NC STATE UNIVERSITY

ARCWulf Unmanned Aerial System

May 23, 2011

ARCWulf Unmanned Aerial System

NC State University
Aerial Robotics Club

May 23rd, 2011

Abstract

The ARCWulf Unmanned Aerial System was designed by the North Carolina State University Aerial Robotics Club to fly an autonomous surveillance mission. The system, housed in a modified telemaster airframe, utilizes a commercial autopilot subsystem which works alongside a custom imagery subsystem to create a geographically referenced mosaic of images based on the location and heading of the aircraft when the image was taken. Flight testing has verified that the ARCWulf system is capable of meeting all threshold mission requirements for autonomy, target imagery and location, mission time, operational availability, and in-flight re-tasking. Additional autonomous take-off and landing testing is expected to occur before the final mission demonstration to ensure repeatability.

Table of Contents

I. Systems Design

The NC State Aerial Robotics Club is on its third iteration of the 8 foot Telemaster reconnaissance aircraft. This aircraft was designed to carry a system capable of autonomously taking high resolution photos of targets and locating those targets with a high degree of precision and accuracy.

Safety was a key design consideration for each subsystem and the entire system as a whole. Ensuring the safety of every subsystem and component reduced the risk to personnel and the system. Risk mitigation also increased the mean time between failures, reducing time spent on repairs as well as the need to test repaired or replaced components, allowing time to be focused on system improvement.

Supporting the imagery subsystem is at the core of the system design due to its importance in addressing the mission requirements. A dependable still camera with a wide angle lens capable of imaging large portions of the target area was found far more useful than a video based subsystem for imaging still targets. The camera is mounted in a gimbal capable of aiming the camera as needed. This improved imagery quality during turns by reducing distortion due to angular velocity. The gimbal also allows for imaging the off-axis target as well as protecting the camera with a "Stow" mode. Accurate telemetry data is embedded in each image to allow for geo-location of the images. Also, in order to receive points for actionable intelligence, the system is capable of transmitting each image as it is taken to allow time for the ground team to evaluate the data.

Supporting the imagery subsystem are the aircraft and autopilot subsystem. The higher payload capacity of the aircraft also allows for a larger imagery payload. The stability of the aircraft reduces perturbations due to gusts and turbulence thus improving image quality and handling by either the safety pilot or the autopilot. The autopilot provides reliable flight performance allowing for better evaluation of the imagery subsystem.

System integration was also important to improving system performance. By integrating the autopilot's telemetry data into the imagery system, extra hardware and complexity were eliminated. This also reduced the number of failure points, total payload mass, and cost of the payload. The smaller component count also reduced the amount of time required to test all the components of the system.

Parameter	Threshold	Objective
Autonomy	Navigation	Take-off & Landing
Imagery	2 Target Characteristics	5 Target Characteristics
Target Location	Within 250ft	Within 50ft
Mission Time	Within 40 Minutes	Within 20 Minutes
Operational Availability	50%	100%
In-Flight Retasking	Additional Waypoint	Additional Search Area

Table 1: Mission Performance Goals, Green Indicates Expected Capabilities

The competition rules specify a number of system threshold requirements and objectives. Based on mission performance at regular flight tests, the system has been shown to surpass all threshold requirements. Currently, work is on-going for autonomous take-off and landing maneuvers. Although these maneuvers have been successfully demonstrated, they are still in testing as discussed in the "Testing and Evaluation" section. High-accuracy targeting is also still in development and is expected to be achieved by competition due to planned simplifications in the imagery processing system that should improve performance. It is not expected that the mission will be completed in less than 20 minutes, but the mission is expected to be completed within 40 minutes.

To insure operational availability objectives are met, NCSU will be attending competition with a spare aircraft, autopilot, and flight computer. These components are interchangeable with the primary system to ensure a complete functioning system at the time of flight, even if an unexpected problem may arise after extended travel. This provides a backup to every component of the primary air system with the exception of the magnetometer and AGL sensor which are not mission critical.

II. Safety

Safety was the most important concern for all tasks. Protocols were put in place to insure the safety of the team and other persons first and the aircraft second. Checklists were implemented to insure these protocols were followed. Safety was also the primary consideration in the implementation of each component of the system. An example of this analysis is the failure modes and effects criticality analysis (FMECA), which can be seen in Appendix B.

A. Design

Throughout the design of the system, the safety of each component was evaluated before inclusion. Components were not included until their inherent risks were reduced to an acceptable level. The Telemaster airframe reduces the inherent risks as a stable, robust platform. Several other design features, including a safety switch and communication redundancy, were implemented to reduce risk when testing the system.

1. Safety Switch

The safety switch allows control of the aircraft to be transferred between the safety pilot and the autopilot. Mounted in the fore of the aircraft, it allows control to be transferred at any point in the flight, even if the autopilot is not functioning properly. Additionally, if the primary radio control link is lost, the system defaults to the autopilot control system.

2. Communication Redundancy

Three wireless links provide communication between the air vehicle and the ground. These three links are the primary 2.4 Ghz radio control transmitter, the 900 Mhz autopilot ground station, and the 5.2 Ghz imagery ground station. The safety switch is configured to allow the autopilot to assume control of the aircraft if the primary transmitter link were to fail. A secondary transmitter is also connected to the air vehicle through the autopilot connection to allow the safety pilot to perform a landing using the 900 Mhz autopilot link. Since the chance for simultaneous failure of these links is low, and has not been experienced in any flight or ground testing, it is expected that a catastrophic incident involving loss of communication would be rare.

