CUAIR
Cornell University Unmanned Aerial Vehicle

2007 Project Team Report

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Introduction

CUAIR is a relatively small project team from Cornell University. Members receive academic credit for their participation in the form of a 3 credit adviser approved elective. Team leaders are elected at the end of the year to serve for the coming year. New members are then admitted to the team after an interview process headed by the team leaders. Old members are allowed to continue on the team without this interview, and are sometimes asked to help with the interview process.

Goals

Aside from striving to meet the competition's goals of building an autonomous aerial vehicle with searching capabilities, the CUAIR team aims to give its members experience they would otherwise not receive in a classroom environment. For our team this included learning machining skills, working with design software, conducting individual learning projects, meeting realistic deadlines and completing checkpoints that may be affected by shipping and other delays, and learning to work within a common lab space shared by other project teams.

Our team also has competition-oriented, team wide goals such as designing with temporary and permanent loss of component fidelity, creating and testing fallbacks during these situations, compacting our designs, creating a set-up and user friendly product, and creating a versatile, durable, and flexible design.

Competition specific goals were:

- Perform autonomous flight through a series of waypoints
- Return images and GPS data of targets in the area surveyed as well as detailed reports on targets
- Complete whole mission within 40 minutes

Furthermore, additional credit would be given for the following abilities:

- Autonomous Takeoff
- Autonomous Landing
- Dynamic re-tasking while in flight
- Minimum required time

Finally, the mission would be considered a failure if any of the following were to occur:

- Time goes past 40 minutes
- The vehicle descends below 75 ft. during flight or above 100ft
- The vehicle leaves the mission boundary areas
- Any flight systems fail or cause a danger to the team or spectators.

Changes

This year we made comprehensive changes to last year's model. The mechanical portion of the plane was completely scrapped and replaced with a new model we devised from scratch. This allowed us to redesign every aspect of the plane around the new electrical components and desired flight characteristics. We also used this opportunity to make progress towards one of the long-term goals of compacting our design and making the plane, especially the body and the wings, as modular as possible.

These changes were made by both the mechanical and electrical sub-teams working in tandem to produce a body that assembles and disassembles with relative ease.

Other changes, including the main impetuous to change the design, came from our performance results last year where we launched, and summarily crashed, our plane towards the judges' panel using a motorized winch. We have returned to a more conventional launching and landing method involving landing gear.

General Challenges and Solutions

The CUAIR team faced several unique challenges this semester that we first address to create the context in which many subsequent decisions were made, including the unconventional order of completing certain tasks.

This year, the team was moved to new lab space in an effort by Cornell Engineering to consolidate all the project teams' space on campus. Though there were many benefits, such as increased collaboration with the other project teams, this presented challenges. The first challenge was relocating the lab and all our property. This turned out to be a blessing as new members became acquainted with all the tools and materials previously used by the team that was stored in the lab. This also resulted in the discovery of tools and old plane parts that were not previously aware of. The downside of the move was the need to store everything from the old lab in a much smaller office that was shared with another team.

We also faced not having proper network and internet access for nearly half a year in our new home. Our team had previously had used an online submission system where weekly progress reports, general announcements, tasks allocation, and general purpose multi-user coordination were conducted. This had been run through a server in our lab using our available network connection, but without adequate facilities, this system was not available to us. We worked around this by reverting back to paper-based weekly progress reports and emphasizing discussion during the biweekly meetings.

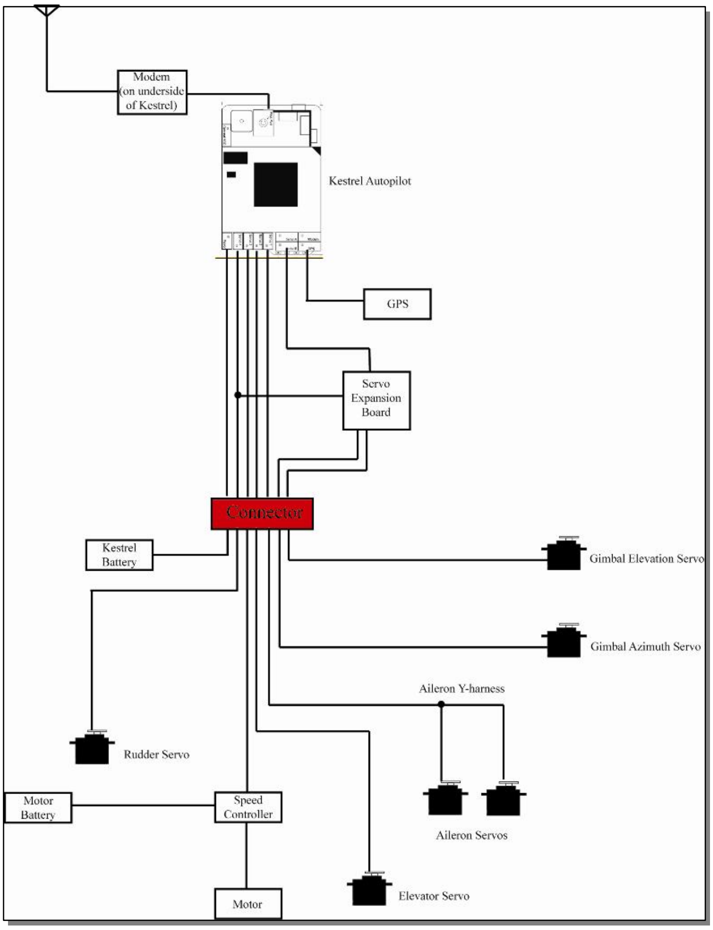
The final, and most serious challenge, was a lack of funding for the first half of the year. Due to a mix up with Cornell's business department, CUAIR had no funding, leaving us with no purchasing power and no way to refund purchases. Since we crashed our plane at last year's competition, this presented a fairly serious problem. The end result was that we used the last of our supplies to create a prototype based off of a pilot trainer and testing plane we used last year, and then concentrating on building our plane design. Since we could not buy materials to begin construction or to begin modeling our plane, we depended a lot on three-dimensional CAD programs to work out our final design.

