Pack-A-Plane: Designing a Compact RC Aircraft for Rapid Deployment

Matthew Jeng
matthewjeng18@gmail.com

David Tian
davidtjfk@gmail.com

Shravan Kumaran
shrav.k97@gmail.com

Amol Lotia
amollotia98@gmail.com

Sahaj Patel
sahajpatel2407@gmail.com

New Jersey Governor's School for Engineering and Technology

Abstract

The objective of this project was to design a compact, remote-controlled surveillance aircraft for rapid deployment. A lightweight aircraft designed for assembly before each flight was hypothesized to be optimal. To test this hypothesis, the final model would be required to fit within a shoebox with dimensions 12.5" L x 7.375" W x 4.5" H and to be assembled within two minutes. Two additional goals were established to increase the model's effectiveness: maximization of overall plane size and constraining plane weight to sixteen ounces or less. The approach of the project involved developing conceptual designs, which were then put through two optimization phases. The final design was then 3D modeled, constructed, and tested. Results confirmed the hypothesis, as a plane with detachable parts allowed for a 42.53 second assembly time and fit inside the designated shoebox. All objectives were met or exceeded, as the plane sustained flight at an altitude of 60 feet ± 10 feet. The results indicated a successful prototype of a rapidly deployable drone. Future work will involve use of stronger and more reliable materials, more precise construction, and potentially some design optimization.

1. Introduction

In today's world, technological progress is being made every day. These developments allow for the enhancements in the lives of individuals as well as increase the efficiency of government programs. Some of these improvements have directly impacted the aerospace industry. The influx of new technologies has led to improvements in commercial aircrafts, the space industry, and in Unmanned Aerial Vehicles (UAVs).

The implementation of automated drone technology has been a huge advancement in the aeronautical world. These UAVs are extremely beneficial in areas such as military scouting and disaster relief, providing vital intelligence. In fact, the Red Cross has recently drafted a document highlighting the advantages of using drones in these high-risk situations where an immediate response is necessary.[1]

Another illustrative example of the utility of drone technology is the usage of complex UAVs in United States Army to obtain information about Al-Qaeda and other terrorist organizations.[2] Remotely controlled and equipped with cameras, these drones are the perfect reconnaissance tools. The information gathered from them is often instrumental in neutralizing threats and saving lives.

As useful as drones sound, they have limitations. For example, the majority of these vehicles are very large and cannot be carried and used by ground troops. Soldiers on the ground may be in need of a scouting drone, but may not have access to such massive military drones. This project may provide a suitable alternative. The objective was to develop a remote controlled (RC) plane that could be quickly assembled from parts a small box and rapidly deployed. Such a design could mitigate some of the problems current drones experience while aiding ground troops.

2. Background

2.1 Forces in Flight

The movement of any airplane is the result of four forces: weight, lift, drag, and thrust, as displayed in Figure 1. Weight describes the force of gravity upon the aircraft due to its mass, acting from its center of gravity. This force always pulls the aircraft toward the ground.

Lift acts perpendicularly to an aircraft's motion, pointing upward when the plane is travelling level. This force is caused by differences in air pressure above and below the wings.[2] Lift can be calculated using Equation 1.[3] *CL* is the coefficient of lift, ρ refers to fluid density, v refers to the velocity of the plane, and A refers to the total area of the wings.

Equation 1: $$L = CL * \frac{\rho * v^2}{2} * A$$

If an aircraft is flying at a constant height with constant speed, its lift and weight are equal and opposite forces[3]; they cancel one another, leading to no changes in elevation.

Drag is a force acting in an antiparallel direction to an airplane's direction of motion. It is caused by friction with air and by changes in air pressure. Drag can be calculated using Equation 2, which is the same as Equation 1 above with the exception of *CD*, the coefficient of drag, replacing *CL*.[4] When the plane is angled upward, the horizontal component of the lift acts as a drag force known as induced drag.

Equation 2: $$Drag = CD * \frac{\rho * v^2}{2} * A$$

The final force is thrust, which is mainly responsible for an aircraft's forward motion. Thrust is created by the plane's propeller or engine and always acts in the direction of the plane's motion. If the plane is not flying level, thrust can change the elevation of the plane by moving it forward at an angle to the horizontal, called the angle of climb.

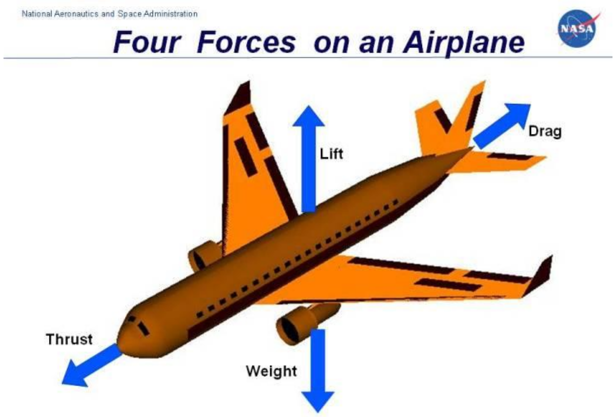

Figure 1: Four Forces on an Airplane.[4]

2.2 Parts of a Standard Airplane

RC airplanes, while simpler in design, usually contain the same components as any other planes. Figure 2 illustrates the different pieces that make up an average RC airplane. The fuselage is the main body of the plane, responsible for holding the other pieces together and to carry the payload, such as cargo or passengers. The wings, depending on the design, are connected directly to the fuselage and are responsible for controlling lift and drag on the plane. Furthermore, they house other components that impact the plane's movement, such as the ailerons and flaps. At the back end of the plane is the tail, which is composed of the horizontal and vertical stabilizers. The horizontal stabilizer provides stability in flight and contains the elevator. By balancing the forces above and below the tail, it stabilizes the back end of the plane. The vertical stabilizer is perpendicular to the horizontal stabilizer, and acting similarly to its horizontal counterpart, it prevents the plane from rotating to the left or right.

