UAV for Reliability

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Abstract

With UAVs becoming more prevalent in public airspace and less expendable, they need to be reliable to avoid any catastrophic events. For this reason the reliability of the Ultra Stick 120 is being analyzed for the UAV lab group at the University of Minnesota-Twin Cities, with the requirement that the reliability be improved by a factor of ten in a redesign of the aircraft systems where the cost of the redesign does not exceed double the original budget. The initial analysis of the 120 shows three severity categories with the catastrophic failure (severity category 1A) having a failure rate of 2.17 failures per 100 hours, the possible landing (1B) having a failure rate of 2.14 failures per 100 hours, and the mission critical (2) having a failure rate of 2.32 failures per 100 hours. Only catastrophic was focused on because getting the UAV back is most important.

A conceptual design which split the rudder and elevator control surfaces, added a redundant battery, and added a redundant failsafe switch improves the reliability of the aircraft to 0.128 failures per 100 hours, being slightly over a magnitude better while only requiring around $250.00 to be spent. While this design works it is too complex for the current system to be feasible. For this reason a more practical design was chosen includes everything from the conceptual design except for the redundant failsafe. The reliability of this redesign is 0.762 failures per 100 hours. Even though it is not a magnitude better, it does still improve the reliability by 65% and is actually feasible. With many unquantifiable possibilities to add in, it is believed that the reliability of the aircraft can be made closer to a magnitude better with more time and research.

Introduction

As unmanned aerial vehicles – UAVs – become more integrated into common airspace, it becomes ever more apparent that they must become increasingly more reliable. Not only are UAVs becoming more complex and expensive, they are also being used in a wider variety of settings. They have been used extensively in the military for high-risk attacks as well as surveillance, and they will soon be more common outside the military as they begin taking on various civilian tasks – such as crop-dusting or delivering packages soon after they are ordered. However, there are definite drawbacks to using UAVs: first, they can be prohibitively expensive – one MQ-1 Predator drone costs the US government just over $4 million alone. A second drawback is that – being unmanned – these vehicles have no crew to physically work on them during missions should problems arise. Due to these factors, it is vitally important to ensure that UAVs are reliable to prevent expensive failures that can lead to loss of the vehicle.

The University of Minnesota's UAV lab is focused on the development and implementation of a low-cost UAV flight research facility. Their goal is to "support research activities within the department including control, navigation and guidance algorithms, embedded fault detection methods, and system identification tools" [7]. Even though the research itself is relatively inexpensive, one of the UAVs used in research can cost upwards of $6,000. Losing one of these aircraft would be detrimental to the research not only from a financial standpoint, but also from a research standpoint; time spent collecting flight data is wasted if it is somehow lost in-flight.

The design project described in this report aims at quelling these issues by focusing on improving the reliability of the UAVs used in lab research at a reasonable cost. In order to achieve this, requirements were set imposing an increase in UAV reliability by a factor of ten at no more than twice its original cost. The specific UAV used in this redesign is the Ultra Stick 120, shown below in Figure 1. There are two methods of meeting the second objective pertaining to cost: the first includes a design that takes into account the total cost of the UAV, but it will not be implemented due to the limited budget available. The second method of design does not include the cost of components already present in the UAV, but will direct the available budget only to different or redundant parts that are not in the current UAV. By focusing on the latter, it is possible to approach the goal for improved reliability at a substantially reduced cost.

Figure 1: A picture of the UAV studied in this paper, an Ultra Stick 120. The Ultra Stick 120 is a conventional tailplane with a symmetric airfoil, marketed as a trainer-level R/C aircraft. It is relatively easy to pilot but can perform highly dynamic maneuvers that enables it to perform a wide variety of tests.

To improve the reliability of a UAV, it first must be quantified and analyzed appropriately. There are two main tools used in this project that can accomplish this task: a Failure Modes and Effects Analysis (FMEA) and a Fault Tree Analysis (FTA). The FMEA contains tabulated data for each component in the UAV, assigning various failure types (modes), causes, and effects to each part and determining the severity of each mode as well as potential compensating actions and features. The FTA branches out to consider each part and its various failure modes that can potentially result in an end-effect failure, assigning rates of failure to each mode that together result in a total probability of failure for that top-level end-effect. Both of these methods are described in greater detail in the following Methods and Results section.

Current UAV Analysis

Methods and Results

Scope

The scope for this project is defined to provide reasonable limits for the factors considered in the reliability analysis. All components of within the aircraft are included in the analysis, but the airframe itself is neglected as it is assumed that the aircraft will be flown within an envelope that does not stress or strain the airframe to the point of failure. Furthermore, the chance of airframe failure from flutter is negligible. Elements not immediately related to the aircraft itself are also excluded as they cannot be changed significantly, only minimized; these include environmental factors (e.g., inclement weather and bird collision) and human factors (e.g., pilot-induced crash). Environmental effects can be ignored as a flight cannot begin unless requirements laid out by the UAV research group's Ultra Stick Operations and Maintenance Plan [1] are met; these include 1 statute mile of visibility, clear skies, and temperatures between 10° (including wind chill) and 88° Fahrenheit. Also included in the maintenance plan are requirements for the qualifications of the crew, which consists of a pilot, an observations lead, and a mandatory observer to maintain a constant lookout on the aircraft and its surroundings. These stipulations are enough to assume that the crew is competent and will only fly in acceptable weather conditions.

Failure Modes and Effects Analysis

The first step in this reliability study was performing a Failure Modes and Effects Analysis (FMEA), a tool for widely used qualitatively analyzing the ways in which a system fails. This method uses a bottom-up approach to assess reliability, analyzing failure by starting at the component level. The effects of component failures are then considered for low and high level systems, including the final effect on the entire system. The complete FMEA is shown in Appendix 1. Sections from an example entry are also shown below to explain the details of each column.

The entire system is broken down into its individual components for analysis. Failure modes – ways in which a component malfunctions – and their causes are identified for each component. A failure cause initiates a process which leads to failure modes; it is the underlying root of the malfunction. For every component, there is a failure mode that includes a loss of connections. Wires and connectors (e.g. clips, solder) are not included as individual components, but their failures are taken into account for one of every component's failure modes. An example of the failure modes and causes for the aircraft's IMU is shown in Figure 2 below.

Failure Mode Number	Part	Function	Failure Mode	Failure Cause
8.1	IMU	Measures angular rates and translation accelerations	Circuitry overload	1.) Power surge 2.) Electrical static discharge
8.2	IMU	Measures angular rates and translation accelerations	Loses calibration	Reset to factory default
8.3	IMU	Measures angular rates and translation accelerations	Disconnected from BEC	1.) Vibrations undo connections 2.) Wire failure

Figure 2: Section of the FMEA for an IMU that includes its failure mode number, function, failure modes, and failure causes.

Another aspect of the FMEA is determining the effects of a component failure on the entire system. These effects are considered chronologically when necessary, including the local subsystem effects before reaching a final end result. Based on these end results, the components are assigned a level of severity quantifying how their failure impacts the entire system. Severity categories based on the component's failure effects are listed below.

