UAV for Reliability Build

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AEM 4333 – Aerospace Vehicle Design

Table of Contents

Abstract

Continuing the design project from Fall Semester 2013, the UAV for Reliability group worked towards using previous design considerations to build a more reliable UltraStick 120 research platform. Ultimate considerations towards improving reliability included supplying redundant avionics batteries as well as splitting the control surfaces for the elevator and the rudder. Other features of the existing UltraStick model were modified to accommodate the build process culminating in an aircraft that is at least ten times more reliable, as per the initial design requirement. Calculations were completed to determine the optimal location for the split in the rudder, and electronic equipment requirements were evaluated to determine the most suitable avionics batteries available to provide redundancy. After finalizing the design, construction and modification of the UAV for reliability was started on a pre-existing UltraStick 120 airframe. Due to time constraints and availability of equipment, the UAV was not built fully to completion and flight; rather, the aircraft was concluded to ensure the success of the pre-existing build changes, and engaged in demonstrations proving the efficacy of design changes aimed at improving reliability. Use of a Fault Tree Analysis (FTA) program yielded a theoretical increase in reliability of 20.118 times over the original UltraStick 120 design. Future plans for the reliability platform include fixing issues shown during the demonstration, altering the simulation and flight code to accommodate the design changes, and completing the unfinished physical and electronic components necessary for the UAV to achieve successful flight.

Introduction

The reliability analysis completed in the previous assessment of the UAV Research Group's current Ultra Stick 120 provided the backdrop for the build section of this project. During the analysis, failures were broken into three categories: 1A, 1B, and 2. 1A was defined as an uncontrolled emergency landing with a high risk of catastrophic damage; 1B as a controlled emergency landing with a low risk of catastrophic damage; and 2 being a mission critical failure, or loss of flight data. The focus of the redesign, and subsequently the build, was primarily to evaluate and reduce the likelihood of the 1A failures. A sensitivity analysis of the 1A fault tree revealed which components impacted the reliability the most. Based upon the severity and feasibility of improving the reliabilit, three components were selected to be made redundant: the avionics battery, and the control surfaces of the rudder and the elevator.

With the basis of the design in hand, the final details were worked out which allowed for the improvements to be made. The locations of the cuts to split the control surfaces were calculated, followed by the determination of the new wiring and pinouts for the additional servos and consequent potentiometers, along with their placement. Other aspects of the aircraft, including an upgraded receiver, higher discharge batteries, and an extra analog-to-digital converter, were integrated into the final design. The next phase of the project was the build , highlighted by stripping an old airframe down to its core, building the UAV from the ground up, and working through issues as they arose. To make the UAV an effective research platform , the idea was to make the aircraft as similar to the UAV Research Group's current Ultra Stick 120 as possible while incorporating all of the new, more reliable features. To achieve this, UAV Research Group personnel and documentation were consulted to complete the assembly. In support of both the design and build portions of the project, a few behind-the-scenes tasks were used as substantiation for the requirements of the original analysis and design. These included updating the Research Group's simulation to take into account the split rudder and elevator and also revising the 1A fault tree to incorporate the features implemented in the finalization of the UAV design.

The initial goal of the build phase was to complete, systems test, and fly the aircraft, but as the project progressed, the concentration shifted away from recording an actual flight to making sure that what was accomplished was done correctly. The end result was an aircraft with all internal components wired, operational, and flight computer test ready, culminating in a final demonstration displaying the added redundancy of not only the original avionics battery, rudder, and elevator, but also the multiple redundancy of the receiver. While the aircraft has not yet achieved flight, work on the UAV will continue and eventually will produce an aircraft that can be used for years to come as a reliable research platform by current and future graduate and undergraduate students at the University of Minnesota.

Methods and Design Changes

The redesign presented in the previous report "UAV for Reliability" covered the main points of the design without going into explicit detail for each. Before the build section of the project could begin, the design had to be expanded upon and exact details for the parts needed to be determined. During the process of finalizing details, information and issues came to light which caused other parts of the design to be modified. One component at a time, however, the final design was pieced together.

<u>Split Control Surfaces</u>

The control surfaces on the tail were split for redundancy. The elevator surface was divided symmetrically. As shown in Figure 1, the rudder is not symmetric.

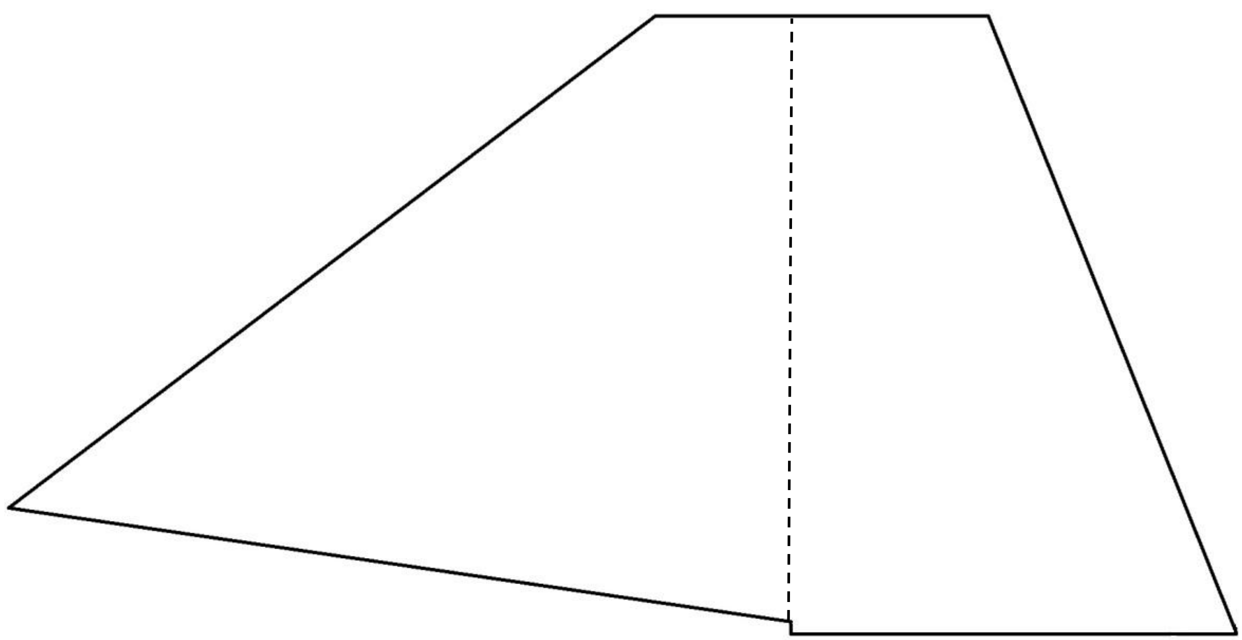

Figure 1: An outline of the vertical section of the tail where the dashed line divides the vertical stabilizer and rudder.

The rudder was divided so each section produces the same yaw moment. These calculations to find the ideal cut location were simplified by modeling each section as a flapped 2D airfoil as viewed from above. The dimensions of these flapped 2D representations were determined from the mean aerodynamic chord (MAC) of each section. To find the MAC, first an imaginary cut line was drawn through the vertical tail as shown in Figure 2.

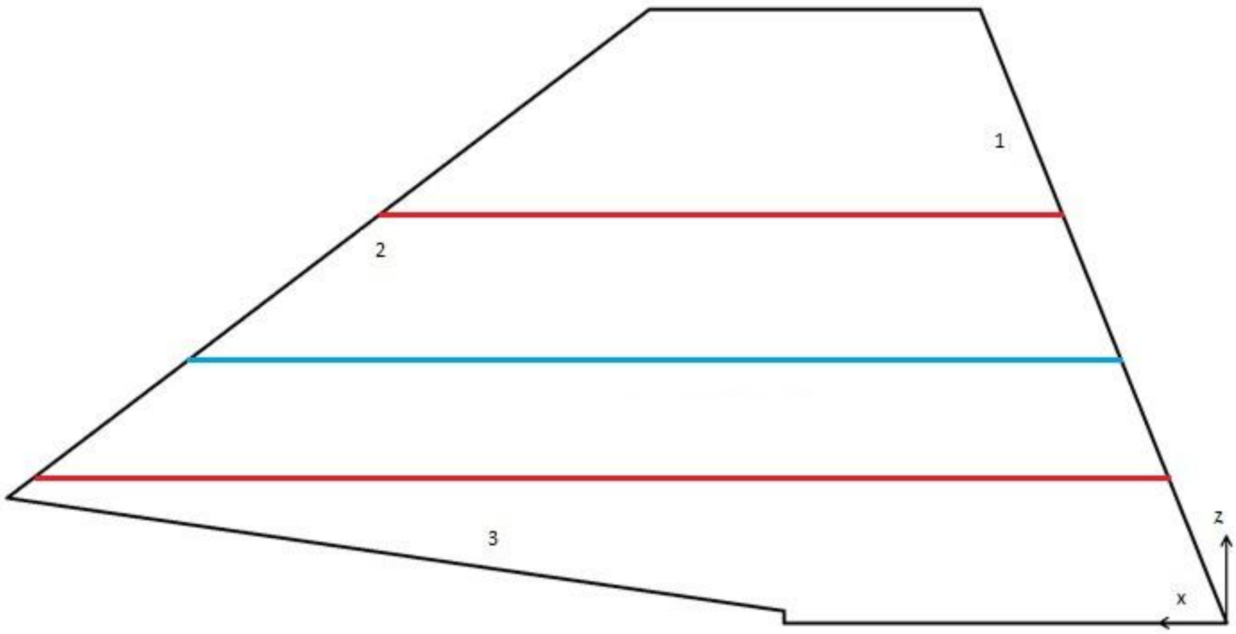

Figure 2: The vertical tail with the blue line representing an arbitrary cut and red lines indicating the MAC of the top and bottom sections relative to that cut. The coordinate axis and lines are labeled.

The centroid of with respect to the x axis was determined for each section. The outline of the vertical tail was described by lines in slope intercept ($z = mx + b$) form, where the origin was located on the lower aft tip of the tail. By substituting the centroid x-value for each section, points along the outline of the tail were connected by a horizontal line to run through the centroid. Since the MAC runs through the centroid, these lines also represented the MAC for each section. Figure 3 shows the notation and geometry used to describe the flapped airfoil.

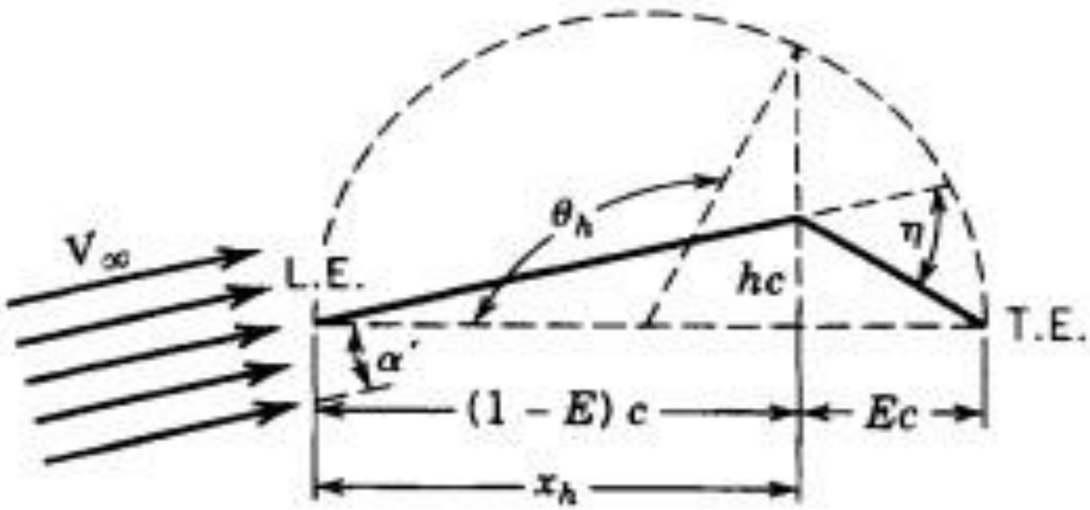

Figure 3: Geometry of a flapped airfoil.

The MAC of each section had a vertical stabilizer component $(1-E)c$, and a rudder (or flapped) component Ec, where E is the ratio of flapped chord to total chord and c is chord length. The hinge angle, θ_h, is given by

$$\theta_h = \cos^{-1}(2E-1).$$

The Aerodynamic coefficients, A_0, A_1, and A_2, are given by

$$A_0 = \frac{\eta(\pi - \theta_h)}{\pi}$$

$$A_n = \frac{2\eta \sin(n\theta_h)}{n\pi}$$

where η is the deflection angle of the rudder. The aerodynamic coefficients were used to calculate the lift coefficient per unit span, c_l, given by

$$c_l = 2\pi A_0 + \pi A_1.$$

The lift coefficient per unit span is also given by

$$c_l = \frac{L'}{q_\infty c}$$

where L' is the lift per unit span and q_∞ is the dynamic pressure. Thus, the lift per unit span is given by

$$L' = q_\infty c[2\pi A_0 + A_1].$$

The lift force, L, is given by

$$L = L'b$$

where b is the span length. In this case, the span of the lower section is the vertical distance from the root of the tail to the cut location. The span of the upper section is the vertical distance from the cut location to the top of the tail. The lift force (in this case acting sideways on the vertical tail) acts through the center of pressure, x_{cp}. The center of pressure is also governed by the aerodynamic coefficients

$$x_{cp} = \frac{c}{4} - \frac{\pi c}{4}\frac{A_2 - A_1}{c_l}.$$

The yaw moment, N, is given by

$$N = (x_{cp}^{AC} - x_{cp})L$$

where x_{cp}^{AC} is the center of pressure for the entire aircraft. Using these equations, an ideal vertical distance from the origin of the rudder coordinate system was determined to split the control surface. This ideal distance was $z = 3.85$ in. It was also found that the moments balance at equal and opposite control surface deflections. Therefore, if the top section happens to stick at, say, 5°, the bottom section can cancel out any induced yaw moment by moving to -5°.

