ARCwulf UAS Development, Refinement and Testing for 2012 AUVSI SUAS Competition

Aerial Robotics Club
North Carolina State University

Designed by the North Carolina State University (NCSU) Aerial Robotics Club (ARC), the ARCwulf UAS has been further developed, refined, and extensively tested for the 2012 AUVSI Student Unmanned Aerial System Competition. Now in its fourth year of use, the ARCwulf UAV has continued to prove itself as a reliable platform. The vehicle is capable of fully autonomous flight including take-off and landing. The robust onboard imagery system provides high quality, reliable images to the autonomous target recognition on the ground. The system is capable of bridging the team's ground network to the SRIC via the aircraft. Thanks to the extensive flight testing activities with the current system, the team is confident that the UAS will excel in all mission parameters.

Table of Contents

Nomenclature

c	=	circle of confusion (in optics)
e	=	measurement of error
f	=	focal length
H	=	hyperfocal distance
m	=	distance
N	=	f-stop
p	=	altitude performance
s	=	seconds
θ	=	glide slope

Introduction

The NC State Aerial Robotics Club (ARC) has been lucky enough to participate in the AUVSI Student UAS competition since its inception in 2002. As such, the club's history has given insight into systems engineering background needed in order to develop a successful UAS. Entering is fourth year of service, the ARCwulf UAS has received several modifications in order to more effectively address the mission objectives. These rationale behind these improvements and their effects on the systems expected performance are described within this paper.

A. Analysis of Mission Requirements

In order to effectively address all customer requirements, the North Carolina State University (NCSU) Aerial Robotics Club analyzed the Request for Proposals in order to determine the characteristics needed for full mission completion. In order to provide the most accurate intelligence information possible to the SEAL Team's rescue of foreign diplomats, the team divided the overall mission into several smaller primary objectives. Shown below in Table I.1, this table shows both the threshold of minimal mission success and the objective for full completion marks. Based on prior flight testing performed with the UAS, the team is confident that all customer thresholds will be met. Furthermore, system improvements are proving that autonomous take-off reliability will be extremely robust. Imagery accuracy and mission completion time will not likely reach the full objective, while autonomous landing capabilities may improve by the time of competition due to further flight testing and improvements to this system.

Table 1: Mission Performance Goals, Green Indicates Expected Capabilities

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
SRIC Data Relay	Connect to SRIC System*	Correctly Relay Data

B. System Preview

The improvement of the imagery subsystem was placed at the forefront of the team's attention. Due to its high influence on the success of the mission, a dependable Digital Single-lens Reflex (DSLR) camera with an improved lens was chosen instead of a full motion video based system. By mounting this camera in a custom gimbal, the camera is highly controllable by the Ground Control Station (GCS) Personnel. This system also decreases the need for orthorectification methods integrated in software, as well as distortion effects due to high angular velocities during turns.

The aircraft and autopilot subsystems have also been modified in order to improve the entire system. By successfully integrating the AGL sensor into the aircraft, the autopilot system is more precise during the autonomous landing portion of the mission. Also, improvements made on the airframe have improved the weight and balance, as

* Team Imposed Threshold

well as increased flight time due to proper engine tuning. 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. 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.

C. Safety

During the design of the ARCwulf UAS, safety was held paramount. The safety of all flight test personnel, spectators, and flight test facilities were taken into account before the safety flight vehicle and its onboard systems. Also, a rigorous Failure Mode Effect and Criticality Analysis (FMECA) was performed in order to develop safety protocols in case of system failures. The results of the FMECA can be found in the Appendix. Risk mitigation protocols helped to increase the amount of time between component failures, which drastically increased the reliability and availability of the platform. The following systems have been integrated into the vehicle in order to ensure safety during flight.

1. Safety Switch

The safety switch, manufactured by Acroname Robotics, allows control of the aircraft to be transferred between the safety pilot and the autopilot through the use of a dedicated switch on the safety pilot's transmitter. 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 5.8 GHz imagery ground station. A secondary transmitter, in addition to the primary safety pilot transmitter, is connected to the air vehicle through the autopilot link to allow the safety pilot to perform a landing using this 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. (1)

3. 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 in the form of a safety brief led by the flight test director before any missions can begin. During this preflight brief, roles assumed by the flight test personnel are reviewed. 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 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, which is shown in for decision making eliminates confusion and expedites the decision making process.