None the less, if both of these communication links fail, the autopilot is configured to then track to an orbiting waypoint. From there, the aircraft will remain in the orbit while the communication issues are addressed. While communications are lost the link used by the imagery ground station can be configured to send commands to the autopilot. If the control issues have not been resolved after 3 minutes, the air vehicle will terminate flight in accordance with the competition rules. This safety feature prevents catastrophic loss of the aircraft due to a fly-away.

B. Operations

A number of procedures and checklists work to keep team members, guests, and the system safe. Before each flight test the entire team is required to review the protocols before any missions can begin. All team members not within the trailer are required to keep an eye on the aircraft while it is in the air, and spotters watch out for those within the trailer. During periods of heads up flight, typically during autonomous takeoff's and all landings, all team personnel at the field are required to be standing and have eyes on the aircraft. During normal flight, all unnecessary talking and noises outside the trailer are suspended. A chain of command for decision making eliminates confusion and expedites the decision making process.

C. Personnel Assignments

Individuals attending a flight test are given assignments to insure that everyone remains focused and on-task. An individual may be assigned to flight line crew, aircraft crew, or trailer crew.

1. Flight Line Crew

Only members of the flight line crew are allowed at the flight line while the engine is on. The flight line crew consists of the flight test director, the safety officer, the safety pilot, and the backup safety pilot if present.

The flight test director briefs the team before each flight on the tasks to be performed. During flight, the flight test director is kept aware of the mission status by the imagery and autopilot teams. Based on this information the flight test director has the discretion to continue or cancel any particular task. At the conclusion of the mission the flight test director initiates a debriefing.

The safety officer is in charge of providing the checklists for the flight crew, and ensuring that the protocols are followed.

The safety pilot handles the transmitter and controls the aircraft when not flying in autonomous mode. The safety pilot is responsible for the safety of the air vehicle while it is flying, as well as initiating the hand-offs to and from autonomous control. If the safety pilot feels that the aircraft or its flight crew is at risk then the safety pilot may immediately assume control of the air vehicle. If the safety pilot assumes control, it will be declared by the safety pilot such that the autopilot team and the flight test director are aware. The backup safety pilot will assume the role of safety pilot if anything interferes with the primary safety pilot's ability to do his duties.

2. Aircraft Crew

The aircraft crew is in charge of the air vehicle. The aircraft crew must unpack the air vehicle, put fuel in the tank, change batteries, test the R/C systems, and start the airplane. During flight, all members of the aircraft crew are required to be back off the flight line and away from the runway. The aircraft crew serves as spotters for the trailer crew, who are unable to see the aircraft.

3. Trailer Crew

The trailer crew is comprised of the imagery team and the autopilot team. The imagery team typically has two members who set up and run the imagery software. The imagery team is responsible for manipulating the imagery viewer and locating targets. The autopilot team is normally a two man team in charge of the autopilot. The autopilot team is responsible for accepting hand-offs to and from the autopilot and for commanding the path to be followed by the air vehicle.

D. Mission Planning

All tests to be done on a flight test must be planned before the flight test begins. Each subsystem must perform flight readiness tests before a flight test. For the autopilot subsystem, new flight plans are simulated to show that the air vehicle is capable of safely flying the expected flight path. For the imagery subsystem, all new code must be tested and the full system evaluated to insure proper functionality. For the air vehicle subsystem, each control surface and servo must be checked to ensure proper deflections and secure mounting. The engine must be started and run through its full RPM range. A taxi test and primary transmitter range test must also be performed. If any of these preparatory checks locate a problem, the problem must be resolved before the flight test. If the problem requires more time to solve, the flight test is then postponed.

III. Air Vehicle

The air vehicle is a modified 8ft Telemaster aircraft. Four primary modifications were performed to the original Telemaster design to facilitate easy implementation of subsystems on the aircraft. The first major modification, the camera bay, was cut out of the forward fuselage. This was done to allow room for the custom built gimbal and the camera. The air vehicle fuselage is also wider than the original Telemaster design. This modification was performed to allow more room for the on-board imagery computer. To account for the extra weight that the airplane must carry, the wing spar has been strengthened with Carbon Fiber and Fiberglass, and the landing gear converted to a tricycle configuration for easier takeoffs and landings.

The air vehicle is a tractor configured airplane pulled by an OS Engines FS 120S-III engine. Mounted on Aluminum brackets, the engine draws fuel from a 24oz fuel tank just aft of the engine. The avionics are powered by two batteries located in the forward bulkheads, next to the fuel tank. Power to all servos is supplied from a 6V, 2200 mAh, Nickel Metal Hydride (NiMH) battery. The payload, including the autopilot, the on-board imagery computer and its peripherals are powered by an 11.1V, 5000 mAh, Lithium Polymer (LiPo) battery. The aircraft's safety switch is located immediately behind a bulkhead separating the battery and fuel compartments from the rest of the payload bay. Romulus, the on-board imagery computer, is located under the wing in the fuselage.

The ground power interface and power switch panel is installed on the tail of the aircraft. Directly under the switch panel is a distribution board which provides power to the autopilot, flight computer, RC, and gimbal control systems. Power can be turned on and off individually, making testing easier and allowing the components to boot in the correct order. All connectors used to carry power are locking connectors. The ground power system, which consists of a power supply and necessary connectors, allows the plane to be powered off a standard 120V source, such as from a generator.