Servo Locations

To accommodate the split-tail control surfaces, additional servos were mounted on the fuselage. A side view of the aft section of the fuselage is show in Figure 4.

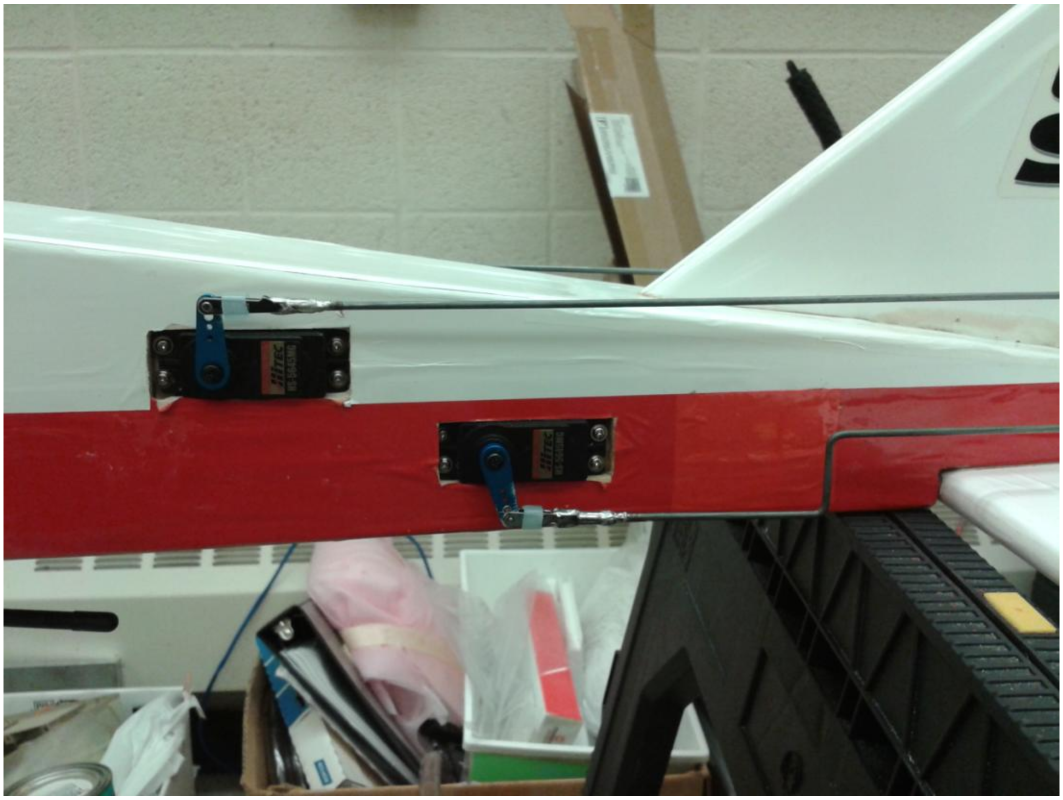
Figure 4: A side view of the tail control surface servos mounted into the fuselage.

The servo on the upper left actuates the rudder and the servo on the lower right actuates the elevator. They are on the same horizontal plane as the servos on the opposite side of the fuselage. There is a gap between the mount locations to ensure that the pushrods will not interfere with each other. They were mounted parallel to the x-axis.

Batteries and Receiver

The original Ultra Stick 120 used by the UAV Research Group has a single LiPo battery powering the entire flight computer, avionics suite, receiver, servos, and other electronics. The reliability analysis revealed two important things regarding the current battery setup: 1) the avionics battery was critical to the UAV, so making it redundant would significantly increase the reliability of the aircraft; and 2) the flight computer and the rest of the avionics and sensors were considered non-critical and therefore did not require a redundant battery system. The initial concept based on this knowledge, as presented in the Practical Design section of the previous report, was to introduce a second avionics battery – of the same voltage and capacity – in parallel with the current battery. These batteries were to then be isolated from each other using either a diode or fuse isolation circuit before sending power to the daughterboard and – via the BEC – to the receiver, failsafe switch, and servos. The isolation circuit was initially going to be made specifically for this aircraft, but it was found that a more advanced receiver, the Spektrum AR12120, had built-in battery isolation redundancy.

Further research into the receiver showed that it had more channels than the current 120's (12 versus 9) and also provided redundancy for the receiver through its four satellite receivers (compared to the current 120's single satellite receiver). According to the AR12120 manual, three receivers would need to be plugged into the main power hub, making the fourth satellite receiver redundant. This receiver, then, not only provided the necessary battery isolation required for having redundant batteries, but also added redundancy in the receiver itself. The design moved forward with the AR12120, but it was discovered that powering it and the daughterboard with the same batteries was an issue. The daughterboard required between 9-20 V – which could be supplied by a 3-5S LiPo battery – while the receiver required between 6-10 V. To solve this issued, it was decided that three batteries were to be used in place of the original one. Two of the batteries were assigned to power the receiver, which would then power all of the 1A components to ensure that they all had redundant sources of power. The third battery was installed specifically to power the daughterboard and all of those components that it powered. This approach completely uncoupled the flight computer and avionics from the critical 1A components.

With that settled, the size of each type of battery was determined. The battery powering the flight computer and avionics through the daughterboard took the original batteries name, "avionics battery," while the two that power the receiver were dubbed "receiver batteries." The original avionics battery in the original Ultra Stick 120 design was a 3S (11.1 V) 2650 mAh LiPo, with a maximum current draw of 1C, or 2.65 Amps. This battery originally powered the flight computer and avionics as well as the receiver, failsafe, and servos, and only had a capacity of 2650 mAh. A battery of similar or smaller capacity was deemed to be sufficient because it was not going to be powering the receiver, servos, or failsafe anymore. To replace that battery, a 3S 2500 mAh 25C LiPo was found. The receiver batteries, which were to power the receiver – and from there the servos and failsafe switch – had to be in the 6-10 V range set by the receiver, making them 2S LiPos. With the split elevator and rudder, the total number of servos on the aircraft increased from six in the original 120 to eight in the new build. The data sheet for the servos stated a maximum current draw of 500 mA while a test of a servo determined a max current draw of 300 mA. The 500 mA draw was used as a conservative estimate of the current draw for each of the eight servos, leading to a total current draw of 4 A from the servos, and adding extra amps for uncertainty (and to take into account the draw from the receiver and failsafe switch) increased the minimum current from the batteries to around 5-6 A.

The last factor for the receiver batteries was capacity. The original avionics battery had a capacity of 2650 mAh, but with the addition of the two extra tail servos, it was determined that more capacity was needed. Therefore, a minimum of 3000 mAh was set. With the two receiver batteries in parallel, the capacities are added together, opening up an option to lower the capacity of each to reduce weight, while still maintaining the minimum total of 3000 mAh. To be truly redundant, however, if one battery was to fail the other would need to have the capacity to take on the full load. Therefore, both batteries still needed to be 3000 mAh. With a current draw of 6 A and a capacity of 3000 mAh, a minimum discharge of 2C was required. To fulfill all of these requirements, two 2S 3300 mAh 25C LiPos were selected.

The voltage delivered by a 2S LiPo is 7.4 V, which is well within the 6-10 V range for the receiver, but is above the voltage rating of 6 V for the servos and the failsafe switch. Because the AR12120 receiver doesn't regulate voltages, voltage regulators were required between the receiver batteries and the receiver. The chosen regulators were Castle Creations BECs, which had a variable output voltage of between 4.8 and 9 V (to be set to 6 V) and a max sustained current draw of 7 A for the 7.4 V input voltage. The 7 A limit was still above the maximum design draw of 6 A so neither the BECs nor the receiving power hub would be limiting factors, as the power hub could handle up to 35 A continuous.

The final important feature of the power setup for the 1A components would be the means by which to power the failsafe. The original Ultra Stick 120 delivered power from its avionics battery through the 50-pin D-Sub connector on the flight computer, where it would be split with one path leading to the daughterboard to regulate and power the actual computer and avionics, and the other path leading directly to the BEC, where it was regulated down to 6 V. After the BEC, the power was split once more, going directly to the failsafe switch and then through the other branch, back through the 50 pin connector and into the receiver to power the receiver and the servos. The AR12120 receiver does not receive power in one of its main JR ports on the front of the receiver, but is instead powered through two dedicated ports on the back of the receiver. Therefore, the port and the cables between the receiver and failsafe/BEC would not be in use if the failsafe was powered as it is in the current 120. Thus, in order to power the failsafe through redundant batteries, the connection between the original BEC and failsafe needed to be undone (by unplugging the JR connector). In that way, instead of power going into the receiver through the existing cables, the power is going in the reverse direction – from the receiver to the 50 pin connector on the flight computer to the failsafe switch – all of which can be seen in Figure 5.

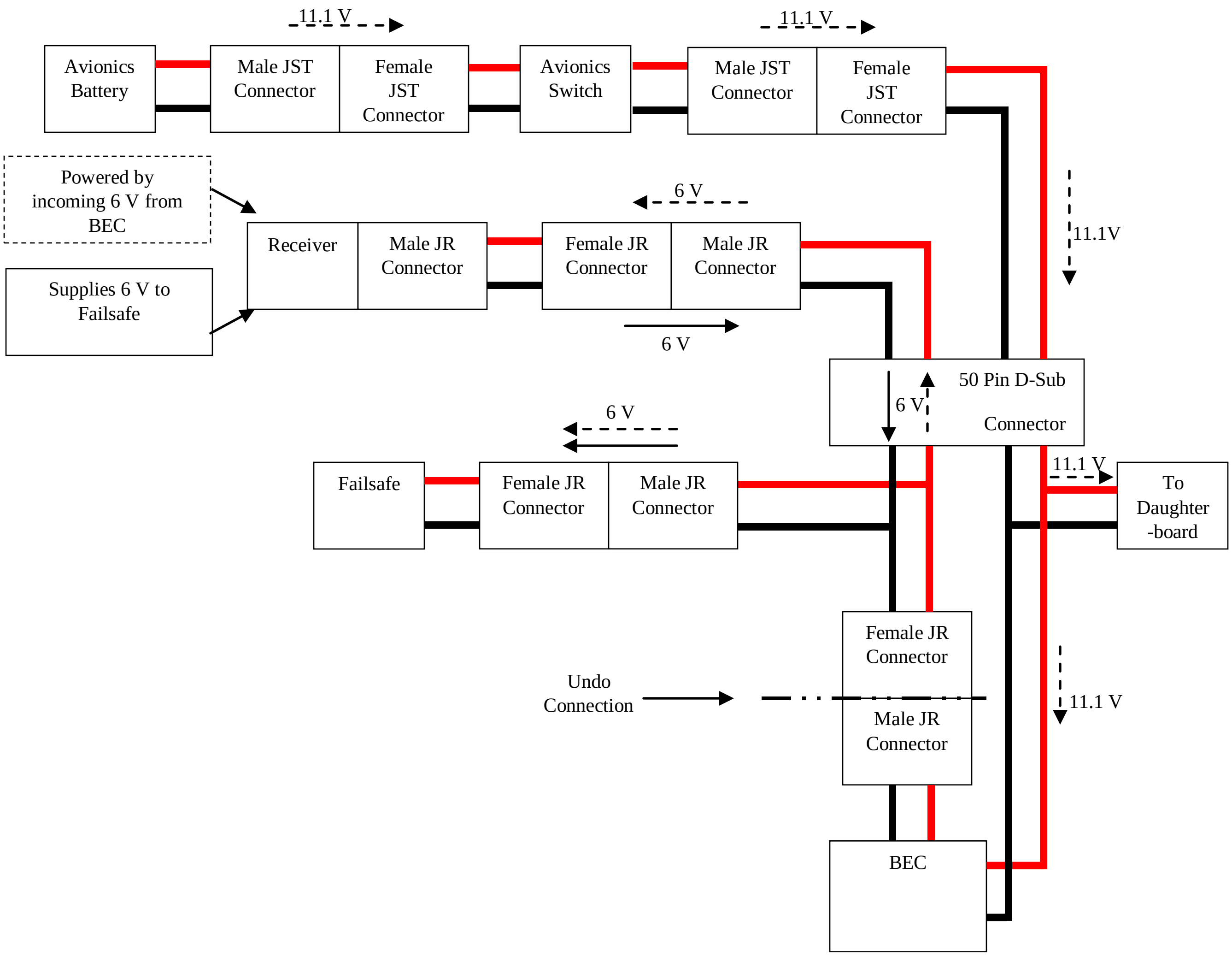

Figure 5: Diagram showing how the failsafe was powered in the original 120 and how it will be powered in this aircraft. The dashed arrows represent the flow of current with the original design, which has the failsafe powered by the Avionics battery through the BEC. The dashed line above the BEC, between the male and female connectors, represents the split (simply disconnect the two connectors) that should be made to stop the Failsafe from being powered by the BEC on the flight computer. The solid arrows represent the current flow when the new system of the receiver providing the failsafe power is implemented.

Wiring

The wiring on the wing harness and connectors to the flight computer were nearly identical to the wiring structure used by the UAV lab, with a few modifications. Refer to "Reliability Wiring and Pinout Guide.xlsx" to see the modified connector pin outs.