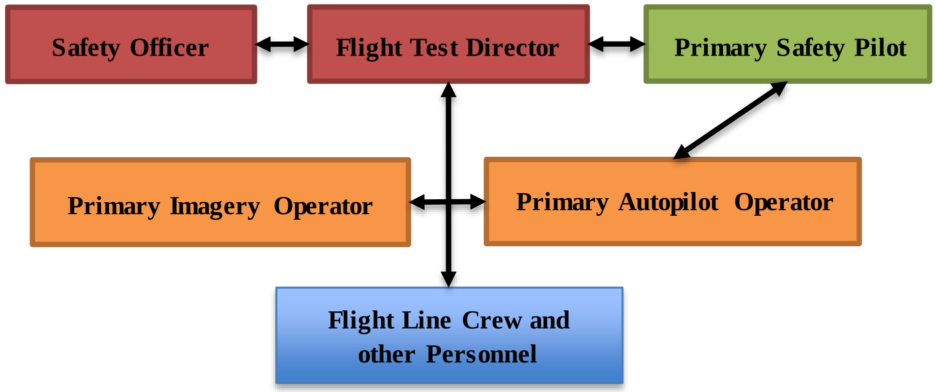

Figure 1: Flight Test Chain of Command

4. 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, the code base 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 in conjunction with a complete taxi test and primary transmitter range test. 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.

Aircraft and Ground Support

The foundation of the ARCwulf UAS is the ARCwulf vehicle itself. Starting out as a popular stock R/C Aircraft, it has been highly modified in order to help complete the mission set out by the customer. Its primary role is to carry the imagery payload through the mission profile in order to aid in Intelligence, Surveillance and Reconnaissance (ISR) missions

A. Airframe and Power Systems

Thanks to its reliability and success, the ARC is returning to competition with our modified 8 foot Senior Telemaster. The aircraft is of conventional design, propelled by an OS-FS120III engine in a tractor configuration. The aircraft is fueled by 24 ounces of Glow Fuel stored immediately aft of the fire wall. This engine and fuel system allows the aircraft to maintain flight for 20 minutes, with an additional 10 minutes of fuel reserved for go-arounds and emergency landing maneuvers if necessary. To separate the two systems to limit failures across systems, the Aircraft Control and Payload electrical systems operate on two separate circuits. Two batteries power the onboard avionics and payload package. A 6.7V 2200 mAh Nickel-Metal Hydride battery powers the Servos and Safety Switch system. The remaining circuit connecting the PandaBoard, Piccolo LT, Ubiquiti Bullets, and other peripherals is powered by a 14.8V 5000mAh Lithium Polymer Battery.

Several significant modifications have been made to the airframe in order to allow better performance in terms of mission capability. The first change, and likely the most noticeable, is that the forward portion of the fuselage has been widened by a couple inches and a large exterior payload bay was added in order to hold the custom gimbal used by the imagery system. Also, a power distribution panel was added to the top surface of the tail boom. This panel allows separate aircraft systems to be powered on and off to allow efficient power-up procedures, as well as aid determining problem sources during troubleshooting. A ground power jack is included in this panel, which allows the aircraft to be powered by a ground based power supply and generator.

Through the use of these devices and modifications, the ARCwulf UAS is expected to fully meet all mission thresholds, as well as several mission objectives. Of particular interest is the system's availability. Through the flight testing activities performed by the development team, much of the system has been troubleshooted for common complications. This prior troubleshooting has led to the development of improved checklists and processes which will aid in the timely completion of the mission.

B. Ground Support

Individuals attending flight activities 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. By limiting each person to a certain role, the operators and ground crew can operate efficiently and effectively; thus allowing successful mission completion

1. Flight Line Crew

Only members of the flight line crew are allowed at the flight line while the engine is running. The flight line crew consists of the flight test director, safety officer, 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 ultimate 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 checklists 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 flight crew personnel and spectators while the aircraft is flying, as well as initiating the handoff to and from autonomous control. If the safety pilot feels that the flight crew or air vehicle is at risk then the he or she 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 perform his duties.

2. Aircraft Crew

The aircraft crew is in charge of the air vehicle. They are responsible for unpacking the aircraft, fueling the aircraft, changing batteries, testing the R/C systems, and starting the engine. During flight, all members of the aircraft crew are required to be 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 is typically comprised of two members who set up, run and monitor the imagery software. The imagery team is also responsible for manipulating the imagery viewer and locating targets. The autopilot team is normally a two man team in charge of the autopilot GCS. The autopilot team is responsible for accepting handoffs to and from the autopilot and for commanding the path to be followed by the air vehicle. This includes any dynamic retasking scenarios or special requests by the imagery team to overfly a certain area again.