Finally, the propeller or engine produces the thrust force that enables a plane to move forward. In most RC airplanes, a propeller is able to sufficiently provide enough thrust to allow the other components to generate lift. Yet, in larger RC airplanes or in actual airplanes, jet engines and turbines are used to propel the heavier planes.

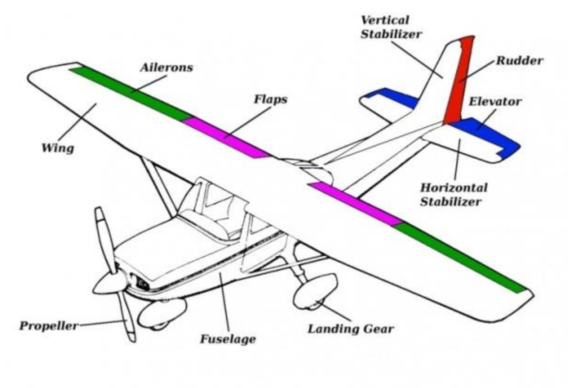

Figure 2: Parts of an RC Airplane.[5]

2.3 Rotation Axes

For a plane to fly with stability, the torques acting about its rotation axes must be balanced. Additionally, for the pilot to have control over the plane, it is essential to regulate the different rotations using control surfaces.

All rotations of an airplane occur about its center of gravity, usually located near the connection of the wings to the fuselage. Each rotation depends on the torques exerted on the plane's parts, which can be determined using two components: moment arm—the perpendicular distance from the center—and force. The moment arm may also be referred to as the lever arm. Since torque is the product of a force and the moment arm, a longer moment arm with a lower force can balance a shorter moment arm with a larger force.[6] This principle is often applied in designing the tail and fuselage, as the tail, having smaller forces acting upon it, must be farther from the center of gravity than the heavy motor in the front.

Airplane rotations occur about three orthogonal axes: the roll axis, the pitch axis, and the yaw axis, as displayed in Figure 3. The roll axis is parallel to the plane's movement direction and perpendicular to the wings. Roll can be seen when one wing moves down as the other moves up, putting the plane in a spin about the roll axis. The pitch axis is perpendicular to the aircraft's movement and is parallel to the wings. Pitch is seen as the tail rotates up or down, thus tilting the plane about the pitch axis. The final rotation axis is the yaw axis, which is perpendicular to both the wings and direction of movement. Yaw can be seen if looking at the plane from the top or bottom, where it would appear to be spinning about the yaw axis. It is a rotation about the vertical axis and serves as a turning method in the air.

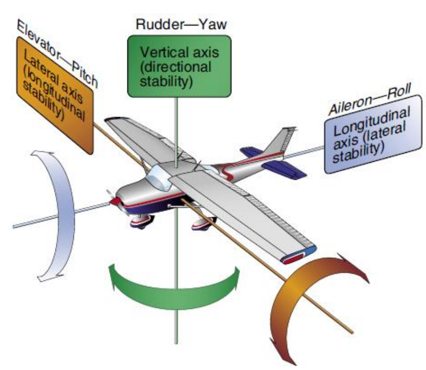

Figure 3: Airplane Rotation Axes.[7]

2.4 Control Surfaces

Control surfaces, as illustrated in Figure 4, are hinged sections on the wing and tail of the plane that can be used to alter the plane's motion. The wings are home to the ailerons and flaps, both of which can be tilted about their hinges to change the plane's movement. The ailerons, located on the outer parts of the wings, are tilted in opposite directions when needed, allowing the plane to roll. The opposite directions of movement of the ailerons produce more lift on one wing and less on the other, forcing one side of the plane to rotate up while the other rotates down.

Next, the flaps are structured similarly to the ailerons, but are located on the inside part of the wing, nearer to the fuselage, or body, of the plane. Unlike the ailerons, both flaps tilt in the same direction, usually downward. By tilting to an angle that is not parallel to the plane's motion, flaps increase the cross-sectional area of the plane as it heads into the air. This increased area creates additional drag on the plane, allowing it to fly at slower speeds. Another benefit of flaps is the additional lift they provide. By angling downward, the flaps direct more of the airflow under the wing than above. This increased air pressure under the wing provides more lift by pushing the wings up. Therefore, flaps are essential for use in large aircraft, where they help the plane stabilize at lower velocities and reduce the takeoff and landing distances.

The tail also contains two control surfaces: the elevator and rudder. The elevator is a hinged section on the horizontal stabilizer that controls a plane's pitch. By tilting similarly to the ailerons and flaps, the elevator can force more air to flow either over or under the horizontal stabilizer, pushing the tail down or up, respectively. The plane then rotates about the pitch axis as a result of the differing air pressure above and underneath the horizontal stabilizer. The rudder is a hinged section at the back of the vertical stabilizer, and it is responsible for the plane's yaw. The rudder is mounted perpendicularly to the horizontal stabilizer. By tilting left or right, the rudder redirects airflow over the vertical stabilizer, which in turn causes the tail to move left or right. This tail movement forces the plane to rotate about the yaw axis; essentially, the rudder allows a plane to turn without tilting in any other direction.

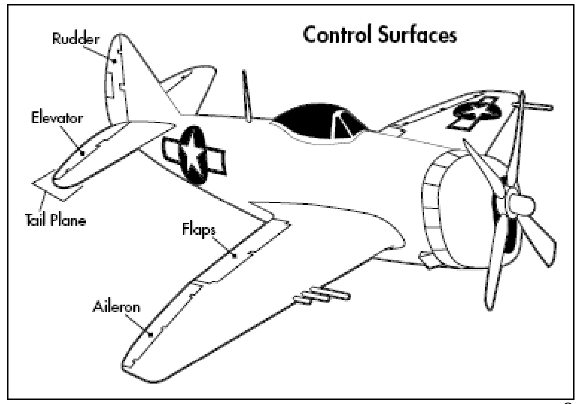

Figure 4: Control Surfaces on an Airplane.[8]

2.5 Airfoils and Reynolds Number

In order to generate lift, a wing needs to have a shape that creates a difference in air pressure above and beneath it. This cross-sectional shape of the wing is called the airfoil. Hundreds of different airfoil designs exist, ranging from simple rectangular shapes to complex curved shapes. Each design has its individual benefits and drawbacks. Figure 5 shows one example of an airfoil with the airflow around it represented by vector lines. Airfoils are evaluated in different conditions, and their official pros and cons are determined through experimental testing, both physically and with software.