On the 26-pin wing harness connector used by the UAV lab, the left and right signals for the flaps and ailerons were sent to separate pins (17, 18, 25, and 26). For this aircraft, the left and right signals are the same for the ailerons and flaps. These signals are still split to the same connector pins. For example, on the normal wing harness connector, pin 17 corresponds to the left flap signal and pin 25 corresponds to the right flap signal. On the modified version, the common left and right flap signal is connected to pins 17 and 25.

The common wing actuator signal and additional tail actuator signals affect the flight computer connectors. Once again, refer to “Reliability Wiring and Pinout Guide.xlsx” to see the modified 15-pin D-sub connector pin outs. Instead of separate left and sight signals for the flaps and ailerons all on different pins, the shared signals are now sent through a common flaps pin and a common ailerons pin. The two additional free pins left four total pins for the tail actuators, which were used for the top rudder, bottom rudder, left elevator, and right elevator surfaces.

ADC

With the splitting of the rudder and elevator, two new control surfaces were introduced, which consequently introduced the need for two additional potentiometers to record the deflections of the extra surfaces. This brought the total number of potentiometers on the aircraft up to eight. The potentiometers (CTS 250 Series 100 kΩ) used output data in analog, so – for the computer to read the data – the signals needed to be converted to digital via analog-to-digital converters (ADC). Each ADC (Semtech SX8724C) allowed for a maximum of three potentiometer input signals, but for ease of operation, only two potentiometer signals were used on a single ADC. This required the use of four ADCs, while the original Ultra Stick 120 uses three. For transmission over an I^2C line, addresses needed to be assigned to each of the converters. This was done by setting two of the bits – D0 and D1 (see document “Reliability Wiring and Pinout Guide.xlsx for more details) – to either a 1 or a 0. With only two bits, and only two options per bit, there were a total of four possible addresses – 1001000, 1001001, 1001010, and 1001011 – which matched the four ADCs required for the eight potentiometers. The rest of the wiring followed the standard ADC wiring used by the UAV Research Group on their 120.

TM1000

The receiver and controller pair from Spektrum allow for telemetry data to be sent from the aircraft to the controller during flight. This capability, provided by the TM1000 (SPM9548), was not initially included in the design, but was added to allow for further data collection. Three sensors were to be attached to the TM1000 telemetry module, including the Brushless RPM Sensor (SPMA9558), temperature sensor, and external voltage sensor. The voltage sensor was to be tied into one of the connectors between the motor batteries – wired in series – and the ESC, while the RPM sensor was to be tied into two of the three cables leading from the ESC to the motor.

FTA

A new fault tree was constructed using the *Logan Fault and Event Tree Analysis, version 7.2* software to model the new probabilities for Category 1A failures. This was done in a similar manner as with the original fault tree analysis (FTA) during the design phase of the project, detailed in the previous paper. One major alteration to this new fault tree was the addition of “common-cause failure” branches, something previously (and erroneously) not included in the original fault tree. These branches model components whose failures result in multiple failures of higher-level redundant components, and they follow the format outlined in the *Fault Tree Handbook with Aerospace Applications* [1]. Because of this change, it was also necessary to heavily edit the old fault tree for the original UltraStick 120 FASER in order to provide an accurate comparison to the new UAV with added redundancy. This new version of the original Category 1A fault tree is available as an electronic file, titled “edited FTA1A for original FASER.gte”. The newest fault tree modeling the UAV with added redundancy is also available as the electronic file, under the name “FTA1A Final spring semester.gte”. Both of these folders are currently available on the project Dropbox folder, under the “new FTA” subfolder.

In the restructured version of the original FASER fault tree, the components responsible for common-cause failures of the control surfaces include failures of either the failsafe switch or of the RC receiver. Lower-level components that can also cause the failsafe switch to fail include the BEC and avionics battery, as well as loss of signal from the RC receiver through the computer block. The RC receiver can also fail due to BEC and avionics battery failures. The fault tree for the new UAV with enhanced reliability has common-cause failure branches for components including the failsafe switch and the “power hub” of the new, redundant RC receiver, which all four of the receiver satellite units plug into.

Failure of this RC receiver power hub requires either its own circuitry to fail, or failure of the newly redundant batteries and BECs used to power it. Besides its own circuitry failure, the failsafe can also cease to function properly due to failures in the RC receiver. These receiver failures can subsequently be caused either from the receiver power hub or from signal loss due to failures of multiple satellite units. Failures of the redundant battery and BEC system would therefore also cause failsafe failure, as well as RC receiver failure. In addition to the added battery redundancy, the control surfaces of the new aircraft are now all effectively “redundant”, allowing for AND gates to be used to link the probabilities of their own independent mechanical failures. For example, the left and right elevators each have two types of mechanical failure branches underneath them, but the elevator system as a whole combines the left and right elevator branches with an AND gate, since there are now two, redundant elevators.

Another major change was the addition of the ailerons and flaps to the Category 1A trees for both the original FASER and the new, more reliable UAV. These were previously only included on the Category 1B failure tree during the earlier design phase. A mechanical failure of both of these control surfaces during the same flight was considered a very low probability, and would not likely result in catastrophic failure. Because of this, they were not included on the original 1A fault tree. However, it was determined that a servo or mechanical linkage failure could theoretically occur in any control surface, and, while unlikely, its counterpart surface could also fail during the same flight. Essentially, either the mechanical failures of all control surfaces had to be included in the 1A fault tree, or none at all. For the most complete analysis, it was decided that all control surface mechanical failures would be considered (meaning both ailerons, flaps, rudders, and elevators) for both 1A fault trees. While the ailerons and flaps cannot be considered truly “redundant” (since both sides are needed to operate in conjunction for correct operation), they can still be modeled with an AND gate as one of them failing should not cause a catastrophic failure of the aircraft.

Procedure

Structure

Many structural alterations and repairs to the airframe were required in order to implement the desired design changes. The initial, unmodified UltraStick 120 airframe was not set up to run on an electric motor, and included a gas tank within the nose. This was removed. The fuselage also included tubing sheaths for the control pushrods used with internally-mounted servos. The pushrod tubing ran through the entire length of the rear fuselage, protruding outside the aircraft near the tail. This tubing had to be removed, and the holes created in the fuselage from their protrusion were patched with balsa wood, smoothed flat with wood filler, and finally covered with MonoKote. The condition of the existing MonoKote on the airframe was fairly worn, so new MonoKote was used to patch several places. The pre-existing MonoKote was also smoothed out and tightened using a heat gun.

To allow easy access to the internal components that were to be installed, two hatches were cut out from the top wall of the UAV: one near the nose, and the other at the rear of the plane a short distance behind the back of the wing. Four small holes were drilled into the corners of these hatches to allow for screws to secure them down tightly during flight. Two sets of two small, basswood mounting brackets were epoxied to the underside of the fuselage's top wall for mounting each hatch. Corresponding screw holes were drilled into these mounts, and matching T-nuts were installed to allow for the screws to fit securely into metal threads. This is illustrated in Figures 6 and 7 below.

Figure 6: The front hatch cutout in the nose of the aircraft, allowing access to the motor batteries and connecting wires. The wooden mounts and screw holes where the hatches are fastened can be seen on either side of the cutout.

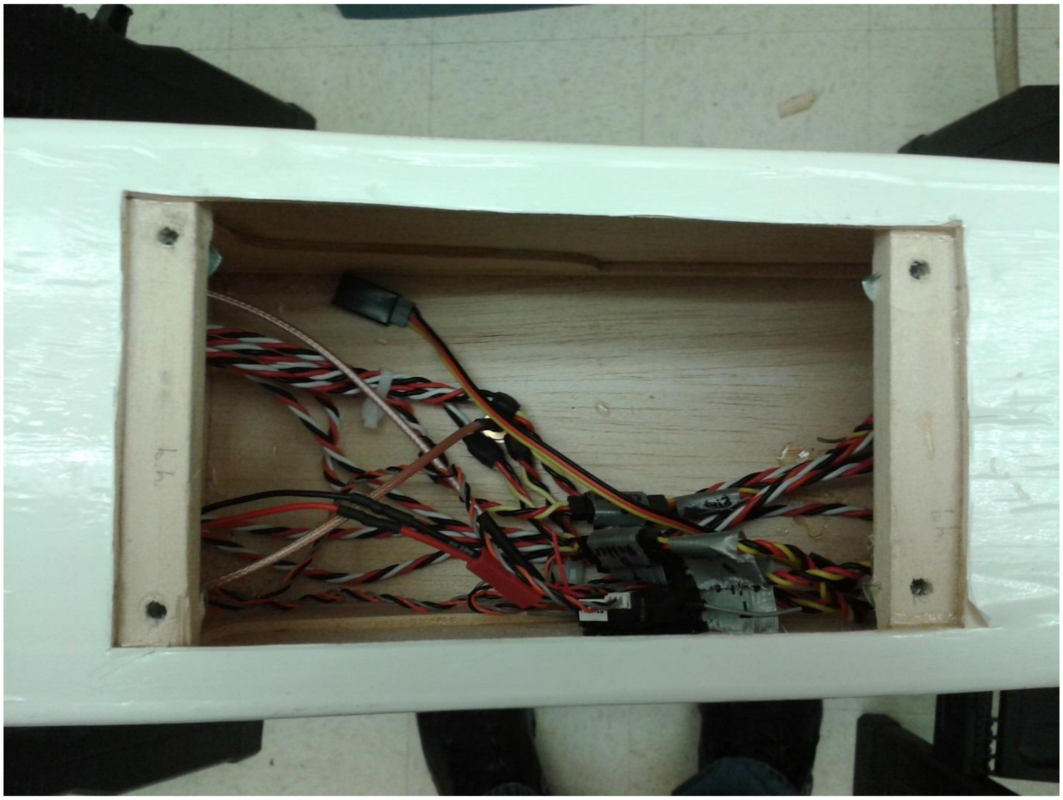

Figure 7: The aft hatch cutout in the back of the aircraft, allowing access to the servo extension wires. The wooden mounts and screw holes are again readily visible.

To implement the splitting of the tail control surfaces, a thin-blade, fine-tooth coping saw was used to cut along guides clamped to the rudder, at the location measured and marked based off of the design calculations discussed in the Methods section. The end result is shown in Figure 3. The elevator was cut in a similar fashion, simply continuing the interior angle cut all the way to the rear edge of the horizontal stabilizer, effectively removing a small portion of the spar that had previously joined the two sides of the elevator into one solid piece. This is illustrated in Figure 4. To mount the four rear servos that actuate these split surfaces, two sets of rectangular slots were cut into each side of the rear fuselage. Two basswood rectangular brackets were cut to size and glued with epoxy inside of the rear fuselage. These were used to provide an internal structure for mounting the servos with small wood screws. The basswood mounting brackets had large square slots cut out of their centers to allow for the wires leading to each servo to travel through uninhibited.

Figure 8: A picture of the horizontal cut made to separate the rudder into two separate control surfaces.

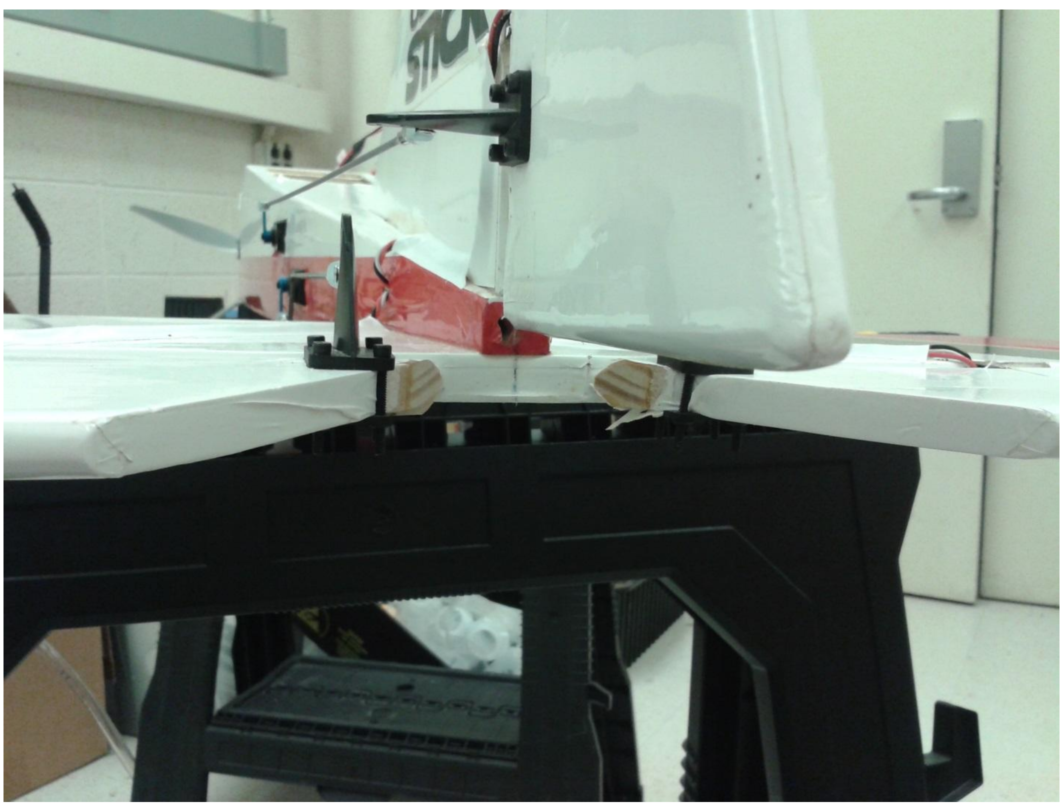

Figure 9: A picture of the two cuts used to separate the elevator into two independent control surfaces.