Electronics

Background

Like the other sub-teams, the ECE team was led by the only returning sub-team member. Since we were working with a completely new team, it was an ideal time to focus on a new architecture. Like last year, it was necessary to have our autopilot, the Kestrel, operationally functional but this year we also started to rethink the entire design of the wiring in the plane. Given our funding issues, and the fact that our autopilot from last year was damaged in a crash and needed costly repairs, we initially focused on how to better fit our electronics in the plane.

Electrical Schematic



- The aileron servos share one servo channel. In order to obtain the differential motion required, the orientations of the two left and right wing servos operate mirrored with respect to each other.
- Power is supplied to the servos through the speed controller, which is powered by the motor battery. The speed controller steps down the voltage from battery's 11.1V to the 5V needed by the servos. Currently we are using one 4800 mAh and one 8000 mAh 11.1V Lithium Polymer battery connected in parallel, which are housed in the lower half of the body of the plane.
- The gimbal's servo control signals are transmitted through a serial port on the Kestrel to the servo expansion board. However, in order to receive servo power, the servo expansion board must also make a connection with the power rail of one of the other servos. In our setup, we chose to splice the rudder servo's rail to do this.
- The GPS receiver is permanently mounted onto the interior of the wing.

Selected Components

Autopilot

At 16.65 grams (2" x 1.37" x .47"), Kestrel 2.2 is the smallest and lightest fully-featured micro autopilot on the market – ideal for surveillance and reconnaissance applications.

The system uses an external GPS unit for inertial navigation and wireless modems communications between the ground station and autopilot. The Kestrel Autopilot can guide mini- and micro-UAVs autonomously and/or receive dynamic user commands through the ground station, RC radio, and game pad controllers while providing live video feeds to the user. It uses three-axis rate gyros and accelerometers for attitude estimation, as well as differential and absolute air pressure sensors for airspeed and altitude measurement. This low-power, small autopilot solution is distinguished by simple, highly intuitive user interfaces, while providing real-time trajectory generation and tracking. Plus, it now includes wind estimation, onboard magnetometer, and auto-trim capabilities (Procerous Autopilot).

Gimbal

Procerus's own camera setup, with forward and sideways looking camera options and varying lenses was used.

Procerus partner, Brandebury Tool, is the maker of the small gimbal shown above. (360 degree, 76 grams)

2.75" high (including ball) x 1.5" Wide x 3.5" Long

801-224-5713

The camera and gimbal setup is approximately 1.5" wide, 3.5" long, and 2.5" in height. The camera outputs an NTSC signal. The resolution of the camera is more than 450 TV lines—or approximately 752x582 pixels.

The speed needed to focus on objects of interest will not be an issue with this gimbal, which can pan more than 360 degrees in less than a second. It can tilt a full 90 degrees, and can tilt approximately 80 degrees in less than half a second. The gimbal's components are made out of a carbon fiber composite. Together with the camera, the entire device is shielded inside a plastic enclosure. The entire combined mass is approximately 90 grams.

The gimbal and camera are mounted on the bottom of the main fuselage, near the back where the detachable rear wheel resides. The gimbal's servos are wired through the fuselage into the Kestrel via a servo expansion board. This board is necessary because the Kestrel itself can only support 4 servo channels, all of which are being used by the plane's control surfaces. The servo expansion board provides the two extra servo ports needed to control the gimbal's movement. The gimbal is controlled through the Kestrel Autopilot via the Procerus Virtual Cockpit software. Manual control via gamepad is also possible with the gimbal, allowing a viewing user to track objects of interest.

Power for the gimbal and camera setup is supplied by their respective closest interacting component. Since the gimbal's movement is controlled completely by servos, the gimbal servos have access to the same servo power (5V) once connected with the servo expansion board that is supplied by the motor airspeed controller, which powers all the other servos as well. The camera also runs at 5V which will be powered by servo power.

Transmitter

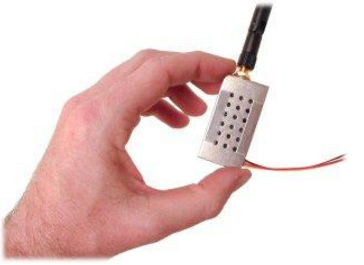
We selected to use Black Widow AV's collection of 2.4 Ghz transmitter/receiver to transmit our NTSC video signal.

Black Widow AV

Wireless Aerial Video Solutions

The video transmitter, purchased from Black Widow AV, is a 2.4 GHz transmitter operating on 12V DC. It transmits NTSC video over 8 possible channels and features 1000mW RF output power. The transmitter is capable of transmitting audio as well as video, but for our purposes we only used video. The antenna of the transmitter is connected through a SMA connector, which allows easy experimentation with different antenna types should the need arise. The transmitter communicates directly to a standalone receiver that has a video output with a standard RCA connection.

The video transmitter is connected to the camera only through a single video signal cable. Since the voltage for the transmitter is different than the camera, it does not share a common power supply. The video transmitter is powered by the same battery that powers the Kestrel autopilot.



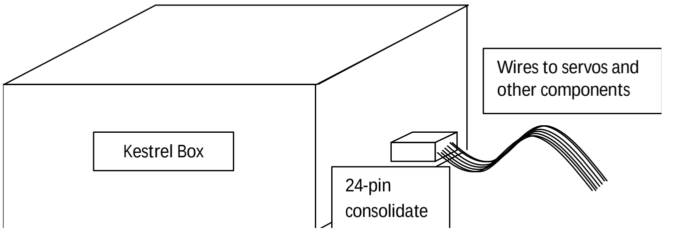
The primary advantage in using this new video transmitter is the large size reductions that it provides. The video transmitting unit used last year is easily larger than fifteen (15) transmitters that we are using today grouped together. By reducing size we are further able to streamline our aircraft design.

The video is received by the ground station using a PCI card from WinTVGo in a Shuttle PC where it can be readily analyzed by software. The PCI card offers an external antenna port making the computer the video receiver and eliminating the need for a video converter and extra hardware to get the video to a computer to be analyzed.