Imagery

A. Payload

The imagery portion of the payload is a major part of the competition. The ultimate objective of the mission is to identify, locate, and characterize targets completely free from human intervention. To accomplish this an imagery system was developed that utilizes both the UAS and computing resources on the ground. An onboard image capturing payload works to capture the imagery data, and then sends it to the ground station where the image processing is done. An overview of the system is shown below:

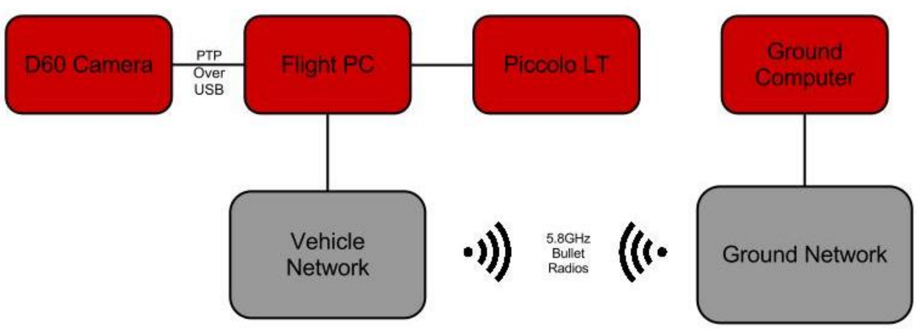

Figure 2: Pictoral Representation of Imagery System

The onboard imagery portion of the payload was designed solely for capturing and transferring images to the ground. Since the objective is the eventual characterization of targets, the ideal payload would have a very high resolution camera. To fulfill this, a Nikon D60 DSLR camera was chosen. The Nikon D60 has a Charge-Coupled Device (CCD) sensor with a global shutter, capable of capturing 12MP images. The global shutter ensures that the entire image is captured at once, eliminating possible distortion that could arise from the airframe moving as the shutter rolls across the sensor, as would happen in with a Complementary Metal–Oxide–Semiconductor (CMOS) rolling shutter sensor. To prevent motion blur, the shutter speed is set as high as lighting conditions allow, typically 1/1000th of a second or faster. At a typical airspeed of 15m/s, with a shutter speed of 1/1000th of a second, the plane only moves only 1.5cm.

$$15\,\frac{m}{s} \times \frac{1}{1000}\,s = 1.5cm \tag{1}$$

Blur from such a small change in location from a high altitude has been found to be insignificant compared to inherent limitations of the lens.

In the past, the team has had occasional problems with the shutter not firing due to the autofocus being unable to focus. It was determined that manual focus mode could be used, as the hyperfocal distance of the lens and camera is less than flight altitude. When the lens is focused to infinity, the hyperfocal distance is the closest distance at which objects are in focus. The hyperfocal distance is defined by the equation below, where f is the focal length, Nis the f-stop, and C is the circle of confusion of the image sensor.

$$H = \frac{f^2}{Nc} + f \tag{2}$$

Evaluated for the Nikon D60, and Nikon 20mm AF-D, the lens used by the system, the hyperfocal is 5.74 meters, significantly less than even the 30 meter minimum elevation required by competition rule 4.6.2.

The lens used with the Nikon D60 is the Nikon 20mm AF-D. The decision was made to move away from the Nikon 18-55m AF-S ED due to concerns with its image sharpness, particularly at the edges of the image. Without the need for autofocus or an adjustable focal length, many options were available. Based on benchmarks from the professional photography community, the decision was made to use the Nikon 20mm AF-D because it has less barrel distortion, suffers less from vignetting, and provides better resolution at the borders and extremes of the image. [(1)] [(2)] Barrel distortion creates distortion in the final image, where objects are not linearly offset from the center as they appear in reality. Significant distortion can affect the accuracy of GPS measurements, particularly in targets that appear near the extremes of the image. Vignetting is an attenuation of the light reaching the sensor at the extremes of the image, resulting in less data in the final image. In the figure below, the clarity at the extremes of an image of the Nikon 20mm AF-D vs. the Nikon 18-55m AF-S ED is clear.

Figure 3: Target Clarity Using Various Nikon Lenses

Once the images are taken, they then need to be transferred to the ground, where target recognition will occur. The images are first transferred from the camera to the onboard flight computer via picture transfer protocol. The flight computer is a PandaBoard single board computer (SBC), which was chosen because it is lightweight, relatively small, inexpensive, and was already supported by many Linux-based operating systems. The images are then stored on an external solid state disk (SSD) after location data captured from the autopilot is inserted into the image exchangeable image file format (EXIF) metadata. This is for later use during processing. The images and their corresponding geolocation data are stored safely on nonvolatile memory in case an event such as loss of power disconnecting the wireless link between the imagery payload and ground station occurs.