The motor arms of each servo were connected to control pushrods via a metal clevis, illustrated in Figure 10. These clevises were secured to the metal pushrods with solder, and the opposite end of each pushrod was also joined to another clevis with solder. This second clevis was attached to a control horn mounted on each control surface. The entire starboard servo-tail assembly is pictured in Figure 11. The pushrod for the upper rudder is bent twice at 90°. This "stagger" was implemented to account for the difference in height between the top rudder's control horn, and its corresponding servo. This control pushrod was bent this way to ensure that the servo provides actuating force to the top rudder in a direction parallel to the other pushrods. This bent pushrod was reinforced with a diagonal crosspiece made from the same material, and soldered securely in place.

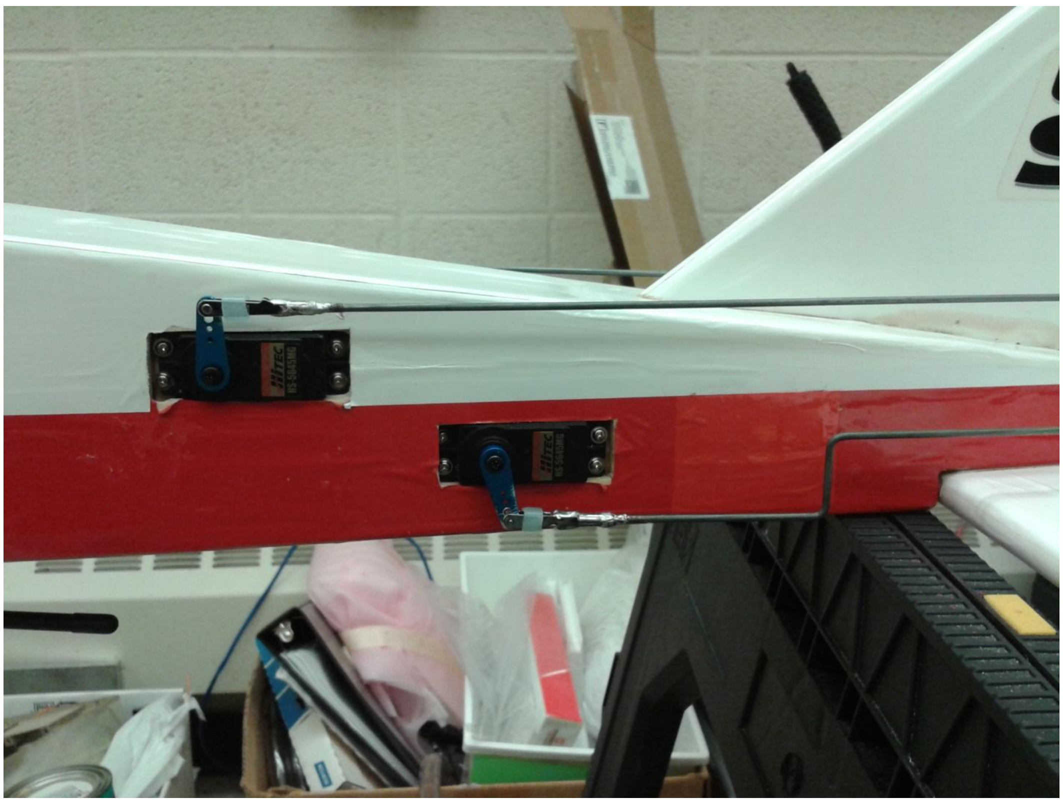

Figure 10: Port servos in the rear of the aircraft, showing the connection between motor arms and the metal clevises soldered onto each pushrod.

Figure 11: The two starboard control rods used to actuate the right elevator and top rudder. The top control rod is bent to accommodate the height difference between the top rudder control horn and its servo motor arm. The reinforcing diagonal cross piece is also shown.

A thin wooden spar located inside the nose of the aircraft was removed to make room for the motor batteries, as it was contributing very little to the structural integrity of the fuselage, and was previously only necessary for the proper housing of the gas tank. The existing wooden plate sealing off the front of the nose (also known as the firewall) was damaged and riddled with holes that interfered with the proper placement of the mount for the new electric motor. It was removed and replaced with a fresh piece of 3/8 inch plywood secured with epoxy on all edges. A 1/2 inch diameter hole was drilled in the center of this piece to accommodate the wires joining the motor batteries in the nose bay to the externally-mounted ESC. An already-existing spare mount (machined from aluminum) was connected to the new firewall, and used to secure the rear of the motor in place with its three bolts. A small plywood mount was horizontally secured to the aluminum motor mount with Velcro, and the ESC was bolted on top of this wooden mount, placing it just behind the motor and directly in front of the firewall. The entire assembly is depicted in Figure 12 below.

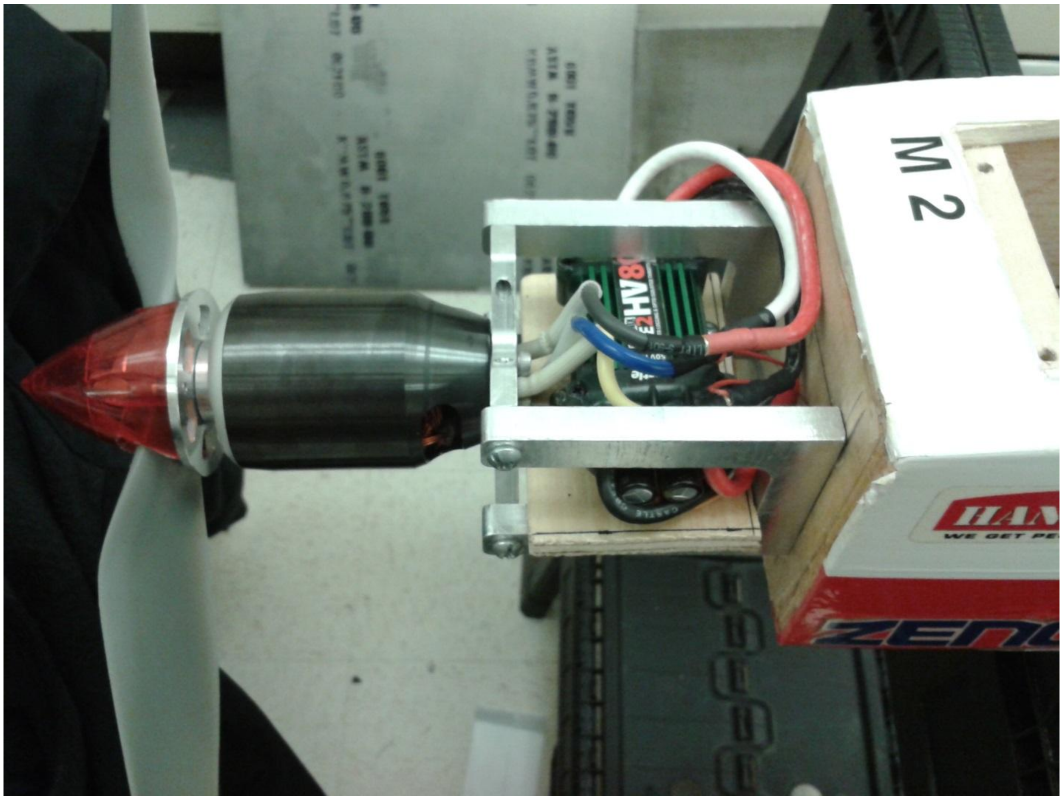

Figure 12: The aluminum motor mount, to which the motor and propeller are attached. Sitting inside of this mount is the small plywood mount, with the ESC bolted on top.

The propeller was bolted to the front of the motor with an adapter (an Actro-Nabe 35mm M8 bolt), and a small plastic cone was placed over the center of it for aerodynamic purposes. Small portions of this plastic cone had to be cut out in order to accommodate the size of the propeller blades, and the cone itself was secured to the propeller via two screws threading into an aluminum back-plate. Switches used for the Ethernet data dump port, the motor shunt plug, the RC Receiver power switch, and the avionics battery switch, were installed into the sides of the fuselage by the avionics bay under the wing. This was accomplished by cutting appropriately-sized slots into the fuselage, and mounting each switch to its corresponding faceplate with the included screws, effectively “sandwiching” the fuselage wall between the two pieces of each switch (shown in Figure 13). An aluminum landing gear wheelbase was mounted with four bolts to the underside of the fuselage, using the existing holes and T-nuts previously used for the same purpose. The landing gear wheels themselves are not yet properly mounted, as discussed further in the Future Plans section.

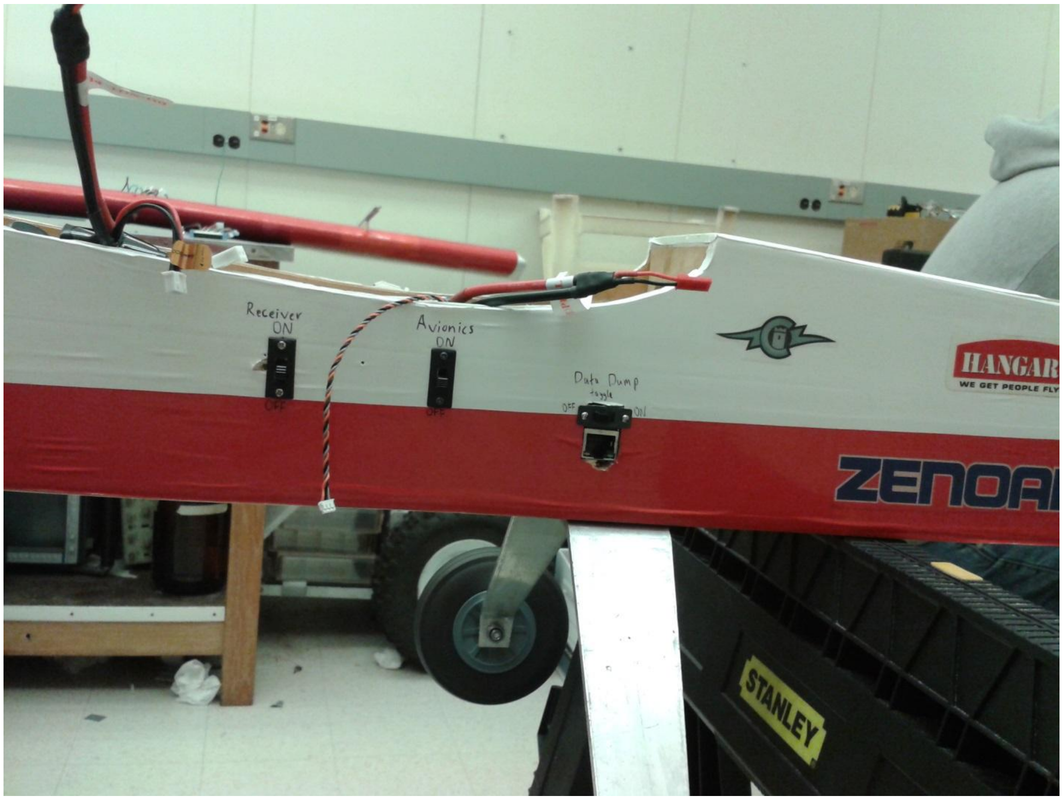

Figure 13: The receiver, avionics, and data dump switches mounted on the outside wall of the aircraft, along with the landing gear bracket.

A potentiometer is included at the hinge point of each control surface (both ailerons, flaps, elevators, and rudders, making eight in total), to measure their rotation and thereby determine the deflection angle of each surface. To install these, a small slot in the shape of each potentiometer was cut out of the "front edge" of each control surface, near the hinge point. These were cut out in between the actual control surface hinges, and in such a way that resulted in the center of the rotary portion of the potentiometer to be aligned exactly in between the front edge of the control surface, and the back edge of the stationary structure that each was attached to. For example, half of the cutout for the top rudder potentiometer was on the back edge of the vertical stabilizer, while the other half was cut out of the front edge of the rudder itself. This allowed the axis of rotation of the potentiometer to be aligned exactly in between the vertical stabilizer and the rudder. The stationary head of each potentiometer was epoxied in place, while the rotating portions of each were taped, starting from one face of each control surface, wrapping around the potentiometer, and then ending along the other face of the control surface, with nylon tape. An example of an elevator potentiometer is pictured in Figure 14. This allows for the tape to cause the potentiometers to rotate when the control surface deflects at an angle. In the future, MonoKote should be used in place of the tape, for a more secure connection.

