North Carolina State University
Aerial Robotics Club

Autonomous Reconnaissance System

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Abstract

This paper describes the North Carolina State University Aerial Robotics Club Autonomous Reconnaissance System designed specifically to meet the 2006 AUVSI's Student UAV Competition mission. Without human control, the UAV flies through a series of GPS waypoints to reach a search area. Once arrived, the vehicle searches for ground targets, reporting the number, orientation, and location of the objects through a custom imagery viewer program developed by NCSU ARC members. NCSU's design uses mostly off-the-shelf components to create a modular and simple system. The overall system is broken down into four sub-systems: vehicle, autopilot, aerial imagery, and ground station. In event of an in-flight failure, backup systems and failsafe modes attempt to regain control before a hard-over failsafe is used, creating a robust and safe system.

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Mission Requirements

The 2006 AUVSI Student UAV competition mission is two-part:

1. Fly autonomously through a series of GPS waypoints
2. Survey a search area for ground-based targets – feeding back target count, location, and orientation

In addition, new waypoints will be given mid-mission and must be uploaded in flight. Time to complete the mission is 40 minutes. An emphasis on a user-friendly and robust system is important. Spectator and operator safety is paramount, requiring the observation of no-fly zones and flight termination procedures.

Design Overview

A modified, twelve-foot Telemaster airframe carries a 20 lb max payload at 40 mph for 35 minutes flying time assuming a five minute reserve. After a manual takeoff, a Micropilot 2028g autopilot guides the aircraft through given GPS waypoints and begins a semi-circular orbit pattern over the search area. A wireless modem connects the ground station and autopilot for in-flight reprogramming. Once in the air, an orthogonally stabilized Nikon D50 regularly takes pictures encoded with GPS and heading information and sends them to a ground server for saving and viewing. The images are then loaded into a custom imagery program which displays a continually updated mosaic of the pictures downloaded from the flying aircraft. A ground operator can then search this mosaic for possible targets, tagging them to get location and heading reference. Once all targets are found, a target reference sheet is printed for the judges.
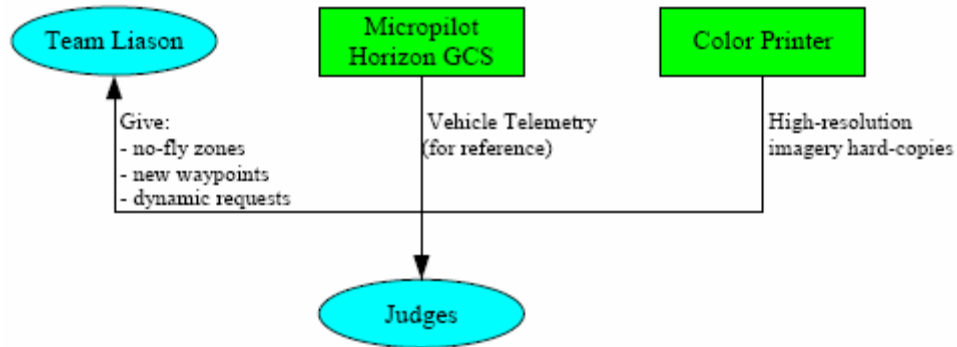
Systems Engineering

A. Interface Requirements

Before system design, NCSU examined the team-judge interface requirements. The judges need to:

- Distribute **GPS waypoints** and mission boundaries before mission
- Distribute **dynamic re-tasking** requirements during mission
- Receive an **imagery hard-copy** for post-flight assessment

To meet these requirements, NCSU created an interface control diagram to govern the exchanges of information. Judges will hand a list of waypoints or dynamic targets to the team. The team will return a hard-copy of selected target imagery to include target location, orientation, and a list of all sited targets. The judges will confirm waypoint capture via independent verification.

Interfaces Block Diagram

B. Systems Engineering

Starting with the interface requirements, NCSU designed a system that can meet the AUVSI Student UAV Competition mission requirements. The system is broken into four separate sub-systems:

1. Vehicle
2. Autopilot
3. Aerial Imagery
4. Ground Station

These four sub-systems are further divided into discreet components, maintaining modularity and utilizing commercial-off-the-shelf (COTS) parts when possible.

