Mechanical Design of an Autonomous VTOL Aircraft

Jordan Austin
Riley Doering
Wesley Fritzke
Rowan Walsh

Project Sponsor:
UBC Unmanned Aircraft Systems

ENPH 479
Engineering Physics
The University of British Columbia
January 11, 2016

Project Number 1565

Executive Summary

This project designed and built a plane for UAS to use in the Medical Express Delivery competition which involves autonomously flying 20 to 30 km to a remote location, retrieving a sample, and returning to the starting location. The plane we created is a hybrid tricopter/plane. The reason for this is we need vertical takeoff capabilities for landing at the remote location and high cruise efficiency to reach the location.

The plane was designed to land and take off in a field and fly for 60 km. The motors for the plane were tested to analyze the power consumption of the plane. The results showed that hovering consumes 7 times the power of level flights at 0.85 A h/min for hovering compared to 0.12 A h/min for level flight. A round trip of 60 km is possible on 10 A h if hovering is kept to a minimum.

The plane itself is still in construction. All major components have been built, but the foam cores are still in the carbon fiber layup process as the epoxy resin takes over 12 hours to cure each coat. Construction will be finished through the end of January, in line with the UAS team's desire to start flight tests in February. Build documentation is attached supplemental to this report.

The key recommendations for moving forward are to upgrade the propeller to carbon fiber in order to increase the motors' efficiency, use bi-directional carbon fiber weave in future repairs or construction to make the construction easier, and to minimize the time hovering as the power consumption for hovering is much higher than it is for horizontal flight.

Contents

List of Figures

1 Introduction

1.1 Background & Motivation

Unmanned aerial vehicles (UAV's) are becoming more and more common in today's society. The market has expanded from hobbyists and professional film-makers to search and rescue, the military, and everyday photography. This growth has led to many opportunities for smaller-scale aeronautical design through competitions accessible to students in universities and high schools. The 2016 Medical Express UAV Challenge[1] aims to do this through a competition centered around returning a medical sample from a remote patient. The competition intends to begin bringing UAV developments into other industries such as medicine. Many drone companies are already starting to look into the possibilities of a medical market, and this competition is the perfect place for new design ideas and innovations to emerge.

The UBC Engineering design team Unmanned Aircraft Systems (UAS) has entered the 2016 Medical Express challenge. As our project sponsors, the UAS team requested that we provide the mechanical design prototype for their entry into the competition, given that they would develop all the controls software and communications electronics in parallel. We decided that a hybrid between a vertical take-off-and-landing (VTOL) and fixed wing aircraft would best deliver for the competition. The aim of this report is to inform UAS on all the technical aspects of the project and to explain our progress with the deliverables of the project.

1.1.1 The 2016 Medical Express Challenge

Medical procedures do not necessarily need to be done in a hospital or doctor's office. Private practitioners often carry out home appointments to preform various tests. The problem arises when the patient is not easily accessible: what if they live far from the city in a cabin or on one of the smaller satellite islands of Vancouver island? The Medical Express competition aims to make the remote patient decently hard to access in order to broaden the scope of the UAV to fit more unique scenarios. Specifically, the requirement is that the drone must fly a distance of between 20–30 km to a small secluded clearing where it must land without the benefit of a runway. Once it has landed it will be loaded with a mock "blood" sample and take off again to fly back to the starting point.

[1] Full contest rules can be found at `http://uavchallenge.org/medical-express/`

1.1.2 RC Planes and Multicopters

RC aircraft have been around for several decades and have traditionally been scale models of airplanes. The planes consist of a forward facing motor to produce horizontal thrust and wings to produce vertical lift. Recently, with the miniaturization of certain electronics, a new type of RC airship know as multi-coptors were developed with vertical take-off capabilities. Multi-coptors have gained increasing popularity due to their ease to build, control, hover in the air, and the ability to launch without a runway. The most common multi-coptor is a quadcoptor which uses four vertically aligned motors to produce a vertical force to get airborne (as opposed to having wings generate lift). When in the air the quadcoptor can be rotated or tilted to move forwards; this is done by changing the speed at which one or two of the motors spins. The motors are controlled by a flight controller, a small computer, which interprets the signals from the pilot into the correct motor changes. The flight controller also contains several gyros which allows it to automatically correct from wing gusts and thermals making multi-coptors much easier to fly.

1.1.3 VTOL and Horizontal Flight

Vertical take off and landing aircraft have several advantages over fixed wing planes. Their greatest advantage is their ability to take off and land without an unobstructed, level piece of land. This allows them to land at locations without a purpose-built landing strip. This makes a VTOL aircraft extremely desirable for the Medical Express UAV Challenge which will require a landing at a location without viable approaches for glide-slope landings.

The main disadvantage VTOL aircraft have over fixed wing aircraft is their efficiency. A fixed wing aircraft is much more efficient at producing lift from its wings than having a motor try and pull an aircraft into the air against gravity. For this reason fixed wing aircraft are also highly desirable for the Medical Express UAV Challenge, which requires 40–60 km of horizontal flight. Due to the conflicting requirements of the competition — VTOL and endurance — a hybrid method that incorporates both VTOL and a fixed wing design should be employed.

1.2 Project Objectives

The main deliverable required by the UAS team is a functional VTOL aircraft with all mechanical and power electronic components integrated. The

UAS team leaders also provided some additional technical requirements for the aircraft:

- There must be a cargo bay that is easily accessible from the outside and should be able to contain a cylinder 20 mm in diameter, 100 mm in length and of a weight of up to 100 g (the "sample").
- It must repairable in one week in case of a crash occurring.
- It must be able to fly 60 km[2] in fixed wing mode and hover for approximately 10 minutes in vertical rotor mode.
- It must be able to land and take-off vertically and be mechanically able to transition in the air between fixed wing flight and hover modes.
- It must weight less than 10 kg gross.
- It must use an electric power source (batteries).
- It must have a wingspan no larger than 2.5 m.
- It must have payload space for autopilot, electronics and batteries. It must include space in the wings and tail for radio antennae.
- Project must not go over the budget of $1000 not including motors, autopilot systems, batteries, and ESCs[3].

1.3 Scope & Limitations

This project deals with the physical design, construction, and some testing of the aircraft. Due to time and technical constraints we never planned on performing a full test of the plane which would include changing from vertical to horizontal flight. The reason for this is that a program to perform the change has not been created yet and the development of the autonomous flight software is outside of our scope. Testing was performed to judge the motor performance and efficiency. We additionally desired to conduct wind tunnel testing on a scale model and test horizontal flight, but were unable to due to not having a powerful enough wind tunnel and time constraints.

[2] This distance was corrected by UAS from 30 km to 60 km part of the way into the project.