Changes

One of the problems with last year's design was the lack of wiring organization. Not only was it a mess to look at, but it also posed problems for anyone trying to learn the wiring of the plane. While redesigning our plane, the ECE team and the Mech-E team established goals that we wanted to achieve with our new design. Most importantly, we wanted a clean and easy removal of the Kestrel (our autopilot) for maintenance. This would enable easier trouble-shooting, documentation, and teaching of the system.

One of the problems was the sheer number of wires that went into and around the Kestrel box. We had inputs from all the servos, power cables, antenna, and airline tubing to consider. Attaching and removing all of them just to remove the kestrel from the plane became quite a hassle.



To assist with this process, we decided to consolidate what used to be separate connectors for every servo and the associated power lead into one header. We reasoned that since we use up to 6 servo cables and one power cable input, all with 3 pins each, we could solder all those cables onto a 21- or 24-pin connector and eliminate having to attach cables, detach cables, and remember the individual configurations in order to work on the Kestrel box. Removing the cables would now be simply a matter of unclipping a large connector.

One of the bulkier components on the plane that we decided to change was the video transmitter for the camera. Almost a third of the Kestrel box in volume, it seemed unnecessary to carry a transmitter that large when there were other far smaller and relatively inexpensive transmitters on the market. Naturally power and range considerations were taken into account, but given our requirements these were not a large concern. Our new proposed transmitter is scarcely the size of 4 matchboxes with a sturdy casing and boasts 1000mW of signal power. With this transmitter aboard, video quality should no longer be a problem.

Other design aspects that we decided to implement included a sleeker autopilot box profile that allowed the canopy to be built closer to the plane. This was an improvement in space utilization since much of the space inside the previous box was wasted. We also decided to change the composition of the housing from plastic to aluminum, eliminating the need for flimsy copper foil shielding to create a Faraday cage which was used last year. The usage of a voltage regulator, and the elimination of batteries operating at two different voltages onboard the aircraft (between the autopilot and servos), was also discussed, researched, and adopted.

Camera and gimbal components were also discussed and researched for alternatives. Given that the competition will now be using color in addition to shapes for targets, obtaining a color camera would be a logical step from our previously black-and-white camera. 480 horizontal lines, we decided, was enough resolution for our purposes. Since that our in-house gimbal was crudely hand-made, buying a decent gimbal is a must for this year, although those researched thus far have proven to be less economical than purchasing the one designed by the manufacturer of our autopilot.

Innovations

Innovations for this year were the introduction of the new camera gimbal, which is much smaller and lighter than previous years'; the use of a voltage regulator to minimize the number of separate batteries needed; the installation of a one plug system to eliminate the need for complicated individual wiring; and a true attempt at a modular design.

Other innovations include separate on/off switches for the control switches and the motor, which was useful for testing and safety. There is also an additional switch to toggling the number of Kertrel controllable servos between four (4) and six (6).

Areas for Improvement

Despite all the new changes we have made this year, there remain areas for improvement. For the coming year, we have already planned are to minimize the size of the electrical components; to improve the integration with the mechanical components; and to increase the accuracy, range, and efficiency of all component

Computing

Background

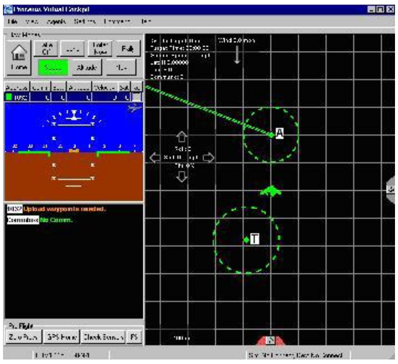
Since the mechanical and electrical characteristics of the plane were being reformulated, the CS sub-team didn't want to make too many drastic changes to the basic operational principles that would be guaranteed by the Kestrel's software. In addition, the lab move made us lose a tremendous amount of time due to the lack of an adequate network connection. Despite these limitations, there are four areas that are fit for inclusion: our ground station, our use of Procerus' Virtual Cockpit software, vision processing and our new website.

Ground Station

One major addition that CUAir added to last year's model was an all encompassing ground station. This system consists of the Commbox v1.1 from Procerus, a Compaq Presario v2000 laptop, a RAM laptop mount, a USB-to-serial converter, a 900 MHz antenna, and a plastic case that houses everything. The Commbox is made by Procerus and houses the Aerocomm Modem and the hardware interface to a serial connection. The serial connection gets passed through an off the shelf USB-to-serial converter, which is then plugged into a USB port on the laptop. The laptop itself is securely mounted to the inside of the Platt case by a RAM Tough Tray Universal Laptop Mount. We chose the Compaq Presario v2000 laptop for its economic pricing as well as its compact size. With a screen of only 14 in. the laptop is small enough to be housed in the case along with all the other necessary components. The Platt case itself, model 1419, is made of ABS plastic and measures 18 in wide by 13 in deep by 5 in high.

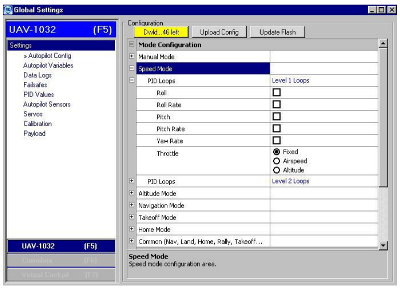
The mounting hardware for the 900 MHz antenna is attached to the outside of the case. The antenna is made by Nearson, model number SG101N-915, and was chosen for this application on the recommendation of Nearson for its operation gain of 5 dB and VSWR of less than 2.0 which is adequate for our frequency range and power. We found through testing that we received more data packets per second using this antenna over the stock 900 MHz antenna that came with the Commbox. After a little training a user can set up and power up the ground station in less than five minutes.

