RUTGERS UNIVERSITY

RU AUTONOMOUS

Journal Paper
AUVSI UAS Student Competition 2013

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ABSTRACT

For the 2013 AUVSI competition, the Rutgers University Autonomous team has created an unmanned aerial system consisting of a flying wing airframe, onboard communication and imaging systems, and the ground station. The team approached the challenge as a true systems engineering project, working in separate teams on the various subsystems that make up the final design while collaborating in both design and testing phases in order to ensure that all of the components will function as well as possible as one complete system. The team's goal was to create a system that would accomplish the Key Performance Parameters reliably and completely. This journal report details the processes used to make the design decisions that lead to the final system, the design of the system itself, and the testing performed to ensure that the system will accomplish its goals.

COVER LETTER

The Rutgers University Autonomous team has devoted countless hours towards designing and building a complete and well integrated unmanned autonomous system. Due to the nature of the competition, the mission was approached from a systems engineering perspective in addition to a design problem. With this dedication and united approach, the team from Rutgers University is able to proudly present its X-8 Skywalker flying wing, the result of meticulous design, careful system integration, and complete full system testing.

The system utilizes three distinct frequencies to eliminate noise. The autopilot connects with a telemetry kit at 900 MHz frequency to communicate with the ground station, the R/C controls use a transmitter running at 2.4 GHz to provide manual controls when needed, and the imaging system transmits data through a bullet antenna at 5.8 GHz. This unique frequency for the imaging system enables data transfer through the onboard computer and antenna to be fully viewable on the ground station.

The plane weighs in at approximately 8 pounds at takeoff and sports swept wings with a 7 foot wingspan. Combining this with careful placement of the two 4500 mAh Lithium Polymer batteries and the Canon T2i DSLR camera near the center of gravity facilitate extensive control of the UAS's payload.

After comprehensive testing and thorough preparation, Rutgers University Autonomous team has prepared a UAS that is safe, reliable, and has proven to be able to complete the mission requirements it is tasked with.

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1.0 SYSTEMS ENGINEERING APPROACH

1.1 Requirements Analysis

The first step in any engineering project is to define precisely what requirements the final product must fulfill. Only once the goals of the project are fully understood can meaningful work begin. Before starting work on the competition, every team member was required to read through the rules thoroughly in order to completely comprehend the components of the mission. These components are outlined by the Key Performance Parameters (KPPs) stated in the competition rules. The parameters include autonomy, imagery, target location, mission time, operational availability, and in-flight retasking. Each one of these parameters has a threshold (or minimum) requirement and an objective requirement. The threshold requirements are those which the final system must be able to accomplish to avoid major loss of points, while objective requirements are those which the team can attempt to attain once it knows that the system can achieve the threshold requirements. The team worked on the system with the philosophy of aiming for the threshold requirements initially, and then to explore options for obtaining the objective requirements. For example, while the team was eager to get autonomous takeoff and landing functional to obtain the objective goal for autonomy, the first priority was ensuring that autonomous flight was functional for the way point navigation and search area portions as it is more mission critical based on the specifications given in the rules.

1.2 Design Rationale

1.2.1 Airframe

There were several major aspects that were addressed when making decisions related to the design of the airframe. In terms of functionality and logistics, these included payload capacity, ease of assembly and modification, and its size when deconstructed. Other key factors in the decision for the airframe were the performance, reliability and cost of the airframe. The plane had to have a high safety factor in terms of the conditions it could handle, it had to be able to hold up after many flights, and it needed to be easily replaceable or reproducible.

Using prior knowledge, the team was able to rule out a couple of different options. The previous years' high wing balsa trainer did not provide the level of accessibility desired and its single piece wing design was troublesome in terms of transportation. In-house designs did not allow the time for the necessary amounts of test flights or the team's desired ease of reproduction. The mission goals and objectives allowed the team to further reduce its search to obtain an airframe capable of the necessary flight time and flight conditions. Due to the importance of the imaging goals, an upgraded and subsequently heavier imaging system would be necessary, leading to the need for a relatively high payload capacity.

From this knowledge, the design was narrowed down to an aircraft that was light for its size but had the capability of a higher wing loading to accommodate the upgraded imaging system. A two piece mid-wing aircraft was desired for the sake of transportation and accessibility, a low cost plane for the purpose of having a backup, and it needed to be commonly used and well regarded for the purpose of safety and ensured reliability.

Together, these considerations led to the choice of a commercially available, foam flying wing. The Skywalker X-8, a platform specifically meant for first person view (FPV) was perfect for the team's needs. With large, detachable swept wings (7 foot wingspan), it provides the perfect combination of lift capacity and maneuverability. Its foam build provides a light platform capable of high speeds to ensure that the mission is completed in the specified time. With its wide use and easily repairable nature, the X-8 provides a reliable system that can withstand as many test runs as necessary. Its large interior provides enough space for all of the subsystems, its low cost allows the team to keep a backup, and its build design offers ease of construction and transportation. Therefore, it meets all of the team's functionality and safety requirements.