Moreover, airfoils for planes are chosen based on the Reynolds number that the plane will be flying under. A Reynolds number is a dimensionless value representing the conditions that the plane will be flying through. Specifically, a higher Reynolds number indicates a tougher flying environment. Mathematically it is the "ratio of inertial (resistant to change or motion) forces to viscous (heavy and gluey) forces."[3] Figure 6 shows the formula for computing the Reynolds number. For RC airplanes, Reynolds numbers tend to be much smaller than those experienced by commercial and military jets. Airfoils perform better or worse depending on the Reynolds number they are designed to operate in. Also, lower Reynolds numbers tend to be more forgiving to airplanes in the air, meaning that slight construction errors or design weaknesses will not be as impactful as in a high Reynolds environment.

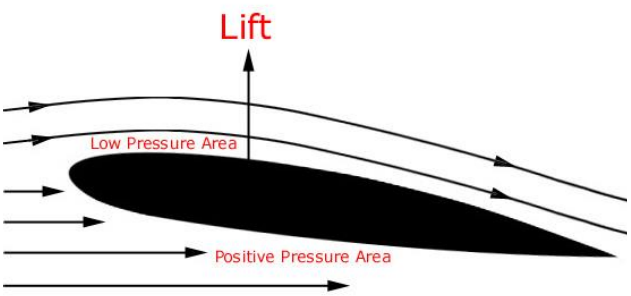

Figure 5: Example Airfoil with Airflow Diagram.[9]

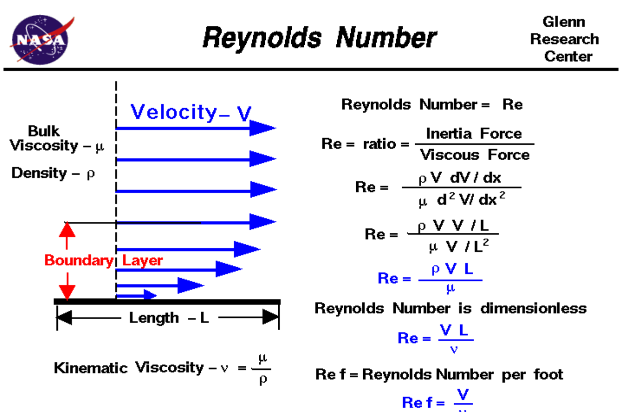

Figure 6: Reynolds Number Formula.[4]

2.6 Wing Design

Since the wings are primarily responsible for lift forces on an airplane, many details are incorporated into their design. Important components include the wing loading, the aspect ratio, maximizing lift, and angle of attack.

Wing loading is a crucial characteristic of any wing, as it is connected to the minimum speed the plane will need to maintain in order to stay in flight. Lower wing loadings cause the wing to generate a large amount of lift from a certain throttle value while not gaining much flight speed. The opposite is true for higher wing loadings, indicating that the higher the wing loading, the more suitable an aircraft is for high-velocity flight. For glider style RC planes that focus on stable flight rather than speed and control, an appropriate wing loading is approximately 10 oz./ft^2. Wing loading is calculated using Equation 3, where W is weight of the plane and A is surface area of the wing.

Equation 3: $Wing\ Loading = \frac{W}{A}$

The aspect ratio is a value that relates the dimensions of the wing, indicating what kind of flight they are ideal for. Equation 4 represents the formula for calculating the aspect ratio of a wing set, where b is the total wingspan and A is the surface area of the wing. An aspect ratio of six or greater is ideal for stable, glider-style flights, whereas lesser values are better for more maneuverable, acrobatic planes.

Equation 4: $AR = \frac{b^2}{A}$

In order to maximize lift, it is important to maximize the ratio of the coefficient of lift to the coefficient of drag, both of which can be calculated with Equations 1 and 2, respectively.

The angle of attack refers to the angle at which the wings meet the air that is flowing over them. The air will be flowing in an antiparallel direction to the plane's movement, so angling the wings from the sides allows more of the air to go below the wing, thus providing more lift. However, the angle of attack cannot be excessively high or else the plane will stall in the air, meaning it will stop moving. Figure 7 shows the coefficient of lift vs the angle of attack α. The peak of the graph shows the optimal value, known as the critical angle of attack.

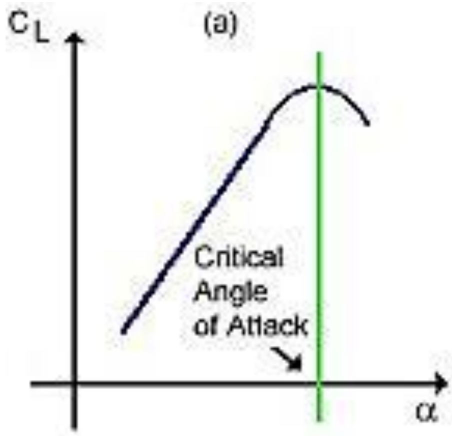

Figure 7: Coefficient of Lift vs Angle of Attack.[10]

2.7 Power System and Electronics

The primary step in determining which motor to use for a plane is calculating the power-weight ratio, which is shown in Equation 5, where P is power and W is weight of the plane. A power-weight ratio of 70-90 watts/lb is ideal for an RC glider-style plane.

Equation 5: $PW\ Ratio = \frac{P}{W}$

The basic electronics system for RC planes uses simple components controlled with a transmitter on the ground. The transmitter sends signals to the receiver, which communicates with the electronic speed controller (ESC). The ESC, powered by connection to the battery, outputs commands to the propeller motor and controls the speed at which it spins. The receiver also sends commands directly to the servo motors to operate the control surfaces. The rotation of the servos causes the control surfaces to tilt in the desired direction.