IV. Autopilot

In accordance with the mission requirements, the autopilot subsystem had to fulfill three primary requirements. The first of these requirements was the capability to safely maneuver the air vehicle through various waypoints at specific altitudes and GPS coordinates. The second primary requirement was that the system display real-time telemetry data, including altitude, airspeed, and GPS coordinates, as well as all flight boundaries, to ground operators. The final primary requirement was that the autopilot subsystem must have the capability to adjust mission search areas and waypoints mid-flight.

A Piccolo LT autopilot, manufactured by Cloud Cap Technologies, was selected for implementation within the system because of its capability to accomplish all three primary requirements. The Piccolo LT was designed to guide the aircraft to waypoints based on GPS coordinates and altitudes. Through a wireless link with the ground station, the state of the aircraft is displayed in real-time through an intuitive interface. The ground station connection also allows real-time changes to the waypoint instructions followed by the autopilot.

A. System Integration

An important feature of the Piccolo LT autopilot is its compatibility with the other subsystems. The autopilot device needs to communicate appropriate surface deflections to the air vehicle, provide telemetry to the on-board imagery subsystem, and transmit telemetry and waypoint information to the ground station.

The interface between the autopilot and the air vehicle allows the autopilot device to command servo positions for the ailerons, elevator, rudder, and throttle. The rudder signal is additionally split off to the nose wheel. Four output ports on the autopilot are connected to the safety switch as is the RC receiver. The safety switch is connected to the control surface servos.

The interface between the autopilot and the on-board imagery system provides aircraft telemetry to the imagery system. This telemetry, which is transmitted over a serial connection to the on-board imagery computer, is embedded within the images as they are captured to provide a means of locating targets. The autopilot also controls the camera gimbal.

A half-wave 900MHz whip antenna, mounted to the tail of the aircraft, is connected to the autopilot to provide a wireless connection between the autopilot device and the Piccolo Ground Station (PGS). The PGS has a helical antenna to communicate with the autopilot. The PGS connects to a computer via a serial connection, allowing telemetry to be displayed on the computer and commands to be sent from the computer to the autopilot.

B. Peripherals

To improve performance of the entire system, the autopilot was connected with the air vehicle and imagery subsystems as well as a number of sensors and antennas. To simplify the interface with these other components, a wire harness connects all input, output, and power wires to a single connector which is connected directly to the autopilot. The antennas and pressure lines must be connected to separate ports on the autopilot.

A GPS patch antenna, also mounted on the tail of the air vehicle, is connected to the autopilot device to provide real-time GPS coordinates to the autopilot. Using this GPS input, the autopilot is also capable of determining more accurate state information with the help of a satellite-based augmentation system (SBAS) built into the autopilot device.

A pitot probe, mounted on the right side of the wing, and a static probe, mounted on the left side of the wing, are connected to pressure ports on the autopilot to provide altitude and airspeed data. Each probe is 10 inches forward of the wing to reduce the effects of the body on the data. The probes are located 23 inches from the center of the wing on each side to clear the propeller. Quick disconnect links were implemented on the pitot and static lines such that the pitot probe could not be connected to the static port and the static probe could not be connected to the pitot port. These quick-disconnect links prevent careless errors and simplify setup of the air vehicle.

A Honeywell HMR2300 magnetometer, which provides 3-axis magnetic field data to the autopilot, is connected through the main harness. This magnetometer was mounted in the left wing to reduce interference from other electronics. Output from the HMR2300 magnetometer allows the autopilot to interpret the magnetic field data in order to provide heading data. With this precision heading data, the autopilot can more easily account for disturbances such as wind. This precision also carries over to the telemetry embedded into each image, allowing images in the viewer to be oriented according to the heading of the aircraft when the image was captured.

A tachometer utilizing a Hall effect sensor circuit is connected to the autopilot device through the main harness. To allow the tachometer to read engine RPMs, two holes were drilled into the drive hub and magnets were inserted so that the poles were at opposite orientations.

An AGL Laser Altimeter from Latitude Engineering was implemented into the system to provide more accurate altitude data than that provided by GPS or barometric measurements. After initial testing of the device, however, it was determined that the AGL sensor was malfunctioning, and it was removed from the system pending further testing.

C. Flight Path

Upon the completion of the waypoint path, the aircraft will enter the search pattern. This pattern is based on a typical "lawn-mower" pattern. The row width has been determined through flight testing by finding the minimum turn radius that the aircraft can achieve without excessive roll. The turn radius is also considered when placing waypoints near the no-fly boundary.

Once the main search pattern has been created, the aircraft's flight through the pattern is simulated using the Piccolo Simulator. The validity of the simulator has been confirmed by comparing the predicted flight of the aircraft with actual flight test data. The search pattern flight is simulated in calm winds as well as high winds coming from a direction that will push the aircraft towards the no-fly boundary. Corrections are then made to the flight path in accordance with the results of the simulation.