From there, the flight computer will send them to the ground station computer through the use of the secure copy (SCP) utility. The SCP utility was chosen for its simplicity and security over secure shell (SSH). This is made possible by a bridge between the aircraft's onboard network and the ground network which uses two 5.8GHz Bullet M5 radios. These are affordable, relatively lightweight, and reliable, making them the perfect drop-in solution to connect the imagery payload to the ground station computer. Reliability is further improved through the use of an automatic tracking antenna on the ground, which continuously points towards the plane. Once the ground station computer receives the images from the payload, the images are available for viewing in a near real time in-house mosaicing viewer. Manual analysis could be done if necessary and the pop-up target can be identified. As well being available for manual viewing, automatic target recognition software begins to analyze the images once they are transferred the ground.

Extensive testing has been done on the imagery payload. Over 2000 images have been seamlessly downloaded over the 5.8GHz Bullet Wi-Fi during flight. Furthermore, the team has tested the ability to complete the "pop up" target portion of the competition. In Figure 4, the image on the left shows a dummy placed in the field during a flight test, posing as a sniper from a previous competition year, seen on the right.

Figure 4: Pop Up Target Testing for 2012 Competition

B. Automatic Target Recognition

One of the team's primary goals this year was to achieve a fully autonomous target recognition system, which identifies and labels a target with as many characteristics as possible, completely free from human intervention. The characteristics the system was aiming to use are listed in Paragraph 3.5.2.3 of Reference 3.

The characteristics are identified with a multifaceted collection of tools developed throughout the past year. These tools run on a ground computer as the imagery system downloads images from the plane. The decision to run the automatic target recognition on the ground provides the benefit of the powerful and cost effective desktop computers available today, while taking advantage of the existing fast and robust imagery downlinking system.

The target recognition software first identifies potential targets through a pixel-by-pixel search of the image. No initial orthorectification is necessary since the camera is gimbaled and always points on nadir. The software looks for bright, contrasting regions in the image, which are identified as potential targets. The candidates are further narrowed down using altitude telemetry from the autopilot. This allows the software to determine the size of the candidate target, and eliminate it if it does not meet the competition specifications. Candidates are further eliminated based on rough shape estimation, such as a candidate that is significantly longer than it is wide.

At the end of the first stage, all targets should be identified, and most false positives eliminated. Testing has shown the first stage alone regularly identifies less than 50% false positive targets. When run on the team's imagery from the 2011 AUVSI SUAS competition, the first stage had only a 40% false positive rate, while imagery from the 2010 competition had a 38% false positive rate.

From these identified targets, individual smaller images containing only the identified target are cut out from the original image. Letters are identified by finding a region within the target that contrasts from the rest. Like the target, the letter is extracted to its own image, where it is converted to black and white, and saved as a set of rotated instances of the original.

Figure 5: Identified Target (Left) and Letter Extraction for Optical Character Recognition (OCR) (Right)

Alphanumeric characters are recognized using a program that utilizes the Tesseract OCR engine. Upon testing, Tesseract was found to work most reliably and accurately when parsing characters that were already properly oriented, which is the reasoning behind generating sets of rotated instances of identified characters. The OCR program splits these sets into individual characters and identifies those characters with Tesseract. Tesseract returns a confidence value along with the character found, thus the most confident letter found can be returned as the letter in the target.

One advantage of the high dependence on orientation is that the character recognition phase can be used to identify the orientation of the target. Once the correct character is found, the orientation of the target can be determined calculating the rotation necessary to achieve correct identification.

Color recognition is done by finding the most common Red Green Blue (RBG) (Color Space) values in the target and letter. The values then undergo a transformation before being matched with reference colors. This transformation is necessary because testing showed that there was enough discrepancy between human perception and the RGB color space that a direct comparison was inaccurate.

Work is ongoing to achieve shape recognition for the competition. While several methods have been explored, a reliable solution has yet to be implemented.

Throughout testing, the automatic target recognition has shown that it places target locations at least as well as human operators have in the past, consistently placing targets within the 50 foot high accuracy radius. Over a sample acquired during the last year of test flights, 14 out of the total 17 targets placed by the system have been within the high accuracy radius.