3. Plane Prototyping

3.1 Requirements/Constraints

In addition to building a remote controlled (RC) plane that could fly, the project had two additional conditions: the plane, when disassembled, had to be able to fit in a box with dimensions 12.5” by 7.5” by 4.5”; and beginning in its boxed state, it had to be fully assembled in less than two minutes. Although not an official constraint, the group also challenged itself to maximize the dimensions of the RC plane and to keep its weight less than 16 oz.

3.2 Construction Preparations

Structural design began with an overall plan and transitioned into detailed development of each part. The initial design was a plane with a single-piece fuselage with horizontal wings, a horizontal stabilizer attached directly to the back of the fuselage, and a vertical stabilizer attached directly to and above the horizontal stabilizer. The wings in the original design were single-layered and contained both flaps and ailerons. The tail housed both an elevator and rudder, meaning that each control surface was included in the original design.

As the design progressed, the team decided on a few major changes in order to optimize the overall design. The rudder and flaps were deemed nonessential to the final design and were removed. The tail would no longer attach to the main fuselage. Instead, a telescoping carbon fiber tube protruding from the main fuselage would connect to the tail piece. This connection method would maximize size by increasing the length of the plane and minimize weight by substituting carbon fiber tubes for solid foam. The wings were given a dihedral—angled connection to the fuselage—of about 7°, which made the plane more stable and increased the effectiveness of the ailerons.

Due to this dihedral connection, the ailerons were able to control the turns of the plane, rendering the rudder unnecessary. For space efficiency, the plane would no longer have takeoff or landing gear. Rather, it would takeoff via a throwing launch and would land with a low impact crash. The final designs are detailed below:

3.2.1 Fuselage

The fuselage cross-section, as displayed in Figure 8, consists of a semicircle with a diameter of about 1.97” sitting on top of a rectangle with a height of about 2.01” and a width the same length as the half circle diameter. Additionally, there is a 0.5” diameter circle-shaped hole on the top half of the cross section to house the carbon fiber tube that attaches to the tail of the plane, and a rectangular hole in the bottom half. The majority of the bottom of the fuselage is empty in order to house all the electronic components of the plane (*See section 3.4*). The entire cross section is extruded 10.5” forward.

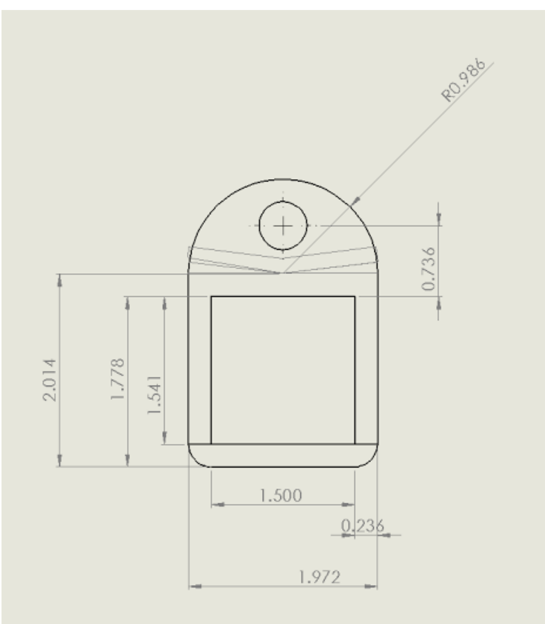

Figure 8: Dimensioned Cross-Section of the Fuselage.

3.2.2 Wings

The wings are designed as KFM-2 airfoil wings, meaning that the front half is 12mm thick whereas the back half is only 6mm thick. The KFM-2 airfoil design appears as a step halfway through the wing, as seen in Figure 9. Each half of the wing has dimensions 7” by 21”, which gives an aspect ratio of 6, an ideal value for a drone plane requiring stability. The total estimated weight of the plane, 16 oz., divided by the total wing area of 2.04 ft^2, would result in a wing loading of 7.84 oz./ft^2. As a wing loading of 8 to 10 oz./ft^2 was the target, the proposed wing dimensions were satisfactory. Overall, using these calculations, wing design was optimized to provide stable flight.

Figure 9: KFM-2 Airfoil in SolidWorks.

To ensure the fitting of the wings in the box, each wing is split into two sections. Each section has dimensions 7” by 10.5.” Tape hinges connect the two sections, allowing the entire wing to fold in half during disassembly. Scotch tape was chosen as an effective hinging material due to its flexibility and connection strength; for an RC airplane, it is strong enough to resist detachment in the air and provides a simple and quick construction mechanism.

Carbon fiber tubes and rods of different diameters are inserted in the wings for greater rigidity. Two of these rods extend out one end of the wing as a way to attach the wings to the fuselage, as shown in the left side of Figure 10. Magnets are included for further attachment security. Three magnets are embedded at the edge of each wing and in the fuselage, leading to a secure connection between the two. Finally, the ailerons, with dimensions 20” by 0.75”, are attached by tape hinges and controlled by servos that are located inside the fuselage.

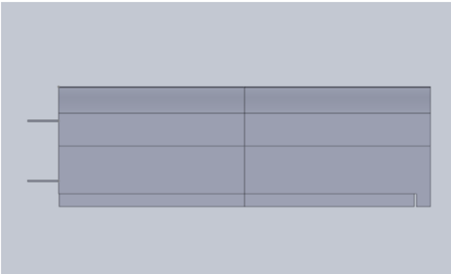

Figure 10: Wing in SolidWorks.

3.2.3 Horizontal Stabilizer

The horizontal stabilizer, a rectangle with dimension 15” by 4”, is shown in Figure 11. This size follows the rule of thumb stating that the horizontal stabilizer surface area should be approximately equal to 20% of the area of the wings. The elevator is cut out of the back end of the tail with dimensions 11” by 1.25”, and similarly to the ailerons, is attached by tape hinges and controlled by servos. The stabilizer is attached to the rest of the plane by the telescoping carbon fiber tube that extends out of the fuselage.

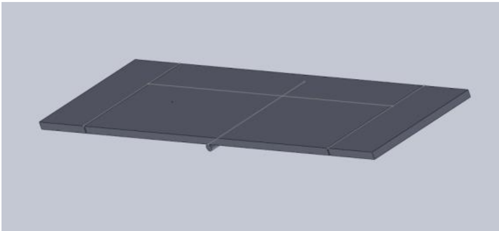

Figure 11: Horizontal Stabilizer in SolidWorks.