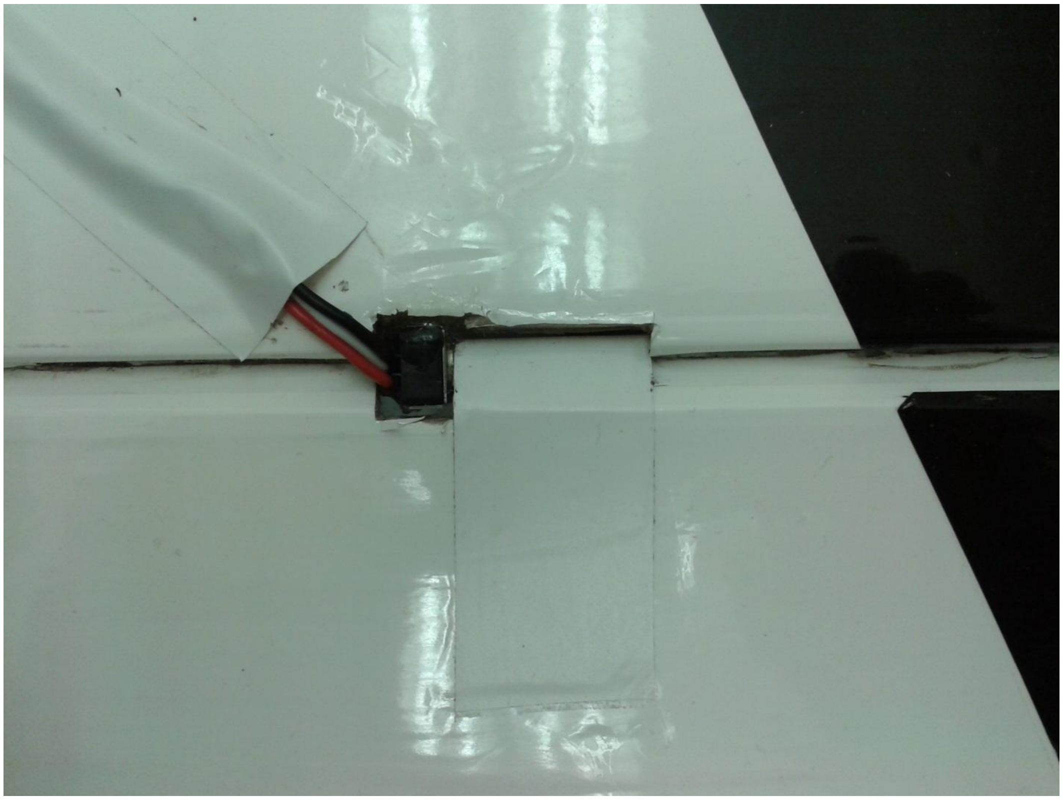

Figure 14: An example of a potentiometer mount inside the joint between the right elevator and the horizontal stabilizer. The head of the potentiometer is epoxied within the cutout, and nylon tape secures the rotary portion to the control surface. Nylon tape is also used over the wires leading from the potentiometer to the fuselage.

The wing provided for this project was stripped down to the basic structure, with the exception of control surface control horns still present on both ailerons and flaps. While inspecting the wing for damage, it was found that part of the leading edge was “caved in”, with a hole also present above it. The perpendicular spars (or “ribs” of the wing) were still intact. A section of MonoKote was cut out around it, and a balsa wood patch was epoxied over the hole. Wood filler was used to reshape this section of the leading edge, and smoothed using sand paper to ensure that it was flush with the rest of the wing. New MonoKote was then placed over top. Small holes in the MonoKote over other areas of the wing were also visible, and were fixed using small MonoKote patches. The four control surfaces in the wing required four servos to be mounted. The existing holes for the placement of the servos were too large for the servos being used. To resolve this problem, small balsa wood rectangles were cut and epoxied to the inside of each hole, effectively making them smaller and allowing the servos to be mounted. Four small wood screws were used to attach each servo. For the wing pushrods, the end near the servo was attached to the servo motor arm with a Z-bend, as opposed to clevises. The other side of each pushrod was still attached to the control horns with the standard clevises, however. One pair of completely-mounted servos on the left side of the wing can be seen in Figure 15.

Figure 15: A pair of wing servos, one used to control the left aileron, and the other used to actuate the left flap.

Next, the potentiometers needed to be mounted. This was done the same way as for those used in the tail's control surfaces. Small slots were cut in the wing surface to fit the potentiometer and again ensure that it was properly aligned with the axis of rotation. The head of the potentiometer was again epoxied into the surface of the wing between the wing's edge and the control surface. The rotating part of the potentiometer was taped using the same nylon tape as for the tail surfaces. The potentiometer wires were fed up to the servos and then through the servo slots, threaded through the wing spars, and lead out to an opening in the center of the wing. This precut opening allows the wing wiring harness to connect to the flight computer. The exposed potentiometer wires on the outside of the wing were again taped down.

Two other slots in the wing's MonoKote were cut on either side of the wing, between spars. These were the locations for the GPS antenna and the pitot tube mount. To mount the GPS antenna, a thin, rectangular piece of plywood was epoxied between the spars. The GPS antenna was attached with Velcro to the surface of this wooden mount, which will ultimately face the ground during flight. Unfortunately, the GPS antenna needs to be mounted facing the top of the wing, and this problem is discussed later in the Future Plans section. The completed mount is displayed in Figure 16. The long length of wire from the GPS antenna was fed to the other side of the wing internally, through small, pre-existing holes in the wing spars. The excess wire was then coiled up and secured in place in order to properly balance the wing about its center. The pitot tube was mounted in the other slot, cut into the opposite side of the wing.

Figure 16: A picture illustrating the wooden mount and placement of the GPS antenna within the wing.

To mount the pitot tube, a piece of plywood was epoxied in place, parallel to the wing spars. The tube itself was placed on top of the edge of this piece, allowing it to sit above the surface of the wing. This was done so that the airflow entering the pitot tube would not be disturbed by the flow around the wing. The actual metal pitot tube was epoxied into the end of a 12-inch-long carbon fiber tube that served as an extension piece, allowing the pitot tube to be placed in front of the wing's leading edge, as seen in Figure 17. This extension tube was zip-tied to the wooden mount using four zip ties. Smaller, flexible tubing attached to the back of the pitot tube was run through the carbon fiber tube and epoxied at the back end of it. These flexible tubes were then fed through the wing to the pressure transducers, located near the center of the wing.

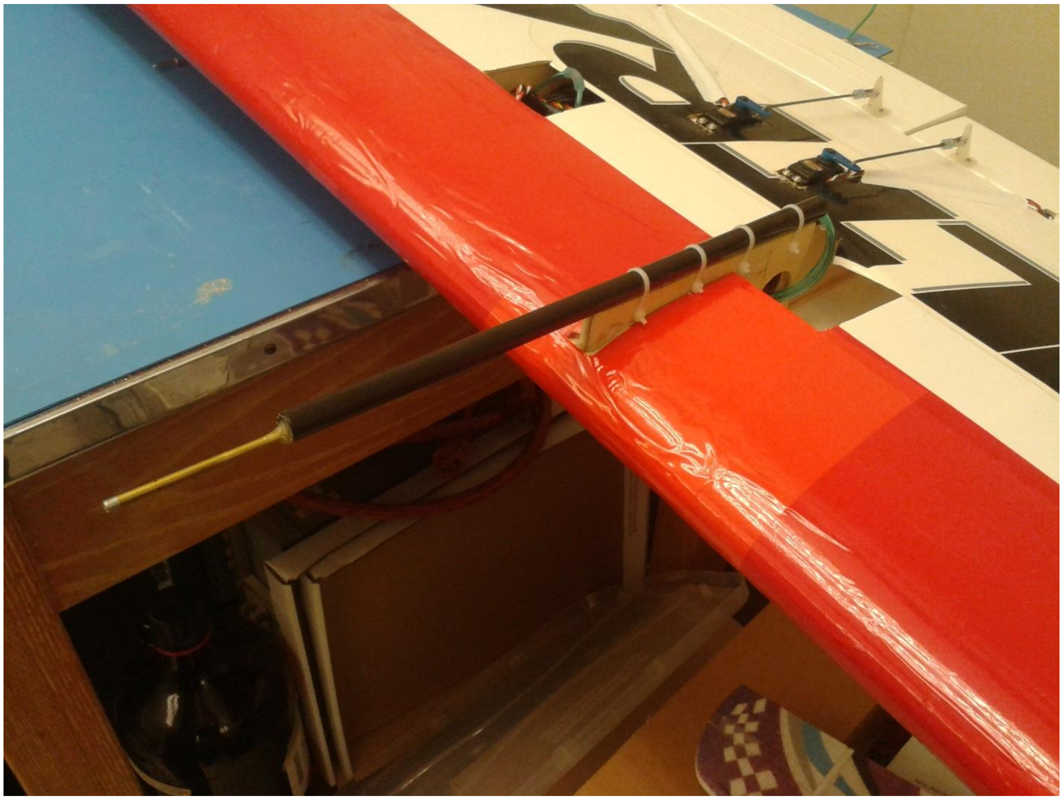

Figure 17: The pitot tube, its carbon fiber extension tube, and the wooden mount used to secure it to the wing. The zip tie connections used to secure the carbon fiber tube to the wooden mount can be seen.

The two pressure transducers were mounted near the center of the wing in a small section cut out to allow access to wiring within the wing. This hole had to be expanded in order to leave enough room to place the pressure transducer mount into the wing. This mount consisted of two small pieces of plywood that were epoxied to the wing, and a small plank of plywood laid over top of them, to which it is attached with screws. This created room underneath the mount for the pressure transducers' wiring. The pressure transducers were epoxied to the top of the mount itself. The flexible tubing from the pitot tube assembly was then connected to the pressure transducers themselves. A Y-connection was used to split the static tube for the static pressure transducer.

Figure 18: The full wing once completed. The pitot tube mount and the slot for the GPS antenna can be seen, as well as the center hole for all of the wiring meant to connect to the flight computer. The servos and potentiometers attaching to the control surfaces are also visible.

Batteries, BECs, and Receiver

The implementation of the three batteries, the BECs, and the receiver was straightforward. To start, the BECs came with no connector on the power and ground lines on the input side, and a JR connector on the output side. The Castle Creations BECs have a variable output, which defaults to 5.1 V. The receiver, servos, and failsafe all required 6 V, so the output voltage needed to be increased. To do so, a program called Castle Link (free download from the Castle Creations website) was installed on a computer and the Castle Creations USB Adapter was plugged into the USB port on the computer side and connected to the BEC via the JR connector on the other side. In the software, the output was set to 6 V.

After the BECs were programmed, the connections to the batteries and receiver were made. The batteries came with large Traxxas connectors, which were cut off one at a time to avoid shorting the battery, then soldered to the corresponding leads on a male JST connector. The avionics battery was treated the same way as the receiver batteries. The connector that it came with was cut off, and a male JST connector was soldered on to replace it. On the BEC's input, the female JST connector was soldered to the correct power and ground wires. The AR12120 receiver came with two dedicated cable pairs, one for each battery, on the back of the hub which terminated with male EC3 connectors. The receiver package included two female EC3 connectors which were used with the output side of the BECs. As mentioned, the BECs came with a male JR connector on the output cables, so before the EC3 connectors could be soldered on, the JR connector was cut off and the signal (orange/yellow) cable was trimmed so that the only wires being soldered to the female EC3 connectors were the power and ground. All solder connections were shrink wrapped to ensure there were no open wires. Once the connections were completed, the receiver setup was nearly complete. To turn the receiver on and off, the AR12120 package also contained a specially designed soft switch, whose JR cable was inserted into the switch port on the front of the receiver. This switch was mounted on the right side of the aircraft, approximately under the mid chord of the wing.

The receiver power hub was mounted with Velcro to the bottom of the fore wing attachment strut. The four satellite receivers that came with the receiver were plugged into the power hub (one has to be plugged into Port A and two others have to be plugged into two of the remaining three ports for the receiver to operate) and then each was attached to either a wall or the floor of the UAV interior. The four satellite receivers were oriented such that three of them had their antenna aligned with one of the three coordinate axes – x, y, and z – while the fourth was set at an angle. This method of mounting provided for the best coverage for the aircraft during any maneuver by establishing an array of antennas. The receivers were mounted, again using Velcro, as far away as possible from any batteries, electronics, or other antennas to decrease the amount of interference.

Motor, ESC, and Motor Batteries

To obtain the required voltage to power the motor, two 5S LiPo batteries were to be hooked up in series. Figure 19 shows the wire diagram of how the batteries and shunt plug were connected. All wires were 10 gauge and all connections were soldered and shrink wrapped. The shunt plug, whose function it was to break the circuit to the motor so the motor could be securely powered off, was mounted on the left side of the fuselage above the landing gear attachment using the included screws and housing.

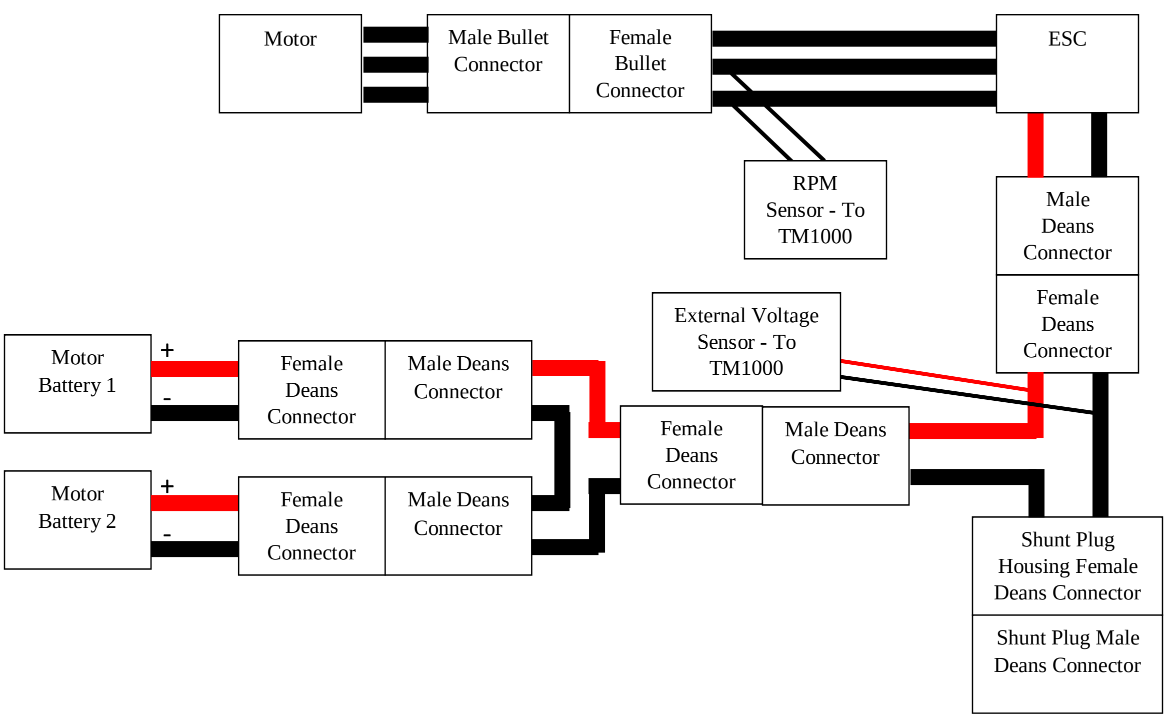

Figure 19: This figure shows the layout of the connections between the motor batteries, the ESC, and the motor, including the connector types. Also shown are the sensor tie ins for the TM1000, mentioned in a later section. Up to the ESC, red wires signify power and black signify ground.