System Block Diagram
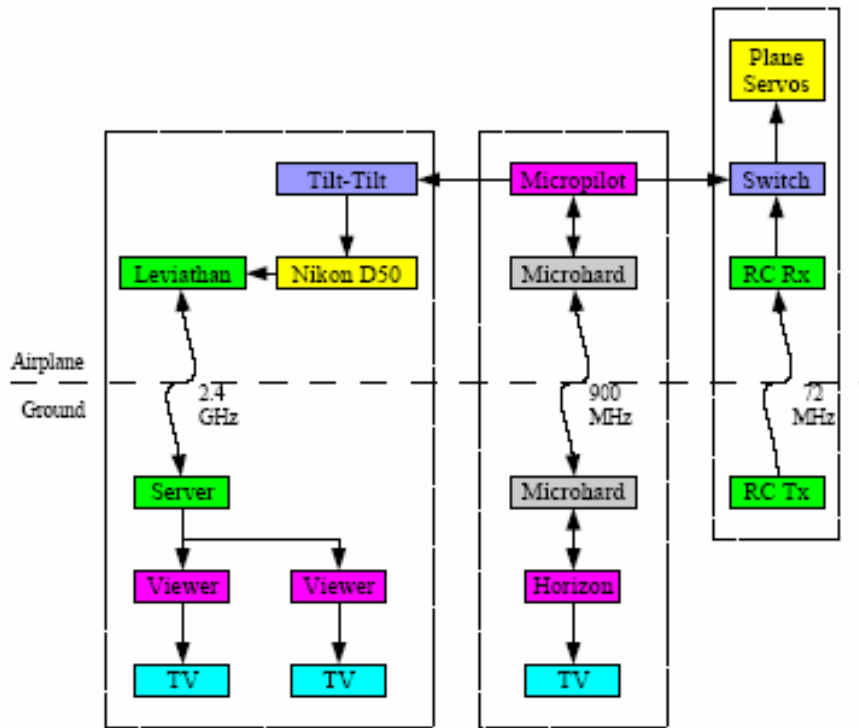
C. Test Philosophy

To ensure quality manufacturing and to certify the system, NCSU adopted a thorough testing policy. First, each sub-system was tested individually to ensure proper operation with a minimal risk. Then, each sub-system was test-flown individually to ensure proper airborne operation. Last, the sub-systems were added together one at a time and test flown. This ensures any failures are easily traceable and do not result in loss of the entire system. In-flight failure testing of parts is conducted in controlled environments when possible.

D. Procedures

NCSU created and followed Standard Operating Procedures (SOP) to control vehicle and autopilot operation, team/judge interactions, and emergency procedures. NCSU also conducted competition simulations to practice target reporting techniques and document the methods.

Example SOP Excerpt

Preflight (At Field):

☐ **Assembly:**
- o Remove from trailer
- o Check all switches OFF
- o Connect and secure battery for servos/receiver
- o Attach wing center section(4x ¼-20)
- o Use (4) 1/4-20 nylock nuts
- o Attach wing
  - ▪ Bolt strut on wing
    (1x 10-24 bolt with washer)
  - ▪ Plug wing into center section
  - ▪ Support the wing!!!!!
  - ▪ Plug in wing tab pins
  - ▪ Bolt on struts at fuselage
    (4x 8-32 bolts with locknuts)
- o Connect wing wiring inside fuselage
- o Repeat
- o Attach wing center section hatch.
- o Run antenna up right wing strut
- o Attach tail assembly
  (4x nylon ¼-20 bolts "short")
- o Connect tail servo connector
- o Attach tail hinge pin and lock
- o Attach rudder control linkage
- o Check Pump Breaks – 100 PSI

☐ **Weight & Balance**
- o Use CG rig to check balance
- o Weigh aircraft & record
  - ▪ _____lbs
- o Place "Do not add/remove items: balanced plane" sign on plane
- o Remove CG rod

☐ **Systems Check:**
- o Frequency Control
- o Tighten Antenna on Transmitter
- o Turn transmitter ON
- o Check transmitter on 12ft Tele model
- o Turn master switch ON
- o Turn RC switch ON
- o Check flight controls, free and correct
- o Turn transmitter OFF
- o Check for fail safe hold mode
- o Turn transmitter ON
- o Check flight controls, free and correct
- o Range check with TX antenna collapsed
- o Remove pitot-static cover

☐ **Engine Start (on runway):**
- o Fill fuel tank
- o Set mixture (3-1/2 turns)
- o Throttle set – closed throttle
- o Put glow driver ON
- o Check all clear
- o Start with 24v electric starter
- o Start Engine
- o Adjust needle valve
- o Test nose wheel steering while taxiing

12ft Telemaster is now ready for takeoff

Checklist Completed by: _____ Date:_____

Vehicle

The competition vehicle requirements are quite simple: integrate and carry a payload with easy access to the payload compartment. Additionally, the autopilot needs a stable, conventional aircraft for the controller for easiest integration. Takeoff and landing distance must be below 250 feet to safely use the 450 foot NCSU test runway. To accommodate dynamic airspeed requests, the vehicle must have a wide flight speed envelope. Since NCSU undergraduates will be piloting the aircraft, handling must be excellent and the aircraft must be Academy of Model Aeronautics (AMA) certified.

E. Twelve Foot Telemaster

To meet the vehicle requirements, Hobby-Lobby Inc. donated a twelve-foot Telemaster fixed-wing aircraft with large fuselage volume and ample wing area for high lift. NCSU constructed the balsa and ply aircraft stock from plans with a few major modifications:

- Fully boxed wing spar and carbon fiber cap-strips – for extra structural margin
- Integrated wiring conduit tubes – for easy payload integration
- Lock-pin attached wings instead of bolt-on wings – to facilitate quick attachment and removal of the wings during setup and breakdown
- Improved strut design – to increase the structural margin of the wings
- Doubling the width of the fuselage – for increased payload volume

A 2-stroke gas engine is mounted in tractor configuration and runs for 35 minutes on a 40 ounce fuel tank at 40 mph cruise speed (approximately half throttle) with a max power of 3.8HP. Ballasted test flights to 45.2 pounds takeoff weight have certified the airframe and verified all handling requirements are met while fully loaded.