3.2.4 Vertical Stabilizer

The vertical stabilizer has a dorsal fin design, as depicted in Figure 12. With an area of approximately 30 in^2, the dorsal fin design satisfies the guideline of the vertical stabilizer’s area approximately equaling 10% the area of the wings. It lacks a rudder because it was determined that the plane could compensate for lack of yaw by using a combination of pitch and roll from the elevator and ailerons, respectively. In addition, a triangle is cut out of the bottom corner of the vertical stabilizer to allow for full motion of the elevator. Otherwise, the elevator would have to have been cut into two pieces, which was more complex than necessary.

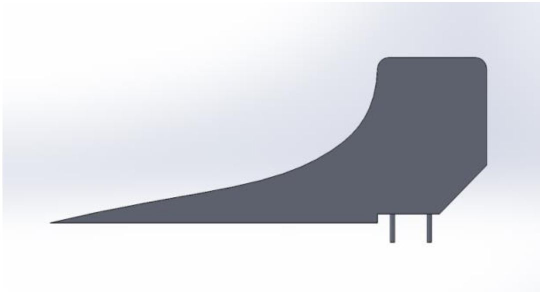

Figure 12: Vertical Stabilizer in SolidWorks.

After being designed and dimensioned, the entire plane was modeled in the CAD software SolidWorks to spot any design flaws and to ease the process of construction. The final assembly model is depicted in Figure 13.

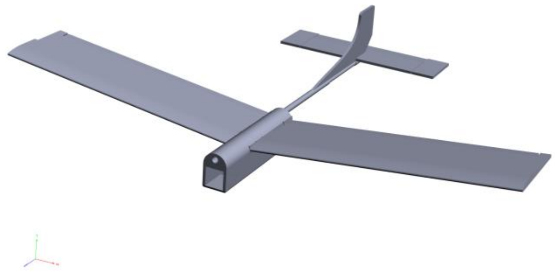

Figure 13: SolidWorks Model of Final Design.

3.3 Construction

After the aircraft was successfully designed and modeled with 3D software, it was time to move on to the most crucial phase, construction. Before beginning, the materials were ordered and organized. The list of components included the Cheetah A2208-17 brushless outrunner motor, Cheetah 2Cell 1300mAh battery, APC 10 x 4.5 Slow Flyer Propeller, 6mm Depron Foam, 2" pink insulation foam, carbon fiber rods and tubes, epoxy glue, magnets, Mobius ActionCam, Velcro, and Scotch Tape. After the materials were prepared, the research team was split into smaller groups to expedite the building process.

The wings and tail pieces were constructed first because they included multiple hinging and folding pieces and were therefore the most complex. The wings had to be cut into two separate parts, 21” by 7”. Each wing would then be separated vertically into two 10.5” hinged halves. Initially, four separate foam pieces were cut and designed to be combined. However, it soon became clear that this would not be effective because the edges of foam would not be flush together. Therefore, each wing was cut separately before being cut in half and tape hinged as shown in Figure 14. This turned out to be more effective and the new wings were very stable when secured together with a carbon fiber tube. In accordance with the KFM-2 airfoil wing design, the leading edges of the wings were layered with an additional layer of foam to make the thickness of the wings 12mm in the front half and 6mm in the back half.

Because ailerons were chosen as the sole mechanism to turn the plane, an approximate 7° dihedral, or 7° deviation from the horizontal, was incorporated into the construction. The dihedral, which adds stability to the plane, was constructed by beveling the edge of each wing at the point of attachment to the fuselage. Next, carbon fiber rods and matching tubes were glued into the wings and fuselage, respectively. Magnets were glued to the wings and to the fuselage to strengthen the wing-fuselage connection. This process was lengthy because determining the optimal position for the magnets and rods was difficult.

Finally, the construction of the wing was completed when the ailerons were attached by a double-sided tape hinge which allows for 45° movement both up and down.

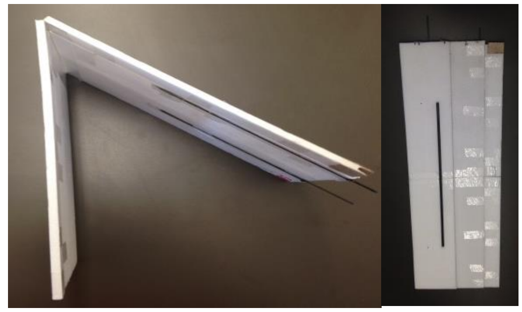

Figure 14: *Left:* Wing in Semi-Folded Position. *Right:* Straightened Wing with Rod Inserted.

While the wings were being constructed, the horizontal and vertical stabilizer pieces for the tail were also being assembled. With guidance from advisors, it was determined that the horizontal stabilizer area had to be 15-20% of the wing area in order to optimize flight performance and maximize stability. Thusly, this area was calculated to be approximately 60 in^2 so the stabilizer dimensions would be 15” by 4”. Once the actual horizontal stabilizer was made, as displayed in Figure 15, the elevator was attached using the same double sided tape hinge used for the ailerons.

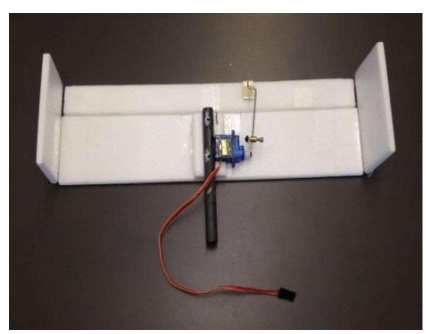

Figure 15: Horizontal Stabilizer in Semi-Folded Position.

Additionally, according to accepted guidelines, the area of the vertical stabilizer must be about half that of the horizontal stabilizer, equal to 30 in^2. In order to accommodate this size without making the piece too wide or tall, a curved dorsal fin, shown in Figure 16, was chosen to be attached to the fuselage. This shape, although easy to model in SolidWorks, was difficult to construct from foam because Exacto knives could not cut such radical curves. It was soon discovered that a hot wire cutter coupled with sandpaper could significantly facilitate this process.