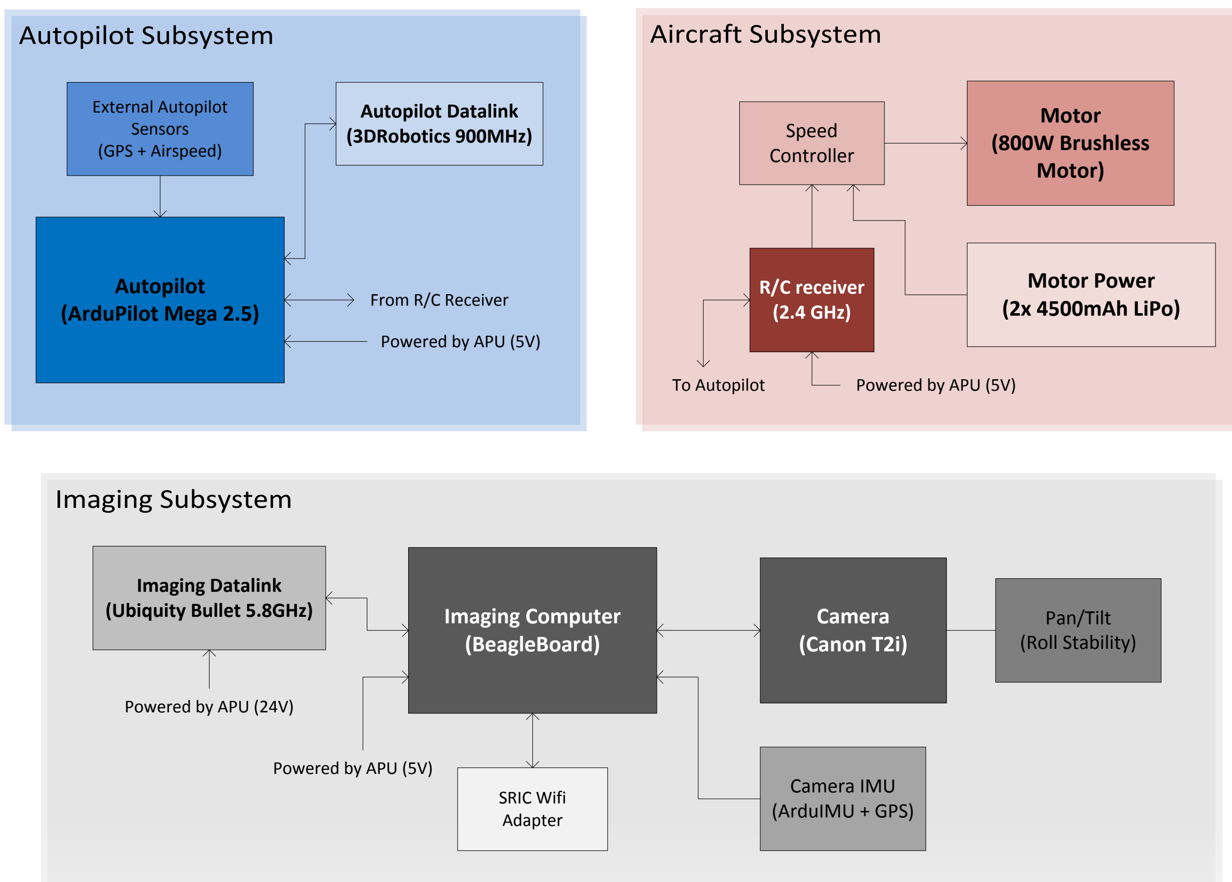

Figure 1: UAS Subsystem Block Diagram

1.2.2 Autopilot System

The autopilot used in the aircraft is one of the most critical components to KPPs for the competition; therefore the choice of autopilot had to be made very early on to ensure adequate testing. In previous years, the Ardupilot Mega (APM) 1.0 was used to control the aircraft and has been upgraded to the Ardupilot Mega 2.5 for this year's competition. The APM 2.5 not only provides the ability to perform all of the threshold autonomy KPP requirements but also the objective requirements of autonomous takeoff and landing of the vehicle. Furthermore the system has both open source hardware and software, which makes it very affordable and customizable to suit our specific needs. The affordability of the APM 2.5 has allowed the team to have a complete backup autopilot system in case of damage or malfunction of the primary system.

The APM 2.5 also has a very user friendly accompanying ground station software that the team's operators have become accustomed to over the past several years, which has allowed for a fairly detailed guide to be made in order to allow any one of the team members to operate the ground station and autopilot in case the main operator becomes unable to perform those tasks.

1.2.3 Payload

When making design decisions for the payload of the system, the team's most important concern was simply ensuring that it would able to meet the threshold imaging requirements in the KPPs. At last year's competition, the team experienced a number of difficulties that influenced the design decisions for this year's payload. Last year the team decided to use a Logitech webcam for the imaging requirements. Throughout testing last year and conditions at competition, the team found that this camera had a number of flaws preventing the attainment of the threshold parameters. The camera was not as high-resolution as it should have been, making it difficult to resolve the images taken in-flight and obtain the threshold KPP of identifying two characteristics of the targets in the search area. In addition, the low-resolution of the camera required the aircraft to fly relatively low to the ground in order to identify characteristics, extending the amount of time needed to cover the entire search area and hindering the team in its effort to attain the mission time KPP.