F. Payload Compartment

Since the measure of a good transport vehicle is how well it carries payload, the Telemaster has been constructed to have an open 21" x 11" x 11" main payload bay and an 11" x 10" x 15" optional payload space in the tail immediately aft the wing. The main volume is roughly centered over the Center of Gravity (CG) and can carry up to 20lb of payload. Vibration sensitive components have been bolted with anti-vibration mounts and all flight critical necessities such as the fuel tank and batteries are located in a 11" x 10" x 9" front compartment for easy access.

G. Wing Hard-Points

NCSU installed generic mounting hard-points in both wings during construction. This allows all wing-mounted payloads to interchange between left and right wing and helps easily correct lateral balance. Currently, the pitot-static probe system is attached at one of these wing-mount locations.

H. Center of Gravity

The Telemaster CG is 4" behind the wing leading edge, per the plans. The CG is rough-adjusted by initial payload location weight & balance estimations. Fine tuning the balance for various payloads is accomplished by shifting the batteries fore or aft in the fuel tank compartment. Lateral balance is fine-tuned by adding/removing lead shot to a small wing-tip hatch.

Autopilot

The AUVSI mission requires a few specific capabilities from an autopilot:
1. Navigate via GPS waypoints
2. Receive new waypoints in-flight
3. Receive new flight parameters (speed, altitude) in-flight

NCSU chose the Micropilot 2028g Autopilot because of our familiarity with the system and because it has the required capabilities built-in, once a wireless modem is attached. NCSU housed the Micropilot in a compact and lightweight aluminum enclosure.

I. Flight Algorithm

To fly the aircraft, the Micropilot uses 9 PID loops with feedback from an onboard 3 axis gyro and accelerometer. A GPS receiver updates the aircraft location with 1ft accuracy at 1Hz. Airspeed and altitude pressure transducers supplement the GPS data.

To set up the Micropilot with an airframe, a series of test flights are needed to tune the PID loops. The included PID gains will roughly fly a 60" wingspan trainer. NCSU conducted the necessary series of tuning flights and found the stock gains to be acceptable even for the larger vehicle. This short tuning process was aided by a smart choice of a stable and conventional aircraft.

For each autonomous flight, a "fly-file" is created that specifies the desired flight behaviors. Commands such as FlyTo (lat, lon) describe how the aircraft should fly through waypoints. Both path-based and heading-based controls are used together complete the flight objectives. This file can be modified in-flight to adjust for new missions or changing environments.

J. Flight Path Requirements

The vehicle must fly directly over top of targets in order to capture them with the imagery system. However, the vehicle can have pitch or roll components, easing workload on the autopilot operator since the attitude can be out of level. Since flying over a target is equivalent to flying over a waypoint, the flight path requirement from imagery is easily accomplished similar to adding a new GPS waypoint. Also, the imagery system has a wide field of view for capturing targets not directly beneath the aircraft.

K. Peripherals

The Micropilot requires a few sensors to be integrated in the airframe, outside of the main compartment.

- The GPS antenna is mounted near the tail to reduce RFI from the payloads.
- A pitot-static probe is mounted 40 inches out the left wing to avoid the slipstream of the propeller; the pressure tubing runs through the wing into the main payload compartment.
- A Microhard 900MHz serial modem is mounted in the payload compartment next to the Micropilot. It is housed in an aluminum enclosure for reduced RF emissions and easier handling. It constitutes the low-bandwidth (57600 baud), high reliability command and control link to the plane.

Micropilot System Diagram
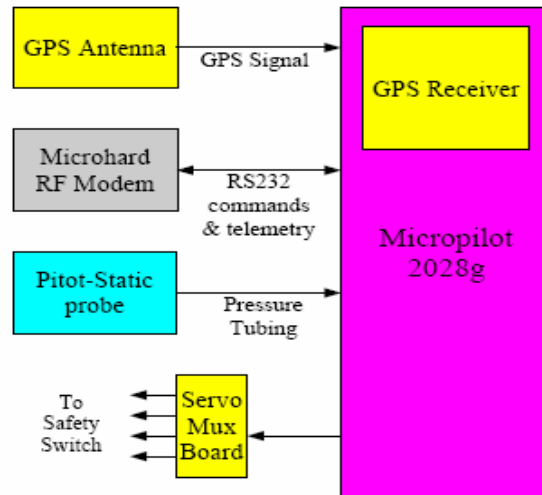
L. Servo Control

NCSU implements servo control differently than suggested by Micropilot. The autopilot servo outputs are sent to an RC Safety switch and then sent to the servos. The NCSU switch can change to manual control mode even with loss of autopilot power. This separates the autopilot from the critical path of manual servo control. This also allows ability to change autopilots without affecting the aircraft's critical flight systems.