TM1000

Two of the three sensors attached to the TM1000 – external voltage and rpm sensors – required solder connections during hookup. The external voltage sensor's power and ground leads were soldered to the corresponding pins on the female Deans connector leading from the motor batteries to the ESC. For the Brushless RPM Sensor, the two leads were soldered to any two of the three cables between the ESC and the actual motor, on the ESC side so as to allow for the removal of the motor. The temperature and voltage sensors were plugged into the included y-harness and then plugged into the corresponding port on the TM1000. The rpm sensor was similarly plugged into the rpm port on the telemetry module. To connect the telemetry to the receiver, the 2.5" data lead was inserted into the data port on both the TM1000 and the AR12120 receiver during operation. With all of the necessary cables attached to the module, the TM1000 was mounted on the left side of the aircraft, just aft of the shunt plug, using Velcro. Before the TM1000 can transmit data to the controller, the module has to be bound to the receiver and controller pair. Attempts were made to accomplish this, but they were not successful. To bind the TM1000, reference the TM1000 manual ("SPM9548-Manual_EN.pdf"), the controller (DX9) manual ("SPMR9900-Manual_EN.pdf"), and the receiver manual ("SPMAR12120-Manual.pdf").

Pressure Transducers and Pitot Tube

Mounted at the center of the wing are two pressure transducers. The transducer with one input pressure port on the top measures static pressure while the other transducer measures the pressure differential of total minus static pressure. At the rear of the pitot tube there were two pipes, with the straight pipe measuring total pressure and the bent pipe measuring static pressure. Tubing was attached to both pipes, and at the pressure transducers, the static pressure line was split using a T-connector. One static tube went to the Pressure Port 1 (upper right-most port when looking at the top of transducer with the pin indicator circle in the bottom right) on both transducers and the total pressure line went to Pressure Port 2 (connection in the center) on the dynamic pressure transducer. As for the wiring of the transducers, both were wired for I^2C in the same way. The respective wires from each were joined together and soldered to a male four-pin connector to be connected to the wing harness. Both the tubing hookup and the wiring pinout can be found on the Pressure Transducer tab in the "Reliability Wiring and Pinout Guide.xlsx."

Potentiometers

Each of the eight potentiometers had a twisted, three conductor wire soldered to the pins. The signal wire (white) was soldered to the middle pin and the red power and black ground were soldered to either side (reference "Reliability Wiring and Pinout Guide" for pinout). Slots were cut into both the control surface and the actual wing or stabilizer to allow room for the potentiometer to sit. They were located between hinges on each of the surfaces. The axis of rotation for the potentiometers was made coaxial with the axis of rotation of the control surface to make sure that the rotated as smoothly as possible. The base of potentiometers were epoxied to the respective wing or stabilizer and the rotating rod was attached to actual control surface via nylon tape (to be replaced with Monokote once calibration of the potentiometers has been completed).

ADC

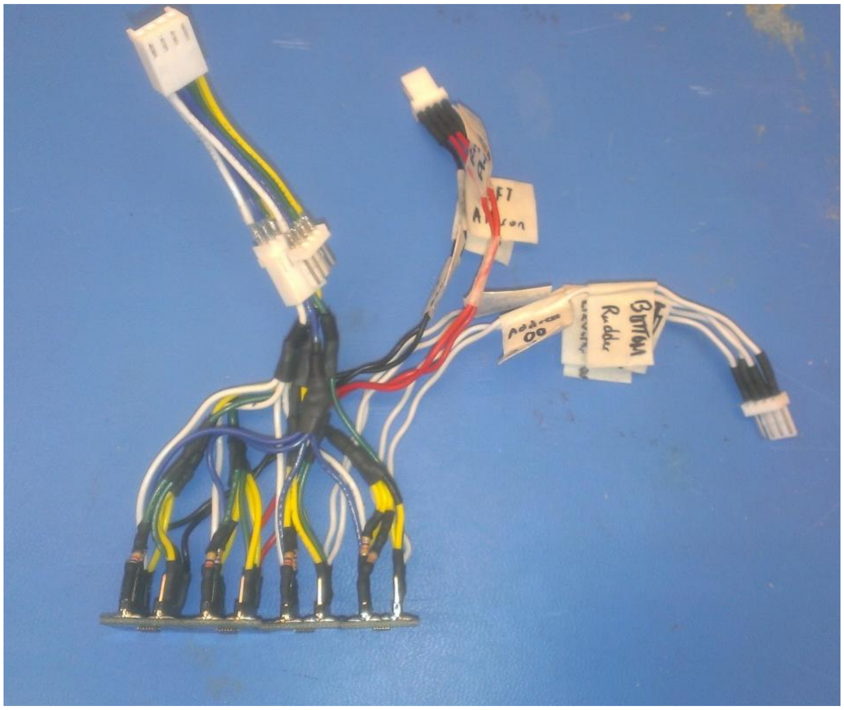

Figure 20: ADC subassembly showing the four separate converters in the bottom left with the I^2C cables in the upper left, flaps and ailerons potentiometer signals in the center on the top, and the rudder and elevator potentiometer signals on the far right.

The wiring of the ADC subassembly was primarily based upon the wiring guide laid out by the UAV Research Group in their document titled "Wiring Diagram.xlsx" which can be found on the TRAC website main page under User Manuals. An updated version of this document, which pertains specifically to the reliability UAV built in this project, can be found with the name "Reliability Wiring and Pinout Guide." There were four total ADCs, with two potentiometers going to each. The exact pinout can be found in either of the two documents above. One of the potentiometer signals was to be wired to pin AC3 and the other to AC5, while the ground for each was tied into the main ground for the chip. There were two potentiometers on the flaps, ailerons, rudders, and elevators, and the pair pertaining to each of the types of control surfaces were on their own ADC, as seen in Table 1.

Address	Control Surfaces
1001000	Rudders
1001001	Elevators
1001010	Flaps
1001011	Ailerons

Table 1: Address for the ADC that the control surfaces are connected to.

As mentioned previously, each chip required a specific address. Those addresses can be found Table 1 above. To set bits 0 and 1, 47 kΩ resistors were used to tie pins D0 and D1 to either 5 V power or ground. D0 and D1 corresponded to bit 0 and 1, respectively. To set a bit to a value of 1, a 47 kΩ resistor was used as a pull-up resistor, tying into the 5 V power line. On the other hand, to set a bit to 0, a resistor was used as a pull-down resistor, tying into the ground line. In that way, the four addresses could be set by making the first two bits 00, 01, 10, or 11.

To complete the wiring of the ADC subassembly, all four of the ADCs were connected so that the four I^2C lines – clock (SCL), data (SDA), power (5V), and ground (GND) – were in parallel with the respective lines from each ADC. From there, the I^2C lines were attached to a female four pin connector which connected the ADCs with the rest of the I^2C bus, which also contained the pressure transducers from the wing. Lastly, the ADCs were not mounted in the aircraft for the demonstration because they had yet to be tested. They should be mounted along the side of the aircraft using epoxy after they have been thoroughly tested.

<u>Remote Control</u>

The controller currently used by the UAV Research Group for this aircraft is the Spektrum DX9. On the DX9 itself, a user can program nearly every aspect of the manual operation of the aircraft. To do so, a model was created for this aircraft, titled “Reliability.” From there, the type of aircraft was set to 1 Aileron/1 Flap and 2 Rudder/2 Elevator, so that there would be the correct number of control surfaces. The channels were then assigned to match those in Table 1. One thing to note is that in the controller, there are only right and left rudders, which for the actual aircraft, are the bottom and top rudders, respectively. The last major piece of setup was for the servos, which can be done using the Servo Setup option from the Function List. For the demonstration, the Travel, Sub Trim, Reverse, and Balance settings were adjusted to obtain the required results. The settings for those can be found in Tables 2, 3, 4, and 5 below:

Travel								
THR	AIL	REL	RRU	LRU	LEL	FLP	GER	AX2
150	135	148	101	150	140	100	100	100
100	135	129	122	150	150	100	100	100

Table 2: These values set the end points for each of the servos. The value on the top is the travel to the left end point for the rudders, and up for the elevators, flaps, and ailerons, while the bottom is the opposite value.

Sub Trim								
THR	AIL	REL	RRU	LRU	LEL	FLP	GER	AX2
0	36	35	65	185	119	0	0	0

Table 3: These values set the center of the range which were set in the Travel settings shown in Table 2.

Reverse								
THR	AIL	REL	RRU	LRU	LEL	FLP	GER	AX2

Table 4: This setting controls which direction, clockwise or counterclockwise, the servos will rotate for the same input on the controller.

Balance						
R Rudder						
0	0	0	0	10	10	10
L Rudder						
40	30	20	10	0	-20	-40

Table 5: The balance sets a curve for the servo actuation. A number other than zero causes the servo to either speed up or slow down. This can be used to make sure that two servos, say the top and bottom rudder, move at the same speed at all points in their range of travel.

To get the controller to talk with the receiver and the aircraft, the controller needed to be bound to the receiver. To do so, the provided bind plug was inserted into the BND/DATA port on the front of the receiver (unplugged the telemetry data cable if it was currently in that port). With the bind plug in, the receiver was turned on using the soft switch. If all of the lights on the satellite receiver were flashing, it meant the receiver was in bind mode. The final step was to hold the bind button on the controller and power it on. The controller automatically bound itself to the receiver and when completed, reverted back to the main screen. Refer to the controller manual (“SPMR9900-Manual_EN.pdf”) or the receiver manual (“SPMAR12120-Manual.pdf”) for more detailed instructions for setting up the aircraft and all of its Spektrum related components.

Data Dump

The Ethernet port, associated breakout board, and data dump switch were all wired following the the “Reliability Wiring and Pinout Guide.” They were mounted using epoxy on the right side of the aircraft, opposite the shunt plug.

Telemetry Radio Antenna

The telemetry radio is housed on the flight computer, but the antenna which transmits the data to the ground station is not. The antenna was located on the bottom of fuselage in the center of the aft hatch. A hole was made to allow for the threaded shaft which was tightened using a nut, and onto which the antenna was mounted. A cable extends from the antenna fore toward the location of where the flight computer will sit, where the cable will attach directly to the telemetry modem.

Results

Fault Tree Analysis

The new FTA yielded promising numerical reliability results. After reconstructing the original fault tree for the FASER, it was found that the new calculated probability of its catastrophic failure was lessened to 0.762 failures per 100 flight hours. The probability of catastrophic failure for the newly constructed, redundant airframe was then calculated to be only 0.0379 failures per 100 flight hours, making the new aircraft 20.118 times more reliable than the original FASER, according to this amended fault tree analysis.

Demonstration

The demonstration provided an opportunity to show that all the control surfaces move, that the split control surfaces move together, that motor properly works, that the telemetry radio sends data to the controller, and the redundancy in the batteries and receivers. First, various components of the aircraft were displayed – e.g., what types of batteries were used and where they were located in the aircraft, how the pitot tube was rigged, and the orientation of the GPS unit, which was found to be installed upside down. Next, the tail control surfaces were controlled via the remote, showing that they moved concurrently at nearly the same rate. As expected, simultaneous movement between split surfaces was not achieved, but future calibration will help to eliminate the disparity. Another point of interest was the conclusion that some of the control surfaces did not hold position perfectly, most likely due to flexible linkages between the control surfaces and servos. As such, linkages will require optimization, as well as the orientation of certain potentiometers.

Following the control surface demonstration, the motor and batteries were observed. First, the batteries were attached, then the shunt plug was removed to show that it properly stops the motor from receiving power. The shunt plug was re-attached to demonstrate operation of the motor and propeller. Next on the agenda was a demonstration to the TM1000 telemetry radio, but this could not be performed as the radio was not properly binding to the controller. However, the inability to bind the radio to the controller was posited to be a minor issue, relatively easily fixed. A demonstration of battery redundancy followed, in which one of the avionics batteries was disconnected and it was shown that the control surfaces would still respond to controller inputs. While the battery was still disconnected, one receiver out of four was also disconnected from the main receiver to demonstrate redundancy in the receivers. A second was then removed to no loss in functionality, which indicated that only two receivers were necessary for operation.

Finally, the wings were attached to the main body to demonstrate the functionality of the wing control surfaces. While the control surfaces responded correctly to controller inputs, it was determined that the flaps rotated within the wrong range of motion. Fixing this issue would only require rotating the control arm on the servo arm to the proper orientation. One other issue that was brought up was that the wing itself was slightly imbalanced, but shifting the center of gravity of the wing is a trivial issue that can be quickly corrected.

All of the demonstrations besides the telemetry prove successful. Flight computer testing and demonstrations were not possible due to time constraints and inability to verify correct wiring prior to the demonstration. As such, the flight computer was not demonstrated and therefore various sensors could not be tested either. This problem can be remedied in the future when a flight computer becomes available to use.

