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# UAV AIRFRAME X-4 – ROBUST AERIAL PLATFORM

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## ABSTRACT

The objective of this design project is to provide a successfully built and tested robust unmanned aerial vehicle (UAV) for the purposes of departmental research projects. This airframe is to serve as a test mule for projects related to imaging science, remote aerial imagery, sensors and measurement. This airframe will meet standards of payload and structural integrity and will build on the past successes of the family of projects. As a result of minimal deviations from the basic design concepts, this paper will chronicle our innovate ideas in areas of structural materials, mounting mechanisms, space optimization, weight reduction and overall construction process.

## INTRODUCTION

Unmanned Aerial Vehicle (UAV) defines an aircraft which operates without a human pilot. UAVs are used in situations where the risk of sending a human piloted aircraft is dangerous or a where using a manned aircraft is impractical. Today, modern UAVs have developed to be controlled with both autopilots and human controllers in ground stations. The primary uses for UAVs are military aerial reconnaissance, combat operations, scientific research, logistics & transportation, remote sensing and environmental surveillance. Thus, UAVs represent an area of rapid development in both military and civilian applications; their unique capability of flying dangerous, long, or precision missions gives them a unique advantage over conventional aircraft.

## NOMENCLATURE

**ailerons -** movable control surfaces hinged at the trailing edge of the wing used to generate a rolling motion of the aircraft by varying the lift produced on the wing.
**CAD -** computer aided design; use of computer technology to aid in the design and production of a product.
**camber -** the symmetry between the top and bottom surfaces of an airfoil.
**center of gravity, CG –** the mass center of the aircraft or the theoretical point at which the entire aircraft weight is assumed to be concentrated.
**chord, c -** the distance from the leading edge to the trailing edge of an airfoil
**dihedral-** the upward angle that the wing makes with respect to a horizontal plane
**elevator -** movable control surfaces attached to the horizontal stabilizer at the rear of an aircraft which provides stability and orientation by controlling the pitch or up/down motion of the aircraft.

**fuselage -** long hollow main body section of an aircraft that holds passengers and payload.
**leading edge -** the front edge of a wing that first contacts the air.
**NACA airfoils -** National Advisory Committee for Aeronautics; airfoils developed by the committee are described using a series of digits following the word 'NACA'. The parameters in the numerical code can be entered into equations to generate the cross section of the airfoil.
**ribs -** forming elements of the structure of a wing that produce the airfoil shape.
**R.C. -** radio control; the use of radio signals to remotely control a device.
**rudder -** movable control surface attached to the vertical stabilizer of the aircraft to provide stability by controlling yaw or side to side motion of the aircraft.
**spars –** structural members of the wing that run span wise with respect to the fuselage.
**trailing edge -** the rear edge of the wing, where the airflow separated by the leading edge rejoins after passing over the top and bottom of the wing.
**sweep** - an angle introduced to the wing as it progress from wing root to it tip to give it a tapered structure.
**XFLR5 –** an interactive analysis tool for airfoils, wings and planes operating at low Reynolds numbers, principally used for model aircraft design.

## BACKGROUND

The open architecture, open source unmanned aerial imaging platform is a five year research project working towards the goal of delivering a successfully built unmanned aerial imaging platform. The UAV family of projects through the years has produced three successive airframe iterations. Of these, P10232 UAV Airframe C was the most recent successfully designed and built.

## PREVIOUS RESULTS

UAV Airframe C was aerodynamically and structurally well designed for stable flight as evidenced from their flight test reports. However, during the first test flight, Airframe C sustained a nose dive crash due to severe weather resulting in extensive but repairable damage to its front modular section.

An investigation revealed that Airframe C had various shortcomings that combined to result in a less optimal design. Airframe C had a heavily cambered NACA 9412 airfoil for its wing design; this high lifting capacity of the plane along with the wind gusts was the major contributing factor to the flight crash. Additional testing proved that the airframe batteries were insufficient to meet the goal of a thirty minute flight time. However in spite of their recovery from the test flight crash, Airframe C's major drawback lied in their inability to meet flight time requirements and multiple repeated test flights to prove the durability of the airframe. A detailed incident report is available on the P10232 edge website.

In light of this information, our design strives to improve on the shortcomings of the previous design and construction to successfully meet the specified goals. The most important concern will be designing an airframe towards overall robustness and durability.

