North Carolina State University

Aerial Robotics Club

Autonomous Reconnaissance System

Author:
Dan Edwards

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Abstract

This paper describes the North Carolina State University Aerial Robotics Club Autonomous Reconnaissance System designed specifically to meet the 2005 AUVSI 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. 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 2005 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 Senior Telemaster airframe carries 7 lb payload at 35 mph for 30 minutes flying time. After a manual takeoff, a Micropilot 2028g autopilot guides the aircraft through given GPS waypoints and begins a circular orbit pattern over the search area. A wireless modem connects the ground station and autopilot for in-flight reprogramming. A ground operator controls a pan-tilt live video-downlink to survey the search area for target count. The ground station overlays a GPS grid pattern for easy target location and orientation assessment. A downward-looking digital camera also sends live video and is overlaid with current GPS position info. High-resolution 4.1-megapixel photos are downloaded and printed after landing. Three additional monitors and a printer give the judges independent access to the imagery and data.

Systems Engineering

A. Interface Requirements

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

- Distribute **GPS waypoints** before mission and during mission
- Distribute **dynamic re-tasking** requirements during mission
- Monitor **vehicle position** for waypoint and dynamic re-tasking confirmation
- See **live imagery** feeds for real-time assessment
- Receive an **imagery hard-copy** for post-flight assessment

Following these requirements, NCSU created an interface control diagram to govern the exchanges of information (see Appendix 1).

Waypoint information will be exchanged on a slip of paper between the judges and team liaison. Real-time video feeds from the aircraft will arrive at the judge station monitors. Target imagery will arrive at the judges' printer and will include target location and orientation. Total target count will arrive at the judges' printer in a list of target number, coordinates, and orientation.

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. The complete system design can be found in Appendix 2.

C. Test Philosophy

To ensure quality manufacturing and to certify the system, NCSU adopted a safe and thorough testing policy. Each part has its own individual test flight. After all components are tested individually, only one complete system is added at a time. 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.

Vehicle

The competition vehicle requirements are quite simple: integrate with 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. Senior Telemaster

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

- change from a tail-dragger to a tricycle landing gear – for better ground-handling
- fully boxed wing spar and integrated wiring conduit tubes – for easy payload integration and extra structural margin
- bolt-on wings instead of rubber banded wings – to facilitate easy access to the payload bay
- removable tail – for easier aircraft transportation

An OS .61FX engine is mounted in tractor configuration and runs for 30 minutes on a 16 ounce fuel tank at 35mph cruise speed (approximately half throttle) with a max power of 1.5HP.

Ballasted test flights to 17 pounds takeoff weight have certified the airframe and verified all handling requirements are met while fully loaded. See Appendix 3 for a picture.

F. Payload Compartment

Since the measure of a good transport vehicle is how well it carries payload, the Senior Telemaster has been constructed to have an open 4.5" x 14.5" x 7.5" payload bay and optional payload space in the tail immediately aft the wing. The main volume is centered on the Center of Gravity (CG) and can carry up to 7 pounds of payload. Vibration sensitive components have been bolted to anti-vibration mounts. The tail compartment includes integrated hard-mount shelves for additional components.

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 tube and pan-tilt camera systems are attached at these wing-mount locations.

H. Center of Gravity

The Senior Telemaster CG is 4.75” behind the wing leading edge, as recommended by Hobby-Lobby. The CG is rough-adjusted by locating the internal payloads strategically and locating the belly payload to achieve approximate balance (within 1/2" possible). Fine tuning the balance 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. 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

To decrease autopilot and operator workload, the approach to a target waypoint is not governed by aerial imagery requirements. The autopilot must not fly directly over ground targets. The imagery systems compensate independently for the aircraft attitude and heading. Having no flight-path requirement has helped speed autopilot development considerably and allows the GC operator to add new waypoints with minimal aerial imagery knowledge.

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 Micropilot computer. A ground plane increases the antenna's receive sensitivity and RFI resistance.
- A pitot-static probe is mounted 20 inches out the left wing to avoid the slipstream of the propeller; pressure tubing runs through the wing into the main payload compartment.
- An Aerocomm 2.4 GHz, 9600 baud wireless card is mounted in the tail payload compartment to get it away from Micropilot RF. It is housed in an aluminum enclosure for reduced RF emissions and easier handling.

