant testing. The NCSU imagery software aims to speed up the analysis process by arranging each photo *spatially*. Rather than stepping through a sequence of photos sorted by time, the imagery operators see *all* the pictures that have been taken by the onboard systems at once. This has the effect of reducing the search space for each image (once a target has been found, or an area already searched, it does not need to be searched again.) The GUI interface overlays the pictures on top of a satellite 'truth' image, scaling and rotating them to the altitude and heading at which they were taken and translating them to the location the capture was started. Over an ordinary flight, the onboard systems may capture hundreds of photos. The ImageryViewer is capable of displaying all of these simultaneously with little penalty in performance, due to multithreaded operation on a dual-core computer and hardware graphics acceleration. The ImageryViewer application includes interactive tools designed for the AUVSI mission, including a target marking mode which designates the center location, heading, diameter, and name for each target. To further improve measurement precision, the software can perform camera lens distortion correction *in hardware*, negating barrel distortion error for calibrated cameras. A report can be generated suitable for immediate printing of target close-ups, or the GPS coordinates can be read off the screen in a variety of formats.



**Figure 7: 'ImageryViewer' Screenshot**

### **Automatic Target Recognition**

A new component of the ground station imagery system is a separate software application designed to automatically detect targets in photos. At the time of writing, this application is in the process of being merged with the ImageryViewer software, but the base software has been tested as a separate system. The imagery team started from a basic list of characteristics unique to a target that differentiates it from the typical airfield terrain at Webster Field. The result was an algorithm that is capable of detecting most targets on a signal level, i.e., the program does not need a library of targets for it to look through and find matches. Instead, the software uses properties of the HSV (Hue, Saturation, and Value) color space. As opposed to the usual RGB description of a pixel value, where each band represents a color level, color in the HSV space is represented by a single field, hue. Saturation represents color intensity, and value indicates brightness. Unlike RGB, the HSV description of a color more closely models human perception. Thus the target recognition software weights variations in HSV space and uses a gradient algorithm to detect the greatest change in these values, which occur at regions of interest, usually targets. A region growing algorithm is then used to define the outlines of the detected area, constraining the size of the target to reasonable surface areas and geometries.



The software has been tested on images from Webster Field at AU VSI 2006, and worked extremely well. The only false positives were generated when the corner of one image caught the edge of our trailer and bright blue tent. Images from our test flights at Butner, NC (essentially a cow farm) have more subtle variations in terrain, and more false positives were generated from the Butner set. Based on these results, we hope to use the Automated Target Recognition step as a filter to improve analysis performance even further. Although the final integration is incomplete, the current plan is to generate a transparency 'mask' based on the target recognition data. The imagery operator will have the option of clicking a button and 'hiding' all the extraneous grass, runways, and other background features while highlighting the areas considered to be target regions. This should allow for immediate target identification, while still enabling the operator to confirm that nothing has been missed.

## **Data Links**

### **900 MHz Autopilot Command and Control**

The Piccolo LT uses a pair of 900 MHz transceivers to transfer command information from the Operator Interface to the aircraft and send telemetry and diagnostic information from the aircraft to the ground. Both transceivers have a maximum transmit power of one watt. On the ground side, a large dipole antenna with 8 dbi gain is used. Onboard, a smaller unity gain antenna is used. The 900 MHz signal passes freely through most obstacles and is hardly attenuated by air. For this reason, relatively low gain antennas are used without penalty in the open line-of-sight scenario of the AUVSI mission. Very low-speed communications with the onboard computing system may be piggybacked onto this signal by way of the Piccolo LT's link bridging protocol.

### **2.4 GHz Payload Communications Link**

The onboard computer, 'Leviathan,' has very high bandwidth requirements, since it is capable of pushing out new pictures quickly with less than three seconds between shots. To maintain this kind of bandwidth, it communicates with the Imagery ground station computers over a high power 802.11a/b/g wireless connection, with a maximum speed of 54 Mb/s. Both ends of the system use identical 400 mw peak transmit power cards. Our testing has shown this link to be reasonably tolerant of interruptions and distance. The 2.4GHz spectrum is highly attenuated by water vapor and other obstructions, so high-gain antennas are used to guarantee sufficient range and transmit rate. The ground station wireless access point uses a single 24 dbi gain parabolic dish antenna. The onboard system is currently configured to use an 8 dbi gain patch antenna and/or a 5 dbi flat blade antenna. The 802.11 protocol supports diversity reception, and automatically selects the antenna with the best reception. Combining two antennas with different polarizations allows the system the best chance of maintaining high-speed communications.

### **72 MHz Manual R/C Override Link**

The R/C receiver component of the safety switch subsystem receives the one way transmission of pilot servo commands from an off-the-shelf R/C transmitter. The NCSU system uses a top of the line JR 10X radio, ten channel JR receiver, and JR servos. The transmitter operates on channel 40 of the 72 MHz aircraft control frequency.