## CUSTOMER REQUIREMENTS

In order to design in accordance to our customer's needs, the priorities and goals that our design should accomplish are outlined below:

- The airframe must be designed to serve as a medium to perform testing, experimentation and research in the field of remote aerial imagery.
- The airframe must possess the ability to withstand multiple flight exercises with minimal maintenance.
- The airframe must be capable of integrating easily with an imaging system payload.
- The airframe must possess trainer style aircraft characteristics and be capable of flight from an adequate RC airfield under reasonable weather conditions.
- The key flight requirements are a 30 minute flight time with a 15 pound payload.
- Design and construction is limited by a 50 pound overall weight celling and a $3000 total financial budget.

## AIRFRAME DESIGN

The airframe design and construction is divided into three main subdivisions of the fuselage, wing, and tail configurations. The detailed design of each is outlined below followed by the construction methods.

***Aerodynamics***

The aerodynamic design process for the airframe was formulated by analyzing the design used by Airframe C, which was based on a NACA 9412 airfoil on a rectangular wing with a 10 ft. overall wingspan. While this design does provide the lift required to meet specifications, the heavily cambered NACA 9412 airfoil produces excess lift with instability in the pitching axis. This was one of the major contributing factors that resulted in the initial crash. To counteract this problem a group of less cambered NACA airfoils were aerodynamically analyzed in XFLR5 program. The concern that a reduced camber would produce less lift was corrected by increasing the wingspan. Additionally, the concerns of roll stability of the plane were addressed by introducing a wing sweep angle and constructing a high wing. The choice of sweep over dihedral was made due to ease of construction. Thus, after extensive runs in XFLR5 the final wing design was decided upon.

- A NACA 5412 airfoil with 12 ft. wingspan
- The wing has a 22 in. root cord and 10 in. tip cord.
- With an aspect ratio of 8.84 and a taper ratio of 2.20
- It produces 55 lbs. of lift at an angle of attack of 2 ° at 40mph.
- Induced angle of attack of 4 deg.

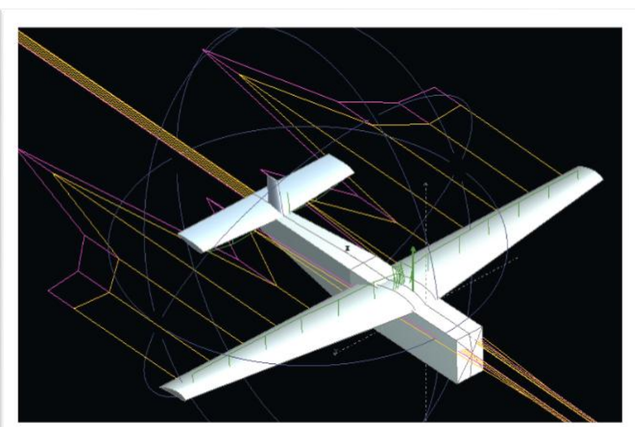

*Figure1: Isometric view of X-4 in XFLR5 at an angle of attack of 2 deg.*

***Wing Design***

To ensure strong wing geometry, several options were considered for the wing core constructions. The options included a balsawood build up with fiberglass, a foam core with balsa sheeting and fiberglass, or a combination of the two with the front half a foam wing and a balsa build-up for the rear half, both sheeted and fiber glassed. Additionally the wing would be reinforced with spar located at the quarter chord and a secondary spar to prevent twist. After consideration the final design method was chosen so as to provide the optimal balance of weight, strength, and manufacturability.

- Foam core wing with basswood ribs.
- Fiberglass main spar nested in tubes located at the quarter chord spanning the entire wing.
- Fiberglass secondary spar nested in tubes located close to the trailing edge of the wing.
- Externally sheeted with balsawood layered with two sheets of fiberglass.
- A Kevlar leading edge to sustain impacts.
- Carbon fiber strips placed on the underside along the wing span to provide additionally stiffness.

***Fuselage Design***

The basis for the fuselage design depended on the airframe being capable of supporting and accommodating a payload. The optimal internal space for electronic systems and payload bay location were determined by calculating the center of gravity of the airframe and locating it along the quarter chord. The fuselage is a consistent cross-sectional area up to the rear of the payload bay where it tapers down to the tail for weight reduction. Thus the agreed upon design for the fuselage consists of:

- A chamfered rectangular basswood core of formers with balsawood stringers.
- Electronics systems located in the front of the airframe with the payload bay located under the wing to ensure proper balancing about the center of gravity
- Bombay doors to protect the camera system payload during taxi, take-off and landing.
- A tricycle landing gear to help with ground control and landing.

***Tail Design***

The tail components, both vertical and horizontal were designed with a modular approach for ease of assembly and repair. Surface areas for both the vertical and horizontal tail were derived from the aerodynamic analysis. Control surface areas were calculated using parameters for a heavy lift plane. A simple formula relating design parameters of the wing to the tail components provided sufficient and reliable information based on wing span, mean aerodynamic cord and a coefficient of relation.