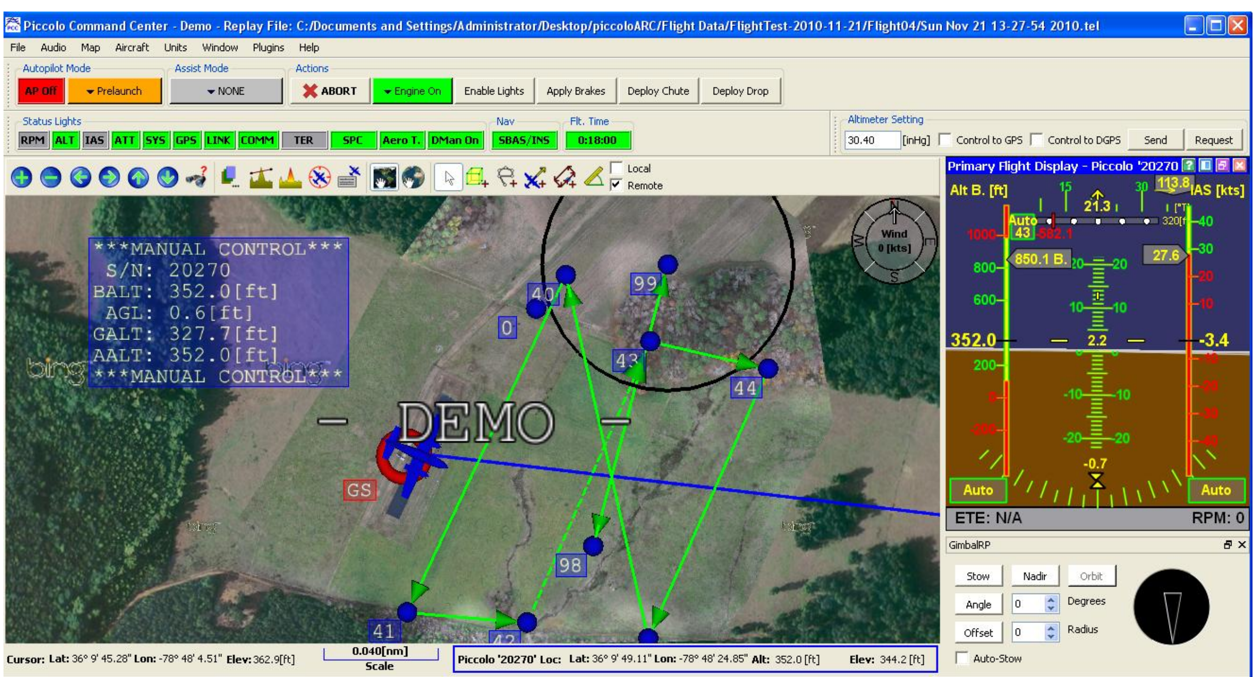


Figure 1: Piccolo Command Center With Custom Gimbal Control Plugin and Map

D. Gimbal Control Features

The aircraft's camera is nominally kept in an ortho-rectified position during flight to capture images. However, to photograph off-centered targets and to protect the camera during take-off and landing, the camera's orientation can be modified. This is accomplished using a custom plug-in that integrates with the stock Piccolo Command Center software, as shown in Figure 1. This plug-in allows the camera to easily be transitioned between the Stow, Nadir, and Angle modes required to complete the mission. Additional modes are included for support of other missions including distance offset and orbit centering modes. An arrow on the display provides a visual confirmation of the gimbal's current commanded position. The auto-stow feature helps alleviate operator workload by automatically stowing the gimbal when the autopilot is commanded to land.

E. Ground Station

The autopilot subsystem is controlled via the autopilot ground station. The ground station consists of the autopilot computer linked to the Piccolo Ground Station (PGS) console. The PGS, a Cloud Cap Technologies product intended for use with the autopilot, is connected to the 900 MHz antenna to allow communication with the autopilot on the air vehicle. The PGS also connects to a GPS antenna and a pilot console. The Piccolo Command Center (PCC) software running on the autopilot computer displays telemetry of the air vehicle to the autopilot operator and allows the operator to control the autopilot through an intuitive interface. The entirety of the autopilot ground station is located within the NCSU trailer, excluding the GPS and 900MHz antennas located on top of the trailer. This configuration prevents sunlight from impairing visibility of the monitors. A background map, shown in Figure 1, was generated using imagery previously captured and provides a higher resolution and up-to-date map.

V. Imagery

A. Subsystem Overview

The imagery subsystem is designed to capture high-quality photos of the ground, transmit them in near-real-time to the ground, and provide an intuitive interface which allows an operator to analyze them for target information. This starts with a digital single-lens reflex (DSLR) camera mounted to the gimbal on the aircraft. The camera is controlled by the flight PC which commands the camera to capture images. Upon receiving images from the camera, the flight PC embeds telemetry, stores, and then transmits the packaged image and telemetry to the ground station. This embedded telemetry allows for an initial projection of the image into the latitude/longitude coordinate system. On the ground, the images are received and then stored in a database accessible by other computers on the network. As well as being stored for long term use, the imagery information may then be processed by custom software on the primary imagery computer, or may be analyzed by alternate methods on other computers.

B. Aerial Components

To ensure a complete mosaic of the search area, the camera needs to be capable of taking photos at a minimum rate of 1 image every 3 seconds to ensure a 25% image overlap at an altitude of 250ft. Using a Nikon D60 controlled via the Picture Transfer Protocol (PTP) the system is able to take more than 1 image every 3 seconds.

The camera is mounted in a custom designed and fabricated 2-axis gimbal that, in accordance with competition requirements, allows the camera to be rolled 60° in flight. In conjunction with the camera's field of view, the system is capable of photographing targets off to the side out to the horizon. During the search pattern, the gimbal rotates the camera to counteract the roll and pitch of the aircraft such that the camera is kept ortho-rectified to within a tolerance of a few degrees.

Due to the low computational workload experienced by the onboard computer, the previous flight computer was replaced with the much smaller ARM-based PandaBoard. This lowered the weight, as well as power consumption, of the imagery system without compromising capabilities. Data is temporarily stored on a solid state disk for the duration of each flight. This data is also transmitted to the ground in near-real-time using an Ubiquiti Bullet5HP. The Bullet5HP is a self-contained wireless network card that uses the 5GHz portion of the 802.11n wireless standard to maintain a connection. The HP designation means the unit uses a full watt of transmission power to maintain a link over the ranges expected at competition. It has been shown experimentally that images can be transmitted over the 5GHz link faster than images are captured by the DSLR camera.