Virtual Cockpit Control Software



The ground station runs Procerus's Virtual Cockpit software. This software interfaces with the Commbox through a serial port to interface with the Kestrel autopilot device on the vehicle. It displays telemetry data from the plane, as well as communication and battery status of the Kestrel autopilot and the Commbox. It allows for high-level mission management functionality as well as low-level access to PID coefficients and other flight parameters. The top left of the main window allows the user to set the autonomous mode of the plane (which is active when the pilot switches off channel 5.) The plane can be set to return home, take off, land, maintain a certain speed, altitude or waypoint.

Under the mode selection is the heads up display, with an artificial horizon, some telemetry information, and communication and battery status for the Commbox and Kestrel. The main part of the screen is a map showing the current location of the plan, the home, landing, and approach waypoints, and the path of the plane since takeoff.



The settings window is where all the low-level flight parameters are set. The PID loops active during each autonomous mode, the actual PID coefficients, the payload settings (in our case, the gimbaled camera.) The Virtual Cockpit software also has a TCP/IP socket server that allows outside applications to access data and communicate with the autopilot. This is used by CUAir's Telemetry Server (see Section 5.3), which allows client applications to subscribe to certain data points. Client applications include the mosaicking app and the antenna tracker.

Vision Processing

The system that we're implementing will present a bird's-eye map after and during the flight. The user will have to identify the targets manually from the image. Features of the program include:

- Real-time mosaic map of the ground that is rendered as the plane flies.
- Each pixel of the mosaic will have its GPS coordinates figured out by the program; this will assist in identifying the location of targets on the map.

Everything is handled inside one main class; the code footprint for this system is quite small.

The algorithm that we're using to glue together the images from the camera and put together the map of the ground follows these steps:

1. Use OpenCV to identify key "features" of the current image that are easy to track. Usually the algorithm will return around 10 to 20 points on the image.

2. Identify where the points from the last step are in the next image.

3. Calculate the transformation from the first image to the next.

4. Apply the transformation to the second image, and draw it on the main map. It willbe aligned to the previous image.

5. Repeat.

What we will also do is use the plane's current GPS location each frame to get a rough estimate of the GPS location of each pixel in the frame, so when we identify targets we will also have a GPS location for them.

Program

This section will walk through the major sections of the code and explain what each piece does.

```
numCorners = 50;

cvGoodFeaturesToTrack( lastYImage, eigImage, tempImage,
lastcorners, &numCorners,

/*quality_leve*/.3,

/*min_distance*/15.0,

/*mask*/ NULL,

/*block_size*/ 3,

/*use_harris*/ 0,

/*k*/ 0.04 );
```

This code accomplishes the first step given in the algorithm above. The function takes in the last image that we have, along with a few other parameters, and fills the array last corners with the features to track across frames. We also do a quality check right after this; if we don't have N features to track (where N is about 15 for our purposes), then we'll just abort this frame and try again when the next frame comes.

```
cvCalcOpticalFlowPyrLK(lastYImage, YImage,

/*prev_pyr*/NULL,

/*curr_pyr*/NULL,

lastcorners, corners, numCorners, cvSize(10,10),

/*level*/4

,LKstatus,

/*track_error*/NULL,

cvTermCriteria(CV_TERMCRIT_ITER,10,.05),

/*flags*/0);
```

This function takes in both images (the one used in the previous function call and the new image), and calculates where the feature points from the last image went in this frame, and stores the resulting points in corners.

Next the program does a little linear algebra with the resulting last corners and corners arrays. A 2-d transformation of an image can be expressed as:

$$Ax' + By' + C = x \quad (1)$$

$$Dx' + Ey' + F = y \quad (2)$$

where (x, y) and (x', y') are the coordinates of a pixel in the previous and current frames, respectively. We want to use the features that we just picked out from both images so we can figure out the coefficients A through F.

We can use matrices to solve the system of equations efficiently, by setting up the matrices in the following manner:

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} A & B & C \\ D & E & F \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

The program fills the previous points and next points matrix, then uses OpenCV to solve for the coefficients matrix. It then uses the coefficients to transform the current transform matrix:

```
composeAffineTransform(curTrans,cumuTrans);
```

Then the program uses this transformation to draw the current frame into the right place on the map:

```
cvWarpAffine(frame,mosImg,cumuTrans,0,cvScalar(255,0,0));

cvShowImage(WIN_TITLE,mosImg);
```

Website

Our previous website had been difficult to maintain. Thus, we were delighted when a new recruited member expressed interest in and volunteered to create a new website. Since we were not able to host it on our own server, the new website was developed static and eliminated all the user-unfriendliness of a dynamic, database-driven solution. While having an easier to maintain website is in no part related to the design of the plane, the website demonstrated to potential sponsors that we had the facilities to make our design known and available for interested parties to see.

Mechanical

Background

The members of Mech-E sub-team were one returning junior and several new freshmen and sophomores. Because so many members were new to the team, we decided to completely overhaul the previous plane's design and begin anew with a brand new plane. Although an analysis of the pros and cons for redesigning the plane is included in the comparison section of this report, one advantage to this approach was that we could now design the wing and fuselage to the meet flight requirements and better carry ECE's components.

Selected Components

Balsa: Balsa was selected to be the main internal structure of the tail and wing due to its stiffness and low density.
Basswood: Since basswood is slightly more impact resistant than balsa wood, basswood was used for the outer covering of the tail. It was also used to join portions of the main wing, where high stresses were expected.

Cyanoacrylate (CA) Glue: Thin CA was used to bond the wooden components together. A thin application of CA glue dries quickly and was shown to be strong enough for our purposes. Thick CA glue was used to fill in sections with gaps to bridge.

Ultra coat: UltraCote is the thin outer film that is wrapped around the entirety of the tail and wing. This is used as a lightweight cover that reduces drag and adds aesthetic appeal. It is applied using a heating iron and adheres directly to the basswood outer frame.

Carbon fiber: Carbon fiber hollow tubes were used to connect the tail to the rest of the plane. It was also utilized in creating the hinge for the stabilator. This material was chosen due to its lightweight yet incredibly strong nature.