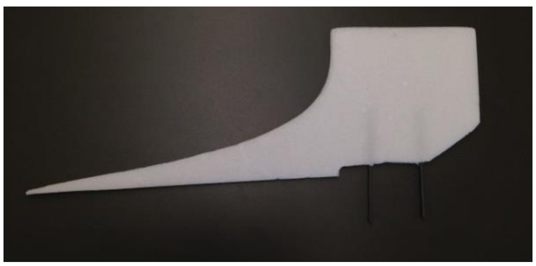

Figure 16: Vertical Stabilizer.

Once the vertical piece was done, the remaining tail pieces were sculpted rather easily. In order to accommodate the telescoping tube design for the fuselage, the carbon fiber piece attached to the horizontal stabilizer had to be drilled through so pins could secure the tubes together. The pins in the vertical stabilizer lined up to holes in the horizontal stabilizer, and the completed tail assembly is shown in Figure 17.

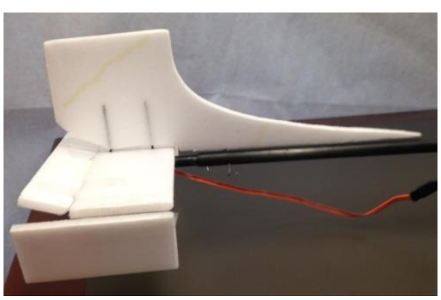

Figure 17: Assembled Tail.

The final apparatus left to construct was the fuselage, which was to be separated into a foam section and a carbon fiber tube section. This design made it easy to telescope the tubes as shown in Figure 18 and fit them within the parameters of the shoebox. In order to easily connect the two halves, a hole was cut into the top of the pink insulation foam where the carbon tubes would connect. The next steps were to cut the necessary carbon fiber tubes, drill holes into them, and make the pins required for securing them.

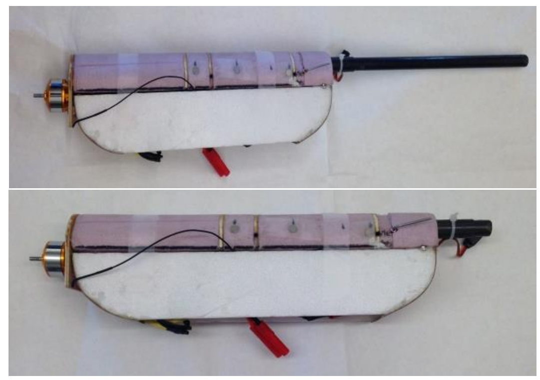

Figure 18: *Top:* Fuselage with Extended Tubes. *Bottom:* Fuselage with Collapsed Telescoping Tubes.

During construction, it was realized that the slots to connect the wings to the fuselage could not be directly in the foam as this would compromise the stability of the wings and risk damage to the foam body. Therefore, wooden formers—wooden plates with holes for necessary parts—were designed in the shape of the fuselage and inserted at the points where the wings would attach. The wooden formers contained slots for the wing connection rods; this way the formers would absorb the stress generated by the wings rather than allow the foam body to be damaged. Inserting the formers required the fuselage to be cut into multiple pieces, but this was evaluated as an acceptable compromise. The magnets were then aligned and attached to both the wings and fuselage. The magnet connections and wooden formers are displayed in Figure 19.

Figure 19: Wing Connection to Fuselage.

In order to contain the battery and other electrical parts, a hatch, which is displayed in Figure 20, was created below the pink insulation foam. This hatch was made out of two pieces of Depron foam and was connected by two thin pieces of durable plywood. Although simple in design, the hatch is extremely useful because its easy detachability allows for direct access to the battery. Additionally, the hatch was designed to come off during the crash landing of the plane in order to absorb the force of impact and protect the inner mechanisms.

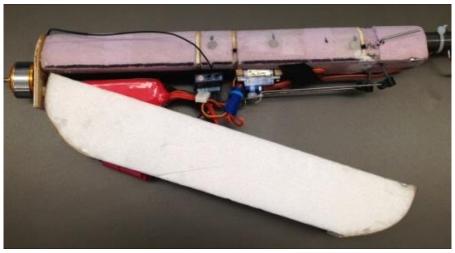

Figure 20: Hatch Partially Detached from Fuselage.

3.4 Electronic Assembly

After construction, the motor-servo setup was integrated. The motor was attached to a piece of plywood, which was glued onto the front of the fuselage with an epoxy. The wires were strung through a gap in the foam into the fuselage where it attached to the electronic speed controller, or ESC. The battery and servos were also connected in order to provide power and control plane motion respectively. The entire setup, as can be seen in Figure 21, was, through the ESC, connected to a receiver which was programmed to relay commands from a remote controller on the ground.

After determining the general electronic setup, the team had to decide on the placement of each of the aforementioned items. The battery, weighing about 5 ounces, was one of the heaviest parts in the plane and was key in determining the center of gravity of the plane. The design had the center of gravity at 1.25” behind the front edge of the wing, and since the plane had a long tail moment arm, the battery was attached with Velcro at the front of the fuselage. The rest of the parts of the setup were also attached in calculated locations in the fuselage to adjust the center of gravity.

The placement of the servos was planned with disassembly in mind: they were controlling the ailerons and elevators, but they also had to be connected to the electronic setup, which was located inside the fuselage. The single servo controlling the two ailerons was embedded into the foam inside the fuselage with the attached pushrods sticking out of it. The servo setup was designed so that when the wings were attached, the rods would slide into the ailerons. The other servo was embedded into the underside of the horizontal stabilizer and it moved the elevator using a pushrod and control horn. This servo had a long, detachable wire stemming from it that could be quickly plugged into the main system once the plane was assembled.