Safety Switch Diagram
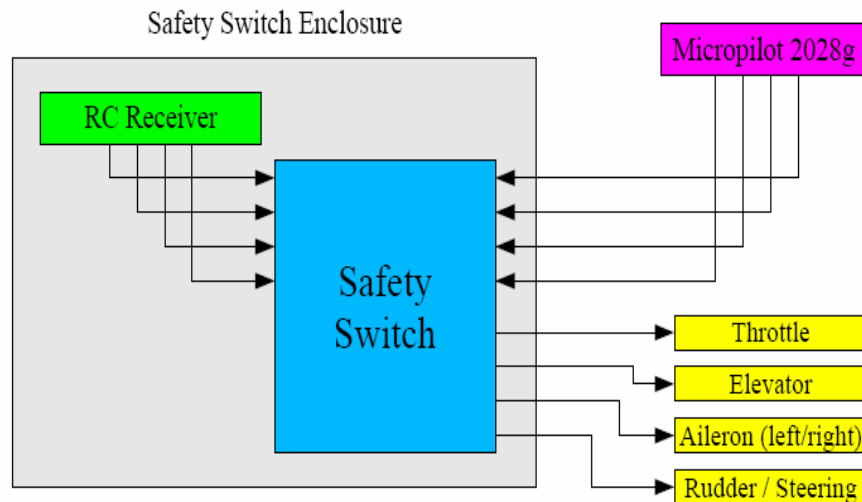
M. Payload Control

The Micropilot partially supplements the imagery payload. Micropilot stabilizes the D50 camera mount to point straight down through the use of a simple table lookup function. This stabilization occurs at approximately 30 Hz, fast enough to eliminate problems from induced camera shake.

Aerial Imagery

The Aerial Imagery payload is the most important sub-system. The imagery system operators must be able to locate and identify targets while ensuring complete coverage of the target area and balancing key factors like field of view and target resolution, both of which are affected by altitude and zoom level. Judges also need high quality imagery and accurate target data in near real-time to assess and evaluate the ground targets. Judges need very concise and detailed target information.

To fulfill these requirements, NCSU has opted for a digital imaging system that consists of the following components:

- Nikon D50: A high-resolution camera that can be controlled remotely and interfaces with onboard computers for the retrieval of picture data
- An onboard computer that interfaces with the camera, position sensors, and the 802.11g 2.4 GHz data link to the ground station computers.
- Imagery analysis software that enables the quick processing of collected imagery and generates a report suitable for printing or display.
- A printer that creates hard copies of high-resolution target imagery and position information for post-flight analysis.

This system relies on the successful interaction between ground station computers and the onboard systems. But, each component is configured to permit imagery collection and analysis to be performed regardless of the status of the data link.

N. Nikon D50 and Camera Stabilization System (D50)

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 runs a stabilization function that reads from the autopilot gyros and moves two servos to cancel out aircraft pitch and roll. This code (implemented in the form of a table lookup function) runs at 30Hz to provide smooth and accurate motion stabilization. The camera is also fitted with a servo-controlled zoom lens to ensure the optimal field of view at the desired flight altitude.

O. Onboard Imagery Computer ("Leviathan")

The onboard camera controller and wireless link is built on a 3.5" embedded mini-board computer, nicknamed "Leviathan." It has a 666MHz processor and boasts standard desktop computer features (USB, Ethernet, sound card, serial ports, video, etc). The device has been extended with the built-in PC/104+ expansion slot to include an 802.11g wireless data transmitter capable of 400mw transmit power. The D50 is operated over the built-in USB 2.0 interface. Custom software enables the camera to capture photos and send them to the computer without ever saving them to a flash memory card.

The onboard software then inserts position and orientation data into the EXIF header of each image. This data is parsed by conventional photo editing software or NCSU's custom imagery viewer. The position and orientation data is derived from external sensors: a single GPS receiver determines position and approximate heading and altitude, while additional sensors, such as a magnetometer or altimeter, can be added to improve

the precision of these measurements. Each photo is saved on the 4GB miniature hard drive, which has room for approximately 1,350 photos.

Leviathan
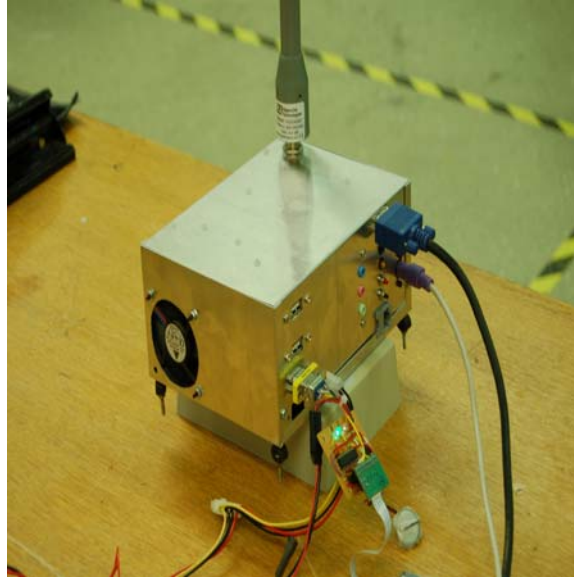
P. Wireless Image Transfer
The images stored on the onboard computer must be transmitted to the ground station before they can be analyzed. Operators can choose to download pictures once the vehicle has landed (by connecting to the computer with a standard Ethernet cord) or attempt to transmit them over the 802.11g data link while in flight. Initial tests showed that this wireless link was prone to interference and intermittent failures. This problem has been moderated by sending the photos with a custom server that configures the connection for the unreliable link. An incomplete picture transfer is resumed once the link is regained. This wireless link is further enhanced by the use of high-power (400mw) transmitters, an 8.5dbi omni-directional antenna on the plane, and a 23dbi parabolic grid antenna on the ground.