Severity Categories

1A: Uncontrolled emergency landing; high risk of catastrophic damage
1B: Controlled emergency landing; low risk of catastrophic damage
2: Mission critical failure; loss of flight data

Table 1: Severity categories

Category 1 corresponds to a component or system failure that affects the aircraft's ability to fly manually. It is divided into sections A and B. In a 1A scenario, the aircraft's controls are critically altered and an emergency landing with moderate to high damage is likely. These system failures include loss of radio control or a stuck control surface that leads to an aircraft that is not trimmable. Here an uncontrolled landing is expected with a high potential for significant damage. In a 1B scenario, the aircraft's controls are not critically altered, and a landing with no greater than minimal damage is likely. These system failures include loss of thrust and a control surface stuck where the aircraft will remain trimmable; thus a controlled landing is still expected. It is assumed, however, that no two 1B failures occur simultaneously; in this event, the failures may compound and raise the severity category to a 1A.

If a component or system failure does not affect the aircraft's ability to fly in manual mode, it is considered a category 2. This type of failure is regarded as mission critical because it will result in altered or lost flight data. In this sense, the entire system failure refers only to the impending skewed research data.

A continuation of the IMU example is shown below, listing the failure effects and corresponding severity category.

Failure Mode Number	Failure Effects (Local/Subsystem)	Failure Effects (Next Higher Level)	Failure Effects (End Effect)	Severity Category
8.1	Inaccurate inertial measurements	Data incorrectly reported to flight computer	Inaccurate flight data	2
8.2	Inaccurate inertial measurements	Data incorrectly reported to flight computer	Inaccurate flight data	2
8.3	Inaccurate inertial measurements	Data not reported to computer	No flight data	2

Figure 3: Section of the FMEA for an IMU that includes its failure effects on various system levels. The severity category of 2 indicates an IMU failure is only mission critical and will not affect the manual flight of the UAV.

The FMEA also includes columns for possible failure detection methods and compensating actions. Failure detection methods apply to only current ways of recognizing failure. Compensating features consider future redesign possibilities to increase reliability. These sections are shown below in the continued IMU example. It includes the column for failure causes to show the relationship between individual causes and ways to mitigate them.

Failure Mode Number	Failure Cause	Failure Detection Method	Compensating Features/ Action
8.1	1.) Power surge 2.) Electrical static discharge	Inaccurate flight data, UAV flies unexpectedly if in automatic mode	1.) Current, surge protection 2.) Properly ground circuit
8.2	Reset to factory default	Inaccurate flight data, UAV flies unexpectedly if in automatic mode	Periodically inspect, ensure programming is correct
8.3	1.) Vibrations undo connections 2.) Wire failure	Inaccurate flight data, UAV flies unexpectedly if in automatic mode	1.) Securely mount, add redundant line or connection 2.) Reinforce wires, add redundant line

Figure 4: Section of the FMEA for an IMU that includes its possible failure detection methods and compensating features that correspond to the failure causes.

Control Surface Severity

To determine the severity of control surface failures, simulations were run using the UMN UAV simulation model. Initial control surface positions and other flight conditions were input, and possible trim states (if any) were calculated. These were used to find an envelope for each control surface where the aircraft remains trimmable. The baseline trim conditions were straight and level flight at 23 m/s. The calculated trim states resulted in speed changes along with control surface compensation when necessary. These trim states are listed below for each control surface.

Control Surface	Initial Trim Position	Trim Range
Aileron	0°	-20° < 20°
Elevator	-4.21°	-20° < -3°
Rudder	0°	-1° < 1°

Table 2: Trim values and trim envelopes for control surfaces found from simulation.

For simplicity, it is assumed that only one control surface sticks at a given time. It is also assumed that the servo actuating the control surface seizes. Furthermore, it is also possible that the mechanical linkage connecting the servo to control surface fails, resulting in a fluttering control surface. However, this situation was not analyzed as it was assumed that the most likely failure mode of the servo-linkage system was a servo hard-over.

Under the specified conditions, it is always possible to trim ailerons by using one to cancel the effect of the other. Due to a slightly forward center of gravity, the aircraft cannot be trimmed if the elevator sticks above 3°. The rudder is the most sensitive control surface with the smallest trim range; this range is also conservative because emphasis is placed on being able to properly land the aircraft. Severity categories consider the chances of a conventional landing. To keep the aircraft on a straight path during landing with a rudder stuck outside trim range, the pilot will need to delicately compensate with both aileron and elevator. This is a high risk landing scenario. If any control surface remains stuck within its trim range, it falls into severity category 1B. When any control surface sticks outside of the trim range, the severity is raised to 1A.

Fault Tree Analysis

A Fault Tree Analysis (FTA) is a top-down approach for analyzing reliability that uses simple Boolean logic to determine the failure rate for an entire system. This was performed after the FMEA as it organizes components in terms of failure relationships. It is structured starting with a final end event (e.g. aircraft crashing) in a single top cell, then continuing below with cells representing system failures that must occur to result in the top event. This process is iterated from the system level all the way down to the individual component level. The successively growing rows of cells below the top event takes on the structure of a tree. The FTAs for each severity category are shown in Appendix 2. They were constructed through the use of Logan Fault Tree and Event Tree analysis software [4].

Cells are connected by Boolean AND and OR gates. The figure below shows a two-component fault tree with AND and OR gates.

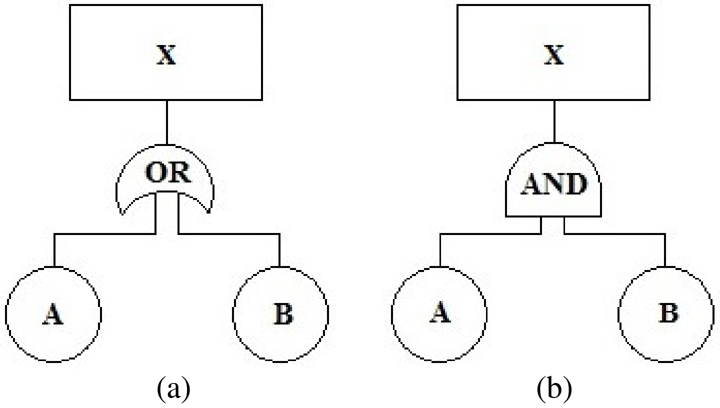

Figure 5: (a) OR gate (b) AND gate

In Figure 5a, the top event, X, occurs if either component A or B fails. Figure 5b shows a redundant system where component A and B must fail for the top event to occur. The probability, p_X, of failure for a system preceded by an OR gate is calculated by

$$p_X = p_A + p_B - (p_A p_B). \tag{1}$$

The$(p_A p_B)$ term arises from the possibility that both A and B fail at the same time. Using the rare-event approximation, this term is ignored. Furthermore, it is assumed that no two failures occur simultaneously. For an AND gate, the probability of system failure is

$$p_X = p_A p_B. \tag{2}$$

This reiterates the redundant system as both A and B must fail for X to occur.