See Appendix 4 for a system schematic that includes the Micropilot peripherals.

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. A system schematic for this setup is located in Appendix 5.

M. Payload Control

The fly file also contains all payload control algorithms, such as a camera stabilization algorithm and high-resolution camera trigger routine. Using the wireless data link, this payload control file can be modified in flight to change the stabilization rates, or other payload parameters.

N. Telemetry

Vehicle telemetry is communicated through the wireless data link. This 5Hz data is in standard ASCII format and contains the user-programmable fields listed in Appendix 6.

Aerial Imagery

The Aerial Imagery payload is the most important sub-system. Judges need high quality imagery and accurate target data in real time to assess and evaluate the ground targets. Judges also want fast and simple access to the information.

To fulfill these requirements, NCSU has opted for a wide range of imagery equipment that includes:

- A computer controlled pan-tilt live video feed with a floating GPS grid overlay for quick target location and orientation assessment.
- A downward looking live video feed with overlaid GPS information for quick reference.
- A printer that creates hard copies of high-resolution target imagery and information for post-flight analysis.
- A Micropilot Horizon GCS screen for waypoint confirmation.

This multi-faceted aerial imagery system ensures all targets are identified and "captured" as the aircraft flies over the search area and gives the judges independent access to the imagery.

O. Wing-Mounted Pan-Tilt

The Pan-Tilt is a servo actuated 200 degree yaw/roll mount that allows a quick surveillance of a large area via the grid overlay program. The large viewing area gives an operator the ability to find targets virtually anywhere around the aircraft.

The camera is located 12.5 inches from the fuselage and 4 inches below the right wing. This location was chosen to allow unobstructed line of sight directly below the aircraft during a 60 degree left bank.

P. Grid Overlay

The Pan-Tilt video output is sent wirelessly to the ground station where a floating GPS grid is overlaid on the video stream. This grid overlay allows judges to quickly determine where targets are located and how they are oriented.

To change the Pan-Tilt's view, a user clicks and scrolls on the grid overlay screen. An auto-tracking mode is also available that maintains view of arbitrary ground targets, reducing the operator workload.

To harvest target information, a double click creates a virtual target tag that moves with the grid. A list of tagged target locations is dynamically updated on the grid screen for immediate and detailed target feedback. In this manner, the grid overlay operator can quickly survey an area and gather target information.

This style of computer-enhanced map overlay is unique to NCSU and has no known commercial equivalent. See Appendix 7 for an example grid overlay screenshot.

Q. Ortho-Optio

The "Ortho Optio" is a Pentax Optio S4i 4.1 megapixel digital camera mounted on a servo controlled two-axis mount underneath the fuselage. The autopilot payload control program runs a stabilization loop that reads from the autopilot gyros and moves two servos to cancel out aircraft pitch and roll. This code runs at 30Hz to provide a smooth and accurate ground-orthogonal view by the Optio camera. See Appendix 8 for a detail photograph.

R. High-Resolution Photographs

The Optio still images are stored onboard (up to 1 GB, roughly 270 pictures). GPS information is overlaid on the Optio video feed only. During still imagery processing, the camera screen goes black for two seconds. At this time, GPS information can be recorded from the screen overlay. After landing, the photos are downloaded and selectively printed for review by the judges.

To ensure imagery capture of all targets, a series of photos are taken over the search area. At 500 feet altitude, the Optio's wide field of view covers a 250 foot radius circle in two to three photographs. Since vibration causes intermittent blurriness, multiple photos are triggered during the flight to guarantee at least one sharp image of each target. The Micropilot triggers the camera at three second intervals. The operator can manually trigger a photo, also.

S. Horizon GCS Screen

While not imagery, the Horizon GCS screen is provided to judges to provide better situational awareness of the live video feeds.

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. Also, to meet the NCSU derived interface requirements, the judges need easy access to the live video downlinks.

NCSU opted to place the ground station in a 6 by 12 foot trailer with a dual operator/spectator screen setup. For the operators, the Micropilot station has a laptop, the grid overlay station has a LINUX laptop, and the Ortho-Optio simply has a TV monitor. The judges have an additional viewing station or can look over the operators' shoulders.

T. 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 manually pointed 23.5dbi grid antenna maintains communication link on a frequency of 2.4GHz.

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.