Changes

Wings

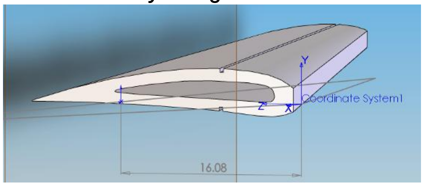
When we began designing the wing, we started with a simple set of requirements. These were based on previous measurements and observations. Primarily, the plane needed to be able to support approximately fifteen pounds, three pounds heavier than our previous plane and five higher than our estimated weight, during the flight. Additionally, the plane should also be able to sustain a slow speed of approximately twenty to thirty miles per hour and be stable, hopefully the most favorable conditions for carrying an onboard video camera. After doing preliminary research in the book Understanding Flight by David Anderson and Scott Eberhardt, an approximate airfoil and wing shape was determined.

Since one of our goals was slow flight, we decided on a rounded leading edge. This also allows for a short take off and landing, maximizing the number of places the plane can take off from while lowering the top speed of the plane.

Next to take into account is the aspect ratio of the wing, or the wing span divided by the chord of the wing. A high aspect ratio is desirable for slow flights, allows the use a smaller engine, and allows slower take off speeds. A lower aspect ratio adds control and typically uses less material, allowing for a lighter plane. As typically seen on airplanes, sweep of the wings reduces drag, therefore reducing the necessary power needed to keep the plane aloft. For a smoother flight, a slight dihedral adds stability.

With these variables in mind, we transitioned to computer aided design using a program called DesignFoil. DesignFoil was able to perform minute calculations for different airfoils and wing sizes. Using this program we determined that NACA 4515-52 airfoil with a ten foot wing span would allow for fifteen pounds of lift at twenty miles per hour, satisfying our design criteria.

The selected airfoil was then exported from DesignFoil and opened in the three dimensional CAD program Solid Works. There, the airfoil was extruded and shaped to the necessary sweep and dihedral From this base drawing, cuts were drawn to fit square carbon fiber rods which were to be placed for support. Cuts were also made where the leading edge could be glued on, for added support and ease of construction of the wing (though we also made the leading edge in our lab). Additionally, holes were extruded throughout the center of the wing, allowing for unnecessary weight to be removed.



This drawing allowed the team to visualize what the final wing would look like. Cross sectional views of the wing were taken every five inches and saved on a drawing file to be used in laser cutting balsa wood to the exact shape and size necessary.

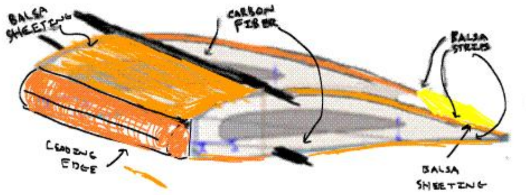
Once the wing was designed, construction began on a learner wing. The fabrication process for both the learner and actual wing began with laser cutting ribs for the wing out of balsa wood. Balsa wood was selected using a combination of market research and CES material selection software, and was used because of its low weight to strength ratio.

Once the ribs were fabricated they were laid out on a life size print out of the top view of the CAD model. This insured that the ribs were aligned and correctly spaced.

Once the ribs were aligned, cross supports were CA glued into place. The supports were made out of balsa wood in the learner wing, but carbon fiber rods were used instead in the final wing. Carbon fiber supports allow for minimal weight while still supporting the lift force across the wing. After the supports were in place, and thus the alignment of the ribs set, we could add servos, supports and cover the wing.

In the learner wing square blocks were glued between the leading edge and were then sanded down to fit the shape of the wings leading edge. In the final version this was replaced with one large balsa block which was then carved to specifications.

Quarter inch thick strips of balsa were placed on the ribs to make a greater surface are for contact with the ultra-coating, which was added later. Strips of balsa were glued to the bottom and tops of the back portion of the wings where the ailerons were to be cut.



At this stage in the fabrication process, the skeleton of the wing was complete. The flaps were cut out of the skeleton to be later attached by hinges and connected to servos.

When designing the wings, we wanted to make them detachable so that they could be easily stored and transported. One of many problems that we encountered was how to connect the wings together and create the dihedral that we designed.

To connect the wing together, hollow carbon fiber rods of different diameters were built into the skeleton of both sides of the wing. When the wing is pushed together, the carbon fiber rods on each side interlock holding the wing together. To create the dihedral angle, as well as a compression force to hold the wings together, fishing wire was attached to the ends of the wing. The wire is then pulled taught at an anchor point at the center top of the wings. This creates a compressive force on both sides, pulling the wings together. The ribs closest to the center on both halves of the wings are angled appropriately so the dihedral is formed when they are pushed together.

Once we found the solution for attaching the wings together, the final stages of fabrication began. Ultra coat was applied to the wing and the ailerons. Servos were attached inside the wing to control the ailerons.

One remaining last challenge was how to attach the wings to the body of the plane. After contemplating several ideas, and observing the crash of a plane using a bolting attachment method, we concluded that the best method is to attach the wing using rubber bands and a fiber glass harness. Rubber bands are extremely light, can go around the wings so there is no need to puncture the wings, and can be easily attached and detached. Also, in the event of turbulence or a crash landing, the rubber bands will give and snap before the wings deform and break. The fiberglass harness however provides the inelastic support needed to fly consistently, regardless of the rubber bands

Finally the wing was balanced and positioned so that its center of lift was approximately above the plane's center of mass. Small weights were added until the center of mass fell directly in the center to keep our plane extremely well balance

Tail

The tail, as with most airplanes, consists of two main components, the horizontal and vertical stabilizers. Together these two parts help give multi-directional stability and control to the airplane .

When designing the tail we kept in mind many of the same assumptions as when we designed the wings. In other words, since the airplane is designed for autonomous flight and needs to be able to view targets from the air well, we assumed the speed will be rather low.

The torque provided by the horizontal stabilizer will pivot the aircraft about its center of gravity (CG) along its lateral axis in order to control pitch. This means that a force must be provided either upwards or downwards by the stabilizer depending on what is needed to adjust to the desired angle of flight.