Failure Rates

Initial estimates for probabilities of component failures were determined using the NPRD 2011 handbook [2], which provides a list of component failure rates that – by definition – are slightly different than probabilities of failure, but can be approximately equal under certain conditions. These failure rates are expressed as lower and upper bounds; generally, the upper bound was chosen for each component. From the NASA *Fault Tree Handbook with Aerospace Applications* [5], the component failure probability, p, is determined from the formula

$$p = 1 - e^{-\lambda t}, \tag{3}$$

where λ is the component failure rate and *t* is the relevant time interval. The units of λ are the failure probabilities per unit time. The standard unit from the NPRD handbook is one failure per million hours. The relevant time interval for this is UAV 1 hour, or two complete missions. As shown in the table in Appendix 3, the maximum NPRD failure rate is 173.79 failures per million hours. This means for each component, $\lambda t < 0.1$, where the above formula for p simplifies to

$$p \cong \lambda t. \tag{4}$$

Here $t = 1$, so the fraction of failures divided by 1,000,000 is the resulting probability of failure.

Conversion Factors and Likelihoods

Using the failure rates from the NPRD handbook provides an adequate initial estimate, but a problem still persists that the components listed in this handbook are all considered military grade while the primarily hobby-part components of the UAV are not at this standard; this is especially true for non-electronic components. To account for this discrepancy, failure rates were scaled by different factors. Servo failure rates were multiplied by 50, a factor determined by dividing the failure rate for servos from a UAV servo reliability analysis by Justin Murtha [3], by the failure rate from the NPRD handbook [2]. Failure rates for every component – excluding servos but including connectors – were multiplied by 25; this factor was determined by dividing the life cycle of a hobby potentiometer from a company spec sheet [6] by the failure rate from the NPRD handbook. Wires were not multiplied by any factor. A complete list of scaled failure rates is given in Appendix 3.

Both sets of failure rates cover the combination of failure modes for every component. In other words, these baseline values indicate that a component's internal and external failures have the same probability. This was problematic for the FTAs, because in some cases, different failure modes had different severity categories. For example, the 1A tree includes a branch for the scenario where the motor is separated from its housing, a rare but serious failure mode. The probability of this failure mode is significantly less than a random internal failure.

To circumvent this issue, each failure mode was multiplied by a likelihood probability. The likelihoods for each component added up to 1. Thus, adding up the failure mode rates after multiplying by likelihood factor resulted in the same overall failure rate. Likelihoods were not taken into account for wires and connectors as they had one constant failure rate.

Likelihoods were also used for the control surface failures. As previously mentioned, the trim ranges for each control surface were determined through simulations. The maximum range for these surfaces is -20° to +20°. The likelihood that a control surface is at any particular deflection was modeled by a normal distribution, with 0° as the average. The likelihood factor was determined by finding the probability that the control surface falls inside or outside of the trim range, given this normal distribution.

Hazard Analysis Matrix

Figure 6 below shows a Hazard Analysis Matrix (HAM), which organizes component failure rates by their severity category.

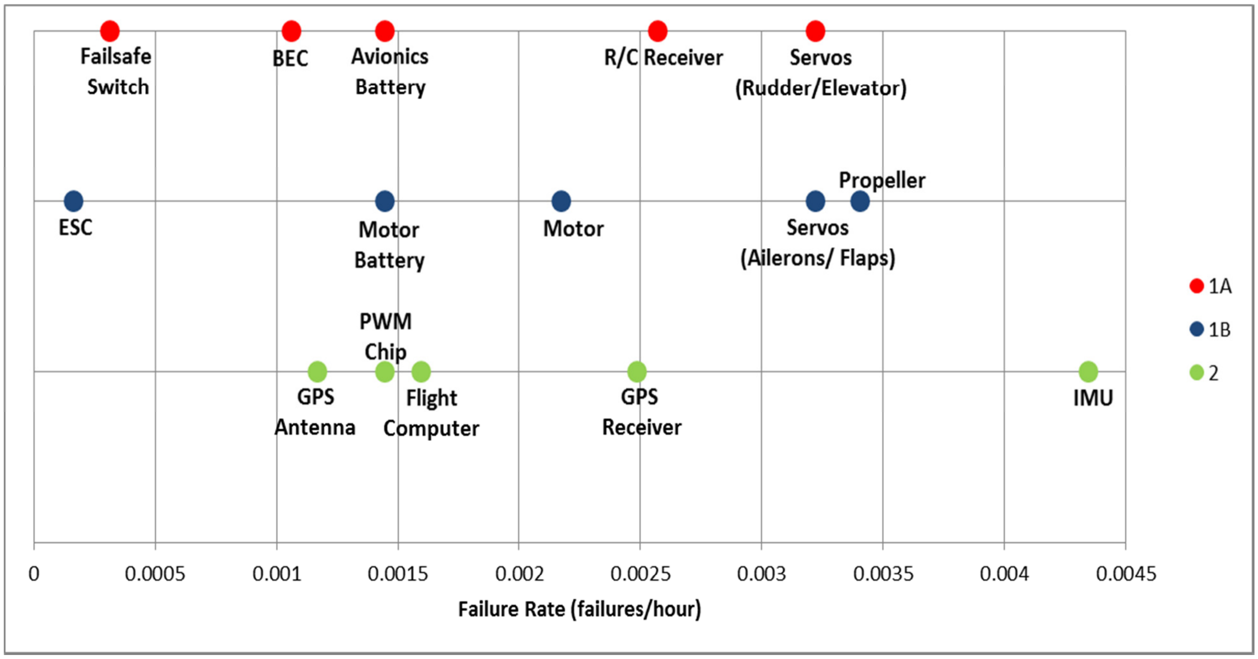

Figure 6: HAM for five components with the highest failure rates for each severity category.

On the horizontal axis is the failure rate per hour, increasing from left to right. The severity categories are divided on the vertical axis. This layout suggests that the most critical components are located in the upper right hand corner of the chart and the least critical components are located at the lower left hand corner. The HAM was used as a guide when redesigning the UAV, providing a priority list for the critical components.

Initial Results

Failure Rates

The table below shows the overall failure rates for each severity category. It includes calculations for both military and hobby-factored failure rates.

Severity Category	Military Failure Rate (failures per 100 hours)	Hobby Failure Rate (failures per 100 hours)
1A	0.074	2.17
1B	0.073	2.14
2	0.105	2.32

Table 3: Results of each severity category FTA for military and hobby failure rates

Weight and Cost

The current mass of the aircraft is 7.41 kg [7], and it can carry approximately 2.5 kg of payload. A cost list for each component is given in Appendix3.