C. Simulated Remote Intelligence Center (SRIC) System

The addition of an SRIC objective to the competition posed a unique challenge that the previous payload system was not able to handle. Given that the system needed to be able to connect to a network which would not be known until shortly before takeoff, the system needs to be easily configurable on-the-fly. Initial considerations for solving this problem included connecting a small USB Wi-Fi card to the PandaBoard flight computer. However, the Wi-Fi card required special drivers which proved difficult to implement. The Bullet M2HP worked fully autonomously, while providing the same power and a better antenna than the Wi-Fi card. Given past club success and proven versatility and robustness of the Ubiquiti Bullet products, the decision was made to use an Ubiquiti Bullet M2HP to provide a 2.4GHz downlink to the SRIC router.

The Bullet M2 has been flashed with the DD-WRT custom router firmware. DD-WRT provides finer grained control over the Bullet hardware, as well as allowing for setting up the advanced networking required for the SRIC connection. The Bullet is configured in Repeater Bridge mode to connect to the SRIC ground router as its host access point. In Repeater Bridge mode, the router searches for its configured host access point, and when found, automatically connects using the specified security settings. The router also creates a secondary wireless network using the same settings as the host access point. Once connected, the router internally bridges all three interfaces -- the host AP, the secondary wireless network, and the Bullet's Ethernet port. Once bridged, all clients on each interface appear on the same network subnet, meaning all communication reaches all clients, and any client on any part of the network can communicate with any other client.

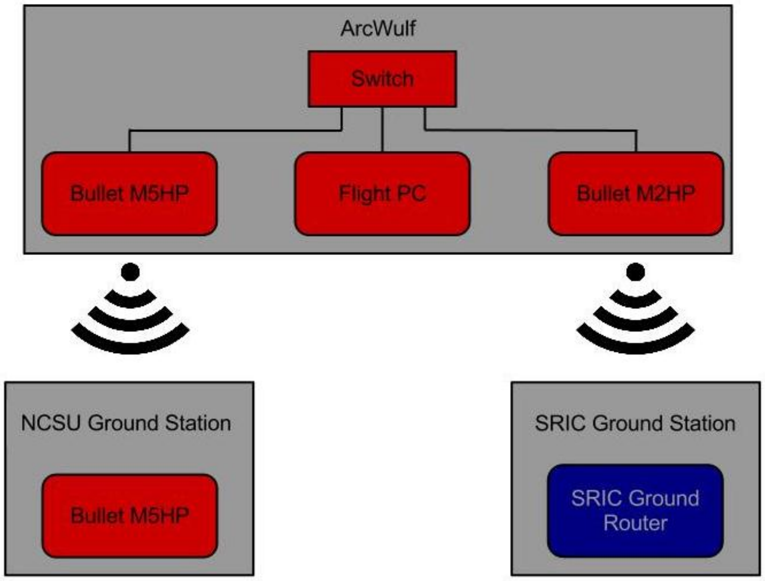

Figure 6: SRIC Network Topology

The advantage of such a system is the ease of communication. Once configured, the Bullet will connect to the SRIC ground router as soon as it is in range. On the ground, a ground PC can connect to the Bullet's secondary wireless network, however, with the addition of a switch in the plane, the Bullet M2 is wired with the flight PC and flight Bullet M5. Since the Bullet M2 bridges all interfaces, any devices on the SRIC network will appear on the ground network, simply using the Ground-Air Bullet M5 5.8GHz wireless connection. This provides the advantage of not needing to maintain two Wi-Fi connections with the plane; rather, only requiring the 5.8GHz network to reach the ground station.

Autopilot

Following years of development, the system is capable of a number of maneuvers that have been thoroughly tested including:

- Navigation by GPS waypoints
- In-flight retasking
- Autonomous Landing
- Autonomous Take-off
- Providing telemetry to peripherals and to the ground station

A Piccolo LT autopilot, manufactured by Cloud Cap Technologies, has been used in this system for the past 4 years. Alternate autopilots were considered such as the Piccolo SL, but budgetary constraints precluded an upgrade.

A. System Integration

The autopilot is connected to the flight PC so that the aircraft telemetry can be used by the imagery payload. By separating the payload from the flight control system, an error in the payload will not propagate to adversely affect the flight critical systems.