After this experience, it was clear that the team needed to choose a new camera, one that would better facilitate accomplishment of the threshold KPP's. After exploring options, the team decided that the Canon T2i was the best fit because of its high-resolution (18MP) and the ease with which it can be used for image processing purposes. The Canon is higher resolution than the Logitech webcam previously used, improving the system's ability to attain the imaging, target location, and mission time threshold requirements (due to the larger field of view and fewer passes required over the search area), and perhaps even the objective requirements. The cost of the camera was much greater than that of the Logitech webcam, $500 in comparison to the webcam's $100, but the team felt that this was a worthwhile cost for the advantages it gave the system. The BeagleBoard was chosen as the single board computer to process the images due to its ease of use and the team's extensive past experience with its technology and capabilities.

1.3 Expected Performance

At the current state of the system, there is still some remaining final testing to be performed before the date of the competition, and thus the full potential of the system has not yet been completely explored. Based on the over 120 minutes of flight testing and sub system testing that has occurred thus far, the expected performance in each of the KPPs are outlined in Table 1.

Table 1: Expected performance of KPPs

Parameter	Threshold	Objective
Autonomy	During way point navigation and search area	All phases of flight
Imagery	Identify two target characteristics	all five target characteristics
Target Location	Within 250 ft	Within 50 ft
Mission Time	Less than 30 minutes	20 minutes
Operational Availability	50% within original window	100% within original window
In-flight re-tasking	Add fly to way point	Adjust search area

Requirement Met	Testing Underway	Not Likely to be Met

Currently all of the threshold requirements have been tested and met during sub system and full system testing. The inflight re-tasking objective has been tested and is expected to be met at competition. The team is also expecting to be able to meet the operational availability objective requirements, but further full system testing will ensure the ability to meet that objective requirement. Testing is underway for both of the imagery and target location objective requirements and the goal is to at least be able to meet the imagery object requirement. While the autonomy and mission time objective requirements are an aim for the team in the long run, they are secondary objectives and are not expected to be met this year.

2.0 UAS DESIGN

2.1 Airframe Design

The plane is primarily made of molded EPO foam with carbon tubes embedded through the wings and fuselage for stiffening and reinforcement. EPO foam is lightweight, durable, and flexible so even violent landings in harsh winds cause minimal damage to the airframe. In the event damage does occur, repairs are very simple and can be made in a matter of minutes.

The X8 design sports a long, tapered swept wing with wing tips for excellent roll and pitch stability. Large elevons, a streamlined fuselage, and the long wing contribute to the plane's ability to handle winds near the 15-20 knot limit as specified in the competition rules, which has been tested in constant winds of around 14-16 knots. Flat carbon rods were also embedded vertically in the wings for added stiffness in high wind conditions.

The bay of the airframe is wide and allows all the components to be viewed at one time, so the system can be rapidly evaluated for flight readiness prior to the start of the mission. Once the system is set up, each component can be dealt with individually without disturbing other components, maintaining the integrity of the system.

The UAS flies without landing gear, saving the weight for extra payload carrying capacity and lowering drag. Further, the airframe uses elevons for pitch and roll control so it can eliminate the added servo weight of ailerons and tail surfaces common to other airframes. On landing, the foldable pusher propeller simply conforms to the ground, making for a smooth, controlled touchdown.

The Canon T2i camera is mounted in the front of the plane, connected to a one-axis gimbal for roll compensation. A plexiglass plate is installed under the camera lens to provide a clear shot of the ground and protect the lens on landing. All of the electronic components besides the camera gimbal utilize Velcro for mounting in the UAS, so each device can be easily removed and resecured.

Another important design consideration for the airframe is the choice of power system. Traditionally, the Rutgers team chooses electric motors for their simplicity, reliability, and reduced electromagnetic interference. An 840 watt electric outrunner motor was chosen to drive the plane because it provides the power needed for comfortable takeoff and cruising of this airframe without the unnecessary weight and current draw of higher power electric motors. In addition, two 14.8 volt (4 cell), lithium polymer batteries are connected in parallel for a 9000 mAh capacity that allows the aircraft to achieve the team's desired twenty minutes of minimum flight time.

2.2 Launcher Design

The team chose to replicate a proven launcher design that is known to work with the X8 airframe. The launcher is powered by 3/8 inch latex rubber surgical tubing stretched along the length of the six foot long launcher rail, secured to a panic snap. The panic snap is wound with nylon rope that extends out ten feet behind the launcher so it can be triggered from a safe distance. The carriage that holds the aircraft is made of aluminum and wood, with duckbills on the top to secure the plane, hooks on the bottom

Figure 2: Launcher with UAS

to attach to the bungees, and 8 steel bearings which it uses to slide on the sheet metal rails. The rear legs of the launcher are secured with stakes to prevent tipping of the device on launch. New methods of securing the launcher are under development for faster setup and breakdown.

The launcher is easy to transport to and from the field, as only two bolts need to be removed to fold the long front legs. Removing more bolts, the launcher can be completely disassembled for transportation in a standard sedan.

2.3 Ground Station Design

The ground station control software used is APM Mission Planner. This software is commonly used in small and large scale UAV projects associated with the ArduPilot Mega. The APM Mission Planner provides the ability to rewrite parameters midflight, add or delete waypoints, and acquire data of the plane at any given moment. Crucial characteristics such as GPS coordinates, altitude, airspeed, and relative plane location are visible on the ground station along with the predefined flight path. The ability to set a geo-fence in the Mission Planner is a safeguard to ensure that the aircraft does not leave the predefined boundaries given by the mission. To facilitate maximum safety, the switch that allows the autopilot to be activated is located on the pilot’s transmitter and allows the pilot to return to manual flight at any moment.