[3] Electronic speed controllers

1.4 Report Organization

This report is organized into the following sections:

1. *Introduction:* Provides a background of material related to the project, the project's objectives, and the scope of the report.
2. *Theory:* Describes the theoretical aspects of the project.
3. *Methods & Testing:* A description of the design implemented and the testing performed as part of the project.
4. *Equipment:* Describes the experimental equipment and tools used and created as part of this project.
5. *Results:* Summarizes the results of the design, build, and testing.
6. *Discussion of Results:* Discusses the results and the ultimate project design.
7. *Conclusions:* Summarizes the conclusions we drew from the results.
8. *Project Deliverables:* Lists the project deliverables, a summary of the project budget, and the ongoing project commitments by our team.
9. *Recommendations:* Describes the recommendations of this report.

2 Methods & Testing

2.1 Aircraft Design

The design of the aircraft has deviated from the proposal design in order to better suit the objectives set by UAS. The front propellers have been moved from the end of the wings to a separate mounting bar set in front of the wings. This allows the motors to be rotated between vertical (take-off mode) and horizontal (forward flight mode) on their own bar, removing the need to rotate the wings and also reducing the force carried by the wings during takeoff.

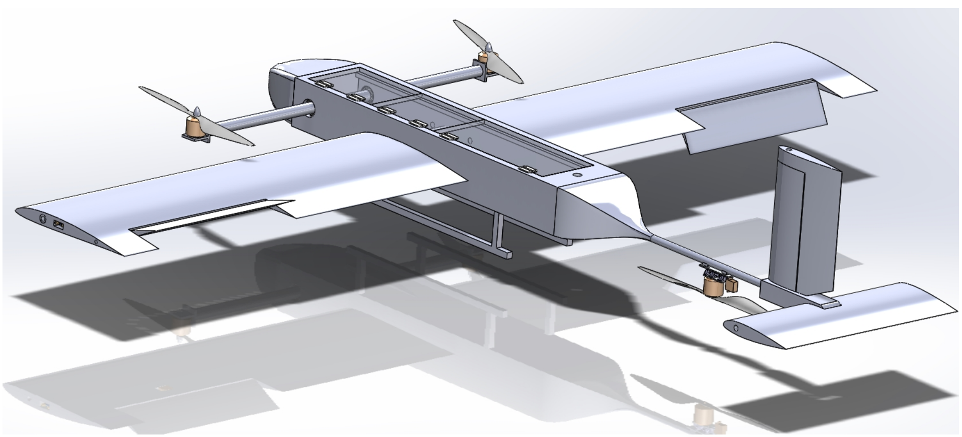


Figure 1: Rendered model of the aircraft design.

The rear twin propellers originally proposed have been changed to a single propeller mounted along the structural element linking the tail and main body. This rear propeller is actuated to tilt along the forward-aft axis of the aircraft. This actuation is able to correct for the imbalanced moment created about the aircraft's vertical axis by the propeller rotation during vertical take-off. This standard tri-copter configuration of propellers (see Figure 2) is compatible with Ardupilot, which is the vertical take-off autopilot that UAS will be implementing for the aircraft in the future.

The aircraft is on the larger size for a model aircraft. It has a total length of 1.9m and a wing span of 2.19m. The wings use a MH32 foil with a cord length (width) of 0.350m. The MH32 airfoil is an excellent airfoil for gliders. The horizontal stabalizer (H-stab) uses a NACA 20315 airfoil and the vertical stabalizer (V-stab) uses a NACA 0015 airfoil.

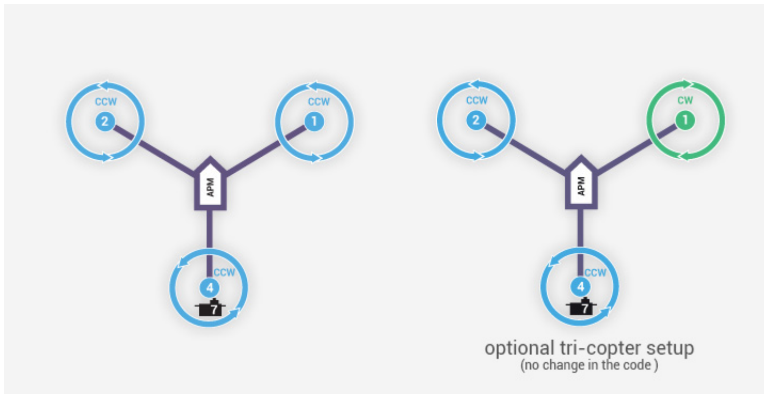


Figure 2: The two possible tricopter configurations compatible with the Ardupilot autopilot. Image re-used from `http://copter.ardupilot.com/wiki/tricopter/`.

2.1.1 Aircraft Structure

As with the previous design, a large body was designed for the aircraft to accommodate the electronics required by UAS. Spaces were cut in the wings and body for the necessary antennae and radio equipment. Mounting the front propellers on their own bar in front of the wings, rather than on the wings, will also reduce interference from the motors to the antennae.

The structure of the plane is made from extruded polystyrene foam covered by a unidirectional carbon fiber skin. The foam was shaped by cutting sheets of extruded polystyrene (commonly used as insulation, easily available in 2'x8' sheets from hardware stores) with the waterjet cutter, gluing layers together with Gorilla wood glue, and sanding the joints smooth with 80 and 220 grit sandpaper. This foam was chosen for its relatively high compressive strength and machinability- unlike expanded polystyrene, insulation foam can be sanded smooth. Unidirectional carbon fiber was chosen for the skin material over a traditional bidirectional weave for weight savings (the unidirectional fiber is only 1.5 oz/ sq yd) and because plane skins typically only experience forces along one major axis. As in any plane, the skin carries the bulk of the load- in a wing, the skin must carry this load along the axis connecting the wingtip and fuselage while the ability to bend about the forward axis is a positive, allowing longer life for the wing and damping the effect of turbulence. Unidirectional carbon fiber allows for this combination of strength and bending. For a detailed guide to the construction of the plane, consult the Build Guide attached as an appendix to this document.

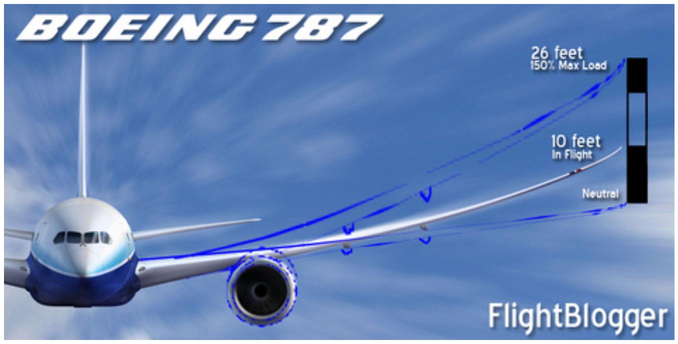


Figure 3: A wing bending during flight. Image from `http://www.flightglobal.com/blogs/flightblogger/`.

From the SolidWorks model, volumes and areas of various plane components could be accurately determined. Using these values with various foam densities and carbon fiber weights, we determined the original weight budget for the plane.