The wing is made primarily from balsa and basswood which have modulus of rupture values of 3140 lbf/in^2 and 8700 lbf/in^2, respectively. Bending stresses of this magnitude should not be reached in the tail due to the amount of material and the expected loads on the tail plane. These low expected loads are a result of the low flight speeds and cooperative weather conditions that are to be expected for normal flight and operation.

If failure were to occur, it would be a result of a high-speed impact with the ground or other object which would cause unforeseen stress concentrations. This could potentially fracture the wood that maintains the tail's structure.

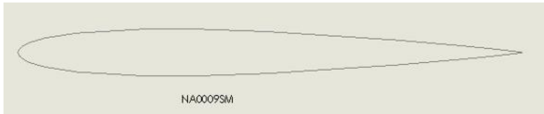
The tail is very lightweight due to a number of factors. First, the tail is hollow inside except for the frame structure made of lightweight balsa wood (with a density of 0.00578 lb/in^3). Also, the tail's exterior surface is made from thin sheet of a slightly stiffer, yet still lightweight, Basswood (with density of 0.0116 lb/in^3).

The control surfaces of the tail will be adjusted using two servos. One servo will be used to manage the rudder of the vertical stabilizer which will be very important during takeoffs, during landings, and for stability in the air. This rudder can either turn left or right as needed. The control of the vertical stabilizer will be governed using the second servo which will be mounted on the body of the plane and will control the pitch of the entire stabilizer. Such a control surface, known as a stabilator, provides a greater deflection surface than a conventional elevator.

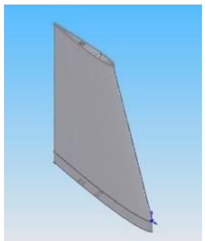
The span of the horizontal stabilizer is 18 inches. The height of the fin is 12 inches. The surface area of the tail is approximately 270in^2 (0.17m^2), which was designed to be about 10% of the wing surface area. The center cord of the stabilizer is 9 inches with a tip chord of 5.4 inches (which is an aspect ratio of .6). The stabilizer wings are swept back with an angle of 18 degrees, mostly for aesthetic purposes. The fin also has the same base and tip chords except it is swept back at an angle of 16 degrees to achieve a perfectly straight trailing edge for the rudder. The weight of the entire tail is approximately 1 pound.

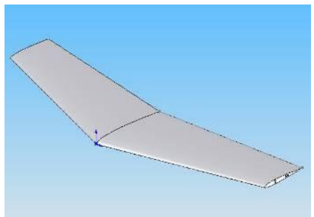
The torque about the center of gravity applied by the stabilizer is governed by the formula $Torque = \underline{R} \times \underline{F}$ where R is the distance to the center of gravity from the center of lift of the tail and F is the lift acting at the center of pressure. In order to be flying perfectly horizontal with stable pitch, the net torque about the CG needs to be equal to zero. Ideally the plane is balanced so that this will occur without any deflection, although trim can be used to fine-tune the deflection so that the net torque is zero.

The airfoil shapes chosen for both the horizontal and vertical stabilizers were selected due to their symmetric nature. Because the airfoils are symmetric, they will only shift the center of pressure back, thus stabilizing the aircraft while not providing any lift that would shift the center of lift. The only two ways that it can provide torque is from its weight and from deflections. The only difference between the airfoils chosen for the vertical and horizontal stabilizers is the thickness of the airfoil at different points along the length of the airfoil. The decision to choose one over the other for each specific component was based on observations of existing autonomous airplanes, as well as considering where a thicker cross-section was needed. The NA0009 SM airfoil was chosen for the horizontal stabilizer and the SD8020 was chosen for the vertical stabilizer. A program called *DesignFoil* was used in order to select and generate each airfoil.



After the airfoils were selected, a CAD model was drawn up which allowed for the ability to fully design and visualize the entire tail. This was a great asset in the design process. With a visual representation of the tail, certain aspects of the design could be tweaked to allow for practicality and aesthetics. The locations and alignment of the spars was also determined using the CAD software





Fabricating the horizontal stabilizer began with laser cutting cross sections of the stabilizer out of 1/8 inch thick balsa at multiple locations along the span. These wooden ribs would be used to create the general shape of the tail as well as provide structural support. With the ribs were laid out in their proper locations, wooden spars perpendicular to these ribs were used to keep them in position and are another key structural element. The ribs would then be glued in place using quick drying Cyanoacrylate (CA). Once in place, blocks of 1”x 1” balsa were glued between the ribs and used to create a strong leading edge. These blocks were then hand sanded in order to match them to the shape of the leading edge of the wing. A similar process was used for the trailing edge for structural support.

Once the skeletal structure of the horizontal stabilizer was completed, it was then covered in thin sheets of basswood that were glued on to further add rigidity and to support to the wing while also providing a nice smooth surface on which to apply a layer of UltraCoat. All rough transitions were then hand sanded once more to ensure a smooth and consistent surface throughout the tail plane.

The process of building the vertical stabilizer was essentially the same as that used for the horizontal stabilizer. The only difference is that the trailing edge needed to be turned into a rudder. This was done by simply cutting the ribs and creating a hinge joint that could be controlled by a servo that was mounted in the center of the fin.

After both key components were created, they were connected to each other using slats of balsa wood and glue with the fin set down into the horizontal stabilizer. The entire tail was then covered in UltraCoat to ensure a smooth surface to reduce drag as well as to add aesthetic appeal to the tail. Finally two carbon fiber rods were glued to a hinge on the bottom of the tail to connect to the rest of the airplane. These rods slide into a tight-fitting slot in the body of the plane and are secured with glue.

There were many issues encountered when designing the tail. The first concern was the laser cutting and the positioning of support spars in the very thin tail ribs. The laser cutting was problematic due to the very small thin pieces of balsa which was very brittle. Since the tail is tapered down, it was difficult to fit two spars all the way through. Also, the spar's orientation was a key decision that had to be made. Additionally there was concern that flaps on the horizontal stabilizer would not provide enough of a control surface to provide the function that would be required.