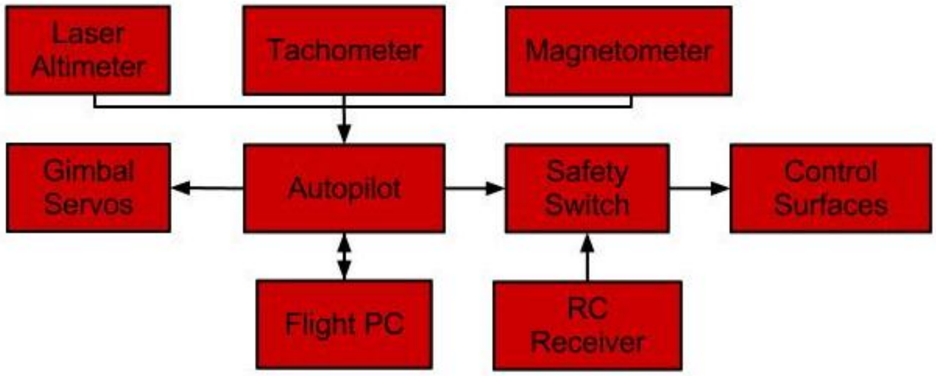

Figure 7: Autopilot In-Air Flow Chart

B. Peripherals

To improve performance of the entire system, the autopilot is connected to a number of sensors and antennas. The standard peripherals include a GPS patch antenna mounted on the tail of the air vehicle. The GPS uses Satellite-Based Augmentation System (SBAS) to get an accuracy of ±5 feet.

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's prop wash. Quick-disconnect links that don't allow the pressure lines to be swapped prevent careless errors and simplify setup of the air vehicle.

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).

A Honeywell HMR2300 magnetometer provides 3-axis magnetic field data to the autopilot. The magnetometer is mounted in the left wing tip to reduce interference from other electronics. This heading data is required for autonomous rolling takeoffs where a GPS track does not yet exist to provide heading information. This data also improves heading information while flying thus allowing captured images to be properly oriented.

A tachometer, utilizing a Hall Effect sensor circuit, determines the engine RPM. Two holes were drilled into the drive hub of the engine and magnets were inserted so that the poles were at opposite orientations.

An in-house laser altimeter has been developed and installed in the aircraft to improve altitude measurement. An Original Equipment Manufacturer (OEM) laser range finder is connected to a microcontroller installed in the aircraft which controls the laser, reads the data, and then pushes that information on to the autopilot's CAN bus. This piece of hardware was created in-house resulting in significant cost savings. Additionally, the laser used in this system has better range and accuracy than those sold by Latitude Engineering, who is currently the only company offering a laser altimeter compatible with the piccolo autopilot.

C. Flight Path

Prior to the mission, the search pattern is created and 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.

During the mission the aircraft will overfly the targets area following a pre-designed search pattern. This pattern is based off of a "lawn-mower" type pattern. The row widths have been determined by flight testing to find 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 so as not to violate the boundary.

D. Gimbal Control Features

In flight 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 takeoff and landing, the camera's orientation can be modified. This is accomplished using a custom plugin that integrates with the standard 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 offset modes required to complete the mission. Additional modes are included to make completing the mission easier 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.

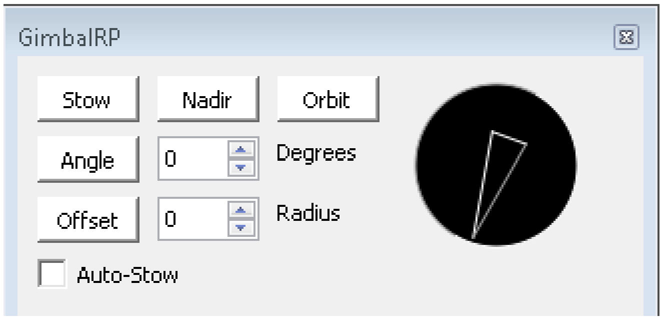

Figure 8: Piccolo Command Center with Custom Gimbal Control Plugin

E. Ground Station

A trailer houses the ground side of both the autopilot and payload systems. This configuration prevents sunlight from impairing visibility of the monitors. The Piccolo Ground Station (PGS) console receives data from the aircraft from an antenna located on the roof of the trailer. The primary autopilot computer makes the data link available on the network so that other operators can interact with the aircraft.