Depending on the exact materials used, the weight can be expected to vary from a minimum of 4 kg to over 4.5 kg. The insulation foam used in the actual construction was roughly 20% heavier than the #1.3 foam budgeted in the second column of the weight budget table, but with a total thrust capability of 9 kg we still have a comfortable margin of safety for the vertical take-off.

Power Electronics

The drive system for the aircraft consists of three identical motor-propeller combinations. All motors drive the propellers directly (1:1 drive ratio). The motor selected is the 400KV T-Motor MN3520, with 16×5.5 plastic propellers. A 16×5.4 carbon fiber propeller is also available from T-Motor, but it is expensive so testing was done with the plastic propellers and our project recommendations will include the option for UAS to purchase the higher-efficiency carbon fiber propellers for the final aircraft.

Afro 30 A ESCs with Simon K. firmware were selected to drive the motors. The same servos were used for actuating the front motors, the rear motor tilt mechanism, and the aircraft's control surfaces: the Turnigy TGY-306G. Based on specifications provided by T-Motor, this propeller-motor combination would produce enough thrust to to accelerate the aircraft at

Part Description	Area/Volume	Mass (g) #1.9 foam 5.7 oz/yd c. fiber	Mass (g) #1.3 foam 2 oz/yd c. fiber
Wing Foam	0.00640441	194.92	133.37
Wing Carbon Fiber	0.62706963	121.19	42.52
Aileron Foam	0.000290726	8.85	6.05
Aileron Carbon Fiber	0.07643381	14.77	42.52
Wing bar		174.73	174.73
Sub Total		514.46	399.19
Fuselage (body)	0.008514631	259.14	177.31
Fuselage (body) Carbon Fiber	0.86253616	166.7	42.52
Fuselage (cover)	0.001125	34.24	23.43
Fuselage (cover) Carbon Fiber	0.249	48.12	42.52
Motor bar		162.81	162.81
Sub Total		671.01	448.59
Tail bar		76.38	76.38
Elevator Foam	0.001871165	56.95	38.97
Elevator Carbon Fiber	0.23546571	45.51	42.52
Rudder Foam	0.00117262	35.69	24.42
Rudder Carbon Fiber	0.15958544	30.84	42.52
Sub Total		245.37	224.81
Motor (ea)		200	200
Propeller (ea)		9.5	9.5
Sub Total		892.5	892.5
Servo (×5)		21	21
RFD900 and antennas (×2)		50	50
Power distribution board (×2)		20	20
Kevlar Strip		10	10
3D printed parts		30	30
Hinges		15	15
Pixhawk		40	40
Pixhawk GPS Unit		20	20
Pixhawk Airspeed Sensor		20	20
RC Receiver and antenna		30	30
WiFi Data Tranceiver		200	200
Raspberry Pi 2 B		45	45
Maxamps 6 Cell Battery		1290	1290
3 Cell backup battery		150	150
Sub Total		2095	2095
Total		4418.34	4060.1

Figure 4: Weight budget for the prototype aircraft.

1.5 g during vertical take-off. This was considered to be an adequate factor of safety since at least 1 g is required to lift the aircraft.

2.2 Alternative Designs

Several other designs for a VTOL aircraft were considered for this project.

1. Two propellers are used for vertical lift (with thrust vectoring to control the ascent/decent) during take-off. These motors then pivot to face forwards for horizontal flight, during which conventional wings provide lift.

2. An aircraft that takes off facing upwards, with a single large nose-mounted propeller, then turns over in mid-air to continue in horizontal flight, with lift provided by conventional wings.

3. A normal (non-transforming) single-lift-propeller helicopter.

Since UAS required the aircraft to be compatible with Ardupilot (an autopilot) for vertical take-off, our choices were limited to designs that did not use thrust vectoring. We also ruled out a helicopter design because of its lower efficiency and speed when traversing large horizontal distances. Ultimately the tricopter design with two pivoting motors was used because it minimized the number of motors, which saved overall weight.

2.3 Testing

Testing was performed to validate the performance of our aircraft. Due to the long amount of time that building our prototype takes, and the chance of a catastrophic crash while testing the entire prototype, we performed initial tests on the aircraft's separate thrust and aerodynamic systems and extrapolated the results up to the performance of the entire aircraft.

Propeller & Motor Testing

In order to understand the performance of the aircraft without (somewhat risky) flight tests, the designed motor-propeller combinations were tested for their thrust versus current draw characteristics. The propeller/motor thrust measurement rig (see Section 3) from the UBC Aerodesign team was used for this testing.

Two 16×5.5 plastic propellers were tested: an APC-style propeller and a T-style propeller. These 'styles' refer to the shape of the blade; the 16×5.5 numbering denotes a diameter of 16" and a pitch of 5.5".

The displays of both the ammeter and the force gauge on the thrust measurement rig were recorded on video during the test (see Figure 5), the data was then transcribed into a spreadsheet for analysis. The results from this test are shown in Section 4.

Figure 5: The view captured of the current and force gauges during the motor thrust test.

Scale Model for Wind Tunnel

A 13 % scale model (see Figure 6) of the designed aircraft was 3D-printed to potentially act as a model for scaled wind tunnel testing. Unfortunately, due to limitations in the available wind tunnel airspeed and the size of our aircraft design we were not able to perform tests on the drag and lift characteristics of the design.

$$Re = \frac{\rho v L}{\mu}$$

Where ρ is the fluid density, v is the maximum velocity of the fluid, L is the characteristic length, and μ is the dynamic viscosity of the fluid. To correlate the drag data from the testing, we planned to match the Reynold's number (Re) of the scale model to the actual aircraft design. However, since the factor L is reduced to 13 % in the scale model, the speed of the air in the wind tunnel would need to be increased by a factor of $1/0.13 = 7.7$. The required top speed for our aircraft design is around 90 km/h, which would require a wind tunnel airspeed of 192 m/s to test. This was not possible in the wind tunnels available on campus at UBC, which have a maximum air speed of 35 m/s.

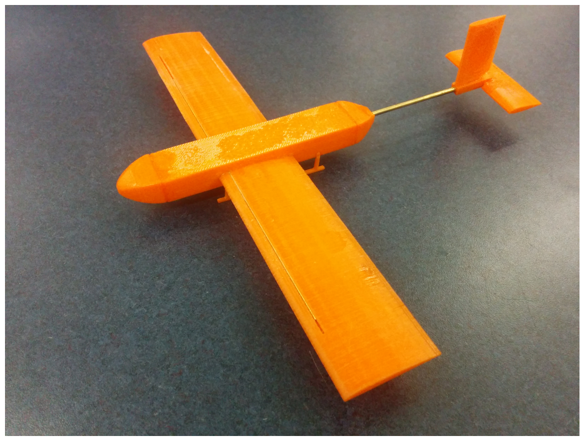


Figure 6: The 3D-printed scale model of the prototype aircraft. This model lacks scaled versions of the three motors and propellers.

3 Equipment

This section contains descriptions of the tools and equipment built or used by our team during the project.

Wind Tunnel

The Parkinson wind tunnel is located on UBC's campus in the UBC Aerolab. It has a speed range of 5–35 m/s. More information is available at `http://mech.ubc.ca/alumni/aerolab/facilities/`.