Figure 3: Screenshot of APM Mission Planner software

An important and commonly overlooked obstacle at the flightline is glare from the sun on ground station displays, which can render the system useless. To reduce glare, the ground station computer utilizes a matte screen monitor as well as backup sunshades in order to provide maximum visibility in bright, outdoor conditions. This ensures that the team can properly monitor the plane in flight, review images from the camera, and demonstrate our progress to the judges without problem.

2.4 Data Link Design

The system incorporates three different radio frequencies in order to ensure no interference between the various systems on the plane. The autopilot communicates with the ground station on a 900MHz spectrum using a 3DRobotics telemetry kit. This kit was designed around the ArduPilot Mega autopilot and accompanying Mission Planner software making it easy to integrate. It provides an air data rate of up to 250Kbps with an advertised range of several miles and tested range of over 3000 feet. In the event that the autopilot is no longer able to communicate with the ground station, it is programmed to use the onboard telemetry to navigate to a predefined "home" location.

Along with this fail-safe, the plane can be controlled using manual R/C controls running on a frequency of 2.4GHz. The R/C controls are communicated through a HiTec transmitter from the ground to a corresponding receiver in the plane which wires the R/C controls through the autopilot.

The imaging system relays information to the ground station using a 5.8GHz Ubiquiti Bullet M antenna to send the data from the plane and a Powerbridge M antenna to receive the data on the ground.

There are also two GPS antennas onboard the UAV, one associated with the autopilot and the other with the imaging system.

2.5 Payload Design

The payload consists of a Canon EOS Rebel T2i Digital SLR Camera for our imaging system. The Canon EOS Rebel T2i offers professional EOS features in an easy to use, lightweight digital SLR featuring an 18.0 Megapixel CMOS Image Sensor and a Digic 4 Image Processor for exceptional clarity and capture rate up to 3.7 frames per second. The camera utilizes an EF 400 lens with a diagonal viewing angle of 57 degrees for greater field of view and clarity. This allows the team to meet the goal of detecting most of the characteristics of all the targets at a high enough altitude while doing as few passes as possible over the search area.

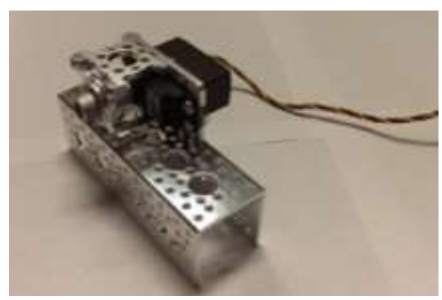
Figure 4: Camera stabilization gimbal

The camera is mounted on a pan tilt controlled by an HS-985MG tilt servo giving a 90 degree roll. The pan tilt rotates counter to the plane's roll and thus sustains a downward view at all times.

The camera data feeds back to the onboard BeagleBoard, which is the computer for the imaging system. Along with capturing and transmitting pictures from the camera to the ground station, the BeagleBoard is also responsible for the connection to the Simulated Remote Information Center (SRIC) through the USB Wi-Fi adapter mounted on the BeagleBoard.

The plane possesses an auxiliary power supply which is dedicated to the imaging computer, Ardupilot, GPS, and Telemetry System. This power supply is designed to make all of the systems independent of one another in terms of power usage. By powering all of the other onboard systems separately, it allows the main R/C motor batteries to drain without risking losing control of the UAS.

2.6 Mission Planning

Since the mission consists of a number of phases and components, the UAS must be prepared in a way that allows it to transition between modes to accomplish the next mission objective. The mission phases are as follows:

- **Phase 1 - Takeoff:** Once mission preparations have been completed and the team has received approval to begin the mission, the Takeoff phase begins. This phase is underway once it has been hand launched or cleared the launcher, after which the aircraft will engage its throttle (for a hand launch) and climb to the altitude needed for the following phase.
- **Phase 2 - Waypoint Navigation:** Once the Takeoff phase has concluded and the aircraft is at the required height for the first waypoint, Phase 2 is ready to begin. This phase is underway once the craft has begun navigating to the first indicated waypoint, and continues as long as there are remaining waypoints to navigate. During this phase the craft is also tasked with identifying targets along the specified path. Once all waypoints, including any points that must be added in-flight, have been successfully navigated, the Waypoint Navigation phase is in its concluding stages and preparation for phase 3 begins.
- **Phase 3 - Area Search:** As the system concludes Phase 2, it will begin to approach the designated search area. Once in the search area, Phase 3 begins. In this phase, the aircraft will begin exploring the search area in an attempt to survey as much of it as possible at a height from which target characteristics can be identified using the payload camera. During this phase the team will also be given a pop-up search area that the craft will need to navigate to and circle in order to identify a target in the form of a human engaged in an activity of interest. Once the search area has been satisfactorily covered and the pop-up search area requirement has been completed, Phase 3 will either proceed to the SRIC to attempt connection (if connection was possible during a previous phase) or will enter directly to its concluding stages, depending on time.
- **Phase 4 - Landing:** There are a number of conditions that can initiate the start of this phase. The planned start condition is the completion of all of the mission components. However, the Landing phase must also begin if there are any unsafe conditions present, such as low battery levels or system malfunctions, or if the time allotted is running low and it is necessary to land the plane to make sure that the mission is completed in time. The Landing phase consists of the aircraft approaching the landing zone, descending to an appropriate landing altitude, and lowering the throttle until it is completely off in order to land safely. This phase, and the aircraft's part in the mission, is completed once the craft is on the ground and the motor is no longer powered.