The Micropilot Ground Station also runs XTENDERmp software. Custom NCSU code accesses the live telemetry data stream from the GCS and pipes it to a TCP server where it is shared between computers. A full list of telemetry parameters is in Appendix 6.

U. Grid Overlay Computer

A laptop running Debian GNU/Linux performs real-time video processing, data assimilation, and display from multiple sources. This computer receives vehicle attitude, altitude, and location telemetry from a TCP/IP server. A real-time video stream provided by the Pan-Tilt camera is input using COTS hardware.

The telemetry stream arrives at a theoretical maximum rate of 5Hz (typically 2Hz), which is unacceptable to the eye when merged with real-time video. To project the vehicle's attitude state forward between telemetry updates, the Lucas-Kanade method is used to compute the optical flow between successive video frames in multiple regions of the source image. The implementation of this algorithm is provided by the Intel OpenCV open-source software library and considerably smoothes the grid motions.

The video stream produced by the Pan-Tilt has a noticeable fish-eye deformation. A real-time polynomial radial-direction scaling algorithm corrects for this distortion. The computationally expensive algorithm is offloaded to the graphics chip for a noticeable performance gain.

For operator convenience, a software-based third axis of rotation automatically levels the source video relative to the horizon.

As a final operator aid, an auto-scaling auto-orienting North-South/East-West aligned grid is overlaid directly on the video stream.

V. Additional Viewing Station

To alleviate spectators crowding around a single video screen, three additional monitors show:

- Pan-Tilt video grid overlay
- Ortho-Optio video with GPS overlay
- Micropilot Ground Station screen

This allows multiple spectators to view the imagery and allows uninterrupted team operation. The judges' station also has a color printer that allows printing of selected target data or imagery hard-copies.

See Appendix 9 for a layout of the ground station trailer including the additional viewing station.

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.

W. 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 in Appendix 10 shows the NCSU system is single-fault tolerant, with the exception of the RC receiver and its 700mah NiMH battery. A loss of any other component is tolerable, showing the NCSU system is extremely robust and safe.

X. 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. 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 drag waypoints around and quickly change the aircraft's heading if needed.

Y. 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. A system schematic for this setup is located in Appendix 5.

Z. 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.

AA. 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 aluminum enclosures to act as faraday cages, 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.

BB. 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. All batteries will be topped off prior to competition flight. Battery duration has been tested to over 60 minutes, so battery life is not of concern. See Appendix 11 for a power system diagram.

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' observation station 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 Micropilot and the ground station.

The grid overlay system 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 2005 AUVSI Student UAV Competition mission.

Acknowledgements

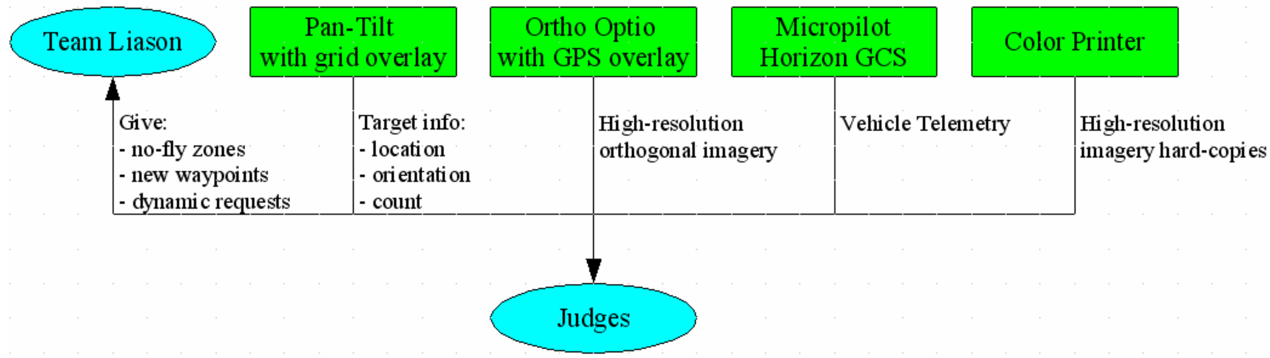
North Carolina State University's Aerial Robotics Club is proud and honored to compete in the 2005 AUVSI Student Unmanned Aerial Vehicle Competition and would like to thank the following sponsors, who made our participation possible:

- Malcolm McAllister
- Micropilot
- Hobby-Lobby
- Boeing
- Square D
- NCSU E-Council
- NCSU SGA
- MAE Department
- NCSU Flight Research

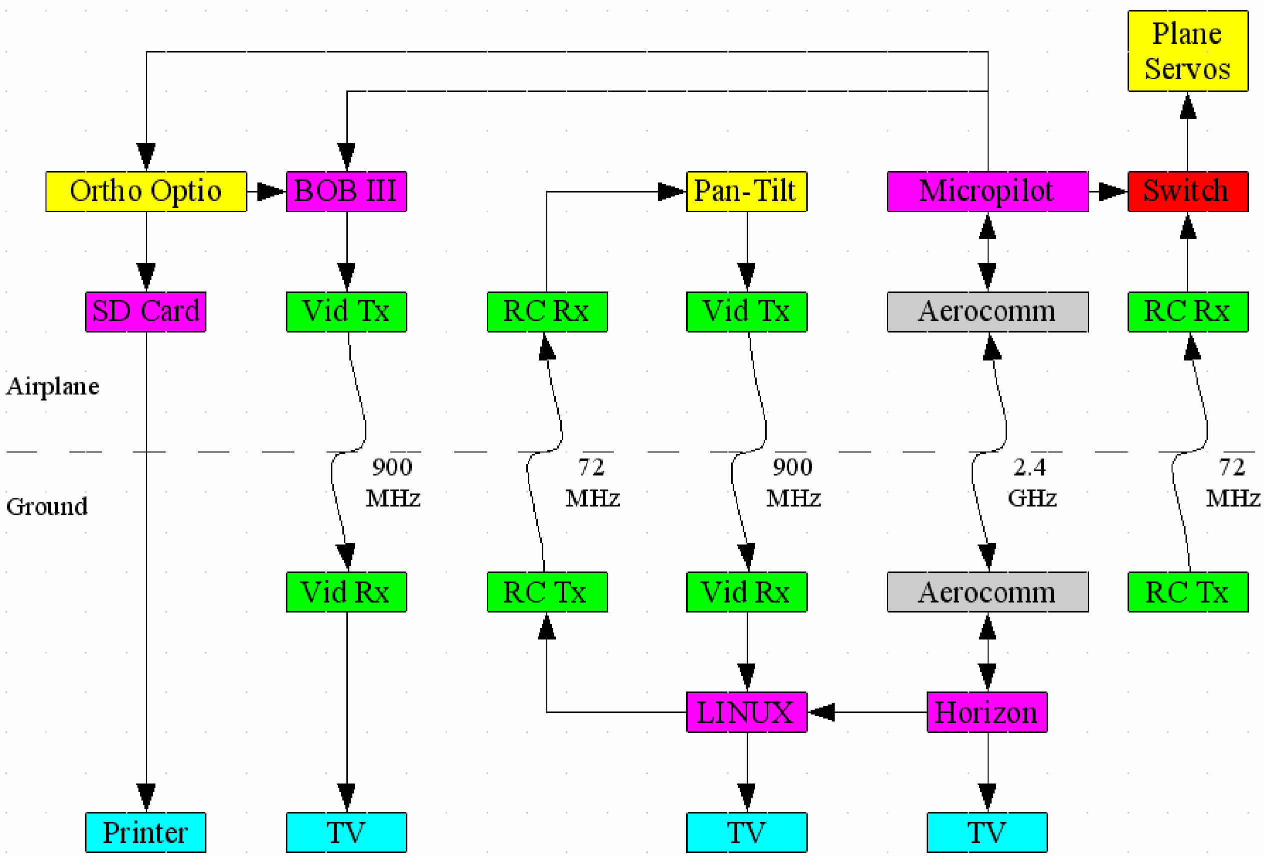
ARC

Appendix

1. Interfaces Block Diagram

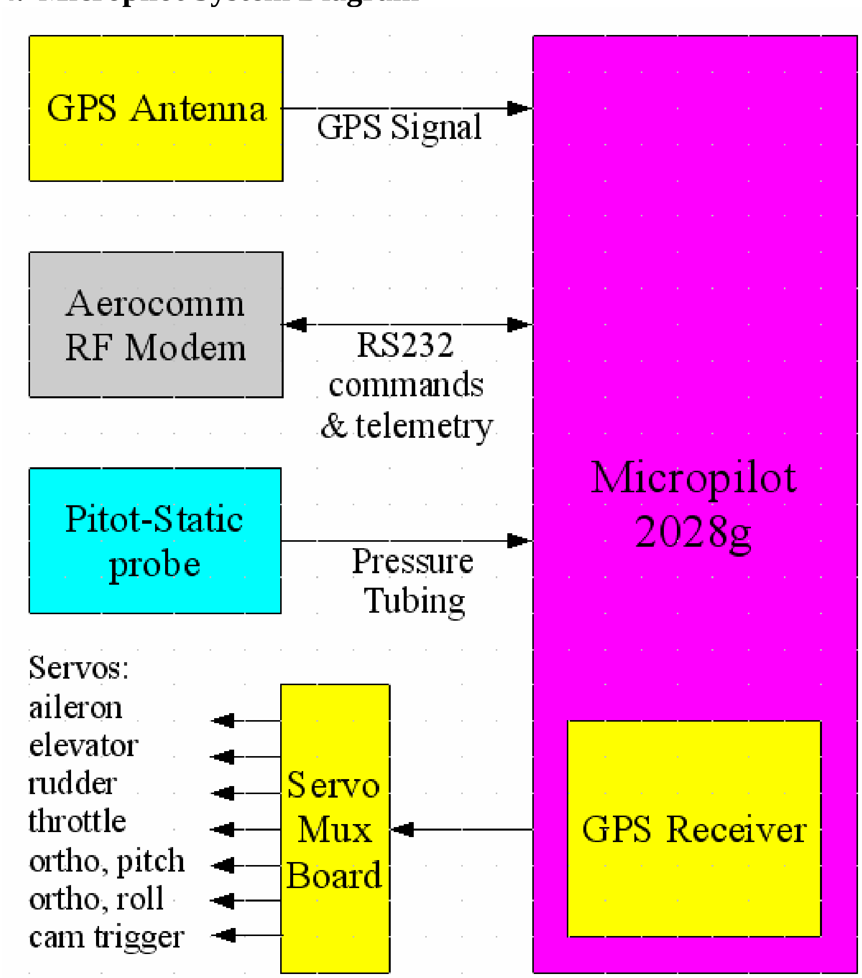


2. System Block Diagram

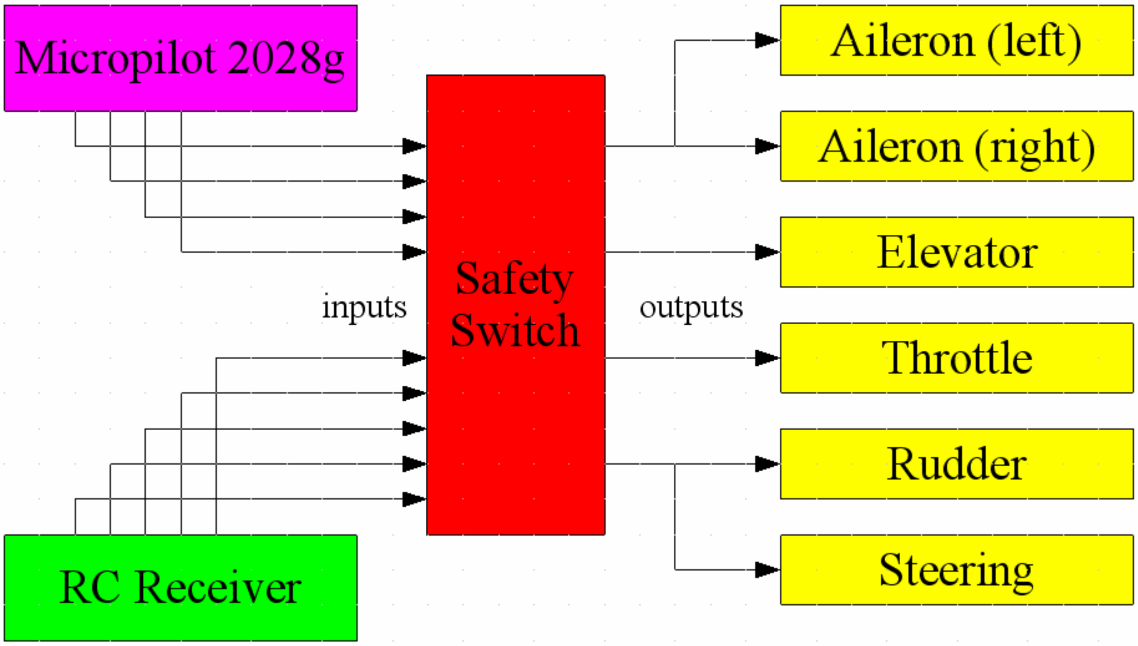


3. Vehicle Photograph

4. Micropilot System Diagram



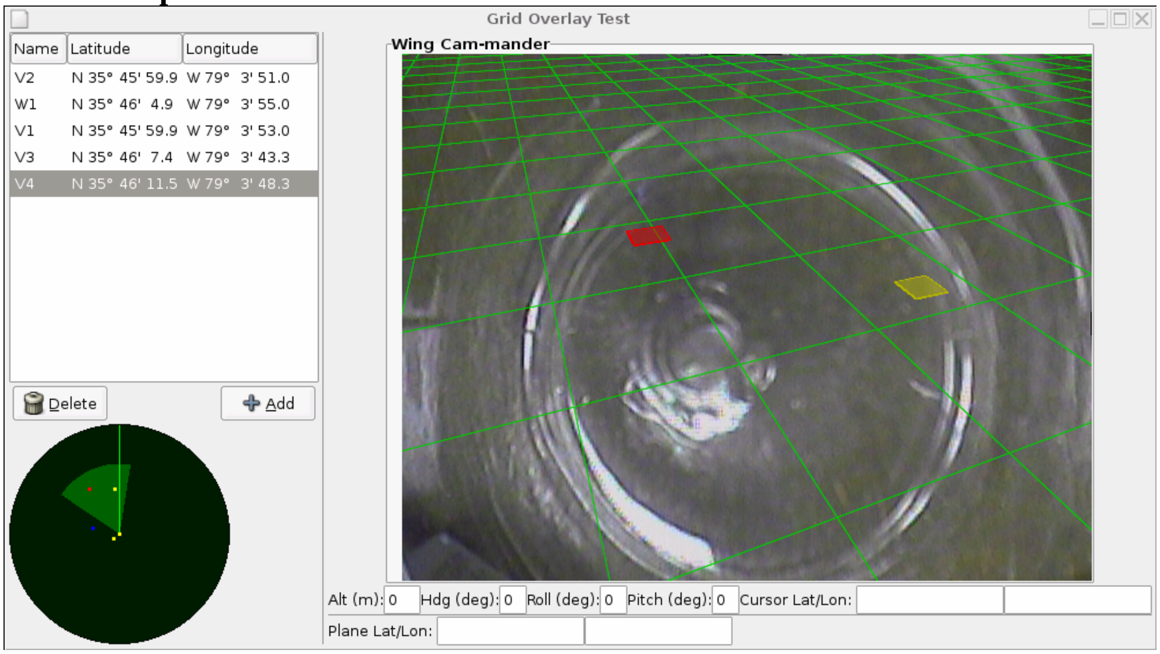
5. RC Safety Switch Implementation



6. Telemetry Fields

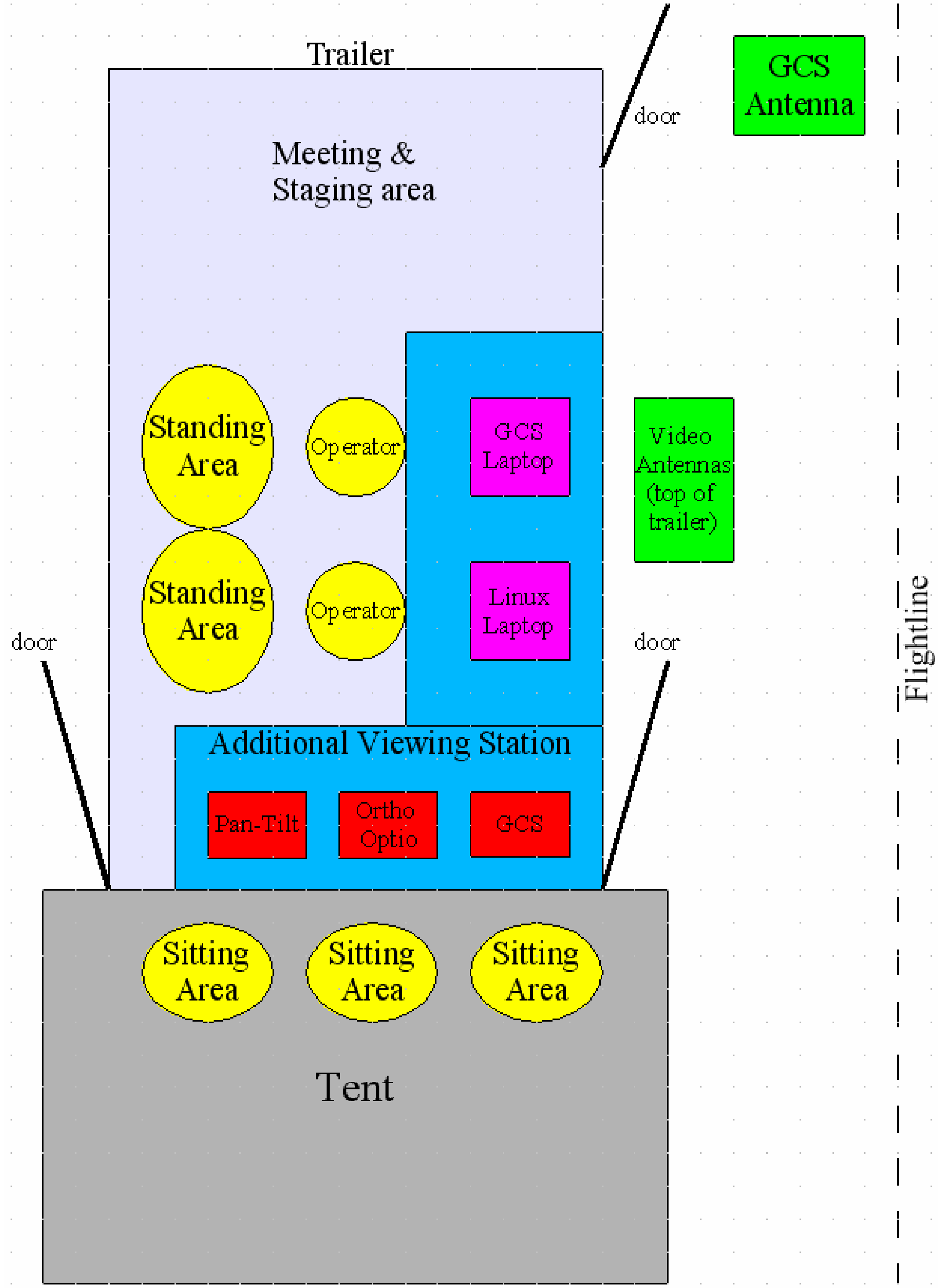
column	data
1	time (hh:mm:ss) from the PC's clock