Propeller Thrust Testing Rig

A propeller/motor thrust rig was available from the UBC Aerodesign team on campus. It consists of a horizontal rail with mounting for a motor and a force gauge. The thrust generated by the propeller engages the force gauge. An ammeter was used to measure the current used by the motor.

Hot-Wire Foam Cutter

A hot-wire foam cutter was designed and assembled by our team to assist with the construction of the body and flight surfaces of the aircraft. These were shaped from various types of foam, initially cut and layered, then trimmed down with the hot-wire cutter, and finally sanded. The cutter itself is essentially a wooden bow with a tensioned (with a spring) nichrome wire between two banana plug ports. The construction of the hot-wire cutter is given in the Build Guide attached as an appendix to this document.

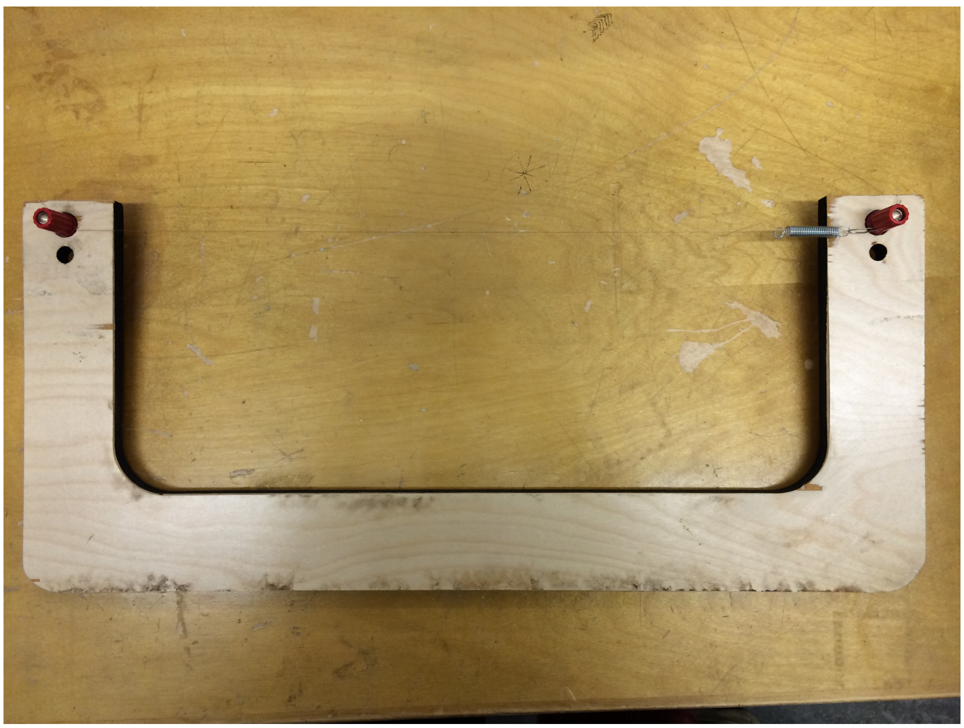


Figure 7: The assembled hot-wire cutter, shown without a power supply connected.

4 Results

4.1 Motor Testing

Initial motor thrust testing was performed on each of the three MN3520 motors purchased to verify that they all functioned as expected. This initial test measured the thrust and current at 50%, 75%, and 100% throttle; however since the throttle is controlled by hand, some variation in the results was expected. All motors functioned uniformly (within the variation expected due to the throttle).

The data collected from the comprehensive motor thrust testing is shown below in Figure 8. The unevenness of the data (particularly the lack of data for the APC-style propeller from 2–11 A) is likely due to motor throttle being controlled during the ramp-up by hand via a wireless transmitter.

During the testing it was noticed that the T-style propeller was noticeably louder than the APC-style propeller. The propellers and motor had not been balanced, so this could have been due to a slight imbalance.

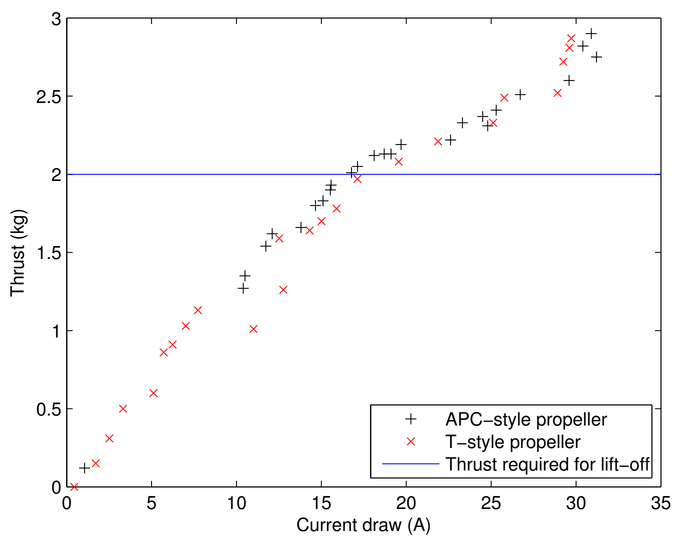


Figure 8: The thrust versus current draw data collected from the motor testing. The horizontal line indicates the point at which the thrust equals the motor's share of the target aircraft weight.

4.2 Prototype Construction

The prototype plane has under construction as per the procedure outlined in the Build Manual. Currently, all foam cores for the plane as well as the mechanical sub-assemblies have been made and the foam cores are undergoing carbon fiber layup to add on the unidirectional carbon fiber skin. Progress during construction was interrupted twice, first by the use of expanded polystyrene foam instead of extruded polystyrene foam (the expanded foam cannot be sanded or smoothed, as it pops rather than crumbles, so the first foam cores made had to be discarded) and secondly by the unexpectedly slow curing time of the epoxy resin used during carbon fiber layup; while the resin is labelled at a 2 to 3 hour cure time, the real-life curing time was found to be over 12 hours. This increase in curing time dramatically extended the time needed to add all necessary layers and coats for the carbon fiber skin, to the point where the prototype is still today undergoing this process. Completion of the prototype plane is expected to take two days after the carbon fiber layup process is complete.

(a) Foam cores made, cleaned and sanded.

(b) Elevator after carbon fiber layup.

Figure 9: Prototype construction.

5 Discussion of Results

5.1 Motor Thrust Data

Based on the motor thrust test results, up to 2.9 kg of thrust is available from each motor. Based on the target aircraft weight[4] of 6 kg, this will allow the aircraft to accelerate upwards at 0.45 g during take-off. While neither propeller had a significantly better efficiency, the T-style propeller performed better (lower current draw) at high thrusts. Further testing, especially with the 16×5.4 carbon fiber propellers from T-Motor, would be useful. Correlating thrust to motor throttle was beyond the scope of our testing since we controlled the motor throttle by hand; acquiring this data would help with autopilot development.