Q. High-Resolution Photographs
Each photo captured by the D50 is a 3008x2000 (6 megapixel) image. The ground coverage depends on the altitude and zoom level, but at full zoom out the camera is capable of a 65° viewing angle. At 500 feet of altitude this constitutes a field of view of over 630 feet, and at 1000 feet above ground each picture will cover up to 1200 feet. The Nikon lens has very little distortion through most of the zoom range, but at extreme wide angles the radial distortion is noticeable, making straight lines appear slightly curved. This effect is compensated for in the imagery viewer.

Testing has revealed that photos from above 1000 feet can be valuable for locating points of interest, but the resolution of actual targets is too low to be useful. For the most part, imagery collection will occur at or under 500 feet, exceeding this altitude only to perhaps get an overview of the entire target area in one photo.

Orthophoto from 2000 Feet AGL. The Runway is 450 Feet Long.

## R. Ground Station Imagery Analysis Software

The imagery viewer/analysis software is a tool to help speed up the processing of collected imagery. A central server accumulates all the collected photos. It parses the orientation information and decompresses the JPEG images as they are retrieved (while the plane is flying, if transmitting wirelessly). Each connected viewer (the system supports multiple analysts) displays a bird's-eye-view of the entire area. Incoming pictures are placed according to their recorded position and orientation, effectively mosaicing them in real time. Each picture is corrected for lens distortion as well.

The user interface provides simple point mechanisms to mark a target's location, heading, and size. The analyst can zoom, pan, and rotate the scene. He can generate an HTML file suitable for printing that contains close-ups of each target. In addition, he can select waypoints (to re-task the autopilot) to areas of interest or correct for gaps in coverage. By displaying all the images in their true geo-referenced position, the system is spatially coherent and user friendly, leading to an increase in operator efficiency, accuracy and speed.

Ground Station

Once the telemetry and video are sent to the ground station, the information still needs to be displayed in a user-friendly setup. NCSU opted to place the ground station in a 6 by 12 foot trailer with three computer stations. Two operators can simultaneously search for targets on the imagery software while the third operates the Micropilot software. For the operators, the Micropilot station has a laptop, and the imagery software has two desktops running LINUX.

Ground Station Layout
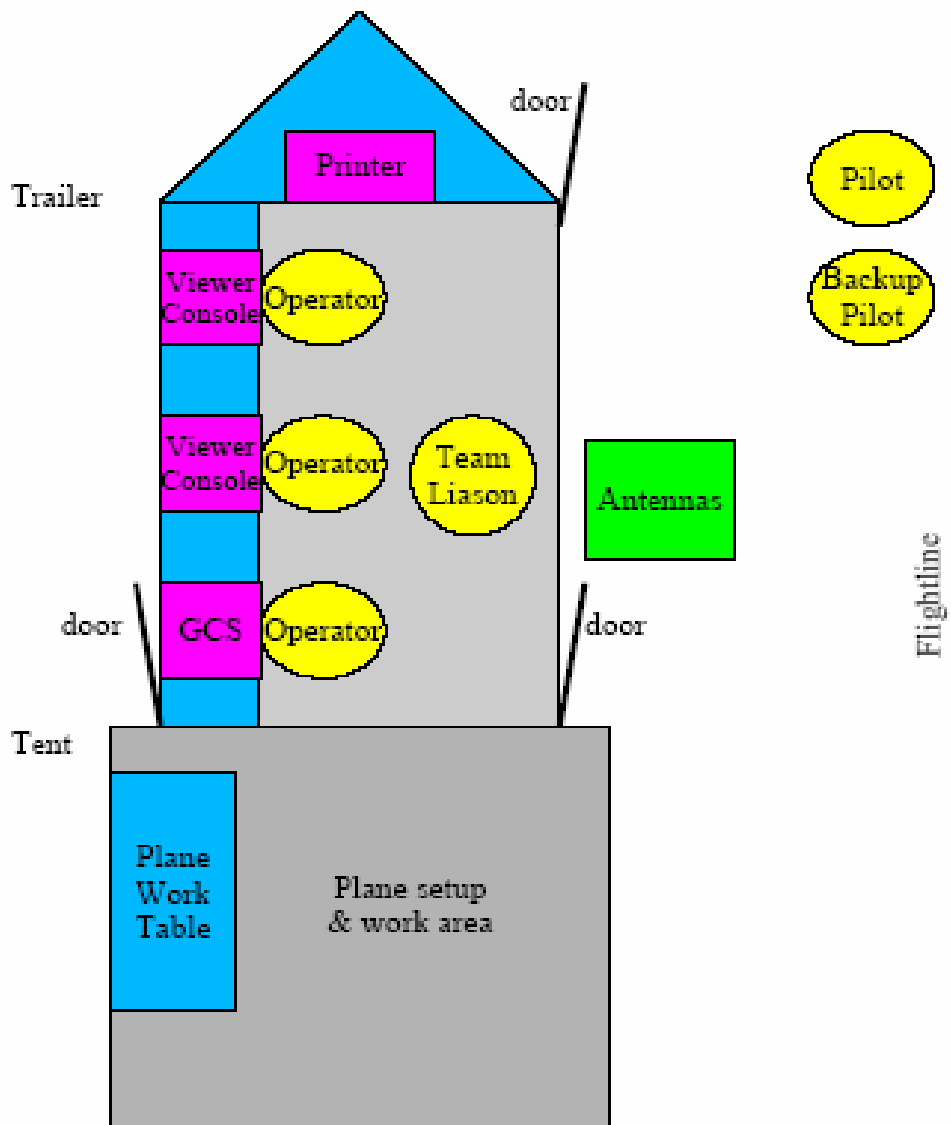
S. Micropilot Ground Station