C. Ground Components

On the ground, the system receives images using another Bullet5HP unit. This unit is attached to a large patch antenna which allows for strong reception of the signal within a 60° cone. The antenna and Bullet5HP are mounted on a servo controlled pan-tilt device. During missions, this antenna is controlled by a tethered remote held by the operator. The antenna system is designed so that it may be upgraded for autonomous pointing in the future.

A high-speed router connects all of the ground computers together, including the Bullet5HP and the imagery PC. Once the Imagery PC receives an image, it is stored in a RAID array and loaded into the imagery database. Additionally, undistorted and downscaled versions of the image are stored to speed up loading times in the viewer.

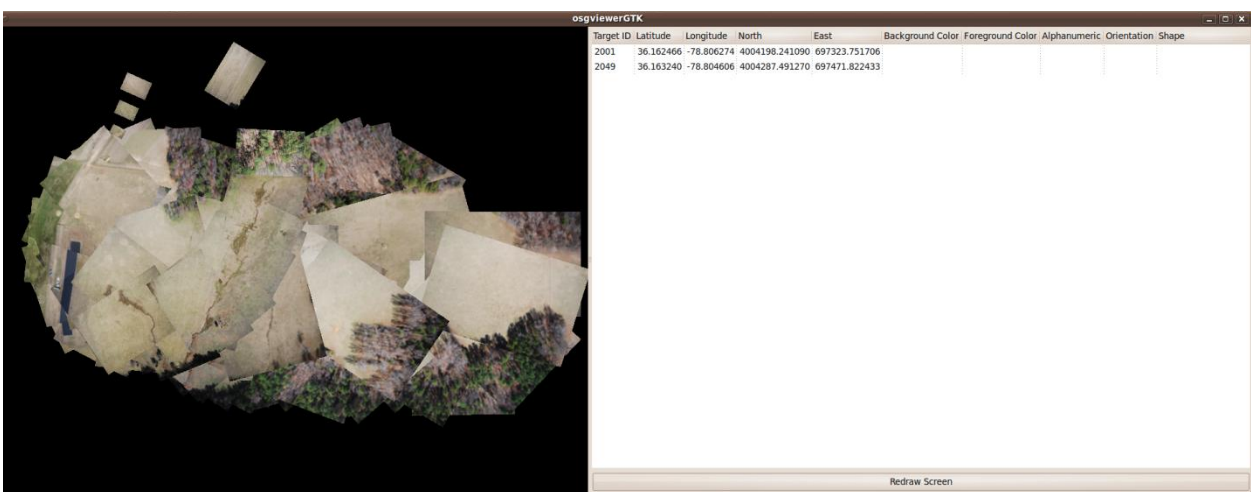


Figure 2: Imagery Viewer Client

This database is accessed by viewer clients, which project the images based on the latitudinal and longitudinal coordinates as well as altitude and heading into a mosaic. Each additional image is added to this mosaic after it is processed to provide a complete visualization of the entire field. Targets within this mosaic can be tagged using the client interface. Once tagged, a close-up snapshot image of the target is saved to the database along with GPS coordinates. This information is also shown in a designated panel on the imagery viewer client, where target information such as shape, background color, alphanumeric, and alphanumeric color can be inserted by the operator. At the end of the mission, a file following the competition format containing target locations and thumbnail photographs of each target is generated from the database of the target information.

VI. Flight testing and evaluation

Flight testing was a critical consideration in the development of the system. Flight testing was instrumental for showing that the system meets requirements and for verifying capabilities.

A. Autonomous Flight

During the last year, the autopilot has controlled the air vehicle in some portion of 24 separate flights over 6 flight test days. Of a total flight time of 220 minutes, the aircraft was autonomous for 139 minutes. This improved the percentage of total flight time spent autonomous from 46% to 63% as compared to the previous year's ratio. During these flights, basic autopilot tuning and performance was validated.

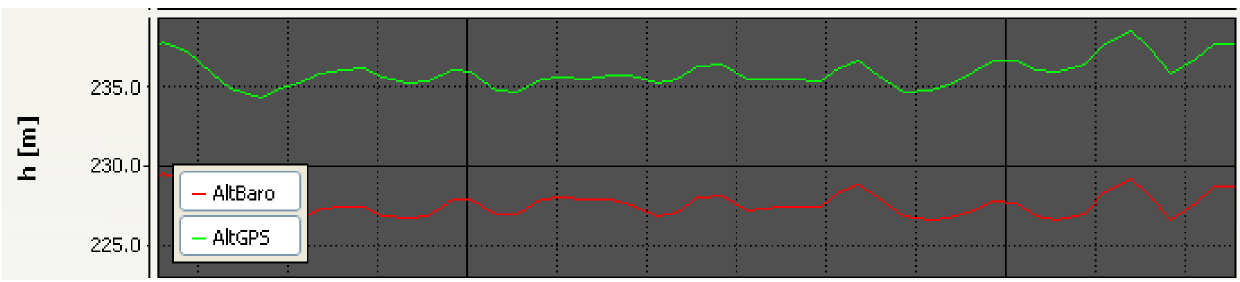


Figure 3: Measured Altitude during Box Patterns with 6kt Winds

In conditions with winds up to 8 knots, it has been verified in-flight that the autopilot is capable of maintaining the commanded altitude within ±10ft during continuous turning flight. During level flight the altitude control improves, with the autopilot maintaining the commanded altitude within ±5ft, as seen in the level portions of data in Figure 3. Lateral performance was likewise shown to keep the aircraft on the intended flight path to within 10 feet.