- The vertical tail was incorporated into a tail box designed to clench the horizontal tail at its given -4° angle of attack.
- A gentle sweep was added to the horizontal tail for added stability.
- The elevator was designed to replace the rear section of the horizontal tail.
- The vertical tail was a balsa buildup with no airfoil providing ease in repair and reconstruction.
- The vertical tail was attached to the tail box through 3¼ in. balsa spars to locate the weak point avoiding critical failure of the surface area and control surface in order to preserve the critical components of the tail during impact.
- The rudder was designed as an extra surface area protruding out the trailing edge of the vertical tail.

*Figure 2: CAD model of X-4 airframe design*

## CONSTRUCTION PROCESS

### *Wing Construction & Assembly*

For transportation and handling purposes the wing is divided into three sections each spanning 4ft. This includes a center interfacing section with the wing-box and wing tips on either side. The wing tips were further divided into two 24 in. sections to accommodate with construction.

The construction process is outlined and described below:

1. For each wing end section, the corresponding airfoil geometry was laser cut into a template.
2. The templates were used as guides in foam bowing sculpting the airfoil shape from foam blocks
3. The nesting tubes that were to hold the primary and secondary spars were glued in their locations into the foam core with epoxy.
4. Each wing section was reinforced with basswood formers and balsawood sheeting.
5. The leading edge was covered with Kevlar strips and the carbon fiber strips were placed on the underside of the wing at their appropriate location
6. The appropriate colored dye was added to the epoxy - resin mixture and was used to layer two sheets of fiberglass onto the external body of the wing sections.
7. This arrangement was placed into a vacuum bag system to obtain a smooth and uniform surface finish during the curing process for the epoxy.

Thus the wing sections were carefully manufactured so as to have maximum durability and strength. Finally each section was assembled together with the connecting spars and grenade pins were placed vertically at the intersection of wing sections to ensure that the entire wing span was held in place.

### *Fuselage Construction*

The fuselage was formed by constructing sections of formers and ribs as sub-assemblies. These sub-assemblies were then assembled together using stringers. After this smaller sheets of balsa were combined to create larger sheets that cover the formers and stringers.

1. The internal core was constructed with basswood formers that determine the cross-sectional area and basswood ribs for added structural support.
2. These were held together by balsawood stringers then covered with balsa sheeting.
3. This was sheeted with two layers of fiberglass on the structure using the dyed epoxy-resin mixture described above.
4. The access hatches, Bombay doors, and hardware mounts were constructed and secured using various mechanisms.
5. The electronics, controls, mechanical connections and hardware were secured at

their appropriate locations in the fuselage.

6. Finally, the motor, propeller, batteries, and speed controller were placed into their locations and tested for functionality.

### *Tail Construction & Assembly*

The horizontal tail is a balsa buildup of ribs, rear plate, and fiberglass spar. The fiberglass spar runs along its quarter chord.

1. The ribs were balsa sheeted with a square dowel leading edge that was sanded to blend the airfoil shape around the nose of the tail.
2. Balsa sheeting was applied to the ribs for covering and two layers of dyed fiberglass were laid across the entire surface area.
3. The elevator was also a split section balsa build up with a 1/16 in. carbon fiber rod and spar joining the two halves.
4. Pin hinges were drilled into the elevator and trailing edge of the horizontal for full elevator motion.
5. The vertical tail was a balsa stick buildup with balsa sheeting and a tie dye fiberglass layup.
6. The rudder was constructed similar to the vertical tail and attached with pin hinges drilled into the back of the vertical tail.

### *Propulsion & Electronics*

In order to determine the propulsion requirements, our assessment was based on first calculating the motor wattage required which then helped determine the specifications for speed controllers and batteries. It is recommended that 75W per pound be available to provide the plane with trainer like performance. For a maximum airframe weight of 55 lbs. it was determined that a 4125W was required by the following equation

$$\max weight \times power\ to\ weight\ ratio$$

Given the calculated motor power, the batteries and speed controllers were sized by the following relations,

$$capacity \times C\ rating > maximum\ motor\ amp$$

$$\frac{weight}{lift\ to\ drag\ ratio} \times estimated\ speed = power$$

$$\frac{power}{E_p E_m E_b E_e} = power\ consumption$$

where the efficiencies for the propeller, motor, battery, speed controller were assumed to be 0.8, 0.7, 0.8 and 0.9 respectively.

$$power\ consumption\ \times flight\ time = energy$$

$$\frac{energy}{voltage} = capacity\ (ampHours)$$

Thus the motor used was a Turnigy TR80-85B 170Kv brushless out runner providing 6500W of power, which was paired with a Phoenix Ice HV160 speed controller drawing 120Amps of current with a 50V max voltage. The lithium polymer batteries used to support this were four 6-cell ThunderPower RC TP3900-6SPL25 with a capacity of 3900mAh. To control the airframe’s control surfaces high torque S3050 Futaba digital servos with metal gears were employed.