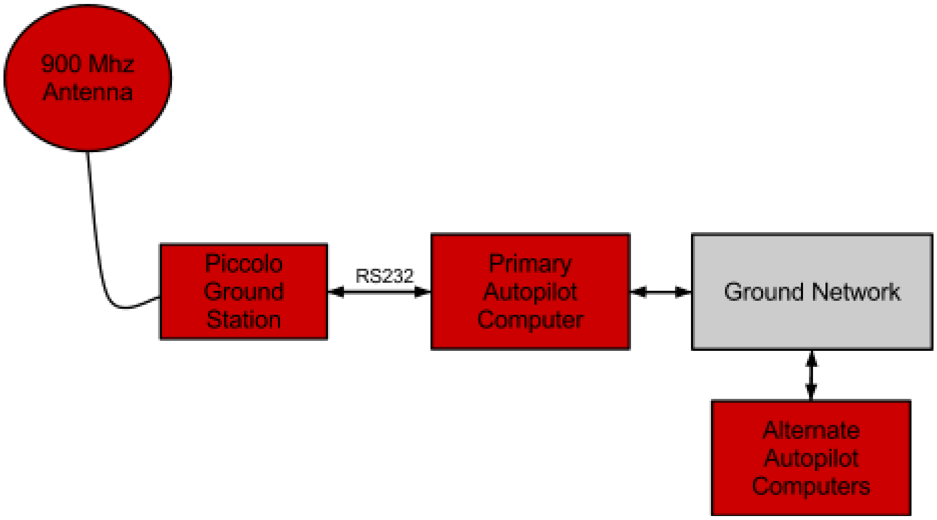

Figure 9: Autopilot Ground Station Flowchart

The Piccolo Command Center (PCC) software and allows the operator to control the autopilot. A background map generated using imagery collected during past missions provides higher resolution and an up-to-date map.

F. Testing

Over the past two years a significant amount of flight testing has been completed on this system. Although the percentage of time spent autonomous is unchanged between the two flight seasons, both are an improvement of the 2009-2010 season when only 48% of flight time was autonomous.

Table 2: Testing Totals

	Total Flights	Flight Time	Autonomous Time	Autonomous Percentage
2011-2012	24	280 min.	175 min.	63%
2010-2011	24	220 min.	139 min.	63%

This testing has shown that, including possible sensor error, the performance capabilities are well within the competition requirements of altitude hold ± 50 feet and lateral control of ± 100 feet.

The autopilot's performance has been verified in conditions with winds up to 15 knots, it has been verified in-flight that the autopilot is capable of maintaining the commanded altitude within ±10 ft during continuous turning flight. During level flight the altitude control improves, with the autopilot maintaining the commanded altitude within ±5 ft. Lateral performance was likewise shown to keep the aircraft on the intended flight path to within 10 ft.

In-flight altitude is measured by the autopilot's barometer. 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.

G. Autonomous Landing

Over the course of a dozen autonomous landings valuable data has contributed towards making the maneuver repeatable, consistent, and safe. Each of the three phases of landing: final approach, short final, and touchdown, have been improved by this testing.

The final approach was modified such that it is sufficiently steep as to avoid obstructions at the test field without gaining excess airspeed. Trichrough a set of descending flight plans it has been shown that the aircraft can descend at a 7° angle with a 10 knot tailwind without gaining airspeed.

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. This information was programmed into the autopilot as its touchdown velocity.

Table 3: Touchdown Thresholds at 7°

Altitude Measurement	Maximum Measurement Error (ft)	Altitude Performance (ft)	Touchdown Threshold (ft)
Barometric	±13	±5	293
GPS	±46	±5	830
Laser	±0.2	±5	85

The greatest challenge of short final and touchdown has been the accuracy of the above ground level (AGL) measurement. Barometric and GPS altitude measurements were used to estimate the AGL measurement, however, neither of these measurement techniques provides 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 3.

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):

$$Touchdown\ Threshold = (2e + 2p)/\tan\theta \qquad (3)$$

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. To safely perform the maneuver it is necessary to test the maneuver beforehand, so the improved performance of a laser altimeter was deemed necessary.