Future Plans

Trac Website Recommendations

The UAV Research Group's website was referenced extensively throughout the project and is divided into three sections: Airframes, Flight Test Data and Reports, and Lab Organization and Procedures. While referencing some subsections in the Airframes section, it became apparent(WC) EB that some changes, suggestions, and updates could be made. These are listed below.

1. A preview renderer on the website would be convenient to view all the PDF files and Excel files without having to download them and open them separately.
2. In the wiki/avionics/SPI page, the link that says "Serial Peripheral Interface" sends the reader to eetimes.com homepage. The article that the link was supposed to reference must have been taken off the eetimes.com site, so this link should be fixed.
3. On the wiki/Sensors/IMU/iSensor page, the DigiKey link is broken.
4. The RxMux link on the Ticket #39 page is dead.
5. The calibration link on the potentiometer page is incomplete.
6. A detailed, all-inclusive parts list should exist for building an Ultra Stick 120 similar to the ones used by the UAV Lab. This list should include manufacturers, retailers, prices, and part numbers for easy reference.

Flight Readiness

The next goal for the UAV is to attain flight readiness. The first part in completing this goal is to correct and finish the structure of the vehicle. During the demonstration on May 12th, 2014 it became apparent that some components needed to be modified. The flap servos and pushrods are currently configured for three modes: negative, zero, and positive. Since the flaps will have no reason to be negative, the configuration needs to change so that the three flight modes allow for straight, positive, and even further positive. This corresponds to straight and level flight, takeoff, and landing. The current configuration does not allow for a landing mode. The GPS antenna in the wing was installed incorrectly as well. The antenna in its current configuration would be directed towards the ground during a flight. The mount for the antenna must be carefully taken out and mounted closer to the bottom of the wing to allow room for the antenna to be mounted on the other side of the mount. The new configuration will have the antenna facing the sky during a flight. The wing's center of gravity is slightly right (starboard) of the y-axis. This can be fixed by repositioning some of the wiring from the antenna to shift the CG towards the center.

Currently the motor mount, the motor, and the speed controller are uncovered. A nosecone needs to be purchased or constructed and mounted. The two left rear servo pushrods need to be reconfigured and reinforced to minimize the buckling effects. This will involve moving the left elevator servo's motor arm and reinstalling the original pushrod that was used when the motor arm was in the original correct position. The decision to change the configuration was based on the rotational direction of the motor arm that causes a positive elevator deflection. It seemed trivial that the same elevator servo rotational directions would have to cause the same direction of deflection, but later it became clear that the rotational-direction-to-deflection correlation was not important. After readjusting all control surface systems, they need to be properly calibrated so that the two rudders and two elevators move in sync.

The landing gear is the last structural component to be added and modified. The main fore gear's bolts that connect the wheel to the wheel mount are currently too short to install the correct amount of collets on the bolts. Currently, there is room for just one collet on the outside of the wheel. The correct configuration is to have one collet on the inside and two on the outside. Without these extra collets, there is a good chance that one or both of the wheels would vibrate off during a flight. The rear landing gear needs to be mounted and an apparatus to connect the rear wheel to the bottom rudder for ground steering needs to be constructed. When all of the structural components are complete, a final MonoKote patch job needs to be completed on all the surfaces that are lacking, and a CG location needs to be determined and modified by moving non-mounted components if need be.

Once the structural issues are resolved, a logical next step is editing the flight code to take the split control surfaces and the pinout changes that occur due to the structural changes. This was ruled out for the design team's scope. Along with the flight code, the simulations associated with the UltraStick family are to be modified to include the split surfaces. The design team modified the simulation, but time constraints did not allow for a completed simulation. The first task will be to simulate a hard over failure or a stuck failure in one or more servos and determine if the other surfaces can make up for the fault. This would serve to validate the proposal that splitting the surfaces would bring them from a 1A failure to a 1B failure, therefore reducing the overall 1A failure rate. See the following Simulation section for further discussion.

Some internal and external electric components and sensors need to be installed and modified before first flight. During the demonstration it was mentioned that it would be favorable to connect all of the grounds to ensure continuity between the electronic components. This is something that should be implemented before flight. The batteries purchased by the senior design team are considerably larger than the Turnigy LiPo batteries that were previously supplied by Hobby King. Since the AEM department no longer orders through Hobby King, a space-saving goal would be to find a valid supplier that could provide smaller batteries with the same specifications. Another possible modification is to add a switch between the avionics batteries and their respective BECs. Battery regulators always draw some power even when everything is turned off, so if it is desirable to keep the batteries plugged in for an extended period of time, a switch may be beneficial to use instead of wearing out the connectors over time through continuous detachment and reattachment.

Since the only failed demonstration was the TM1000 telemetry not binding properly with the R/C controller it will have to be examined to determine what the problem is. Operation of the pitot tube needs to be verified, and modified if necessary. During the demonstration, the connection between the pitot tubing and the pressure transducers was put into question. Epoxy was used to seal the connection from the tubing, but the UAV lab personnel expressed the need to remove the tubing on occasion. The epoxy needs to be removed from the transducers and the tubing and reinstalled with something more removable. The wiring in the aircraft must be inspected and potentially modified. Besides physically looking at the wires and comparing to the wiring diagram and without access to the computer block to connect components, it was impossible to confirm continuity and correct wiring. Since all connections were soldered and shrink-wrapped and the connectors were tested for fit, the only thing left is in terms of wiring is to have it inspected for correctness and tested for proper function.

The aircraft should be fully assembled at this point. In the UAV Lab's Operations and Maintenance Plan (OMP), they have an inspection plan. Appendix 1 is an excerpt from the standard inspection procedure before each flight. After the inspection, the aircraft should be ready for first flight.

<u>Simulation</u>

The MATLAB/Simulink flight simulation software needs to be further edited to account for the newly split control surfaces. This will allow for further theoretical verification that the aircraft can be successfully trimmed, even with a control surface failure. It can be accomplished by duplicating the rudder and elevator blocks in the "FASER_Aero_Lib.mdl" file. This file is located in the "Simulation" folder, under the "Libraries" subfolder. To implement these changes, one must click within the highest level block in the Simulink model, simply labeled as "FASER". In the underlying level is a block labeled "Control Surface Effects". Within this block is yet another child level, this time containing both the "Elevator" and "Rudder" blocks. In its current format, the elevator is fully modeled at this level, and can be edited directly. The rudder, on the other hand, has one more underlying model under the block labeled as "Rudder". This is what must be edited to allow for the modeling of the split rudder.

For the sake of uniformity, it may be advisable to create a parent block for the elevator model, and store its underlying structure in the same lowest child level as the other control surface models. Then, one has the option of creating separate rudder and elevator blocks at the parent level, or altering the existing ones to model the split surfaces all at the lowest child level. Either way, a top and bottom rudder must be created from the existing single rudder model, and a left and right elevator must be created from the current single elevator model. The present method of using data table lookups combined with interpolation blocks can still be utilized, but this means that the tables being referenced must also be altered to contain the correct values for the aerodynamic variables corresponding to the new split control surface configurations.

The rudder and elevator blocks in the Simulink model currently reference values from the "FASER_Aero.mat" file, located in the same directory as the "FASER_Aero_Lib.mdl" file. The discrete numbers that the Simulink file uses to model the rudder are stored within the "dC2_rud" table in the .mat file. These include tables for a range of angles of attack (alpha), sideslip angles (beta), advance ratios (J), and rudder deflection angles (rud). These, in turn, affect the change in total side force (CY) through the aircraft center of gravity, and the yaw moment (Cn) about the center of gravity.

One way to remodel the rudder would be to create a second, nearly identical rudder block in the Simulink folder, as previously described, and then reference two different sets of tables within the “FASER_Aero.mat” file (for example “dC2_rud_upper” and “dC2_rud_lower”). These tables should at least include new values for the resulting changes in CY and Cn for each rudder for each given range of variables. To make the model more complete, it would be best to expand the range of values for rudder deflection angles to include more than the current three numbers located in the “rud” table. The model would also be more accurate if the rudders’ effects on other aerodynamic forces and moments were included besides just CY and Cn. These could include lift and drag forces (currently modeled elsewhere as “CL” and “CD”, respectively) and pitching and rolling moments (currently modeled as “Cm” and “Cl”, respectively).

Ideally, the effects of all control surfaces on all of these forces and moments could be modeled, in order to create the most realistic simulation. Values for all of these aerodynamic forces and moments, based on changing control surface deflection angles for any given flight conditions (alpha, beta… etc.) could be calculated in a manner similar to that described in the Methods section, in which the optimum rudder cut location was determined. This procedure could be extended to all of the control surfaces, making for more complete tables for the Simulink model to look up and interpolate from. The new split elevator could be modeled exactly the same way as the split rudder, this time altering the “dC3_ele” table within the “FASER_Aero.mat” file (to “dC3_ele_left” and “dC3_ele_right”, for example). Creating two separate elevator blocks in the Simulink model would then complete the process.

Conclusions

The goal of the project was to increase the reliability of an unmanned aircraft in a cost-effective manner. Specifically, the goal was to increase the reliability by a factor of ten at no more than double the cost. While time constraints prevented the team from completing the build and therefore fly the UAV, the work completed by the team will provide the UAV Research Group with extensive groundwork towards a highly reliable research vehicle.

The design phase of the project included a comprehensive Failure Modes and Effects Analysis (FMEA) and detailed Fault Tree Analysis for three levels of criticality. The 1A level considered failures that would result in a catastrophic failure, or loss or major damage to the aircraft. This was the focus of the build phase of the project, since these failures were most critical. A sensitivity analysis was conducted on the 1A tree to determine which redundant components increased the reliability the most compared to the cost of the new design. The final design included adding a redundant avionics battery and splitting both the rudder and the elevator. An updated FTA factored in these changes and calculated an increase of 20.118 times more reliability, meaning there will theoretically 20.118 times fewer catastrophic failures per unit time than the original configuration of the vehicle.

With the design in place, other work had to be done before beginning the build phase. Aerodynamic analysis was conducted on the tailplane to determine where to cut the rudder to have equal yaw moments if a servo were to become stuck or hard over. The split of the rudder and elevator aimed to reduce failure from the 1A level down to the 1B level, which corresponds to a mission critical landing without any major damage. Again, this has yet to be proven as a valid method to eliminate the rudder and elevator failures from being catastrophic by both simulations and field tests, but the design group has made significant advances towards validating these theories. The consequential addition of two servos along with control horns, pushrods, and potentiometers had to be implemented in the design. Their placement, along with wiring involved and pinout changes had to be determined before the build phase could begin. The integration of these new control systems involved an upgraded receiver, higher discharge batteries, and an additional A/D converter to accompany the extra potentiometers.

After receiving the airframe and stripping it down to the bare wood, the build phase began. It became clear, as issues continued to arise during the build, that the plane would not leave the ground before the semester was over. Since the goal of the project was to provide the UAV Research Group with a reliable platform for future research, the design incorporated all of the necessary and common components that the current Ultra Stick 120 research aircrafts feature, while including the new reliability implementations. The focus shifted from getting a flight in before the end of the semester to making sure the work completed this semester was thorough and as complete as possible. Since a flight computer was not provided, focus shifted towards a ground demonstration that would display the correct implementation of redundant and original components.

Before receiving the wing, the UAV Lab had told the design group it would have to be rewired. Not only was the wing not wired, but there were other missing parts like pushrods, potentiometers, and pitot tube. In addition, there was a large crack in the balsa wood on the leading edge of the starboard side. These issues – as well as the unavailability of a flight computer – led to the decision to focus on the demonstration of the redundant components and finishing the wiring and installation of mechanical and electrical components, along with completing the structure of the airframe. This resulted in an aircraft that included all necessary components, wires, and connections ready to be flight computer tested.

During the demonstration, the new split control surfaces along with the original wing's control surfaces were displayed to operate correctly. The synchronous movements of the two elevators and rudders were shown, but the calibration was slightly incorrect resulting in very small discrepancies between the deflections of the rudders and elevators. The motor and propulsion system was shown to work properly, as well as proving the redundancy of the avionics battery and R/C receiver by physically removing one battery and two of the four satellite receivers and showing that the control systems still operated properly. Overall, the demonstration was successful in showing the function of the redundancy of the avionics and receiver, as well as the propulsion and control systems without the implementation of the flight computer.

The groundwork provided by the design team towards more reliable UAVs will provide a base for future research at the University of Minnesota. Even though the plane did not achieve flight, extensive effort was applied to provide a more reliable aircraft that would support the veracity of an improved design. In the future, the research group will continue to move towards flight readiness, including both physically modifying the aircraft and working on the flight code and the simulation to accommodate the improved reliability design and build.

<u>Lessons Learned</u>

There were a few valuable lessons learned during this build experience. It sounds cliché, but with better time management and effective communication the project would have gone more smoothly.

Proper time management is imperative. Our group initially thought that with thorough scheduling, time management would not be a problem. However, we found that there was often a discrepancy between what we expected to get done and what we could realistically accomplish. In a way, merely scheduling a task offered a false sense of security that it would be finished on time. As a result, there were spurts where a lot of work was accomplished followed by short dormant periods. One possible excuse for this work trend was the unpredictability of school work for other classes. However, if this project was to be redone, our group agrees that a more realistic work schedule is necessary. In other words, a less optimistic schedule with a generous amount of time allotted for each task would be more practical. We consistently realized that things generally took longer than expected to complete.