Summary

Using a Failure Modes and Effects Analysis in conjunction with a Fault Tree Analysis provides an efficient method of determining how parts might fail, how severe those failures are, possible avenues of recourse, and the overall reliability of a system – in this case, an Ultra Stick 120 UAV. The FMEA is a useful tool for finding the failure modes for each component and categorizing them by the severity of their effect on the UAV. Components that were determined to have failure modes corresponding to the highest level of severity – 1A – were identified in this analysis to be: the failsafe switch, R/C receiver, avionics batter, Battery Eliminator Circuit (BEC), and the rudder and elevator servos. Each of these components was concluded to be the highest priority in terms of redesign; addressing their potentially catastrophic failure modes is crucial to improving the reliability of the aircraft. Components that fit into the other two severity categories – 1B and 2 – are also noteworthy in regards to increasing UAV reliability, but they hold less sway on the overall redesign as their failure will not cause a total loss of the vehicle.

The FTA provides a more quantitative method of assessing reliability. By providing probabilities of failure for each component at the lower level of the Fault Tree, it is possible to calculate an overall probability for failure of an entire system; in this case, three FTAs were completed for their respective severity categories. The overall probability for a catastrophic failure (1A) was calculated to be 2.17 failures per 100 flight hours. The failure rate for an event that causes a controlled emergency landing (1B) is 2.14 failures per 100 flight hours, and the failure rate pertaining to a loss of mission-critical flight data (2) was determined to be 2.32 failures per 100 flight hours. These numbers will be used to assess the increase in reliability for the UAV in the redesign to determine whether or not mission goals could be met. Furthermore, the Hazard Analysis Matrix (HAM) provides a useful visualization to quickly determine which components would be most problematic and would most likely require consideration for redundancy – or some other compensation – in the redesign. The most egregious offenders as seen in Figure 6 are the rudder and elevator servos as well as the R/C receiver. However, other factors also come into play to determine which components are most likely to cause failure.

Redesign

Relating Results to Redesign

The reliability analysis was performed on the UAV for the main purpose of finding the baseline for the requirement of making the UAV a magnitude more reliable. There was a secondary benefit from the analysis, though: the analysis helped show which components of the current setup are the most unreliable, those which are the most critical to the system, and just the overall structure and flow of the control and autopilot systems of the UAV.

From the FMEA, a list of components and their failure modes for each severity category was found and that led directly into the FTA. Fault trees were made for each of the three severity categories – 1A, 1B, and 2 – but 1A was what the requirement was based off of and so was most useful. The main redesign focused on the 1A components and their respective failure rates because any of their failures had the most catastrophic effect and so they were the most critical to the UAV. Both the components' failure rates and their severity category were combined in the HAM. From the HAM, seen in Figure 6, it was easily recognized that the components closest to the top right corner of the matrix were both the highest severity category and the most likely to fail, and so those were the parts that the redesign should focus on. The components that were nearest the corner were again the components in the 1A fault tree, and so the HAM reinforced the list of components for the redesign.

The last, and most beneficial, analysis was done directly for the redesign. That analysis was the sensitivity analysis of the severity category 1A fault tree. There were two aspects to the sensitivity analysis. The first involved going through the fault tree and increasing the failure rate, and therefore probability, of a single component by a magnitude, calculating the top level failure rate, and comparing the new value to the original. This analysis shows which component's failure rate has the largest impact on the overall value, which is important, but at the same time, there are two reasons why this didn't have much of an effect on the redesign. The entire 1A fault tree was made up of OR gates because there was no redundancy in the original design of the system. Therefore, the failure rate of the top level event was simply the sum of all of the lower base events. This means, by way of addition and multiplication – the two numerical calculations involved in the tree with the sensitivity – which are both commutative, the component with the largest failure rate will produce the largest difference in the top level event, therefore making the analysis very simplistic. The other way that the first method of sensitivity isn't very useful is because the way of increasing, or in the design's case, decreasing, the failure rate of a component is to find a more reliable component. The components used to build the UAV are nearly all hobby parts, without thorough documentation, and therefore don't have documented failure rates. That makes it nearly impossible to prove that a new part for the redesign would have a lower failure rate and so replacing a part to make the system more reliable isn't feasible and not part of the scope.

The second method of sensitivity analysis went through the entire fault tree and made each of the components redundant, one at a time. If there were more than one instance of a part in the tree, each was made redundant. For both the rudder and elevator control surfaces, being of a severity category 1A, it was determined they needed to become redundant, but there were multiple ways in which it could be done. After deliberation, it was decided that simply adding a second servo on a single control surface wouldn't work as needed, because if one of the servos was to hard over, it would cause too much force for the other servo to counter. Even if the other servo was stronger, it couldn't be guarantee that the weak servo would fail first, or even that if the weak did indeed fail first, that the stronger servo, when it over powered the failed servo, it wouldn't cause damage to the control surface in any way. That is why the decision was made that to make a control surface redundant, it would have to be split, with two completely independent surface-servo combinations. This analysis produced the most important basis for the redesign, with the results in Table 4 below.

Component	Loss of UAV Failure Rate (failures per 100 hours)
Redundant BEC	0.97
Redundant Failsafe Switch	1.11
Redundant Avionics Battery	1.52
Redundant R/C Receiver	1.53
Split Rudder Surface	1.67
Split Elevator Surface	1.93
Redundant Motor	2.15

Table 4: Results of the redundant sensitivity analysis for each of the 1A components

As can be seen in the above table is that the BEC, failsafe switch, and avionics battery have the largest impact on the overall Loss of UAV failure rate when they are made redundant. That is to be expected seeing as how both the BEC and the avionics battery supply the power to the entire system while the failsafe is the component which directly connects, and sends signals to the servos and ESC. The sensitivity results pointed the redesign in the direction it needed to go to meet the requirements.

Scope of Redesign

The list of components and systems that could be replaced, modified, or made redundant was rather short, being limited by the 1A severity category. That list was made even shorter by a few factors, including the sensitivity analysis. Making the motor redundant was never an appealing option because with the current airframe and with most R/C airframes, there is only room for one motor. Even if there was viable option of where to put the motor, the amount that the overall failure rate for losing the UAV was only decreased from 2.17 failures per 100 hours to 2.15 failures per 100 hours. That is a decrease of only 0.9% and so the idea of adding a second motor was thrown out.

Also established during the sensitivity analysis was the fact that simply replacing a component with a more reliable component wasn't realistic because there wouldn't be enough proof that the new part was actually more reliable without actual data which none of the 1A components had. That made making components redundant the main method of decreasing the overall failure rate.

Lastly, it became understood that in general, some of the least reliable components were those that had any moving parts and batteries, while on the other end of the spectrum, purely electrical components were rather reliable due to the very low failure rates of the individual resistors, capacitors, and other circuit parts. This impacted the choice of which component should be covered in the design with the servos and batteries taking top priority and the electrical components like the failsafe, BEC, and R/C receiver used in reserve.