The system is also programmed with failsafe flight modes in case the craft is not functioning as it should. The flight termination mode is one required by the rules of the competition and is activated manually by the pilot in the event of an emergency. The aircraft's termination mode is slightly different because it is a flying wing and not a standard model of plane. Its conditions are:

- Throttle off
- Full up elevator
- Full right aileron

As there is no rudder it is not included in the flight termination sequence. Furthermore, while the process is to initiate full up elevator and full right aileron, the result will be for the left elevon to be at neutral and the right elevon to be at full throw since there are only 2 control surfaces on the plane.

2.7 Data Processing/Autonomous Target Cueing and Recognition

The imaging system, outlined in Figure 5, is comprised of the Canon T2i camera, the BeagleBoard XM onboard the UAS, Ubiquiti antennas for communication between the UAS and the ground station computer.

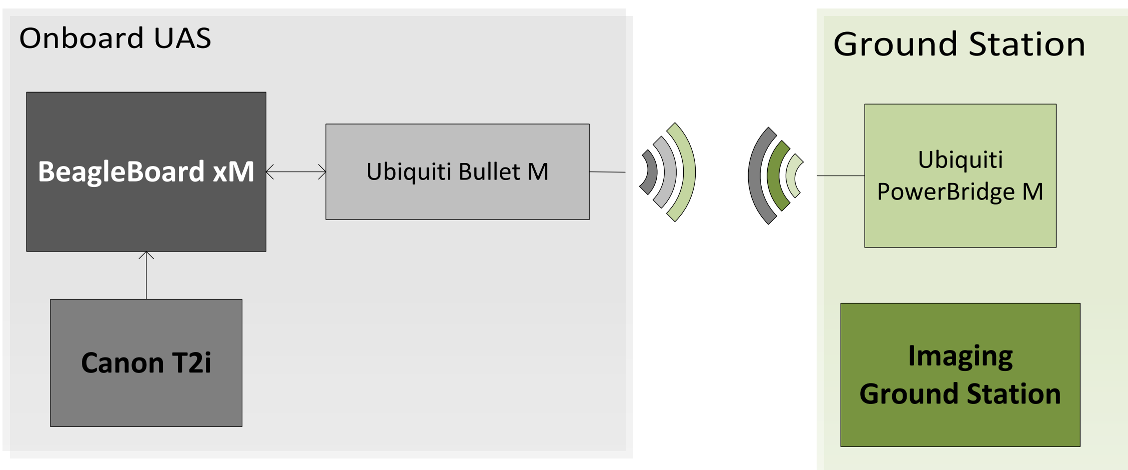

Figure 5: Imaging system block diagram

2.7.1 Image acquisition

The image acquisition process can be summarized as a few key steps. The Canon T2i camera takes pictures and sends them to the onboard computer. The onboard computer communicates the images to the ground station via the Ubiquiti data link. The ground station analyzes the images, identifies any targets, and displays all targets and their characteristics to the operator.

The desired frame rate for the camera was calculated to be at least 1 picture per second using the desired flight altitude (calculated from the desired pixel density of 2 pixels per inch to resolve the targets in a picture), the known average groundspeed (about 35 knots) of the airframe, and the camera’s field of view (57 degrees). This calculation helped in the decision process of choosing the camera and was confirmed during flight testing with the imaging system. Testing is under way to attempt to increase the frame rate in order to allow faster and higher flights in order to minimize the time required to cover the entirety of the search area.

While the camera is more than capable of taking pictures this fast, a problem arises when sending the images to the onboard computer. Since the camera uses an SD card to store the pictures, any program trying to retrieve pictures from the card must make sure that there are no read/write conflicts. Multiple options were explored to accomplish this task. The first option that was tested was using *gphoto2*, a program that can interface with the Canon camera (and many others) to download images. However, gphoto2 can only take pictures at a maximum rate of 1 picture per second. It prevents the camera from taking any more pictures while it is downloading the images. Even though this speed was acceptable for the team's parameters, a buffer was desired in the case that the picture rate needed to be increased. The solution for this problem was to write custom firmware for the camera, and write custom software for the BeagleBoard to interface with it.

The firmware on the T2i is modeled after *Magic Lantern*, which is an open source alternative to Canon's proprietary firmware. The software on the BeagleBoard (called RU-Photo) is modeled after *gphoto2*, and customized for the needs of this system. RU-Photo makes PTP calls using *libptp* to communicate with the camera, and safely retrieve the pictures. The pictures are then written onto a flash drive on the BeagleBoard.

The next part of the process is tagging the photos with all the appropriate spatial information: GPS location and altitude of the plane, the tilt of the camera, and the time the photo was taken. This information is accumulated from an IMU (Inertial Measurement Unit) mounted on the camera specifically for the imaging system. The pictures are stored as JPEGs, and the spatial information is stored in the EXIF data (part of the JPEG).

Once the pictures are on the BeagleBoard and have been tagged, they are sent to the ground station via the Ubiquiti Bullet antennas. As reception can be quite poor during flight, the data is sent using the UFTP protocol. UFTP is an FTP protocol based on UDP packets instead of TCP. This protocol has much less overhead than TCP communication, and was developed specially for wireless transmission of data.