We also learned the importance of effective communication. This included not only communication within the group, but with people outside as well. This project involved collaboration with the UAV lab. There were times when we either misunderstood or misinterpreted what was said by members of the lab, which resulted in schedule delays. For example, we were told that the wing for the aircraft would only need to be “rewired”. Now, the definition of “rewired” is a bit vague. In hindsight, we should have communicated more effectively and asked specifically the state of the wing and what “rewiring” exactly entailed. We were therefore surprised when we received a wing with no wires, no servos, and a crack in the front spar. We were able to work around this inconvenience, but knowing the details ahead of time through better communication would have been more ideal.

Another occurrence of miscommunication involved the flight computer, which was planned to be built by the UAV lab. We assumed that it would be completed near the end of the build in time for initial testing. However, we never stressed its importance to members of the lab. We assumed that by mentioning it during one meeting, its completion would fit our schedule. Due to other priorities in the UAV lab it was not finished on time. Now, this didn’t directly affect our plane’s performance. However, this is another example of how effective communication is needed especially when parts of a project are divided among separate groups.

We also learned throughout the process that it is important to pay attention to detail. There were times when, due to time constraints, we approached a task intending just to finish it. This isn’t to say we were sloppy in our work, but there were times when we didn’t take enough into consideration. Sometimes it’s easy to rely on a quick fix in the short term. However, usually a problem boils up one way or another, so the time saved initially by the temporary repair is wasted. By the end of the project we understood that remaining patient, investing adequate time, and paying attention to detail for a given task was the best way to approach a task.

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Appendices

Appendix 1: Pre-Flight Checklist

This is taken directly from the UAV Lab's Operations and Maintenance plan [2].

1. Airframe structure, check:
    a. Fuselage, wing, and hatches for signs of damage or cracking
    b. For rips and tears in monocote, patch as necessary
    c. Landing gear and motor bolts are tight
    d. Wheels spin freely
2. R/C Equipment, check:
    a. RC equipment is plugged into receiver
    b. Motor plugs are connected
3. Batteries
    a. Charge motor and avionics batteries.
    b. Check for battery pack bloating and signs of damage
4. Flight Control Computer
    a. Check that component wiring harnesses are plugged in, no loose wires, and in good condition

Appendix 2: Operations Manual

Start Up Procedure:

- Connect all of the wire harness connectors to their respective ports on the flight computer, receiver, ADC subassembly, and other components. Verify that none of the connections are loose.
- Attach the wing through the 26 pin D-Sub connector on the wing and the wing harness. Verify the I^2C connection is made for the pressure transducers.
- Bolt the wing in place securely with the four 1/4”-20 by 2.5” bolts.
- Plug in the receiver batteries to the BECs and the avionics battery to the avionics switch.
- Verify that the shunt plug has been removed. Plug the motor batteries into the series Deans connector in the front hatch area. Verify that the connection to the ESC is complete and the connection between the ESC and the motor is complete and secure.
- Cover and secure both hatches by screwing the lids down.
- When all connections have been made and inspected, turn the DX9 controller on, making sure that the throttle stick is at zero percent.
- After the controller is on, turn the avionics switch on to power the flight computer and avionics, and turn the receiver on. The servos should move to their zero setting.
- When the receiver has been turned on, plug the shunt plug back in.
- Test all of the control surfaces to verify that they are working and that they are properly calibrated. Test the throttle to verify that the motor runs smoothly.
- Test switching the aircraft from manual to auto and back to verify failsafe switch is operating as it should.
- Perform any other test necessary to verify that all systems are working and that the flight is a go.

Shutdown Procedure:

- Upon finishing the flight or test, power the throttle all the way down.
- Pull the shunt plug to stop the motor from running during any subsequent operations.
- Plug the computer into the Ethernet port and toggle the data dump switch on. After the data has been received in its entirety by the computer, toggle the data dump switch back to off.
- Turn the avionics battery and the receiver off.
- Turn the controller off.
- Unbolt the wing, detach the 26 pin D-Sub connector, and set wing in safe location.
- Unplug the batteries (motor, receiver, and avionics) to ensure no extra current is being pulled from them.
- Undo any connections. Store any removed components properly and securely.
- Charge batteries if required.

Appendix 3: Parts List

Bolts and Screws:

Description	QTY	Price Per Unit	Where to get it	Part Number	Use
1/4-20 2.5" hex heads bolt	4	$0.39	Menards	2028344	Attach wing to fuselage
#6-32 3/4" Phillips	8	$0.15	Home Depot	887480030310	Hatches
#10-32 5/8" Phillips	4	$0.58	Home Depot	61018	Motor Mount
#10-32 1.25" Phillips	4	$0.98	Lowes	57855	Motor Mount
1/4-20 5/16" T-nuts	4	$0.15	Home Depot	887480023015	Wing Mount
#6-32 1/4" T-nuts	8	$0.15	Home Depot	887480022612	Hatch Mounts
#8-32 T-nuts	4	$0.15	Home Depot	30699188512	Landing Gear
#8-32 3/4" Phillips	4	$1.18	Home Depot	27991	Landing Gear
4mm 3/8"	3	Free	Mechanical Research Lab		Motor
#10-32 5/16" T-nuts	4	$0.15	Home Depot	887480022919	Motor Mount

Wing:

Description	QTY	Price Per Unit	Where to get it	Part Number	Use
CONN DB50 MALE SOLDER CUP TIN	1	$4.03	Digi-Key	250MER-ND	Aircraft Sensors
CONN DB15 MALE SOLDER CUP TIN	3	$2.03	Digi-Key	215MER-ND	Servos and Receiver to flight computer
Titan 3 GPS Unit	1	$69.95	GPSOutfitters	Titan3	GPS Antenna
5245 Hi-Tech Servos	4	$46.99	Servo City	HS-5645MG	Move Control Surfaces
2/56" Push Rods 6"-12"	4	$2.49	Tower Hobbies	LXD867	Servos to Control Surface
2/56" Clevis Steel	4	$1.69	Tower Hobbies	GPMQ3790	Connect Pushrods

CTS 250 100kΩ U or X style Potentiometer	4		CTS Sales Associate		Measure Control Surface Deflection
12" Superduty Female Servo-Lead	4	$2.95	ServoCity	FSL2212S	Servo Extension
10' 22 AWG Twisted Wire	1	$15.95/50ft	ServoCity	SW22JT	Potentiometer Wiring
Static Pressure Transducer	1	$30.00	ServoFlo	AMS5812-0150-B	Airspeed Measurement
Dynamic Pressure Transducer	1	$30.00	ServoFlo	AMS5812-0003-D	Airspeed Measurement
Pitot Tube	1	$10.99	Spektrum	SPMA9588	Intakes Free Stream Airflow
12" Carbon Fiber Rod	1	Free	SAE Team		Holds Pitot Tube
Control Horns Large	4	$1.05/2	Tower Hobbies	LXD934	Connects Push Rods to Control Surfaces
4 Pin Header	1	$0.42	Digi-Key	WM4113-ND	Pressure Transducer
4 Pin Housing	1	$0.20	Digi-Key	WM2002-ND	Pressure Transducer

Fuselage:

Description	QTY	Price Per Unit	Where to get it	Part Number	Use
40-6 Actro Motor	1	$379.95	Hobby Club	KLR700226	Motor
E-Spinner 2" Transparent Red	1	$8.99	Tower Hobbies	GPMQ4717	Holds Propeller
GensAce 2S 1P 7.4V 25C 3300mAh Battery	2	$28.30	Hobby Partz	98P-B-25C-3300-2S1P-TRX	Powers Receiver
GensAce 3S 1P 11.1V 25C 2500mAh Battery	1	$28.06	Hobby Partz	98P-25C-2500-3S1P	Powers Daughterboard
35mm M8 Actro-Nabe Propeller Extension	1	$12.95	Hobby Club	KLR700265	Connects Propeller to Motor
45mm M8 Actro-Nabe Propeller	1	15.95	Hobby Club	KLR700266	Connects Propeller to Motor

Extension					
18x12" APC Composite Propeller	2	$11.40	Aero-Model Inc.	APCE-18x12	Provides Thrust
Castle 12S Lipo 50V Max HU80 ESC	1	$185.95	Castle Creations	010-0075-01	Controls Motor Speed
Male Bullet Connectors	3	$2.99/3	Hobby Town	GPMM3112	Connects Motor to ESC
Female Bullet Connectors	3	$1.99/3	Hobby Town	GPMM3113	Connects Motor to ESC
Series-Deans Connector	1	$12.99	Hobby Town	CSE011000200	Connects Battery to ESC
Female Deans Connector	2	$1.60	Hobby Town	WSD1003	Connects Battery to ESC
JST Female Connector	4	$1.25	HobbyTown USA		Connectors for batteries
JST Male Connector	4	$1.25	HobbyTown USA		Connectors for batteries
Motor Batteries	2	$39.20	Hobby King	T5000.5S.20	Powers Motor
Computer Block	1	UAV Lab	UAV Lab	UAV Lab	Holds Flight Computer
RJ45 Ethernet MagJack-Compatible	1	$1.95	SparkFun	PRT-08534	Ethernet Dump Plug
CTS 250 Series U or X style Potentiometers	4	Donation	CTS Salesman		Measures Control Surface Deflection (Tail)
HS-5645MG HI-Torq Servos	4	$46.99	Tower Hobbies	HRCM0645	Moves Tail Control Surfaces
RJ45 Ethernet MagJack-BreakoutBoard	1	$0.95	SparkFun	PRT-08790	Connects to Ethernet Plug
4-40 Steel Clevis	8	$8.49 for 12	HobbyTown USA	GPMQ3795	Connects Push Rods
4-40 30" Steel Push Rods	4	$1.49	HobbyTown USA	DUB145	Connects Servos to Control Surfaces
Large Control Horns	4	$2.31	Tower Hobbies	DUBQ1985	Connects Push Rods to Control Surfaces

20' 22 AWG Twisted Wire	1	$15.95/50ft	ServoCity	SW22JT	Potentiometer Wiring
24" Superduty Male-Female Servo Extension	4	$5.95	ServoCity	SE2224S	Servo Wiring Extensions
AD Converters	4	$23.28	Digi-Key	SX8724CWLTDTCT-ND	Converts Potentiometers Signal
Landing Gear Mount	1	UAV Lab	UAV Lab	UAV Lab	Connects Wheels to Body
Wheels	2	UAV Lab	UAV Lab	UAV Lab	Connects on Landing Gear Mount
Collets	6	UAV Lab	Uav Lab	UAV Lab	Holds Wheels on Landing Gear
Bolts and Lock Tight Nuts	2	UAV Lab	UAV Lab	UAV Lab	Holds Wheels on Landing Gear
TM1000 DSMX Telemetry Module	1	$56.99	Horizon Hobby	SPM9548	Sends Telemetry to Controller
Telemetry Radio	1	$753.80	FreeWave	MM2-T	Sends Telemetry
3' LMR-240 Coaxial Cable	1		FreeWave	ASC0032SF	Connects Antenna to Telemetry Radio
A900 MHz Antenna	1		FreeWave	EAN0900NR	Sends Signal
Shunt Plug	1	$6.99	SharpRC	AS1-P	Cuts Off Power to Motor
Shunt Plug Base	1	$6.49	SharpRC	SUD0302	Mounts Shunt Plug
10A Peak 25V Max BEC	2	$24.95	Castle Creations	010-0004-00	Lowers Battery Voltage to Receiver
RPM Sensor	1	$21.99	Horizon Hobby	SPMA9558	RPM Telemetry Wire
12-Channel DSMX Receiver	1	$249.99	Horizon Hobby	SPMAR12120	Controller Receiver
6" Standard Extension	10	$3.45	ServoCity	SE2406S	From 15 Pins to Receiver
IMU	1	$810.19	Digi-Key	NQ-13234	Inertial Measurement Unit
GPS Receiver	1	$299.99	HemisphereGPS	CresentOEM	Receives information

					from Antenna
Flight Computer	1	$499.99	Phytec	MPC5200B	Flight Computer Main Processor

Miscellaneous Materials:

Description	Price	Where to Get It	Use
Epoxy	$10.00	Home Depot	Glues Structures and Parts to Aircraft
Balsa & Bass Wood	$30.00	ECE Depot	Use for Structures and Mounts
3/8" Plywood	$10.00	Home Depot	Use for Structures and Mounts
Wood Filler	$5.00	Home Depot	Fill Small Holes in Structure and Mounts
20 GA Wire	$30.00	ECE Depot	Connect Components Together
Shrink Wrap	$15.00	ECE Depot	Cover Solder Connections
Sand Paper	$8.00	Home Depot	Smooth Structures and Mounts

Total Cost of Components, Wiring, and Misc. Supplies ≅ $2,800.00
Total Cost of Shipping ≅ $150.00
Total Cost of Build ≅ $2950.00

The total cost of the components not supplied by or borrowed from the UAV Research Group totals approximately $2,800.00. This number does not take into account the cost of shipping, which totaled around $150.00. That number could be reduced if a few of the orders were combined to only necessitate one shipping cost instead of multiple. The cost of the components is much higher than the initial estimate as found during the original redesign. This is because the $2,800.00 includes the two most expensive components on the flight computer – the IMU and the telemetry, which together add up to $1,564.00 – which were required to finish a flight computer. Without those two components, the total cost of the aircraft, including the cost of shipping, was only $1,386.00, which is significantly lower than $2,950, yet still significantly higher than the original redesign estimate. Part of the difference comes from the receiver that ended up being used. The AR12120 is priced at $250.00 alone. Another added expense that wasn't on the redesign was the telemetry module, the TM1000, and the Brushless RPM Sensor. The three parts from Spektrum added an additional $329.00.

With a total cost of improvements (not including the cost of the IMU and the telemetry radio) of $1,386.00, the requirement of the redesign to not exceed double the cost was met. Even though the number is larger than previously expected, the value is still considerably lower than the maximum cost laid out by the requirement.