5.2 Calculated Flight Times

There are three power states in which our plane will operate: take off, hovering, and cruising. For take-off we need each motor to produce 25 N of thrust each so we can accelerate at 0.25 g. This requires 75 A or 1.25 A h/min to sustain. For hovering (while the ground target is being located) we only need 20 N of thrust per motor which requires 51 A or 0.85 A h/min. The thrust for cruising is the force required to overcome the drag forces on the plane. At a velocity of 20 m/s the drag was approximated to be 10 N which results in a current draw of 7 A [5]. The plane must be able to fly 60 km which would take 50 minutes at 20 m/s. The total power consumption for cruising at 20 m/s is approximately 5.8 A h. Our battery has a capacity of 11 A h, but to keep our calculations conservative we will assume a capacity of 10 A h.

Power State	**Current Draw**	**Power Consumption**
Take-off	75 A	1.25 Ah/min
Hover	51 A	0.85 Ah/min
Cruise	3.6 A	5.8 Ah

Figure 10: Estimated motor current draw in various flight states.

This leaves 4.2 A h for hovering and take-off (assuming typical power draw for the on-board electronics e.g. no high-quality video streaming).

[4]See Figure 4, the actual prototype aircraft weight will be lower.

[5]See Appendix A3 Drag for calculations

With two take-off and landing cycles, for an estimated total of 2 minutes in the take-off power state, 1.7 A h remains for hovering (a hover time of 2 minutes). Unfortunately this does not meet UAS's original request of 10 minutes of hover time in addition to a flight distance of 60 km. Our current configuration uses some of the highest efficiency motors available but still requires 8.5 A h out of an 10 A h battery to hover for 10 minutes. For the size and weight of the aircraft we designed, significantly improved hover-time performance does not seem possible. Significant weight savings would need to be found, perhaps by eliminating the carbon fiber skin from the fuselage and nosecone or by using a spar-and-skin system for the wings rather than a solid foam core, in order to extend the hover time.

Furthermore, as the competition only allows 1 hour to set-up, take-off, fly, and land, a flight time of 50 minutes may be too long. To decrease the flight time more power must be used for cruising. If we dedicate 7.5 A h to cruising we can attain a velocity of 25 m/s, resulting in a total horizontal flight time of 40 minutes. This would eliminate our hover time and only leave us with 2 minutes of take-off power consumption. Ultimately the balance of horizontal flight speed to hover time during target acquisition will be up to UAS.

5.3 Sources of Error

The data from the thrust testing was transcribed from the video taken of the ammeter and force gauge by hand. This likely resulted in the largest source of error. The latencies of the ammeter and force gauge are unknown, so during the test while the throttle was steadily rising, a simultaneous reading of both instruments (as was done by transcribing the video) does not guarantee that both readings apply to the same instant of time. If the motor throttle could be set electronically (not by hand), a specified throttle could be set for a few seconds to allow the readings to stabilize. Done for stepped range of throttles (10%, 20%, 30%, etc), this would provide a less noisy data set and also correlate throttle to motor thrust.

6 Conclusions

This project designed, built, and tested major components of a prototype vertical take-off aircraft for UBC's Unmanned Aircraft Systems (UAS) team to test and develop for the 2016 Medical Express Challenge. The plane is required to land and take-off in a limited space (with no runway) and fly for 60 km. To meet these requirements a tricopter/airplane hybrid was designed that could take off vertically like a tricopter and transform to efficient fixed-wing flight once in the air. The prototype plane is currently being wrapped in a thin carbon fiber skin, with completion and turnover to UAS scheduled for the end of January 2016. Delays in the construction of the plane due to improper foam use and long resin curing times delayed the assembly of the completed prototype beyond the date of this report.

The motors for the plane were tested to analyze the power consumption of the plane. The results showed that hovering consumes about 7 times the power of level flights at 0.85 A h/min for hovering compared to 0.083 A h/min for level flight. A round trip of 60 km is possible on 10 A h if hovering is kept below 2 min, where these figures retain a safety factor of 1.5 against power draw during hovering and 1Ah of battery power is retained for emergency power.

7 Project Deliverables

7.1 List of Deliverables

1. **Detailed 3D Design & Build Method**: The 3D design is complete in SolidWorks. The files are stored in a shared Google Drive, which is already available to UAS. The build method (a current copy of this document is included with this report as an appendix) will be included with the prototype aircraft. This build guide details the aircraft's construction: water-jet cutting the foam, cutting the foam with the hot-wire foam cutter, covering the parts in carbon fiber and resin, and assembly of the components.

2. **Force Analysis and Lift Calculations**: The lift calculations exist in an excel document which will be given to our project sponsors. The force analysis for the motors is included in this report.

3. **VTOL Aircraft**: The prototype aircraft will be given to the UAS team. It contains 2 sets of wings, 1 H-stab, 1 V-stab, 1 fuselage, 1 nose cone, 3 motors, two sets of propellers (with spares), and some miscellaneous components. The aircraft is currently in the carbon fiber layup phase of construction, with full completion scheduled for the end of January.

7.2 Financial Summary

Project requisitions were budgeted at under $1000 excluding motors, autopilot systems, batteries, ESCs, and any other non-mechanical components. The breakdown of the cost of all materials procured throughout the project are as shown in Figure 11.

7.3 Ongoing Team Commitments

The team will continue to assemble the chassis of the aircraft up to January 31, 2016 in order to complete the chassis and mechanical system construction. Once the mechanical assembly is complete the aircraft (and an updated Build Guide document) will be handed over to UAS, who will continue integration of the communications equipment. We will stay on board with UAS to answer questions concerning flight implementation and testing as needed.

Part(s)	**Supplier**	**$ Cost**
Motors	T-motor	479.54
Servos	Hobby King	116.72
Rotors	Hobby King	108.60
ESCs	Hobby King	55.05
Carbon Fiber	CST Composite Store	116.00
Carbon Composite Tubes	Goodwinds	274.61
Wings	Flying Foam	286.59
1” and 2” Foam Slabs	Coe Lumber and Building Supply	83.79
Miscellaneous	McMaster Carr	89.97
Total		1610.87
Total Mechanical		1076.28

Figure 11: Financial summary

8 Recommendations

For future work on this project, our team has the following recommendations:

1. **Upgrade propellers to carbon fiber**
   For the final aircraft version, upgrading the plastic propellers to the carbon fiber propellers available from T-Motor could improve the aircraft's overall efficiency. The 16×5.4 propellers[6] have a lower moment of inertia than the plastic ones used in the prototype aircraft, and based on the tabulated motor specifications available from T-Motor, it would have improved performance than what was observed in the motor thrust tests we performed.

2. **Balancing motors and propellers**
   Once a motor-propeller combination is settled upon, balancing the motors and propellers would reduce their vibration and noise during flight. This would extend the motor's life and prevent screws or other fasteners from working loose within the aircraft.

3. **Regularly replace motor bearings**
   The manufacturer of the motors used in the prototype aircraft (T-Motor's 400 KV MN3520) recommends that the motor bearings be replaced every 60 hours of operation.