Once the ground station gets the pictures and their associated files, it begins to analyze the pictures for any targets. The target recognition is performed by our Target Recognition and Classification (TRAC) system, using Intel's open source vision library, OpenCV.

2.7.2 Target analysis

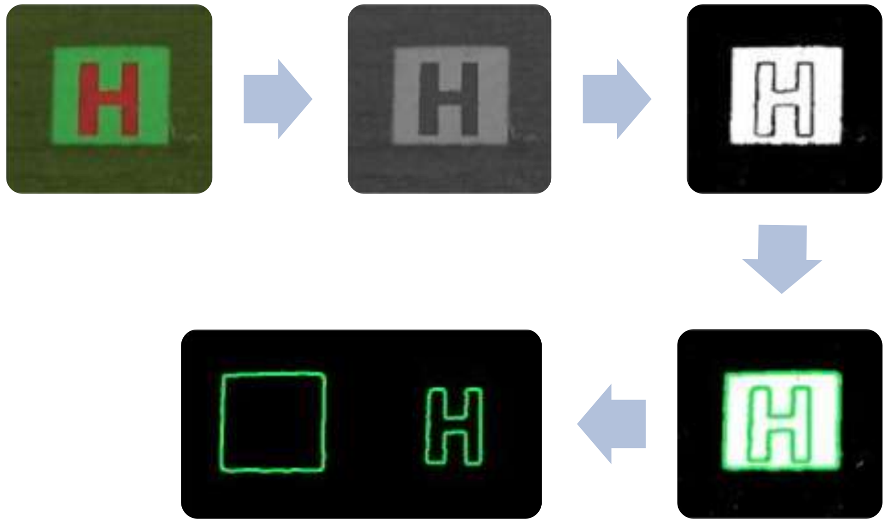

Figure 6: Target shape and alphanumeric detection

In order to determine the target characteristics, each image containing a target goes through a serious of step, depicted in Figure 6. First the image is warped to accout for any tilt in the camera (given by the gyroscope data). Next, this image is converted to grayscale. Thresholding is then done on the grayscale image at several different intesities to yield the image in the 3rd step of Figure 6. From this image, contour recoginition is performed on each thresholded image. Only the contours that can possible correspond to a target are saved. The attributes of the polygons considered are:

- Minimum and maximum area, accounting for the altitude of the UAV
- Regularity of the polygon, so random natural shapes are not counted
- Existance of another countour within the polygon, as each target has an alphanumeric inside it

From each set of contours a polygon is approximated, yielding the result in the last step of Figure 6. For each polygon, straight lines are approximated using Hough Lines and circles and Ellipses are approximated using Hough circles. Shapes such as semicircles are approximated using a combination of the two algorithms.

Each polygon is analysed and classified differently for the shape and the aplhanumeric. The shape polygon is analyzed using the number of sides, the angles between the contours and whether the polygon is concave or convex. In the case that the polygon cannot be identified based on these attributes alone, the polygon is analyzed using a Support Vector Machine (SVM). An SVM uses machine learning to determine whether or not a given object belongs in a set. The SVM was trained with outlines of shapes. It was made to analyze hundreds of predefined shapes, and the polygon approximation of the target is compared against that library.

The polygon approximation of the alphanumeric is analyzed by using the open source OCR (Optical Character Recognition) software *Tesseract*. This program is robust enough that no custom code was required for its functionality.

In order to determine the location, for each possible target, the GPS location of that target is computed based on the Euclidean distance from the polygon's centroid to the center of the image, and the GPS location of the UAV when the picture was taken.

The orientation of the target is determined by first checking to see if the orientation of the alphanumeric can be determined (for example, if it is an 'R') and if so the alphanumeric's orientation is used to calculate the target orientation. If the orientation of the alphanumeric cannot be determined (for example, if it is an 'O'), then the longest side of the shape is considered to be the bottom, and the orientation is calculated based on its slope.

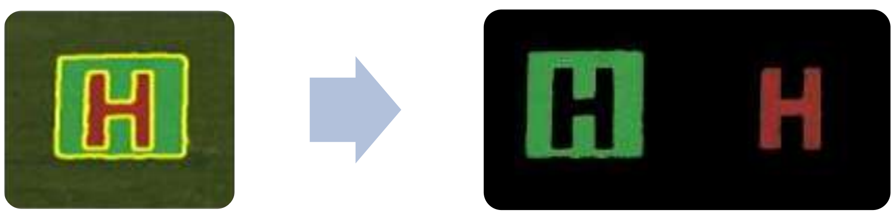

Figure 7: Target color detection

To obtain the color of the target and alphanumeric, the image is further processed as depicted in Figure 7. First the contours are overlayed onto the original target image. The shape and alphanumeric are then separated from the rest of the image. The average color for each is computed and compared against a list of hundreds of colors. The closest match is computed by performing a binary search for the average color's hexadecimal value.