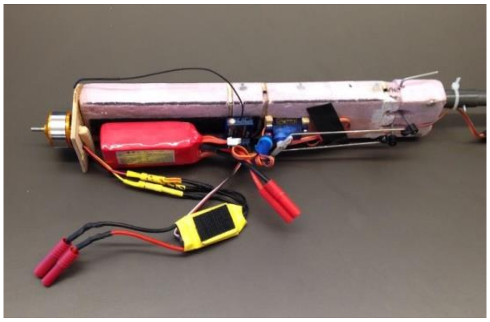

Figure 21: Electrical Assembly Below Fuselage.

4. Results and Discussion

4.1 Summary

Ultimately, all objectives were met and exceeded. The parts of the RC plane fit comfortably within the 12.5” by 7.5” by 4.7” box, as shown in Figure 22, and, when assembled, allowed the plane to achieve stable flight with great maneuverability. The fully assembled plane is displayed in Figure 23. The original goal of a two-minute assembly was well surpassed, with the majority of assembly times being under 50 seconds. The prototype performed well within the desired parameters for rapid assembly and deployment in addition to fulfilling the basic requirements of stable flight and maneuverability. The stability of the plane in flight confirmed that the correct wing dimensions were chosen during the design phase. Also, going beyond the original scope of the project, the Mobius ActionCam video recorder, which is shown in Figure 24, was attached to the top of the fuselage. The camera was used to demonstrate how this plane design could function as a reconnaissance drone model.

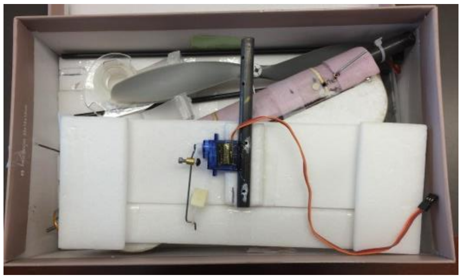

Figure 22: Disassembled Plane Fits Inside Shoe Box.

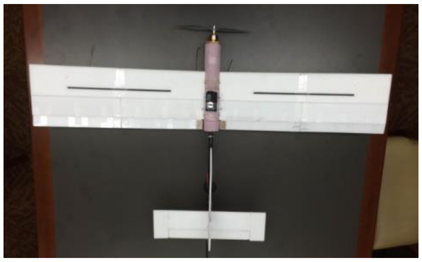

Figure 23: Fully Assembled Plane.

Figure 24: Mobius ActionCam was Attached During Test Flight.

4.2 Flight

In the test flight, the plane was rapidly deployed using a simple throw launch—initial momentum provided by throwing plane over a short distance. The plane flew at an average elevation of 60±10 feet and dealt effectively with wind conditions. Expert pilot and special advisor Mr. Jim Vigani was able to perform a variety of maneuvers and quickly achieve stable flight, demonstrating the responsiveness and effective construction of the plane. Stopping the motors and allowing the plane to glide along a controlled path led to a gentle landing with no damage to any components, despite the fact that the plane lacked landing gear. The total flight time amounted to 3 minutes and 5 seconds over a series of three short test flights.

The plane mainly performed as desired, as the pins along the body prevented rotation of the fuselage and the carbon tubes prevented buckling of the wings. Also, the servos, with their respective push rods and control horns, were able to precisely control the ailerons on the wings and elevator on the horizontal stabilizer, providing maximum maneuverability. The carbon fiber rods and Scotch tape attached to the dorsal fin were able to effectively secure the vertical stabilizer. Overall, the plane maintained its structural integrity through takeoff, flight, and landing.

Yet, there were some parts that did malfunction. Some of the malfunctions that did occur were results of weak attachment of the hatch, battery, and magnets. However, these malfunctions were rather minor and easily resolvable. They did not affect the flight or landing significantly, and the plane was able to effectively function even after they occurred.

The hatch was attached to the fuselage using a balsa wood locking mechanism and magnets, designed to be easily detachable to facilitate access to the electronics. However, this design also caused the hatch to become separated from the plane during throw launch in the second test flight. Taping the hatch in addition to these connections during assembly of the plane resolved this issue.

The battery was attached to the fuselage using Velcro, allowing the position of the battery along the fuselage to be changed, and with it, the center of gravity. The Velcro itself was attached to the fuselage using an adhesive that came with the Velcro used to construct the plane. This adhesive was not strong enough, and the Velcro and battery separated partially from the fuselage. This issue was resolved simply by using an epoxy to secure the Velcro to the fuselage as opposed to only the adhesive.

The magnets were attached to the fuselage using an epoxy. As construction time had become more limited, a faster drying but also weaker epoxy was used to secure the magnets. As a result, one of the magnets embedded in the fuselage along the wing connections separated during disassembly after flight. Using a stronger epoxy to secure the magnet resolved this issue.

The propeller was attached to the shaft of the motor using a propeller adapter. The propeller adapter used matched the size of the motor shaft but did not perfectly match the radius of the wide hole in the prop. Therefore the propeller was slipping on the propeller adapter during flight, which could eventually cause damage to the propeller through friction and mismatched forces. By purchasing and using a propeller adapter that fit the radius of the propeller more exactly this issue could be resolved.

4.3 Assembly

The first assembly of the plane elapsed three minutes, as the members of the assembly team were inexperienced with the process of assembly and the tasks that needed to be performed, often in a specific order. However, after about five practice runs, the plane could consistently be assembled from the box in less than 50 seconds. This was achieved by delegating roles to each of the four members, such as propeller attachment, wing assembly and attachment, pin securing, and taping. The layout of initial assembly after unpacking the box is shown below in Figure 25. The best assembly time measured 42.53 seconds, and the two most recent times were 47.82 and 47.52 seconds respectively. According to a project advisor's prediction, the plane would likely take an experienced military specialist team less than 30 seconds to assemble.

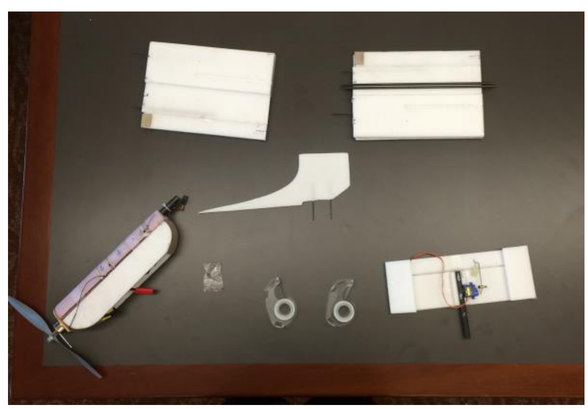

Figure 25: All Parts Unpacked from Box.