Micropilot HORIZON Ground Control Station (GCS) requires a standard PC for command and telemetry, so a laptop with integrated monitor performs this task. For operator feedback and control, NCSU has fitted a wireless modem to the Micropilot 2028g and GCS for real-time flight telemetry at a 5Hz update rate. A stationary 5.5 dbi omni antenna is sufficient to ensure long range operation of the 900 MHz telemetry link.

Telemetry Fields

column	data
1	time (hh:mm:ss) from the PC's clock
2	GPS position East in degrees and decimal degrees
3	GPS position North in degrees and decimal degrees
4	Pitch in radians times 1024
5	Roll in radians times 1024
6	airspeed in feet per second
7	gps speed in feet per second
8	altitude in feet*-8
9	rate of change of altitude in feet*-8 per second
10	heading in degrees times 100
11	error field that contains error indicator
12	status bitfield
13	main battery voltage in volts times 100
14	servo battery voltage in volts times 100
15	throttle postion
16	status2 bitfield

The Horizon GCS gives vehicle airspeed, altitude, heading, and GPS location overlaid on a satellite image of Webster field. For dynamic re-tasking, the operator clicks the floating map to place a new waypoint or clicks a scrollbar to change flight parameters.

T. Imagery Analysis Computers

The imagery analysis portion of the ground station consists of several desktop computers, running Debian GNU/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' or 'viewer' computers. All of the imagery computers are networked with a 1000 Mbit/s link, 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 viewing area, zoom level, and so on. 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.

Screenshot of the Imagery Viewer, Showing 6 Selected Targets
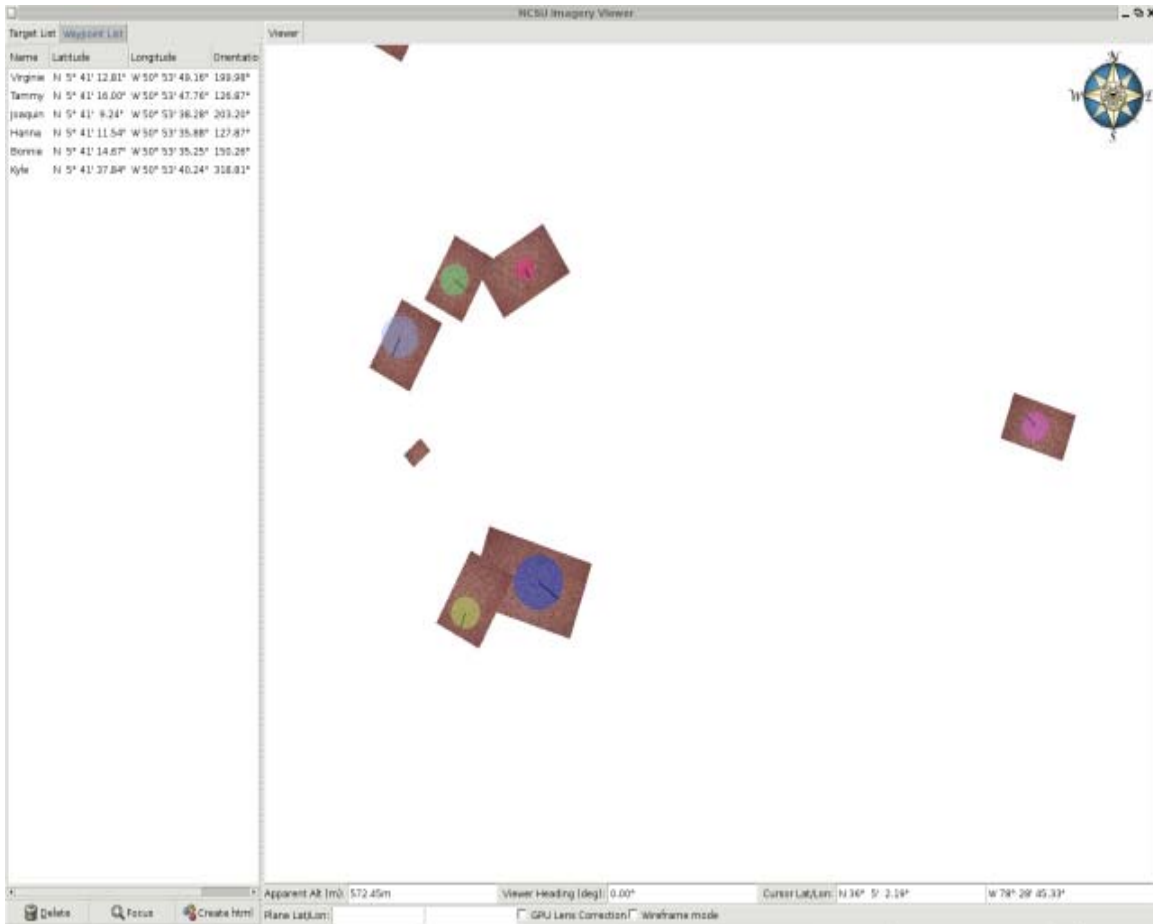
Safety

Both spectator and operator safety is of paramount importance. In addition to a failure mode event analysis (FMEA), specific component and system choices ensure a controlled and safe operation at all times.