2.7.3 Operator Interaction

The TRAC system displays images on the monitor as they arrive from the UAV. The present image is displayed over most of the screen and is moved to a thumbnail queue on the side once new pictures come in. Once potential targets have been identified in an image, that image is moved to a separate queue on the top. If any targets are recognized in the current picture, the program flashes the outline of the target in bright colors to draw attention to it, and its attributes are listed in a popup nearby. If any attributes are incorrect, the operator can correct them here. If the operator sees a target that the system has not identified, he or she can flag the image, and the

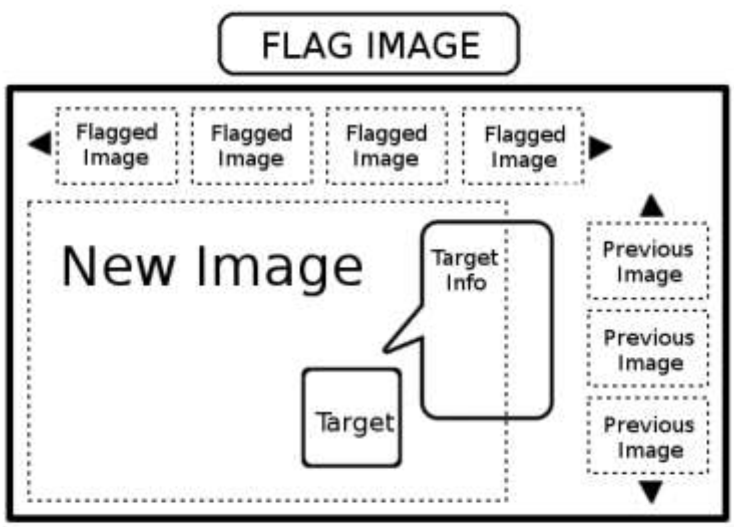

Figure 8: Imaging ground station software schematic

system will put the image in the “Flagged Images” queue, and then attempt to perform a more focused search on it. If this search fails, the operator can manually type in the attribute information. The thumbnails can be clicked on at any time to display the full sized picture.

2.7.4 System Failure

If, for whatever reason, the BeagleBoard or camera onboard the UAV freezes or malfunctions, the operator can reboot the entire imaging system. If a reboot is initiated, the ground station creates an SSH tunnel to the UAV, and sends a reboot command. The system reboots in roughly 20 seconds, and all programs are initialized on startup to reduce delays as much as possible.

3.0 Testing and Evaluations

Testing of the system was done in several steps: subsystem bench testing, system integration testing, and full competition testing. Once the parts for each subsystem were chosen, the subsystem was put together and tested on the bench, separate from the other systems and the airframe.

3.1 Imaging Subsystem

The imaging system was tested in two parts: the communication infrastructure, and the image processing algorithms. The communication infrastructure was tested by stressing the system and insuring that communication did not falter or was able to resume in case of disruption. Some of the stressers were interrupting the communication from the camera to the onboard computer, interrupting the communication to the antennas, stopping the camera sensor and crashing the imaging ground station. All of these situations can be alleviated by rebooting the relevant component. The onboard system is configured so that it can be fully restarted at any time mid flight.

The image processing algorithms were tested by using custom made plywood targets. The targets were constructed according to the specifications of the rulebook. They ranged from 2 feet to 8 feet wide, and their colors were chosen in a way that would test the limits of the imaging system. For example, some targets were extremely close in color to the grass they were placed on. This helped make sure that the algorithms used for object recognition were precise enough to pick up on the minute differences between colors. The targets were a variety of different shapes to make sure that many different types of shapes were recognized. To test the alphanumeric recognition, several different fonts were used on the targets. Test flights over objects of similar size as targets, like puddles of water, were also performed to make sure the system did not report any false positives. Flights were also performed at multiple altitudes to test that changes in relative size of the targets did not negatively affect the results. These tests have sufficiently demonstrated that the system is robust enough to accurately identify most, if not all, targets encountered in the competition.

3.2 Autopilot Subsystem

The APM 2.5 being used this year is an upgrade of the same system used in previous years of the competition, so many of the team members were already familiar with its functionality. This allowed for less time to be taken on getting to understand the workings of the system and more time on tuning it for the airframe chosen. The autopilot was initially tested in the airframe on the bench to ensure that the autopilot-controlled modes (i.e. stabilize, autopilot) moved the servos correctly.

To test the autopilot, it was placed in the airframe and the airframe was flown in manual mode to make sure the autopilot was reading the correct data. Once the pilot and operator were comfortable with the autopilot under manual control, it was placed in stabilize to check the autopilot responsiveness to level the plane and then in a fly by wire mode in order to tune the autopilot parameters to properly fly the airframe. Finally the autopilot was given full autonomous control through several waypoints to further tune the airframe.

3.3 Airframe Subsystem

While the airframe was chosen for its proven flight characteristics that are needed to meet the threshold and objective KPP requirements, testing still needed to be done to ensure its ability to carry the payload weight for this system and learn the flight behavior of the airframe. The plane was first flown stock with no modifications with incrementally increasing weight as the flights went on in order to ensure the airframe could carry the 8 pound payload for the onboard systems. The airframe was also flown in various wind conditions to meet the required wind conditions specified in the Request for Proposal. The airframe was able to handle constant winds up to 18 knots, though with some visible difficulty. Some of this difficulty was due to the increased payload, and reinforcing the wings of the airframe has helped solve that difficulty and strengthen the overall airframe.