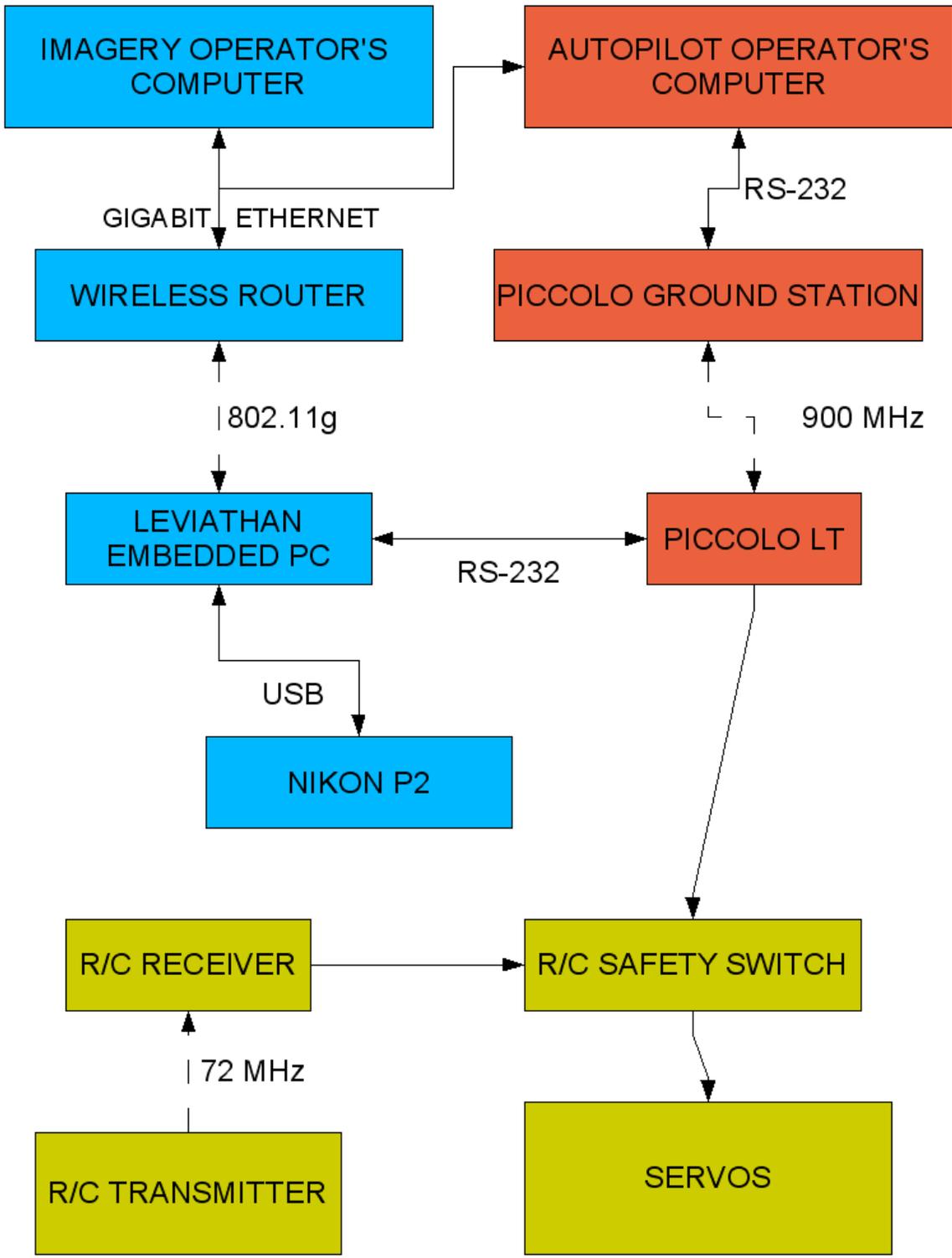


Figure 8: Communications Diagram

## **Safety Features**

There is no question that safety is an important consideration when designing any autonomous system. Especially for airborne vehicles, it is necessary to insure that the system as a whole has a mechanism for a manual override in the case of emergency or mission failure. Therefore, safety was of primary concern during the design of the 2007 AUVSI UAS system. The mechanism was incorporated through redundancy and safety procedures.

### **Redundancy**

Safe operation of the airplane is ensured by maintaining positive control at all times. The default Piccolo installation sends pilot joystick commands over its spread spectrum radio modems, handing control to the autopilot only when the operator 'clicks in.' The NCSU system goes above and beyond by using a discrete safety switching circuit and conventional R/C gear. This way, even in the case of autopilot battery failure or interrupted 900 MHz communications, the safety pilot can still take control of the airplane and resume safe flight.

### **Safety Procedures**

With as many as ten team members performing various tasks at competition, everyone must follow safety guidelines to ensure normal system operation. Checklists detailing vehicle assembly, electronics startup procedures, and pre-flight checks are used as part of NCSU's normal routine. Every component of the aircraft is inspected for damage before and after flights. During flights, NCSU posts the safety pilot, a backup pilot/spotter, and a note-taker on the flight line. The other team members take their places in the team trailer well behind the flight line.