U. No-Fly Zones

AUVSI will designate "No-Fly Zones" on the day prior to the competition flight. For quick visual reference, the no-fly zone boundaries will be outlined in red over the Webster Field GCS image. Horizon GCS is programmed with no-fly boundaries, and will automatically divert from headings which would require exit from the competition area.

To back up this built-in functionality, computer simulations will ensure no boundary violations are planned. The GCS operator will monitor the flight path closely to ensure dynamic waypoints will not result in boundary violations. The operator can also drag waypoints around and quickly change the aircraft's heading if needed.

V. Communication Loss

AUVSI rules state that a manual control system must be in place in case of autopilot failure. Furthermore, in the event of manual system control loss, the vehicle should execute a hard-over. To meet this requirement, NCSU uses a PCM RC receiver with a programmed "fail-safe" that defaults the RC Safety Switch to manual and executes a right-handed hard-over.

W. Radio Frequency Interference

RFI is extremely important since the loss of RC communication triggers a hard-over, potentially destroying the aircraft. Over previous years, NCSU has faced numerous radio hits and other interferences at competition and has therefore worked to increase the RC receiver signal-to-noise ratio. To limit RF emissions from onboard components, all computer boards are mounted in grounded metal enclosures, reducing incoming and outgoing RF noise. Antennas have been located as far as possible away from each other and with short cables to reduce stray RF emissions and overlapping signals. Flight testing has confirmed a reduction in RFI related problems.

X. Power/Battery Safety

During all ground operations, an external power supply powers the aircraft. This reduces operator workload checking and charging onboard batteries constantly. The external power source can be switched on or off without shutting down the complete system for easy transition to a flight-ready mode.

During flight, battery voltages are monitored via the Horizon GCS telemetry link. A low voltage case throws a red flag and appropriate action per the FMEA can be taken. The 6v NiMh is the only flight critical battery; however, all batteries will be topped off prior to competition flight to ensure proper systems operation. Battery capacity has been chosen to give a 60 minute or more duration.

Power Diagram
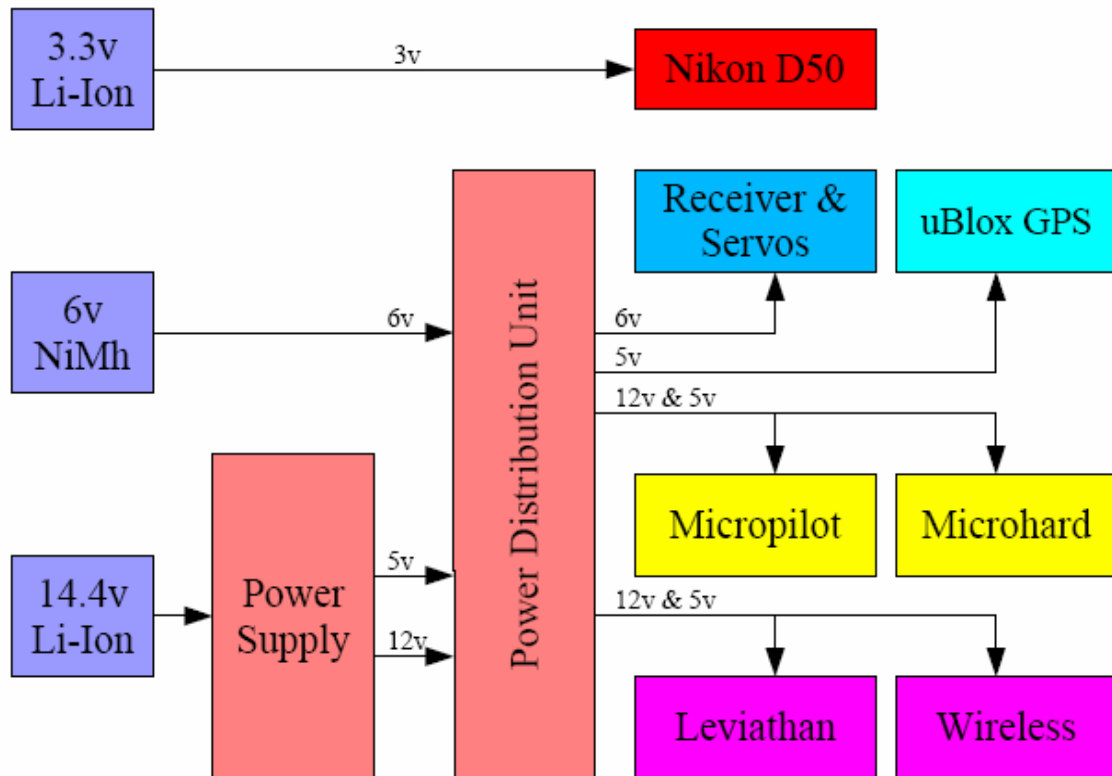
Y. Failure Analysis

To understand the consequences of component failures, NCSU conducted an intense FMEA. Recoverable failures are best, where backup systems take over or compensate for the failure. Mission-critical failures are recoverable, but result in loss of a system needed to complete the mission. Catastrophic failures result in loss of the aircraft.