Designs

Conceptual Design

The process for actually creating the design was to start with one redundant component and add redundancy in others until the magnitude decrease in the failure rate was achieved. Focusing on the ideas from the scope of the redesign, splitting the rudder and elevator were added to the system and fault tree. Two things need to be noted regarding the splitting of a control surface. The original 120 design had the failsafe switch and the microcontroller acting as the central processor maxed out with regard to the number of inputs and outputs. Therefore, when two control surfaces were added, two new servos were also added. This created an issue for the number of pins on both the failsafe and the microcontroller. The solution to this used the fact that previously, the aileron and flaps both had two servos, one per each side of the wing, for a total of four servos on four channels. This change can be seen in Figure 7, which shows the outputs of the failsafe switch of the original UAV and the redesign. The same concept is applied to the microcontroller. Because both the flaps and ailerons were not on the 1A fault tree, the outputs to the ailerons and flaps were reduced to a single channel for each, sending the same signal to both flaps at once and both ailerons at once. This introduced another issue: servos and the linkages to their control surfaces are not exactly for every control surface. The ratios and moment arms can vary so if the same signal is sent to two different servos, it could result in two different deflections. The fix will be to update the firmware on the servos themselves to account for the discrepancies. Finally, the second item to be noted is that when adding control surfaces, not only is the number of servos increased, but the number of potentiometers is also increased. For splitting both the rudder and the elevator, two more potentiometers are introduced, which in turn possibly require the addition of an A/D converter to handle the increase in potentiometer readings. Similarly to modifying the pinout for the ailerons and flaps, adding potentiometers or the A/D converter doesn't affect 1A and so the reliability due to those being added wasn't considered important to this redesign.

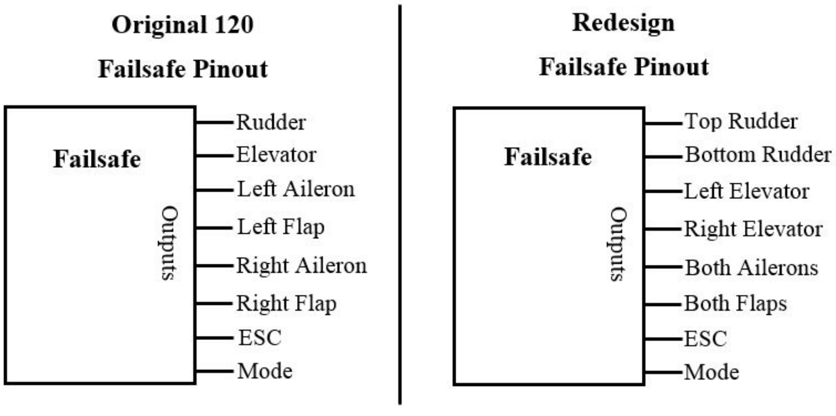

Figure 7: Failsafe output pinout for the original 120 and the redesign showing how the ailerons and flaps were condensed and how the elevator and rudder servos were made redundant. Same concept for the microcontroller for the flight computer as well.

After all problems for the splitting of the control surfaces had been worked out, the top level event failure rate was calculated. It wasn't low enough, so the avionics battery was included in the redesign, and once again, it introduced design issues which needed to be tended to. Having two batteries in the same system be redundant requires that they be in parallel. This creates complications if one of the batteries was to fail. If one of the batteries fails, say with a short circuit, this could draw a large amount of current, which could damage the other, good battery. To resolve this concern, the batteries need to be isolated from each other in a way that will allow the remaining good battery to supply the needed current to the rest of the components but not be hampered by the bad battery. The configuration of this type of setup is shown in Figure 8 which is simple circuit diagram showing the general concept of isolating the batteries. The isolation is achieved by putting diodes large enough to handle the current and voltage in front of both of the batteries on the positive terminal to allow the current to flow out of the battery, but none to be drawn in. The grounds can be spliced together without any ill effect. One more thing considered for the avionics batteries, with each of them required to handle the full load, was that with the addition of the two servos and the potential addition of the A/D converter, the current draw and wattage capability of the batteries could be lacking. To cover the additional current draw and power, the batteries, which currently are 2650 mAh, should be increased to the 3000 or 3300 mAh, while maintaining the three cells to keep the voltage in the correct range. For the batteries, like with the control surfaces and the servos, adding the additional components like the diodes for the batteries, does entail they be added into the fault tree, but because the reliability of individual circuit components is so small compared to the value for the batteries, they are neglected.

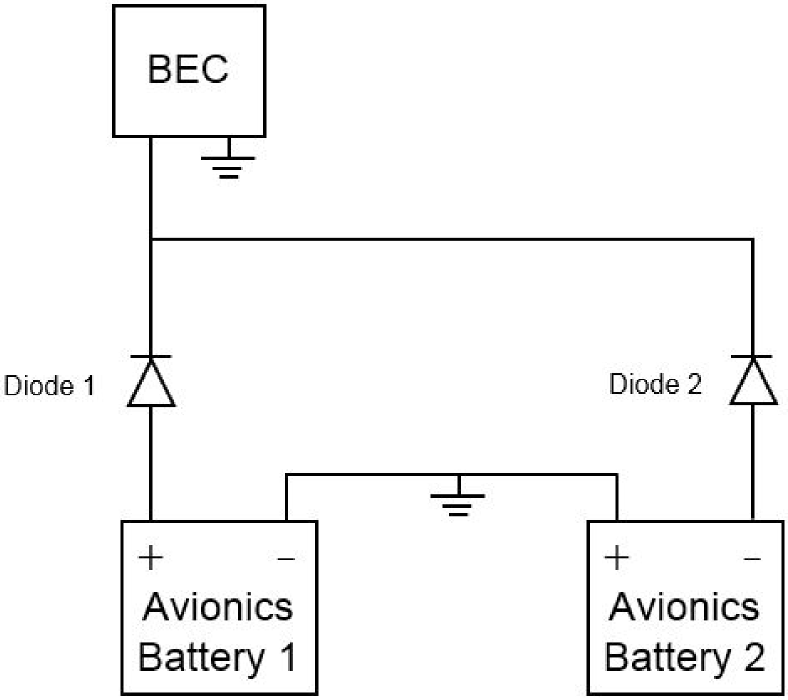

Figure 8: Circuit wiring diagram of how avionics battery is made redundant, highlighted by the isolation diodes which the current to only flow out of the batteries, not back in, to prevent a damage battery from damaging the other.

Once more, after the redundant avionics battery issues had been solved, the top level failure rate was calculated and once more it didn't meet the requirement and so, finally, the failsafe was made redundant. Just like all others, making the failsafe redundant presented new problems with the design. These problems, though, weren't truly solved and make adding a redundant failsafe not feasible. This will be explained in more depth in a later section. Continuing on with the failure rate calculation, with the split rudder and elevator, the redundant avionics battery, and the redundant failsafe, the top level event failure for severity category 1A, Loss of UAV, was calculated to be 0.128 failures per 100 hours. This value meets, and slightly exceeds, the reliability requirement stating that the UAV was to become a magnitude more reliable. This new failure rate is 17 times lower than the 2.17 failures per 100 hours of the original UAV, making the redesign's reliability 17 times greater.