The issue with the laser cutter was resolved by appropriately sizing the ribs as well as strategically placing the holes for the support spars to allow for enough material between them and the edges. The thickness of the ribs limited the ways that the spars could be oriented. Taking this into account the, the two options were to either (1) lay out the spars to make assembly the easiest with the spars perpendicular to the ribs or (2) create an elevator, which was easier to make though difficult to assemble. Since we decided to make a stabilator, the easy assembly method was chosen. If we were to switch from a stabilator to an elevator, we could more heavily consider choosing the first design.

Launcher Versus Landing Gear

Early on in the design phase, we aimed to improve our launch system. For our flying wing design, we had utilized an electric winch system to pull our aircraft along a lightweight launch ramp made of PVC pipes. Among its fallacies, its greatest drawbacks were that it was very a labor-intensive method to launch our vehicle and was not convenient or portable.

In the original system, the PVC would have to be assembled at the launch site and the launch string would have to be wound about the winch prior to every launch. These two inconvenient processes alone greatly increased the launch preparation time. Secondly, the winch motor was considerably massive and not easily portable, and it was powered by an equally hefty 12V Nickel Cadmium (NiCd) battery that would have to be discharged and charged before each test flight. Additionally, since we relied on the launch rack for take-offs, the flying wing design had no landing gear and was restricted to only belly-landing in smooth and soft areas. Even in ideal conditions, the hook on the belly of the plane to which the launch string attached during launch would often become damaged at touch-down since it was the lowest extremity.

By comparison, switching to onboard wheels for the landing and take-off system had several clear advantages. First , it makes our UAV system greatly more portable, since all the necessary launch equipment is now on the aircraft. Second, launch preparation time diminishes to almost zero. Third, launches are considerably less complicated and can now be conducted by a single person. As for landings, the use of wheels greatly expands the number of acceptable landing sites for the UAV and greatly extends the UAV's survivability. The only inherent draw-back to using wheeled landing gear is that it adds a slight amount of weight and aerodynamic drag to the airframe. The incorporation of retractable landing gear seemed attractive at first since we would not have to compromise the aircraft's aerodynamics, but we quickly ruled out that option since it would increase the plane's weight and size and require additional electronic equipment. Furthermore, at the relatively low speeds that we would be flying at, the little extra drag added by the landing gear seemed unimportant given our UAV's requirements.

Our current landing gear system is a tri-wheel setup, with two main gears near the nose in front of the center of gravity, and one tail gear behind the CG. There are still two main flaws that we have identified in our design that have great need for improvement. The first problem is that the rear gear is too near the CG while being the weakest gear. By moving it further back we could lengthen the longitudinal arm-moment of the torque that is applied to the wheel when it is in contact with the ground and thus reduce the stress on it. The second improvement is to use a nose-gear setup instead of a tail-gear setup, and have the main gear in the back near the CG and the weaker nose gear farther forward. This would enable the UAV to be able to pivot back on its main gear during take-off and thus lower the minimum take-off speed. The main precaution that we would have to take with this setup however, is that the aircraft will be more prone to flipping forward on landings. We can easily prevent this by merely applying back elevator upon touchdown until the plane comes to a stop

Fuselage

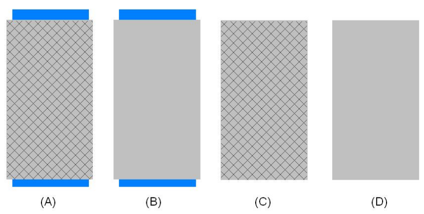
One of the main focuses of the team this year was in the fuselage area, which houses the plane's electronics as well as serving as the central point of contact for all the different parts of the plane.

Originally the main structural element of the fuselage was supposed to be aluminum bars arranged in an open rectangular prism. We decided to construct a box instead made from a mix of balsa wood (for less stressful areas) and birch plywood (for more key structural points). The objective was to lose weight without sacrificing too much structural strength. The sided box also allowed for easier addition of the foam protection around the box.

The box was also extended rearward from previous designs to allow for easier access to batteries and wiring and also to accommodate components such as camera gimbal and rear landing gear.

A major part of research on the fuselage was the protection of the fuselage through its outer shell. We decided on using a fiberglass shell, but desired something a little stiffer then the usually grade of fiberglass, this resulted in experimentation with different reinforcement materials. The final choice was the use of artists wire mesh in conjunction with fiberglass, layered on a structural foam mold. A small sample of 4 different styles of shells was tested

Show at the right is a diagram of different fiber glassing methods. (A) foam covered in fiberglass and wire mesh; (B) foam covered with only fiberglass; (C) wire mesh and fiberglass shell; (D) a simple fiberglass shell.



The results were that the wire mesh increased the strength of the hollow shells but the foam-cored samples were much stronger than the shells. The increase in strength was enough that less overall material (both weight and volume wise) was added to the fuselage. Therefore, the foam-cored wire mesh sample was the lightest and strongest. Our wooden box was first covered with foam (on all but the top side) and then shaped to size. This was another advantage of the foam cored shell: it allowed for the shell to be built directly on the box. The downside to this is that we did not build a mold and so if we ever needed to make a whole new fuselage we would have to shape it manually again.

The last aspect of the fuselage cover is its connection to the wing. The fuselage has a wide flat top that is shaped to fit the curve of the wing this allows for more surface area connection between the wing and fuselage. It also gives an easy access point to thru bolt the wing in place or a platform for other connection methods. There is also a cup-like shape at the front top of the fuselage that the wing fits into that keeps the wing in place as a secondary measure.

Modular Design

The whole plane was then design to come apart into 5'x2' sections. This was changed due to wiring and stability issues with the tail. With the tail permanently attached the plane separates into 3 parts - the fuselage-tail section and two wing segments. The wing sections can then be rejoined using a concentric carbon fiber tube method. This is then attached to the fuselage using both a fiberglass harness and a system of special rubber bands.