The FMEA shows the NCSU system is single-fault tolerant, with the exception of the RC receiver, its battery, and the safety switch hardware. A loss of any other component is tolerable, showing the NCSU system is extremely robust and safe.

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
Vehicle breaks in-flight	erratic behavior, falling debris	1. switch to manual mode	mission failure, recoverable
		2. pilot attempts to fly damaged aircraft	mission failure, recoverable
		3. turn off transmitter to activate hard-over	catastrophic
One servo dies	erratic behavior	1. autopilot attempts to fly without servo	mission continues
		2. if flight appears erratic, switch to manual control	mission failure, recoverable
		3. pilot attemps to fly aircraft, lands	mission failure, recoverable
		4. if condition irrecoverable, activate kill mechanism	catastrophic
Engine dies in flight	change in aircraft sound, noticable drop in airspeed	1. pilot switches to manual mode	mission failure, recoverable
		2. emergency landing procedure	mission failure, recoverable
6v servo battery low	indicated on GCS screen	1. pilot switches to manual and lands immediately	mission failure, recoverable
12v payload battery dies	indicated on GCS screen	1. pilot defaults to manual control	mission failure, recoverable
Autopilot malfuction	erratic behavior	1. pilot defaults to manual control	mission failure, recoverable
Loss of GPS signal	GPS link indicator red	1. aircraft initiates a 30 degree bank orbit maintaining pressure altitude	mission continues
		2. If GPS signal does not return after one minute, switch to manual	mission failure, recoverable
Autopilot uplink lost	telemetry data stops	1. cannot provide dynamic control; watch closely for link to return	mission continues
Imagery uplink lost	picture download intermittant	1. wait to see if link returns	mission continues
		2. GCS operator commands fly-by	
		3. download images after landing	
Loss of sight of vehicle	pilot calls "out of visual range"	1. pilot orders camera operator to point forward	mission continues
		2. pilot flies via the video TV screen	
		3. backup pilot watches sky for vehicle	
		4. pilot resumes watching vehicle in the sky	

Z. RC Safety Switch

As a direct result of an early FMEA, an external RC Safety Switch was added between the manual RC receiver, autopilot, and servos to govern servo control. The safety switch is common power to the manual RC receiver, thus always giving ability to manually override the autopilot. This separation of the servo switching from the autopilot allows the autopilot to fail without affecting manual control.
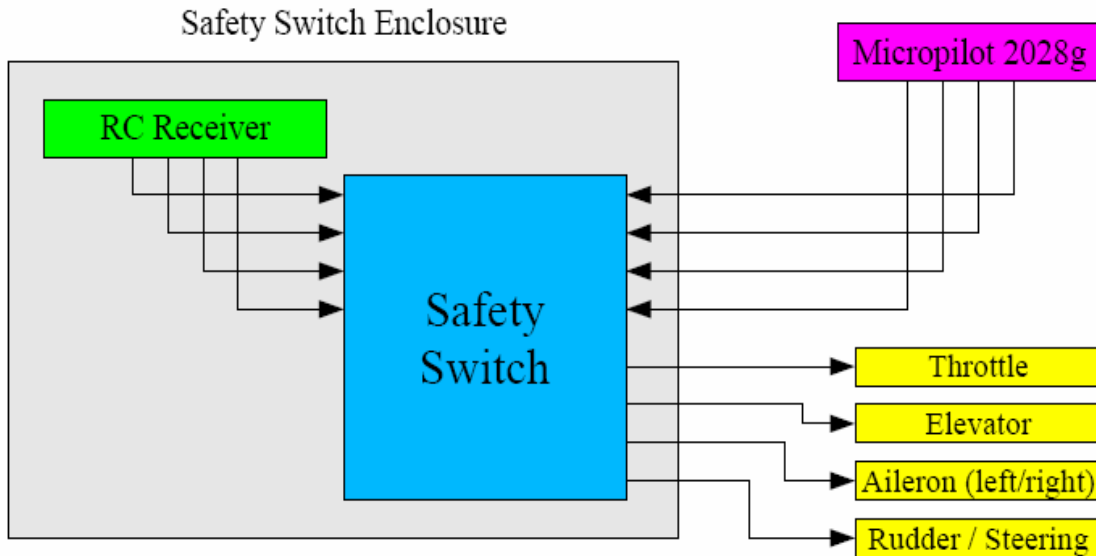
Conclusion

The NCSU system can complete the AUVSI mission fully and within the given time limit while following all rules and regulations. Splitting into four sub-systems helps NCSU divide and conquer, allowing modularity, use of COTS parts, and make easy future modification of individual sub-systems. The judges' target imagery hard-copy printer gives concise target evaluation in near real-time and more detailed high-resolution images upon request. Dynamic re-tasking is accomplished through a wireless link between the Micropilot and the ground station. The imagery viewing software sets us apart from other known UAV systems. NCSU believes it gives unparalleled speed to acquire, identify, and track targets while strengthening situational awareness. Additionally, the ground station trailer setup makes our 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 fully complete the 2006 AUVSI Student UAV Competition mission.

Acknowledgements