The other requirement for the project – achieving the reliability increase at no more than double the cost – was also accomplished in this design. The total additional cost of this redesign was conservatively found to be only $350.00 which is well under the $4,200 allotted for double the cost of the original UAV. The full breakdown of the cost can be found in Table 5. It includes components which will possibly be needed, like the A/D converter which might be included but requires more intense circuit and code optimization analysis before confirmation. There are also conservative assumptions included in the cost relating to adding diodes and fuses in the avionics battery redundancy circuit. Another update to the table is the cost for the battery pack. The value of the original battery is $12.79, but in the case that a larger capacity battery is required, the price was set to that of the 3300 mAh battery. Lastly, it also takes into account an amount of budget which covers miscellaneous items like wires and connectors, which, again, can't be completely tallied.

Component	Quantity	Individual Cost	Total Cost
Servo	2	$46.99	$93.98
Avionics Battery	1	$21.06	$21.06
A/D Converter	1	$23.28	$23.28
Fuses	2	$5.00	$10.00
Diodes	2	$5.00	$10.00
Failsafe Switch	1	$79.00	$79.00
Potentiometers	2	$1.60	$3.20
Other Expenses	N/A	N/A	$100.00

Total Cost = $340.52

Table 5: Breakdown of the additional cost of the conceptual redesign which includes the failsafe switch.

In terms of the requirements, this design seems to work out well, but like previously mentioned, adding redundancy in the failsafe isn't very feasible. Figure 9 below shows the required circuit for making the failsafe redundant. This diagram shows that to make the systems as redundant as possible, four relay switches need to be added, two per failsafe. All four of these relays then have to be controlled by the flight computer's microprocessor, which as also previously mentioned, is maxed out on the inputs and outputs. Therefore, the addition of the relays alone makes this system not possible without the addition of a larger microprocessor. Even assuming the microcontroller could handle the extra outputs, with multiple relays in line with multiple failsafe switches, there would have to be some method of making sure the failsafe and the currently operating relay are working properly. That is not easily done, and if that wasn't redundant, then the entire system would still be single string and making the failsafe redundant would basically be neglected. Building upon that idea, to maintain complete redundancy, each relay would require its own wire from the failsafe switch and to the servos and ESC, like is shown in Figure 9. This complicates the wiring drastically and makes an already messy setup worse. All of these reasons, but primarily the microcontroller not being able to handle any extra outputs, leads to classifying this design as not practical or feasible, and therefore only conceptual.

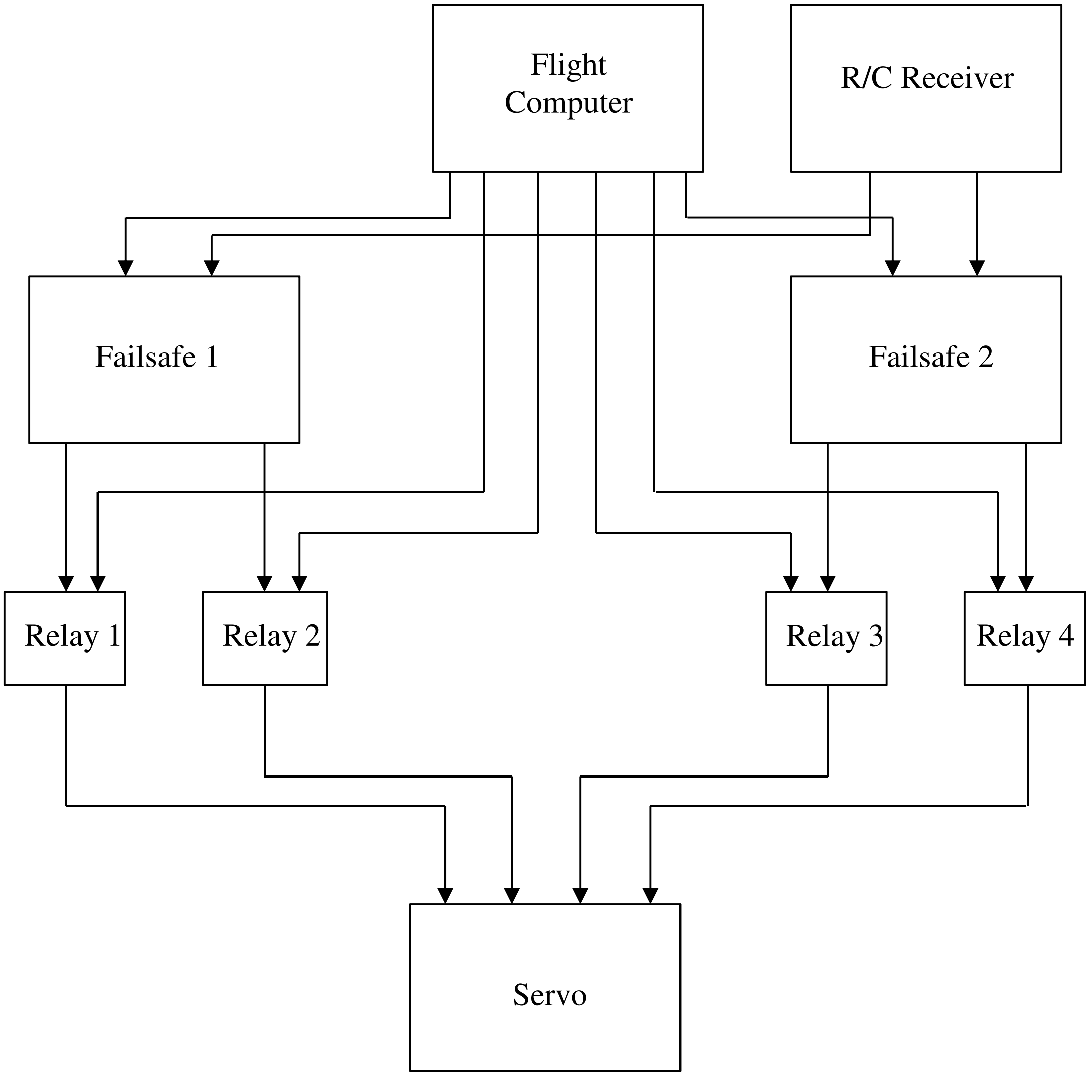

Figure 9: Detailed circuit wiring diagram for adding redundant failsafe with an example of signal to servo. Notice the large amounts of wires required to go to each servo and the BEC

For completeness, the remaining 1A components, the BEC and the R/C receiver were also considered for redundancy, but they too were deemed not feasible. For the BEC, it again would require a massive amount of complex wiring because it powers every component, but more importantly, monitoring the BEC to make sure that if currently running component failed it would switch over to the redundant would be overly complex, and would again require pins on the microcontroller which don't exist. The system would be similar to the failsafe where there would have to be two relays from each BEC, and from there wires to every component. All of these reasons add up to conclusion that making the BEC redundant is not practical. The R/C receiver is also similar, with one main difference. If there were two receivers, and one of them failed, the controller could potentially be switched to the other frequency, but by that point, the UAV would have been lost. If they were the same frequency, and there was a sensor and relays to determine when to switch, once more, the input/output situation with the microcontroller comes into play. No matter the part – failsafe switch, BEC, or R/C receiver – adding redundancy in one of them isn't practical.