4. **Bi-directional carbon fiber weave**
   If the added weight is acceptable in future iterations of the aircraft (which depends on its in-flight handling and autopilot characteristics), using bi-directional carbon fiber weaves is easier for layup and would result in a more uniform composite surface for the aircraft.

5. **Optimize for minimal time spent hovering**
   It was found that a small decrease in the allowable time spent hovering (which consumes a lot of energy) allowed a greater horizontal cruising speed and a significant reduction in the overall flight time[7]. On a single battery charge, the 10 minutes of hover time requested by UAS *and* the 60 km flight distance are not possible for our prototype aircraft, and would be difficult to achieve.

[6] `http://www.rctigermotor.com/html/2013/prop_0904/33.html`
[7] See Section 5.2.

6. **Gather motor thrust versus throttle data**
   With electronic (instead of operator) control over the motor throttle, it would be useful to measure motor thrust and current draw at exact increments of the throttle. This data will probably be needed during the development of the aircraft's autopilots.

A Aircraft Control

The 3 main control surfaces[8] for an aircraft are the ailerons, located on the trailing edge of the wings; the elevators, located on the horizontal stabilizer (H-stab: small wing at the back of the plane); and rudder. The ailerons are used to roll the plane along its nose-tail axis. This is done by having one go up and the other go down; causing the plane to roll to the direction of the wing with the raised aileron. The elevators and the H-stab are used to pitch the nose of the plane up or down by changing the angle of attack. This is done by having both of the elevators either go up or down. The ailerons are not used to perform this action as they are unlikely to have enough moment about the center of gravity as the wings are too close to the center of gravity. The rudder is used to rotate the plane about the yaw axis.

Quadcoptors have slightly different stability from a regular plane as they do not contain control surfaces, only motors. Due to having multiple motors it is important that the moments from the motors cancel out. This is done by having two propellers rotate clockwise while the other two rotate counter-clockwise. This will require two different propellers types; one designed for CW rotation and one for CCW rotation. This leads to a unique solution to maneuvering the plane. To rotate about the yaw axis one can simply increase the speed of either the CW or CCW motors to cause an imbalance in the quadcoptor's moment which serves the same function as the rudder on a plane. To pitch the quadcoptor in any direction simply increase the motor on the side you want to go up. To roll the quadcoptor increase the power to one motor and decrease the power to the motor opposite it. It should be noted that to maneuver a quadcoptor in this method the motors must be running which uses more power than moving a control surface on a plane. Our tricopter design differs slightly in the control method for controlling rotation due to the motor moments, refer to Section 2.1.

[8] Sourced from `http://www.aviastar.org/theory/basics_of_flight/control.html`

B Drag Analysis

This section will go over the calculations for drag. The total drag for a 20 m/s is estimated to be 10.1 N.

Drag is given by:

$$D = 0.5 \cdot C_d \cdot \rho \cdot A \cdot V^2$$

ρ is the air density, A is the wing area, V is the velocity in m/s, and C_d is the coefficient of drag. The coefficient of drag is composed of two parts: parasitic drag from the skin/shape of the plane and induced drag from the wings as shown in the following formula:

$$C_d = C_{d0} + \frac{C_L^2}{\pi \cdot AR \cdot e}$$

C_{d0} is the coefficient constant for the parasitic drag, C_L is the coefficient of lift, AR is the aspect ratio, and e if the wing efficiency. The aspect ratio and coefficient of lift are known design constants. Our plane has an aspect ratio of 5.7 and a design coefficient of lift of 0.45. The parasitic coefficient constant and e can either be found through wind tunnel testing or using estimations. As we were unable to perform wind tunnel testing we based on our drag estimation on on-line literature.

The coefficient constant for the skin/shape can be expressed as the following:

$$C_{d0} = \sum_{n=1}^{i} k_i \cdot c_{fi} \cdot \frac{S_{weti}}{S_{refi}}$$

This requires the plane to be split into subsections and the coefficients for each section to be individually estimated. k_i is the form factor and depends on the thickness of the part, c_f is the skin friction coefficient, S_{wet} is the wetted surface area, and S_{ref} is the total surface area for the part.

The plane was split into four subsections: the wings, body, H-stab, and V-stab. The form factor and skin friction coefficient were found on graphs presented in lecture notes for the course AA241x from Standford[9] and are shown in the Drag Factors table.

The reference area is the the equivalent to the shadow the plane projects onto the ground while the wetted surface area is the area which is in con-

[9] Sourced from `http://adl.stanford.edu/sandbox/groups/aa241x/wiki/e054d/attachments/31ca0/performanceanddrag.pdf?sessionID=e8e399a6a7b6d49345896178d948a84b1c851858`

stant with the air. For the fuselage this is simply the total area while for the wings it can be calculated from:

$$S_{wet} = 2 \cdot (1 + 0.2 * (\frac{t}{c})) * S_{exposed}$$

In this equation t is the maximum thickness of the plane, c is the wing's cord length, and $S_{exposed}$ is the exposed surface area which will be simplified by making it the same as the reference area. NACA specified wings have the value $\frac{t}{c}$ expressed in their name. The results are summarized in the Wetted and Reference Areas table:

These values give a parasitic coefficient of drag of 0.0290. With this the span efficiency can be estimated as 0.80[10].

Now the coefficient of drag can be calculated.

$$C_d = 0.0290 + \frac{0.45^2}{\pi \cdot 5.7 \cdot 0.8} = 0.0604$$

The drag on the plane is:

$$D = 0.5 \cdot 0.0604 \cdot 1.2\frac{kg}{m^3} \cdot 0.7m^2 \cdot 20\frac{m}{s}^2 = 10.1N$$

The power draw from the motors to overcome this drag is approximately 7 A which will result in 5.8 A h for flight.

[10] Sourced from http://adl.stanford.edu/sandbox/groups/aa241x/wiki/e054d/attachments/31ca0/performanceanddrag.pdf?sessionID=e8e399a6a7b6d49345896178d948a84b1c851858

Subsection	**Form Factor**	**Skin Friction Coefficient**
Wings	1.18	0.0025
H-Stab	1.35	0.0025
V-Stab	1.35	0.0025
Body	1.15	0.0025

Figure 12: Drag Factors

Subsection	$\frac{t}{c}$	S_{wet}	S_{ref}
Wings	0.866	$2.035S_{ref}$	S_{ref}
H-Stab	0.15	$2.06S_{ref}$	S_{ref}
V-Stab	0.15	$2.06S_{ref}$	S_{ref}
Body	N/A	$0.702m^2$	$0.221m^2$

Figure 13: Wetted and Reference Areas

C Build Guide Documentation

The documentation of the construction process of the prototype aircraft is attached below. The title of the document is ”*ENPH 479 Capstone Project — UAS VTOL Build Manual*”.