## AIRFRAME TESTS

### *Structural Tests*

The critical components of the airframe were tested to ensure they meet the design criteria. These tests occurred during the building process to ensure that necessary corrections could be made earlier in the process.

- The integrity of the fuselage structure was tested to ensure it could support weight requirements. Three-point bending tests were carried out after the three primary stages of construction. The first test occurred after the formers and balsa stringers were assembled and the structure supported 22 lbs. The structure was tested again with the balsawood sheeting to 70 lbs. and finally tested after fiber glass sheeting which proved it could support 150 lbs.

- The wing underwent two tests. The first test was conducted on the center wing section where the spars terminate and the maximum stress is seen. The section was supported at each end in a 3-point bending test with weight added to the center. The section supported at least 70 lbs. proving that the wings could cope with a fully loaded airframe weight of 50 lbs. The wings were next subjected to a wing-tip test while attached to the fuselage to simulate 1.5g. The wing showed several inches of deflection before the fuselage could be lifted up from the ground. This caused concern and replacing the fiberglass spars with carbon fiber spars was decided upon.

### *Flight Tests*

The flight test plan for Airframe X-4 was a three phase process in order to meet the flight requirements.

1. The first phase requires performing skip tests where the airframe would be airborne for a few seconds and land in the same direction. The goal of the skip tests is to determine if the airframe can produce enough lift for take-off. These tests will start off with an empty plane and after each successful test an additional 3 lbs. of weight will be added to the fuselage until it is capable of lifting 15 lbs. When the airframe has been validated to a take-off weight we proceed to the next step.
2. The second phase is an actual flight for a short duration. This will validate the aerodynamic models and controls of the aircraft. During this flight the pilot will have the ability to trim the aircraft and get acquainted with the airframe. Any necessary adjustments can be addressed from the results of this test flight
3. The third phase of flight-testing is to prove the endurance of the plane. This will be similar to the previous phase, but the focus will be to attain longer flight times. These flights will start off at 5min. flights, and increase until 30min. flights are achieved. The rate at which the flight time increases will be determined from the amount of testing time available as well as the maximum expected life of the batteries.

The final flight validation will require gauging the airframe robustness with an overall flight time of 100 hrs. This metric will require two hundred 30min. flights and will be beyond the timeframe of this project. The airframe will be tested at every opportunity possible but it is not expected to be achieved, and will be validated by future senior design teams.

## TEST RESULTS

In the first phase of testing, the airframe flight resulted in a crash. The plane was taxiing for its initial take-off when a change in the wind direction produced a large lift on the right wing. This resulted in the plane yawing leftwards, which the pilot tried unsuccessfully to compensate with aileron and rudder control. The left wing tip struck the ground first and cart wheeled the nose of the fuselage into the ground. This severe impact crumbled the front of the fuselage and broke apart the structure until the first former behind the payload pay. The fiberglass spar in the left wing tip was sheared, along with the vertical tail. Apart from this, there was no damage to the wing, horizontal tail, and landing gears. Additionally all the electronics were reusable however the fuselage was damaged beyond repair.

## DISCUSSIONS

Given the results of the first test flight, it was determined that the control surfaces of the airplane need to be re-designed while rebuilding the fuselage. The control surfaces of the airframe were redesigned with the following guidelines described in Raymers. [1]

### *Control Surfaces Re-Design*

#### *Vertical Tail*

The surface area for a vertical tail is found using the following equation

$$S_{VT} = \frac{C_{VT} b_w S_w}{L_{VT}}$$

Where the variables are defined as follows:

$S_{VT}$ = Surface area of the vertical tail

$C_{VT}$ = A constant found in Table 6.4 in Raymers on page 122

$b_w$ = wing span

$S_w$ = wing area

$L_{VT}$ = distance between quarter chords

Thus based on the above equation and assuming three different plane styles it is possible to calculate different areas, the three plane styles are sailplane ($C_{VT}$ = .02), general aviation single engine ($C_{VT}$ = .04), and military cargo/bomber ($C_{VT}$ = .08). Once the area is calculated the rudder area can be calculated and should be approximately 40% of the area of the vertical tail. Below are the calculations for all three sets of plane types.