Practical Design

As stated in the conceptual design, the failsafe is not a viable option to make redundant; nor are the BEC and R/C receiver. Therefore the only practical option left is to split the rudder and elevator control surfaces and make the avionics battery redundant. That is the chosen design for this project.

To summarize the features of the practical design, nearly all of the features of the conceptual design will be taken into account, up to the point where the failsafe redundancy was added. The rudder and the elevator control surfaces were split, introducing two more servos, two more potentiometers, and possibly an extra A/D converter. The addition of the servos also requires the pinouts of the outputs form the flight computer and the failsafe to change according to Figure 7. Making the avionics battery redundant followed which not only added an extra battery, but it also added in a simple battery isolation circuit to make sure that one bad battery doesn't impede the operation of the other, as seen in Figure 8. The addition of the two additional servos and the A/D converter requires more current, and so to account for this, the batteries are upgraded to the 3000 or 3300 mAh capacity versions. Both batteries have to be able to handle the entire load, so the existing battery also has to be replaced. A block diagram system overview of the redesign can be found in Figure 10. The redundant components are shown by simply adding a second box for that particular part. The individual potentiometers and A/D converters, though, are not shown in detail in Figure 10, but are instead just shown, with the rest of the sensors, feeding into the flight computer.

The reliability of the practical design was found to be equal to 0.762 failures per 100 hours. This result doesn't quite meet the requirement for a full magnitude better than the original 2.17 failures per 100 hours, but yet it does improve by 65%. On the other hand, though, the other requirement – that of cost – was greatly surpassed. The requirement called for improving the reliability at no more than double the cost, and so there was a budget of $4,200. The final cost of the redesign, as seen in the breakdown in Table 6, was only $260.00. Similarly to the cost of the conceptual redesign, the practical design includes conservative values for the addition of the fuses, diodes, and other expenses, while also including the cost of the larger battery and the A/D converter for which further analysis is required to verify the necessity.

Component	Quantity	Individual Cost	Total Cost
Servo	2	$46.99	$93.98
Avionics Battery	1	$21.06	$21.06
A/D Converter	1	$23.28	$23.28
Fuses	2	$5.00	$10.00
Diodes	2	$5.00	$10.00
Potentiometers	2	$1.60	$3.20
Other Expenses	N/A	N/A	$100.00
			Total Cost = $261.52

Table 6: Breakdown of the additional cost of the practical redesign.

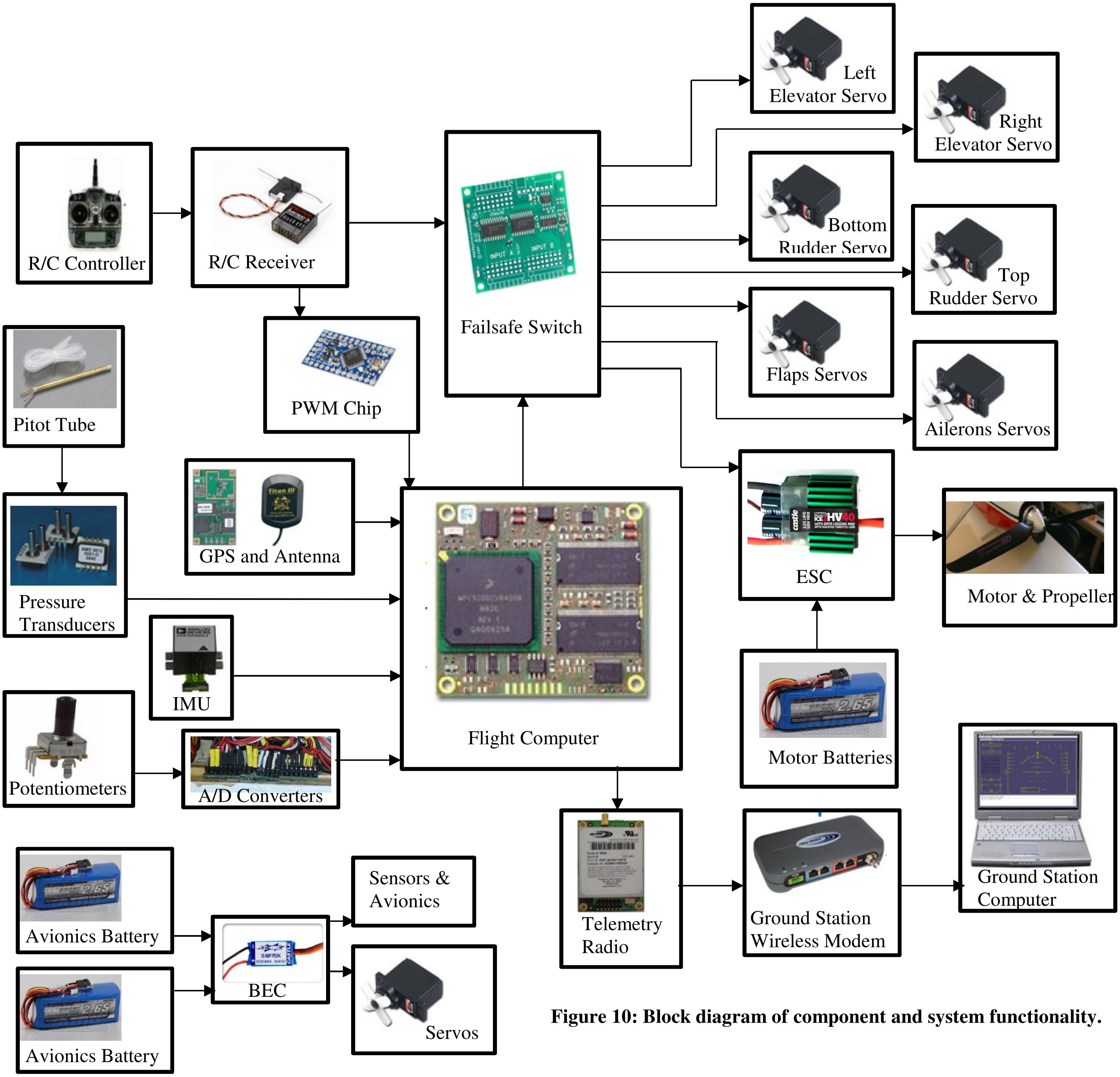

Figure 10: Block diagram of component and system functionality.

One aspect of the added components that has yet to be discussed is that of mass. Each component adds an amount of mass, and like any airplane, the Ultra Stick 120 in its current configuration is only able to carry a certain amount of payload. The 120 could carry a payload of 2,500 grams, in addition to the mass of all of the components already used in the UAV platform. With that physical requirement, the total mass of the added components was required. The total added mass, as calculated in the breakdown in Table Number below, was found to be 514 grams which is well under the limit. Similarly to the cost calculation, there was an approximation for the mass of the diodes and fuses to be used in the avionics battery isolation circuit. For the actual avionics battery, the mass of the larger, more capable battery was used as well. Lastly, an additional amount of mass was added to account for miscellaneous items, like connectors or wire.