University of British Columbia

ENPH 479 Capstone Project
VTOL Plane for the UAS Team

VTOL Plane Build Manual

January 12, 2016

Contents

List of Figures

1 Design Overview

This plane is, as it's core, a tricopter design transplanted on top of a long-range fixed wing plane design. The tricopter configuration allows the plane to take off vertically, while the bar holding the forward two propellors can rotate 90 degrees to transition into horizontal flight.

The body of the plane is made from foam core covered in layered unidirectional carbon fiber. The foam core gives compression strength while simplifying construction, and the unidirectional carbon fiber gives strength along appropriate force vectors while saving weight over a traditional carbon fiber weave. Pultruded carbon fiber tubes are also used as structural elements to connect various parts of the aircraft structure together, primarily to connect the fuselage to the tail section and as stab bars in the wings; these tubes were so chosen for their excellent strength-to-weight ratio.

Other minor parts were created from balsa wood, 3D printed ABS plastic, nylon, or aluminum. This diversity of materials could be simplified in future iterations, but most materials were chosen for their availability and ease of use for the specific parts.

1.1 Equipment Required

- Waterjet cutter: required for cutting foam slices and metal backing plates.
- Laser cutter: used to cut profile guides for wing carving. A laser cutter is not necessary, as this work could also be done on a waterjet.
- Foam hotwire cutter: handbuilt, this device is essentially a NiChrome wire strung along a frame and connected to a 20V power supply. Used for shaping foam and cutting wing cores. Construction of the hotwire cutter is covered in this guide, and the cutter itself is to be given to UAS as part of the project deliverables.
- 20V Power Supply: used to power the hotwire foam cutter.
- Sandpaper: used to shape and smooth foam bodies prior to carbon fiber layup.
- Assorted hand tools, brushes, etc. Access to ordinary hand tools and lab accessories is needed. Details of small items needed for construction are given throughout the build guide.

2 Parts and Sourcing

This section aims to provide as comprehensive guide to all parts purchased for the construction of the VTOL plane, their sources and costs where applicable, as well as notes for future build attempts.

2.1 HobbyKing Components

Part Description	Quantity	Product ID	Price
Afro ESC 30Amp OPTO Multi-rotor Motor Speed Controller	4	9192000213-0	$55.20
T-Style Propeller 16x5.5 (2pc)	4	657000012-0	$63.84
APC Style Propeller 16x5.5 (2pc)	4	657000011-0	$52.96
Turnigy TGY-306G Servo	7	9355000004	$161.70

Extra sets of propellers were ordered in case of crashes or accidents during testing, and two distinct types were ordered to test efficiency differences (see main report for details, but efficiency differences were negligible). For the competition flight, we recommend purchasing T-Motor 16x5.4 carbon fiber propellers for additional durability, efficiency, and weight savings (`http://www.rctigermotor.com/html/2013/prop_0904/33.html`).

2.2 McMaster Carr Components

Part Description	Quantity	Product ID	Price
Aramid-and-Fiberglass Strip	10 ft.	8822K55	$14.60
Surface-Mount Hinge	6	1635A12	$17.28
Lubrication-Free Acetal Ball Bearing	4	6455K78	$37.16

The aramid and fiberglass strip can be replaced with any equivalently sized Kevlar strip- this strip is placed between the foam core and carbon fiber layup, such that after curing the wing section can be scored down to the Kevlar to use the Kevlar as a built-in hinge. The surface-mount hinges are used to close the top bay of the plane, and so could be replaced by a similar hinging system.

2.3 Carbon Fiber Components

Part Description	Quantity	Source	Price
Unidirectional Carbon Fiber, 1.5 oz, 11.5” wide	30 ft.	The Composites Store	$87.00
Ecopoxy Resin + Slow Hardener	-	ENPH Project Lab	-
.625 x 40 Pultruded Carbon Tube	1	Goodwinds	$23.99
.625 SW x 48 Pultruded Carbon Tube	2	Goodwinds	$101.98
.625 SW x 32.5 Pultruded Carbon Tube	1	Goodwinds	$34.99
E.230” LW x 24” Pultruded Carbon Tube	1	Goodwinds	$1.85

The 5/8” x 40” carbon fiber tube is used to connect the fuselage and tail, the two 5/8” x 48” tubes are used as wing stab bars, the 5/8” x 32.5” tube is the tiltrotor bar holding the forward two motors, and the 0.23” x24” tube is used to prevent wing rotation.

Suppliers are The Composites Store (`http://www.cstsales.com/`) and Goodwinds (`https://goodwinds.com/`). Goodwinds in particular has a clearance section which should be checked for equivalents to the smaller rods- the clearance section frequently has small rods in stock for very competitive prices.

Slow hardening resin was used because it was already in stock at the ENPH Project Lab. For future builds or repairs, however, we recommend using a faster-setting epoxy (the Ecopoxy slow cure resin has a ¿3 hour cure time). A faster setting time is useful in layup, as you can more readily shape the fiber into place as the resin cures, and also allows for a faster construction time. Any epoxy resin should work equally well.

2.4 Miscellaneous Components

Part Description	Quantity	Source	Price
T-Motor Drone UAV Brushless Motor MN3520	3	The Robot Source	$329.70
Blue SM Foam insulation board, 2’x8’x1”	3	Coe Lumber and Building Supply	$50.85
Blue SM Foam insulation board, 2’x8’x2”	1	Coe Lumber and Building Supply	$28.95
Balsa wood, 2’x3’	1	ENPH Project Lab	-
Nylon 10-32 x 1 1/2” bolts	4	ENPH Project Lab	-
Gorilla Wood Glue	-	ENPH Project Lab	-

The 400KV motors required were available from The Robot Source (`http://therobotsource.com/`, SKU TM-MN3520). Resources acquired from the ENPH Project Lab are readily available elsewhere, including local hardware stores.

3 Foam Cores

Foam cores, cut from sheets of insulation foam, form the base structure of every part of the plane. It is important to use insulation foam, as most other readily available foams (such as expanded polystyrene/ EPS) cannot be sanded or shaped after waterjet cutting. The foam cores are generally built by slicing the SolidWorks model for that part into 1 inch thick layers (substitute 1 inch for the thickness of the foam you've acquired), waterjet cutting those layers from foam, gluing the layers on top of each other using Gorilla wood glue (many epoxies will decompose the foam, test your glue on a scrap piece before hand) then trimming off excess material using the hotwire cutter and finally sanding everything smooth.

3.1 Hotwire Cutter Construction

The hotwire cutter is an essential tool for shaping foam parts. If the foam cutter is broken or missing, this section provides an overview of the steps needed to construct a new one.

The hotwire foam cutter is essentially a thin (0.005" OD) NiChrome wire stretched taught between a frame, with a high current running through the wire to heat it up.

Figure 1: The assembled hotwire cutter.

The frame was cut out of 3/8" plywood using the laser cutter. Two holes on the ends of the arms allow for banana plug electrical connectors to be inserted, so the hotwire cutter can be powered through alligator clips or banana plugs.