*Sailplane:*

$$S_{VT} = \frac{.02(144in)(2346in^2)}{55in} = 122.845in^2$$
$$Rudder\ area = .4(122.845in^2) = 49.138in^2$$

*General Aviation – Single Engine:*

$$S_{VT} = \frac{.04(144in)(2346in^2)}{55in} = 245.69in^2$$
$$Rudder\ area = .4(245.69in^2) = 98.276in^2$$

*Military Cargo/Bomber:*

$$S_{VT} = \frac{.08(144in)(2346in^2)}{55in} = 491.38in^2$$
$$Rudder\ area = .4(491.38in^2) = 196.552in^2$$

With these calculations, it is possible to determine which model best suits the needs of the X-4. The initial sizing of the vertical area assumed a sailplane model with an area of ~98 $in^2$. This model was deemed undersized after review of the video of the initial skip test showed that it was not able to handle a slight crosswind on takeoff. This means the assumption of a sail plane for sizing is not a good one and one of the other models should be employed. Comparing the areas of the military cargo to the general aviation it is determined that the military cargo will be too large and also is not an accurate representation of the style plane that is the X4. Thus the final design of the area of the vertical tail and rudder will be determined using the general aviation- single engine assumption.

***Wing Ailerons***

Ailerons are sized based on the following two equations that are compared to a chart found in Raymer, page 124:

$$\frac{Total\ Aileron\ Span}{Wing\ Span}$$

located on y-axis, and

$$\frac{Aileron\ Chord}{Wing\ Chord}$$

located on x-axis.

Based on the design of the wing, the total aileron span is the limiting factor and should be set and then the aileron chord should be determined based on that. Based on a span of 42.25 in. on one wing section and an aileron chord of 3.5 in. we would get the following ratios:

y-axis value -

$$\frac{2(42.25in)}{144in} = .5868$$

x-axis value -

$$\frac{3.5in}{16in} = .21875$$

With these ratios and comparing to the graph in Raymers it is determined that the ailerons for the X-4 are slightly oversized, and the lack of roll control on the skip test was a result of insufficient deflection of the ailerons. This problem was correct by extending the control rod attached to the servo from 1in. to 2.5in.

***Horizontal Tail***

The surface area for a horizontal tail is found using the following equation

$$S_{HT} = \frac{C_{HT}\bar{C}S_w}{L_{HT}}$$

Where the variables are defined as the following:

$S_{HT}$= surface area of horizontal tail

$C_{HT}$ = constant found in Table 6.4 in Raymers on page 122

Cbar = mean chord length

$S_w$ = wing Area

$L_{HT}$ = Distance from Quarter Chord to Quarter Chord

Based on the equation above and the assumptions that this plane is a General Aviation-Single Engine airframe, we get the following surface area:

$$S_{HT} = \frac{.7(16in)(2346in^2)}{55in} = 477.731\ in^2$$

The elevator should be approximately 40% of this area so the calculation looks as follows

$$Elevator\ area = .4(477.731in^2) = 191.092\ in^2$$

These are theoretical data; the horizontal tail is actually sized up in XFLR5 when the aerodynamics of the model is completed, this allows for trial and error in the sizing to have more control over the pitching moment that is created. Based on the XFLR5 model, the surface area for the horizontal is calculated to be:

$$S_{HT} = Chord * Span = 8in\ x\ 48in = 384\ in^2$$

## CONCLUSIONS

The key successes of the project were the light weight design of the fuselage relative to its strength and the structural integrity of the wing. The fuselage design could support the required payload weight times a factor of ten in a three point bending test. It was able to do this while weighing less than 6 lbs. Additionally, the undamaged wings, with the exception of the single spar that sheared after the crash, proved its durability. This proves that the conceptual structural design was the proper choice for the wing.

The shortcomings of the airframe were evident through the results of the first test flight described above. The reasons of concern were the structural integrity of the fuselage and the size of the vertical tail. The fuselage though capable of withstanding large static loads failed to survive a frontal impact. One reason identified for this failure is the method used for layering the fiberglass. The fuselage was layered with fiberglass in sections, thus on impact the fuselage was destroyed along those section lines. The airframe's vertical tail was undersized because an incorrect model was chosen in the sizing method. This has been corrected for in the re-design calculations shown above.

In conclusion, though the project suffered a setback with the initial test crash, we were able to recognize our mistakes and appreciate our progress. It is still possible to correct our mistakes with a rebuild of the fuselage and a re-design of the vertical tail and control surface. This would bring the airframe to completion by incorporating the lessons learned into the redesign and construction.

## REFERENCES

{1} Raymer, D., 2006, "Aircraft Design: A Conceptual Approach," AIAA, 4th ed.

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