3.4 Launcher

The launcher for the aircraft initially had many problems with friction, alignment, carriage impact damage, and lack of power to launch the aircraft with full payload. Many features, including lower friction steel rails, leg extensions, and an impact buffer contributed to the success of the launcher. At limited capacity (with an inferior, testing propeller), the aircraft was able to clear the ground by about two feet after launch before starting its full climb. Further testing revealed similar results with consistently level launches, improving reliability compared to the hand-launch method.

3.5 System Integration

Once each subsystem worked as desired, all the systems were put together on the bench and made sure they worked as expected together. This involved making sure the frequencies did not disrupt each other or were disrupted by any EMF generated by the R/C equipment through range testing. Furthermore the auxiliary power unit was checked to make sure it would supply the adequate power for the entire integrated system. Several small modifications were also made to the airframe to comfortably fit all the systems onboard. Testing was done in flight with all the pieces in the plane and functioning in order to do more in depth autopilot testing and image system testing.

3.6 Competition Run Through

The final step to the testing of the RU Autonomous UAS system was to do full competition run throughs, from moving the system to the flightline to breaking it down and removing it from the flightline, all in the required time. For the flight portion, a waypoint path and search area were created at one of the team's larger testing sites. In the search area, one team member would place out an unknown number of targets at unknown locations for the imaging team to find. This testing was set to start on the weekend of May 25th, but due to unfortunate weather this testing has been postponed to the upcoming weekend of June 1st.

Figure 9: Practice way point path within boundary

4.0 Safety

4.1 Protocol

The team is familiar with all aspects of the system and the safety procedures required for the airframe. In order to ensure safety of all members when starting up the system (especially the motor onboard the plane) the safety officer runs through a specific safety procedure that all team members follow. Preflight protocol extends to retrieval of the aircraft, where operators are aware of the location of the propeller arc and how to safely handle the plane.

4.2 Go, No-Go Criteria

Before takeoff, the team runs through a checklist of criteria evaluating various aspects of the system and their readiness for the mission. These criteria operate under the idea that some system components are vital to the mission while others are not critical and that other parts of the mission can be completed even if these non-critical parts are not functioning correctly. For example, servo failure is a mission critical component that must be repaired before the mission can begin, as no mission components can be completed if the servos that control the movement of the elevons are not functioning. Therefore, the mission is only in a "Go" situation if the servo malfunction can be repaired, otherwise the mission is in a "No-Go" situation. As another example, if the imaging system is having issues, waypoints can still be navigated and thus the mission is in a "Go" situation at a limited capacity. The numerous checks on this list ensure that the plane does not take off in an unsafe condition.

4.3 Chain of Communication

To ensure that any pressing safety issues are relayed to the pilot as quickly and efficiently as possible and vice-versa, the team has a chain of communication. The ground station and imaging ground station operators relay any relevant information to the ground station manager, who relays this information to the pilot point of contact via walkie-talkie. The pilot point of contact then relays this information to the pilot. This chain can also be utilized in reverse in case the pilot needs to relay information to the ground station operators.

4.4 Auxiliary Power Unit

As mentioned in "Payload Design", the plane is equipped with an auxiliary power system in order to separate the vital systems required for safe control of the vehicle from less vital systems, specifically the motor. In order to ensure maximum flight time without risking loss of control over the servos due to power loss, the main motor batteries are completely separate from every other system on board the plane. While the main motor batteries have a tested minimum flight time of over 25 minutes, the auxiliary power unit, comprised of 2 smaller two cell batteries, are capable of powering all of the onboard system in excess of one hour, ensuring that the onboard systems will not experience power failure during the flight.

4.5 Takeoff

The potential primary method of launching the aircraft is with the bungee-powered launcher. The launcher is very powerful due to the weight of the UAS, so numerous safety protocols are in place to prevent potentially harmful misfires. The integrity of the system, including the bungees, ropes and security of the legs, is checked before each launch to ensure a safe launch. Verbal and visual cues are used throughout the tensioning, securing, and launching steps in order to ensure that everyone is in their designated places for launch and aware of the current state. Furthermore, the safety officer makes sure all nearby personnel are clear of the propeller arc and physically behind the launcher before giving the pilot permission to launch.

In the event of a hand launch there are certain risks that need to be mitigated in order to safely and consistently launch the plane this way. Until the plane is ready for takeoff, the throttle cutoff is engaged at all times. When in position to launch the plane, a throttle test is performed to make sure the motor is engaged. When launching the plane, the pilot ensures that the plane is safely four to five feet out of the launching operator's hand before engaging the throttle. Repeated testing helps improve the reliability of the hand launch, and there have been no incidents or close calls concerning operator safety since the first day of testing.

4.6 Failsafe

As mentioned in "Mission Planning," the autopilot is programmed with a "failsafe" flight termination mode in case the plane loses connection to the pilot's transmitter or all control of the aircraft is lost. This mode can be triggered manually by a switch on the transmitter and activates instantly if the 2.4 GHz connection is lost in flight. Having a short delay between the connection loss and failsafe activation ensures that the compromised plane does not wander far from the flight zone and minimizes the likelihood of endangering bystanders.

5.0 CONCLUSION

Through evaluation of the mission requirements and analysis of past competition experiences, the Rutgers University Autonomous team has designed and constructed an unmanned aerial system that it believes will be able to complete all of the threshold KPPs as well as some of the objective requirements. The team accomplished this through applying solid system engineering principles as well as the knowledge of its members in the various subsystems that comprise the final product.

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