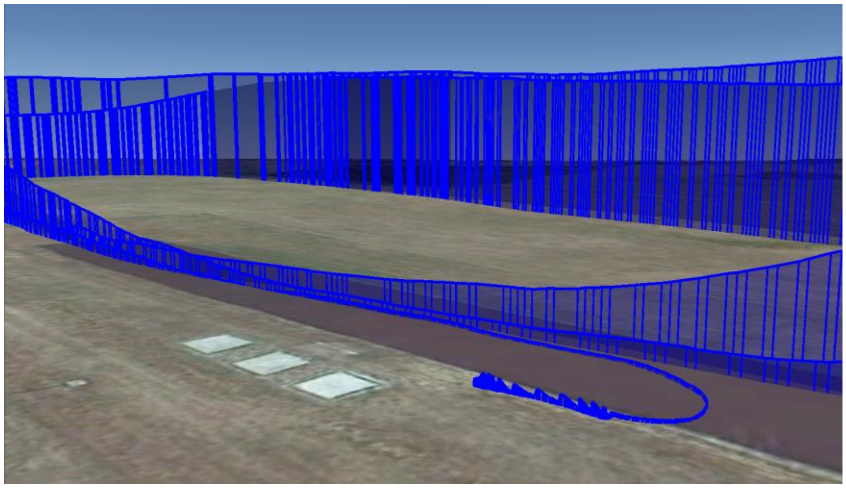

Figure 10: Altitude Data Obtained using AGL Sensor

During flight testing, the laser performed consistently well when the AGL was less than 130 feet. Above this altitude, the laser began to lose its return signal. However, the autopilot recognized the bad data and automatically discarded it. During a set of low passes the readings from the laser matched what was observed by the flight crew.

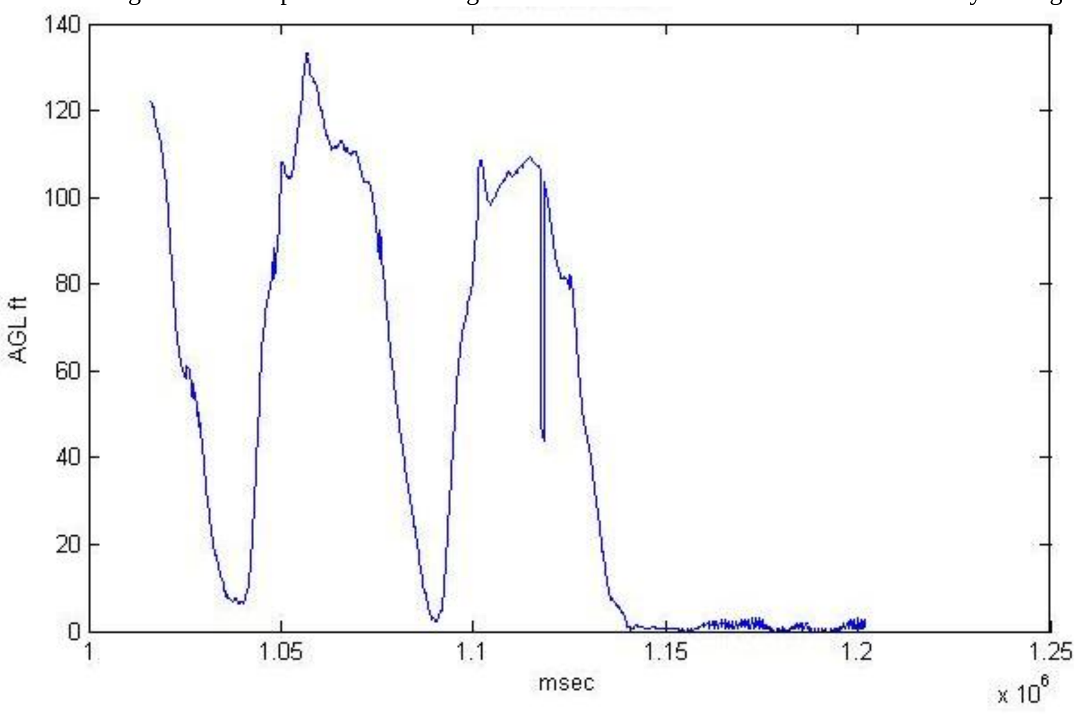

Figure 11: Laser Altimeter Data Stream

H. Autonomous Takeoff

Throughout the past year, 8 autonomous takeoffs were attempted. The data provided from these numerous attempts was used to make changes to the throttle ramp-up. The improvements contributed significantly to making autonomous takeoffs more consistent.

Prior to improvements, takeoff ground roll used 337.5 ft of runway. The delayed time to lift-off meant the aircraft had difficulty clearing obstacles beyond the end of the runway. This often forced the safety pilot to intervene. Upon analyzing the data provided by the piccolo autopilot and the safety pilot, the autopilot was found to take 2 seconds to reach full throttle instead of the safety pilot who took 1 second.

After increasing the autopilot's throttle advancement rate, the ground roll distance was reduced from 337.5 ft to 237.5 ft. After this change, the air vehicle has consistently achieved liftoff at the same location that the human pilot would.

Conclusion

By integrating the new features listed above, as well as improving systems already in place, the ARCwulf UAS is ready to complete the mission as described by the customer. Flight testing performed to this date has shown that successful mission completion is highly likely and any issues that arise during flight activities will be resolved quickly.

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Appendix: 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 navigation 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