Component	**Quantity**	**Individual Mass**	**Total Mass**
Servo	2	60 g	120 g
Avionics Battery	1	278 g	278 g
A/D Converter	1	2 g	2 g
Fuses	2	2 g	4 g
Diodes	2	2 g	4 g
Potentiometers	2	3 g	6 g
Other Mass	N/A	N/A	100 g
			Total Mass = 514 g

Table 7: Breakdown of the additional mass for the practical redesign.

The mass doesn't solely matter with regards to if the UAV will be able to carry the amount, but also matters with respect to the center of gravity. The location of the center of gravity is heavily involved in determining the stability of the aircraft. In the current Ultra Stick 120, the center of gravity is located rather far forward on the chord of the wing. The aerodynamic center for a symmetric airfoil is located at the quarter-chord, and that is where the aerodynamic forces of lift and drag act upon the UAV. With the current layout of the components, the center of gravity is actually located in front of the aerodynamic center and therefore the plane is nose heavy. This was verified with the simulations mentioned earlier. When determining the trim values for the control surfaces, the simulation returned a negative angle of deflection for the elevator at trim, as seen in Table 2 above. This means that the UAV has to produce a nose up restoring moment to achieve trim, which is what is expected when the center of gravity is forward of the aerodynamic center. With the addition of extra mass, the center of gravity can be shifted backward along the chord to allow for a better elevator trim envelope. This will in effect lower the failure rate of the redesign. The issue is that this is difficult to achieve. The further forward the center of gravity is, the larger the static margin and therefore the more stable the aircraft. A compromise has to be made for the best location of the center of gravity, and that is most easily accomplished through simulation. Based off of the redesign, with the split control surfaces, the simulation software, though, isn't capable of obtaining the best location, and so the effect isn't quantifiable.

A last major contribution that the practical redesign could add to the reliability is from the location of the split in the control surfaces. The elevator is simply cut in the middle so that there are two control surfaces, one on the left of the vertical stabilizer, and one on the right. With the rudder, though, there are a few options. The split could occur where the top and bottom rudder surfaces have the exact same area, and therefore the same force, or the split could occur where the moment about the positive x-axis of the UAV is the same, taking into account the area of each surface and the length of the moment arm from the center of force on each surface to the axis. These are only two possible ways to split the rudder, and each has its benefits. The only way to know which one is actually the best, or if there is a middle ground which would be ideal is to run a simulation. Again, though, the simulation isn't capable of this and so once again, the effect on the reliability of the 1A severity category isn't quantifiable.

These two physical design characteristics of the redesign have the ability to increase the reliability of the redesign and move the failure rate closer to the requirement goal of 0.217 failures per 100 hours. In the next section, there are mentioned other design possibilities that too aren't quantifiable but could help improve the overall reliability.

Other Reliability Considerations

As the last few paragraphs of the previous section highlighted, there are options to increase the reliability of the redesign that were not specifically used due to the fact that they are not quantifiable. Connectors which hook into each other or clip together wouldn't have the risk of vibrating apart, but at the same time, there is no way to quantify the reliability gain by adding these parts to the redesign. It is similar to not being able to replace a component with a more reliable counterpart.

This project focused on making the severity category 1A more reliable, but because very little of the budget is needed for the redesign of the 1A system, a portion of the remainder could be put to use improving the 1B and 2 systems. Much of the cost of the original Ultra Stick 120 are in the sensors and flight computer, and so spending money to improve them or make them redundant, like adding a second inertial measurement unit, would improve those fault tree failure rates and in effect improve the reliability of the entire UAV system when looking at the mission.

In the conceptual design, when it came to adding a redundant component like the BEC or the failsafe, it became apparent that the current microcontroller wasn't able to handle any system larger than the current design. That is an issue not only for a reliability redesign, but also for adding more capability like new sensors. If a larger microcontroller was integrated into the system, then not only would the capability of the new system be greatly increased, but so too would the reliability because failure sensors and extra redundancy could be added.

One last contribution that would greatly increase the reliability of the UAV, but which is much beyond the scope of this project is that of prognostics. If a potential failure could be detected before it ever occurred, then there wouldn't be the need for a 1A severity category. This would require a larger microcontroller and a large amount of research to implement. Of all the options, adding prognostics might improve reliability the most, but at the same time would be the most difficult system to design.

There are many different ideas of how to improve the reliability of the 1A system beyond what was specified in the practical design, with the common issue of the ideas being either non-quantifiable or too involved to have been completed for this project. The next semester will include a few things that might make some of these options realistic, specifically, the current simulation software will be upgraded to include options to split the control surfaces and more easily shift the center of gravity location. That will allow for two key aspects of the design which were previously unquantifiable to become quantifiable and the reliability will get closer to the requirement.

Conclusions

The reliability of the Ultra Stick 120 was calculated based off of military failure rates converted with factors to obtain values which were relatively representative of hobby components. For the catastrophic failure 1A, the range was found to 0.074 failures per 100 hours to 2.17 failures per 100 hours, for the military and hobby failure rates, respectively. The possible landing failure 1B had a range from 0.073 failures per 100 hours for the military values to 2.14 failures per 100 for the hobby rates. The mission critical failure 2 has a range of 0.105 failures per 100 hours to 2.32 failures per 100 hours. The failure rates that were found were reasonable, with the result for the 1A severity category being approximately one failure every 100 missions for the UAV. The rates for 1A and 1B had similar rates due to most of the parts being used in both fault trees.

The system redesign focused solely on severity category 1A due to the fact that not losing the UAV is the most important thing. The sensitivity analysis showed what redundant components had the largest effect on the failure rate for 1A and the component that had the greatest impact was found to be the BEC which is due to its multiple locations on the FTA because it powers all of the avionics, sensors, and actuators. A conceptual design was made that included splitting the rudder and elevator, and making the failsafe switch and avionics battery redundant. This design met both requirements with the failure rate being 0.128 failures per 100 hours and being just over a magnitude better. The cost of this redesign was $350.00 meaning it is under budget by over $3,500. Even though this design meets the requirements it is not very feasible primarily due to the limitations of the outputs on the microcontroller. It is much more complicated than simply adding in an extra failsafe. For this reason a more feasible design was made with splitting the elevator and rudder and making the avionics battery redundant. This brings the failure rate down to 0.762 failures per 100 hours which is around 65% better. This design does not meet the requirements but with other unquantifiable possibilities, the failure rate will potentially be closer to a magnitude better than the initial failure rate of 2.17 failures per 100 hours. The feasible design has a budget of $250 which leaves $4000 meaning that the second requirement of increasing reliability at no more than double the $4,200 cost of the original UAV. This is the design the group has chosen and will continue to explore in the spring.

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