Motor selection

The current power plant for the aircraft is a Model Motors AXI 4130/16 electric brushless motor powered by 3 parallel banks of 6 series lithium polymer cells. The motor drives a 3 bladed propeller. As motor selection is one of the most fundamental factors in aircraft design, many aspects had to be considered. First the most basic consideration: gas vs. electric. Gas offers better energy density than batteries and greater power. Electric motors are smaller, quieter, and can be turned off and re-started in flight to save power. The major benefit of electrics is that batteries can be located at any position in the plane at any orientation. Fuel tanks must be placed at the center of gravity (CG) of the airplane so that the weight trim of the craft does not change as the engine burns fuel. Because there were already several other components competing for the CG (autopilot accelerometers, downward-looking camera), the ability to mount batteries in an arbitrary location became a deciding factor. The other three dimensions of the system, motor size, propeller size, and battery selection are all interconnected, and therefore finding the right arrangement is largely iterative. Previous years power systems, on the recommendation of Bob Mellen of FlyingFoam.com, was to use a Hacker Brushless B50 series motor running a 16x8 prop powered by the 6S3P lithium polymer batter configuration. This setup was very good at gaining altitude, but in level flight was simply too powerful for the operational speeds we were planning on using. As a result, we spent much time with the motor running at very low throttle settings, where it was not operating very efficiently. This had the effect of both shortening battery life and causing serious heating problems in the motor and control board. During a November flight test this issue became apparent when the plane emitted a plume of white smoke, and the motor stopped functioning. We later learned that the heat generated from the inefficient operation at low throttle settings had demagnetized the motor. This had reduced the motor's power, and caused the speed controller to draw more current as a result. The extra current caused more heating, and eventually the controller failed. Upon further discussion with Mr. Mellen, we found that he had only used the motor in his aircraft for brief periods of rapid ascent, and then used it as a glider from there. While the motor was well suited to this task, it was not what we had been looking for. For our next motor, we selected an AXI based on its unique outrunner design. In this design, the can rotates around the stationary core, instead of the other way around as in conventional motors. The AXI 4130/16 model was selected because when combined with the battery and propeller configuration we currently owned for the Hacker motor, it met our mission requirement for the ability to operate in a low speed “loitering” mode for long periods. It was also able to produce brief periods of high output for climbing or high speed flight. This meant that its optimal speeds were more in line with our operation requirements. The motor also had 4 large cooling openings which, along with the spinning can of the motor, result in very efficient cooling. This allows us to run the motor over a greater range of loads with less concern for catastrophic failure due to overheating

Comparison

The major differences between the current design and last year's model are in its wing design, addition of tail control surfaces and introduction of landing gear. The wing design is important as it allowed us to customize the flight characteristics of our plane. In addition, the ability to separate the wing into two halves allows us increased storage and maintenance options, versus our previous plane which was made of a solid piece of foam. The addition of a tail and control surfaces on the tail adds more maneuverability to the plane. With the larger wings and a dangling fuselage, this was more important than in the previous planes. Finally, the addition of landing gear allows us to take off and land on a designated runway, versus attempting to work with a balky launching system.

Conclusion

In conclusion, we began the year with young team, no funding, and a transitional lab. Throughout the year we worked on the design, construction and testing of the various components of our plane. Through this process we believe that we have turned out an exceptional product. By working hard in the design phase, and planning everything out before beginning construction and by working closely as a team instead of as individual sub teams we created a solid design.

We believe that the new design we have created will meet the competition requirements and exceed them. This new design also leaves room for further improvement in the coming years, such as implementing the planned GPS drops (using fake bombs from tower hobbies combined with a signaling beacon) as well as the possibility of carrying another smaller, and inexpensive UAV for dangerous or detailed observation.

Appendix I: Safety Report

General Safety Rules

• All people at a test flight operating equipment or near the aircraft are required to wear safety glasses at all times.

• Use of any power tools or other dangerous materials should be accompanied by proper personal safety protection, such as goggles, gloves, aprons, closed toed shoes, etc.

• While not in use all batteries, LiPoly, NiCd, and others, are to be kept in the fire safe in the lab.

• At all times while batteries are being charged they are to be clear of any combustable material and kept under constant observation.

• Prior to powering the throttle on the aircraft varify all areas around the plane are clear and that no one is in the plane of the propeller or behind.

• Prior to flight all bolts and components on the aircraft are to be checked to make sure they are secure and will not become detached.

• If at any time the plane becomes unstable and the pilot cannot control it manually, it is to be brought down as quickly as possible in an open area clear of people.

Appendix II: Flight Checklist

1. Complete wing assembly and attachment
2. Prepare and power on Groundstation
3. Power on plane electronics, except motor
4. Power TV or Vision Groundstation and verify connections
5. Perform range test of plane to groundstation, verify GPS lock
6. Validate all control surfaces respond correctly
7. Verify pilot is able to put plane in and out of autopilot mode safely
8. Perform autopilot self-test on all sensors and reactions
9. Have one person supply power to plane while holding it on launcher for throttle test
10. check wing connections and general flight readiness
11. Begin Countdown and Takeoff

Upon landing

1. Remove power to throttle
2. Retrieve data logs and download any other pertinent information from Kestrel
3. Perform any post processing on vision station
4. Power down autopilot and plane electronic systems
5. Break down wings and Groundstation at end of last test flight

Fail-safe Procedures

Event	Description	Time Elapsed	Behavior
Rate Mode Failsafe	Autopilot does not receive RC packets	>1.5 s	Fly Level
Rate Mode Failsafe 2	Autopilot does not receive RC packets	>5 s	Fly Home
Loss of Comm	Communication with Groundstation lost	>2 s	Perform Competition Fail-safe (i.e. Throttle closed, full up elevator, full right aileron)
Loss of GPS Lock	GPS lock is lost in autopilot mode	>5 sec	Perform a shallow bank of 15 °
Loss of GPS Lock 2	GPS lock is lost in autopilot mode	>15 sec	Land plane immediately
Low Battery	Main Battery Voltage drops below 10 V	any	Fly to Home GPS position
Critically Low Battery	Main Battery Voltage drops below 9.5 V	any	Land plane immediately

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