2	GPS position East in degrees and decimal degrees
3	GPS position North in degrees and decimal degrees
4	Pitch in radians times 1024
5	Roll in radians times 1024
6	airspeed in feet per second
7	gps speed in feet per second
8	altitude in feet*-8
9	rate 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

7. Ortho-Optio Screenshot



8. Ortho Optio Mount

9. Ground Station Trailer Layout



10. Failure Mode Event Analysis

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 malfuction	erratic behavior	1. pilot defaults to manual control	mission failure, recoverable
12v avionics battery dies	indicated on GCS screen	1. pilot defaults to manual control	mission failure, recoverable
Loss of uplink	telemetry data stops	1. NCSU relies on Ortho Optio with GPS overlay	mission continues
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
4.8V servo battery low	indicated on GCS screen	1. pilot switches to manual and lands immediately	mission failure, recoverable
12V video battery dies	video stops responding, overlay turns off	1. NCSU relies on onboard high-res images	mission continues
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
Loss of sight of vehicle	pilot calls "out of visual range"	1. pilot orders camera operator to point forward	recoverable
		2. pilot flies via the video TV screen	recoverable
		3. backup pilot watches sky for vehicle	recoverable
		4. pilot resumes watching vehicle in the sky	recoverable
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
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 attemps to fly aircraft, lands	mission failure, recoverable
		4. if condition irrecoverable, activate kill mechanism	catastrophic

11. Power Diagram