Although the speed of assembly was far superior to the goal time of two minutes, a few issues with the plane parts impeded even more efficient assembly. Since the vast majority of the parts were made by hand, some of them fit imperfectly. The clearest example of this was in the pins. Inserting the pins was by far the most time-intensive part of the assembly process. As the pins were bent using pliers without any guidelines, some were imperfectly shaped and hard to insert. This lengthened the assembly process significantly. Other parts, such as the carbon rods in the vertical stabilizer and the telescoping rod, also contained minor imperfections that slowed the assembly process.

Additionally, the assembly process relied heavily on the use of Scotch tape. Although the tape proved to be effective, the repeated use of it was wasteful and also likely to produce imperfections. Tape was used excessively across the entire body of the plane. Some uses included securing the pins, the hinges on the horizontal stabilizer, the servo wire and dorsal fin of the vertical stabilizer to the telescoping rod, the carbon fiber rods in the folding wings, the transmitter wires, and the hatch. Misplaced tape could have potentially caused less than optimal flight for the plane. Overall, however, the flight and assembly time proved far above satisfactory.

The prototype proves that the implementation of a compact rapid-assembly drone is possible for military and disaster relief. Further improvements will result in an extremely effective and efficient scouting drone that can be rapidly deployed for short term scouting missions. In the end, this model will increase the safety and productivity of military ground troops. The success of the prototype demonstrates the immense potential of such a drone.

5. Conclusion

The objective for this research project was to construct a rapid deployment RC drone that could fit in the parameters of a small box and be assembled within two minutes. Upon completion of the project, these objectives were met and exceeded by spectacular margins. The team was able to construct an effective, 16 oz drone with a wingspan of 42” and a length of 28”. The plane handled well in the air and was even able to record footage from flight. Additionally, the plane was assembled in a record time of 42.53 seconds--over 1 minute faster than the initial goal.

The project’s results have verified that a rapid pre-flight assembly is an effective strategy in designing a compact plane. The quick assembly of the plane demonstrated that having numerous separate components would not be a major issue in the field. Instead, having disassembled pieces would significantly decrease the carrying size of a relatively large aircraft, making this design well worth the short time required for assembly.

6. Discussion

In terms of the use of such a drone in real life, this project provides an excellent proof of concept. A plane with a similar design could be used with great success for scouting missions for disaster relief and military scouting. As this plane was designed under time and resource constraints, improvements can be made in a more finalized version. Due to time limitations, simplicity was occasionally favored over effectiveness in design. Also, the mechanical laboratory where the plane was constructed was limiting in terms of available machinery. Tools like laser cutters and 3D printers would have allowed for more precise and complex construction. The basic design proved effective, but with fewer constraints and more resources, it can be optimized further.

For the assembly, parts precision-cut by robotic machines would eliminate any imperfections that may slow down the assembly process. The telescoping tubes could use a system of indents and extrusions to secure in place faster than the current method of inserting metal pins. Scotch tape may be replaced by latching or clasping connections, which would be faster to assemble and less wasteful of resources. A carbon graphite body, though much more difficult to produce than the foam body of the prototype plane, would also speed up the plane assembly process, in addition to being stronger and more lightweight.

The addition of a carbon graphite body would make the plane more durable and resistant to weather conditions. The reduction of weight as a result of switching from foam to carbon graphite would also allow for additional improvements that would be useful for military purposes. For instance, the reduced weight would allow for a heavier and larger battery. As the purpose of this plane is to be used as a scouting drone for the military, a total flight time of 3 minutes and 5 seconds is unsatisfactory; this issue would be resolved with the higher capacity battery. A more powerful motor, which would increase the power to weight ratio, could be added to extend the range and speed of the drone during reconnaissance missions.

If time for construction was no longer a limitation, airfoils superior to the KFM-2 airfoil at low Reynolds numbers could be used, increasing the lift on the airplane. The KFM-2 was chosen over some more complex designs to provide ease in construction. The camera could also be embedded within the fuselage pointing downward rather than be attached at the top of the fuselage, allowing for more effective imaging.

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References

[1] M. McFarland, "American Red Cross Takes Serious Look at Using Drones for Disaster Relief, Holds Off for Now," The Washington Post, 16 July 2015. http://www.washingtonpost.com/blogs/innovations/wp/2015/04/21/american-red-cross-takes-serious-look-at-using-drones-for-disaster-relief-holds-off-for-now/

[2] J. Levs, "CNN Explains: U.S. Drones," CNN, 21 July 2015.

[3] "The Four Forces," Smithsonian National Air and Space Museum, 14 July 2015. https://howthingsfly.si.edu/forces-flight/four-forces

[4] "The Beginner's Guide to Aeronautics," NASA Glenn Research Center, NASA, 14 July 2015. https://www.grc.nasa.gov/www/K-12/airplane/

[5] "Parts of an Airplane," Start Flying RC, 18 July 2015. http://www.startflyingrc.com/theory/planeparts/

[6] C.H. Luebkeman and Donald Peting, "Architectonics," MIT, 18 July 2015. http://web.mit.edu/4.441/1_lectures/1_lecture5/1_lecture5.html

[7] "Flight Control Systems," aboutflight.com, 17 July 2015. http://www.aboutflight.com/handbook-of-aeronautical-knowledge/ch-5-flight-controls/flight-control-systems

[8] "Control Surfaces," 17 July 2015. http://www.aviastar.org/theory/basics_of_flight/control.html

[9] "Airfoils and Lift," The Aviation History Online Museum, 18 July 2015. http://www.aviation-history.com/theory/airfoil.htm

[10] "Lift and Drag Coefficient," pilotsweb.com, 18 July 2015. http://www.pilotsweb.com/principle/liftdrag.htm