Altitude is measured by the autopilot using a barometric pressure sensor. The error in this sensor has been estimated by comparing take-off and touch-down readings over several flights on several days. This has shown the reading to be correct to within 13 feet, as discussed further in the "Autonomous Landing" section. The position of the aircraft used for lateral control comes from the GPS receiver which has been shown to have a practical lateral accuracy to within 5 feet when SBAS is available. Including possible sensor error the performance capabilities are still well within the competition requirements of altitude hold ± 50 feet and lateral control of ± 100 feet.

B. Autonomous Landing

During the past year a total of eleven autonomous landings were attempted. These attempts have provided valuable data that has contributed towards making the maneuver repeatable, consistent, and safer. Each of the three phases of landing has been improved by this testing. The three phases are final approach, short final, and touchdown.

Through flight testing, the final approach was modified such that it is sufficiently steep as to avoid obstructions at the test field without gaining excess airspeed. For the ARCWulf system, this angle has been determined to be 10° at the test field.

Table 2: Touchdown Thresholds Using Barometric and GPS Altitudes

Altitude Measurement	Maximum Measurement Error (ft)	Altitude Performance (ft)	Touchdown Threshold (ft)
Barometric	±13	±5	204
GPS	±46	±5	578

The greatest challenge of short final and touchdown has been the accuracy of the above ground level (AGL) measurement. During testing, barometric and GPS altitude measurements were used to estimate the AGL measurement, however, neither of these measurement techniques provide direct AGL measurements and as such are more susceptible to error. Through testing, it was observed that barometric errors varied as much as 13 feet and GPS altitude errors varied as much as 46 feet, as shown in Table 2.

Using this data, simple geometric analysis provided an equation for touchdown threshold, which defines the length of runway over which touchdown might occur, based on the maximum measurement error (e), the altitude performance (p), and the glide slope (θ):

$$Touchdown\ Threshold = \frac{(2e+2p)}{\tan(\theta)} \tag{1}$$

For landings based on barometric altitude measurements, the predicted touchdown threshold for a 10° glide slope was predicted to be 204 ft. For landings based on GPS altitudes, the predicted touchdown thresholds for a 10° glide slope increase to 578 ft. Although this large margin of error would be manageable at the large runway provided at Webster Field, these errors are too large for safe landings on the 450 ft runway available at Perkins Field.

Replays of landings performed by the safety pilot were reviewed to determine a typical rate of descent just before touchdown. After reviewing logs saved by the PCC, it was determined that the pilot consistently maintains a descent rate near 2 ft/s before touchdown. Based on an airspeed of 30kts during landing, the required descent rate corresponds to a glide slope of 2.5°. Changing the glide slope to 2.5° near touchdown would greatly increase the touchdown threshold to 824 ft using barometric altitudes and 2336 ft using GPS altitudes.

The error margin using an AGL sensor is expected to be greatly improved over GPS and barometric alternatives based on manufacturer recommendations. An AGL sensor was implemented into the system in an attempt to remedy the complications caused by inaccurate altitude measurements, but after it was determined to be malfunctioning it was returned for repairs. The AGL sensor is expected to be integrated back into the system before competition so that additional testing may be performed.

C. Autonomous Takeoff

Throughout the past year, 35 autonomous takeoffs were attempted. The data provided from these numerous attempts has allowed improvements in the three components of takeoff, namely ground tracking, rotation, and climb-out. These improvements contributed significantly to making autonomous takeoffs more consistent.

Initially, autonomous takeoff attempts exhibited inadequate ground tracking and were aborted before liftoff. Data from these unsuccessful takeoff attempts were used to tune the control gains until the ground tracking was within acceptable limits. With the test field runway being 50ft, the acceptable limit was deemed to be 20ft on either side of the takeoff path to insure that even with potential GPS errors the vehicle would not steer off of the runway.

In addition to changing the tuning of the control gains, the ground tracking data led to a change in the takeoff procedure. Initially the aircraft would be held until the engine reached maximum RPMs to reduce takeoff distance. Upon further inspection of experimental data, it was determined that holding the aircraft was leading to errors in ground tracking linked to integral windup, so that the aircraft would quickly steer to one side after being released.

Once the ground tracking was improved, the gains for the elevator rotation were tuned to insure that the rotation was sufficient to initiate liftoff. The rotation tuning process required only 4 attempted takeoffs. The effect of this tuning on altitude gain performance can clearly be seen in figure 5.

After these changes, the air vehicle consistently achieved liftoff but would pitch down after a period. At this point, the safety pilot would assume control of the aircraft, steering it away from the trees ahead to ensure the safety of the system. Upon further evaluation, these nose-down maneuvers only experienced an altitude decrease for the flights with excess elevator rotation. The nose-down maneuver appears to be an attempt by the autopilot to gain airspeed, occurring both in simulations and experimental tests.

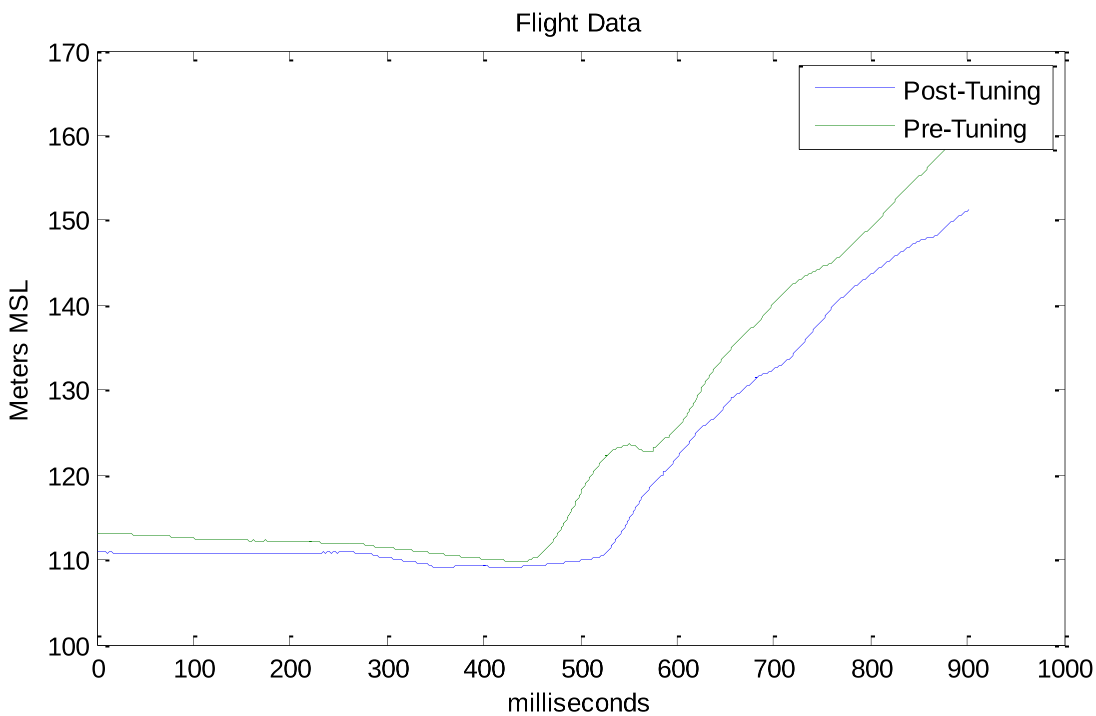


Figure 4: Experimental Altitude during Autonomous Takeoff before and after Tuning

D. Imagery Link

Ground testing of the imagery system's wireless link has shown a strong link at a range of 660 feet. Further evaluation during flight showed similarly strong performance sending images over a ground distance of 500 feet. The range test was limited by safety concerns at the flight testing field. Based on the competition missions from previous years, the aircraft will remain within 700 meters of the ground station at all times, and the aircraft will typically be within 600 meters. Given that the imagery system only requires 30% of the available bandwidth, a reduction in bandwidth due to long ranges will not hinder the system.

E. Imagery Analysis

The imagery system has captured 25 image sets during test flights for a total of over 5,000 test images taken during the last year.

Data from previous flight tests was analyzed to determine accuracy. During flight testing of the system, targets representative of those to be used during the final mission demonstration were placed randomly throughout the test field. Each target orientation and location was recorded using a handheld GPS device. During flight testing, the imagery viewer was used to tag the targets. After returning from the flight test, post processing was performed to compare the estimated locations from the image viewer and the actual locations from the handheld GPS device, as shown in Appendix A. Most of the targets were located approximately 200ft from the estimated point, as shown in Table 3. Some outlier data points were observed in some of the imagery sets, such as the ‘L’ target in Appendix A. Recent improvements to the system are expected to decrease the target location errors to values within the threshold limit of 250ft.

Table 3: Post-Flight Analysis of Imagery System Accuracy for Flight at 200ft AGL

Target	Error (ft)	Error Heading (degrees)
A	196	208
R	182	196
C	184	201
N	206	200
L	293	174

Interestingly each of these targets was estimated at a heading of approximately 200°. This suggested a systematic error, potentially due to incorrect gimbal calibration or delay in telemetry embedding. During tests telemetry output from the autopilot was captured for embedding into the image only after the image was captured and download, a relatively time consuming task. It is expected that by capturing telemetry immediately before capturing the image, target location accuracy will be improved. Testing is required to determine the full effect of this change.

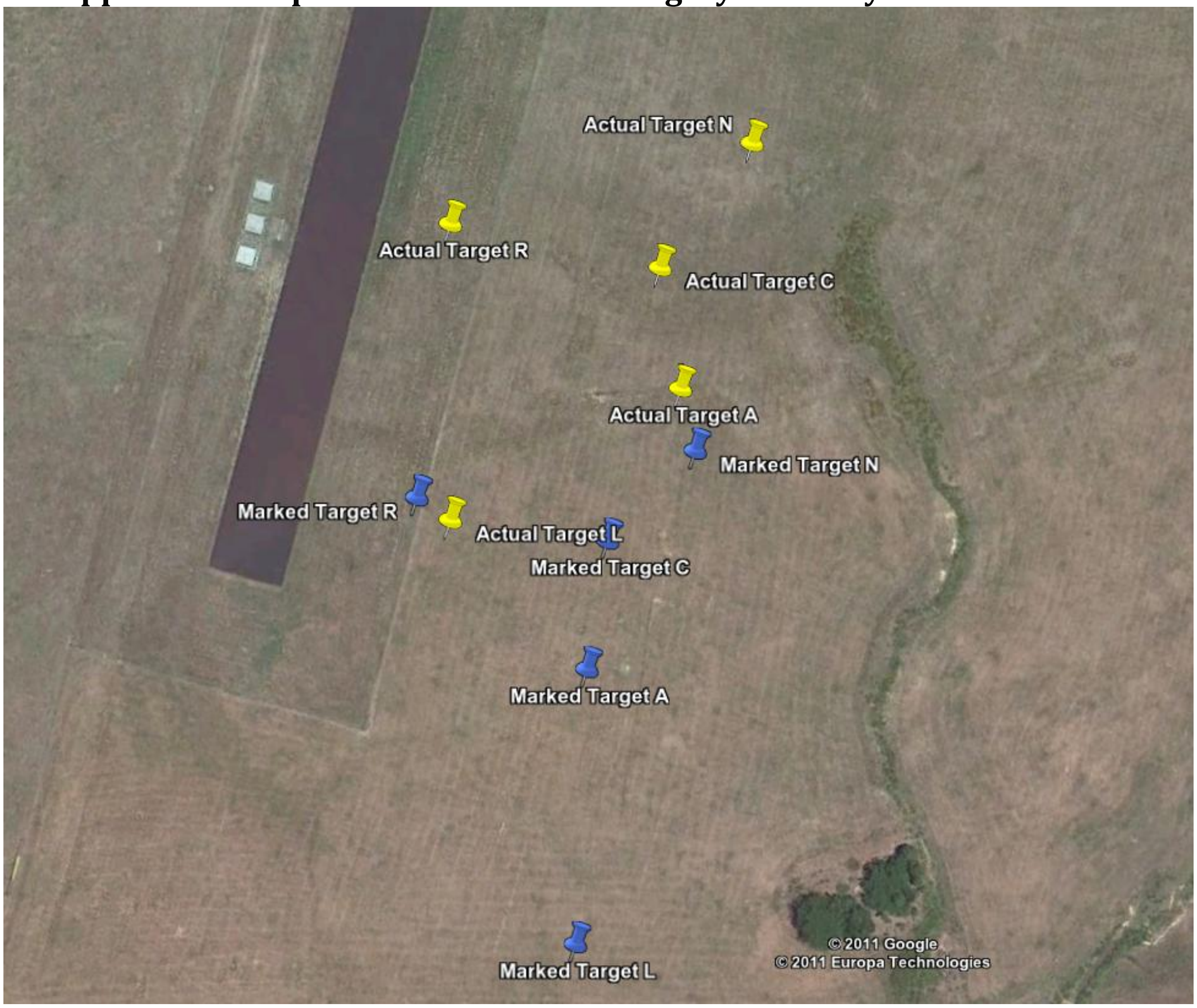
Verification of target characteristics provided no information concerning mission capabilities due to prior knowledge of target characteristics. As a result, the verification method used for characteristic identification was based on whether the team could easily view the target characteristics. Due to the high resolution camera utilized, target characteristics were easily identifiable.

VII. Conclusion

Through extensive flight and ground testing, the ARCWulf UAS has been shown to be a reliable system capable of flying an autonomous surveillance mission that is both safe and high-performance. In conjunction with a team of well-trained operators and procedures, it is expected that the system as a whole will meet all threshold requirements and many of the objectives.

VIII. Appendices

Appendix A: Experimental Data for Imagery Accuracy



Post-Flight Analysis of Imagery System Accuracy in Google Earth

Appendix B: Failure Modes and Effects Criticality Analysis

Failure	Symptom	Action	Status
RC Receiver System Malfunction	Erratic aircraft behavior	1. Safety Pilot defaults to autonomous control.	Mission Failure, Recoverable
		2. If problem continues safety pilot turns off autopilot transmitter when system is a safe distance away from ground personnel. This initiates flight termination.	Catastrophic
Autopilot Malfunction	Erratic aircraft behavior	1. Safety Pilot switches to manual control.	Mission Failure, Recoverable
Loss of Autopilot uplink	Indicated on Command Center	1. If less than 30 seconds, aircraft continues previous flight path.	Mission Continues
		2. If greater than 30 seconds, aircraft goes to lost comms waypoint.	Mission Failure, Recoverable
		3. If after 1 minute, link is not established, Safety Pilot takes manual control.	Mission Failure, Recoverable
Loss of GPS Signal	Indicated on Command Center	1. Aircraft continues on inertial naviagation for 30 seconds.	Mission Continues
		2. If no signal after 30 seconds, safety pilot takes control.	Mission Failure, Recoverable
Loss of Camera Downlink	Real-time image transmission stops	1. NCSU relies on onboard data storage.	Mission Continues
One Servo Dies	Erratic aircraft behavior	1. Autopilot attempts to fly aircraft without servo.	Mission Continues
		2. If flight control is unacceptable, manual control is engaged and the safety pilot attempts landing in safe area.	Mission Failure, Recoverable
		3. Turn off transmitter, initiating hard-over.	Catastrophic
Engine Cuts Off	Indicated on Command Center	1. Safety Pilot defaults to manual control, initiates emergency landing procedure.	Mission Failure, Recoverable
Vehicle Breaks in Flight	Falling Debris, erratic behavior	1. Safety Pilot defaults to manual control.	Mission Failure, Recoverable

		2. If flight control is unacceptable, manual control is engaged and the safety pilot attempts to land in a safe area.	Mission Failure, Recoverable
		3. Turn of transmitter, initiating hard-over procedure.	Catastrophic
6v Servo Battery Low	Indicated on Command Center	1. Safety Pilot defaults to manual control when practical.	Mission Failure, Recoverable
12v Payload Battery Low	Indicated on Command Center	1. Safety Pilot defaults to manual control and lands when able.	Mission Failure, Recoverable
3.3v Camera Battery Low	Loss of Image Capture	1. Auto land initiated.	Mission Failure, Recoverable