Since the NiChrome wire experiences significant thermal expansion as it heats up, a wire simply tensioned during construction will lose it's tension and sag wuhen in use. A sagging wire can be useful when cutting rounded sections, however it is generally preferable to cut using a taught wire. This can be achieved by connecting the wire to a tension spring at one end, stretching the spring during (low-temperature) construction, then allowing the spring to contract and maintain tension as the wire expands during use. Be sure to choose an electrically conductive tension spring, preferably with a low spring rate (such that it can be easily stretched by hand) and looped ends.

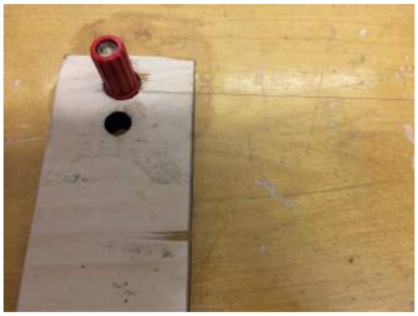


Figure 2: Direct NiChrome connection.

Figure 3: Spring-side NiChrome connection.

The diameter of NiChrome wire used is not important. Thinner wires will heat at lower voltages, but have lower tension strength. Avoid excessively large NiChrome wires, as large wires can hold a non-negligible heat capacity that compromise the accuracy of your cuts by radiating excessive heat.

3.2 Fuselage Core Construction

The fuselage was built from five layers of 1" foam. Extra holes were added to each of the four corners of the fuselage so that small sections of tubing could be used as locating bearings during gluing; these tubes were removed after gluing to save weight. Take care during waterjet cutting to identify each layer as well as the top side and down side. After waterjet cutting the layers, the layers were left to dry overnight as they become waterlogged during the cutting process.

Figure 4: Fuselage layers.

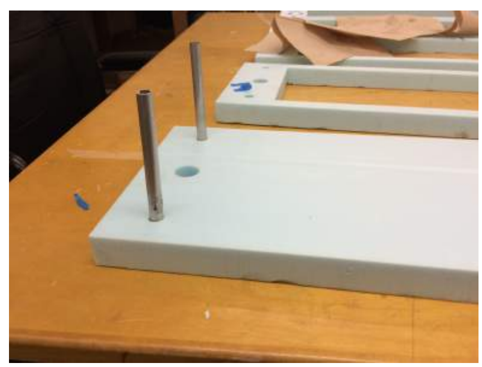


Figure 5: Spare tubes used for centering.

Sections were glued together in quick succession, with weights placed on the top layer to compress the sections together while the glue dried. A wet cloth was used to wipe away glue as it seeps out from between the seams, to save from cutting or sanding away the excess later.

Figure 6: Fuselage mid-gluing.

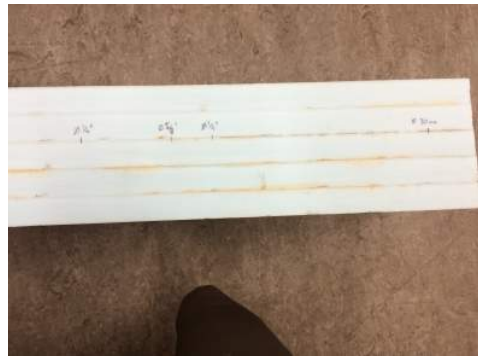


Figure 7: Fuselage all glued together.

After the glue dried, 80 grit sandpaper was used to round corners and shape the body into an aerodynamic surface. After the initial smoothing, 220 grit sandpaper was used to smooth everything further. Be sure to clean all the foam dust off the surface before doing carbon fiber layup.

After the fuselage core was sanded, several holes needed to be created through the walls. These holes are of various sizes, from 5/8" holes for the wing stab bars to 1/4" holes for the locating tubes and the bolts to hold the nosecone in place. The foam insulation board can't be drilled without causing significant damage, and cutting does not create clean lines. In order to create the holes in the fuselage, a tube with a diameter approximately 1/8" less than the desired diameter (to ensure the hole was not made too large, the hole is easily enlarged afterwards) was heated up with a heat gun and then gently pushed through the foam.

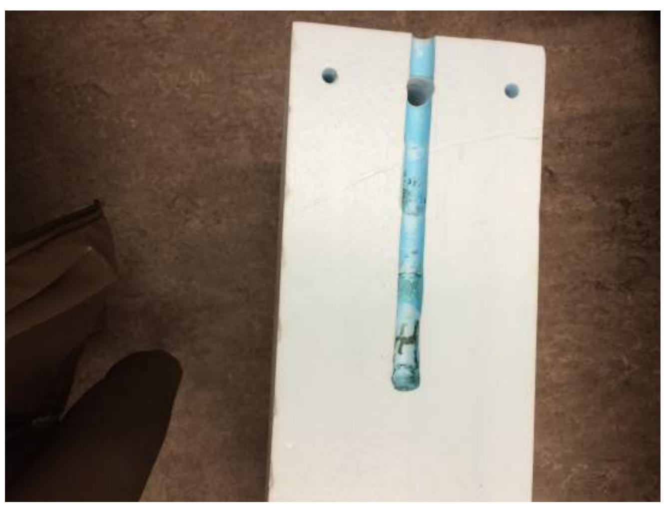


Figure 8: Channel melted in for the tail bar.

3.3 Nosecone Core Construction

The layers were cut on the waterjet cutter in the same manner as the fuselage, taking care to mark each layer as it was completed. Since the nosecone width varies with height, it is beneficial to cut the pieces out of 1" foam (rather than 2") to save time and effort during the later shaping stage. The layers were glued together in the same way as the fuselage was.

Figure 9: Nosecone after gluing, shaping and sanding.

After the glue dried, the hotwire cutter was used to shape the nosecone from a pyramid shape into a smooth aerodynamic shape. Sandpaper was used to further refine the shape, but the hotwire cutter was invaluable for broad shaping.

Since UAS requested that the nosecone be interchangeable for variable payloads, the nosecone will not be glued into the plane but rather bolted on the front. To this end, a balsa wood backing plate was cut on the laser cutter. Washers and nuts were epoxied to the side which will face into the interior of the nosecone, so the bolts can later be inserted and tightened from the interior of the fuselage bay.

3.4 Tail Loft Core Construction

Similarly to the nosecone, the layers were waterjet cut from 1" foam insulation board, glued together, then shaped using the hotwire cutter and sandpaper. Since the tail loft connects the body of the fuselage to the carbon fiber tube leading to the tail, a channel is left open to hold the tube and strengthen the connection during carbon fiber layup.

Figure 10: Tail loft after gluing, shaping and sanding.

3.5 Elevator and Rudder Core Construction

At their widest point, the elevator and rudder (alternatively called horizontal stab/ h stab and vertical stab/ v stab, respectively) are close to 30mm thick. As such, these parts must be cut from 2" foam rather than 1". The waterjet cutter was used to cut blocks in the shape of the top profile from 2" foam.

After the blocks were cut, wooden cutouts of the wing profiles were glued to opposite ends of the blocks. These wooden cutouts were made by cutting balsa wood on the laser cutter; these cutouts could also be made on the waterjet if the laser cutter is not available.

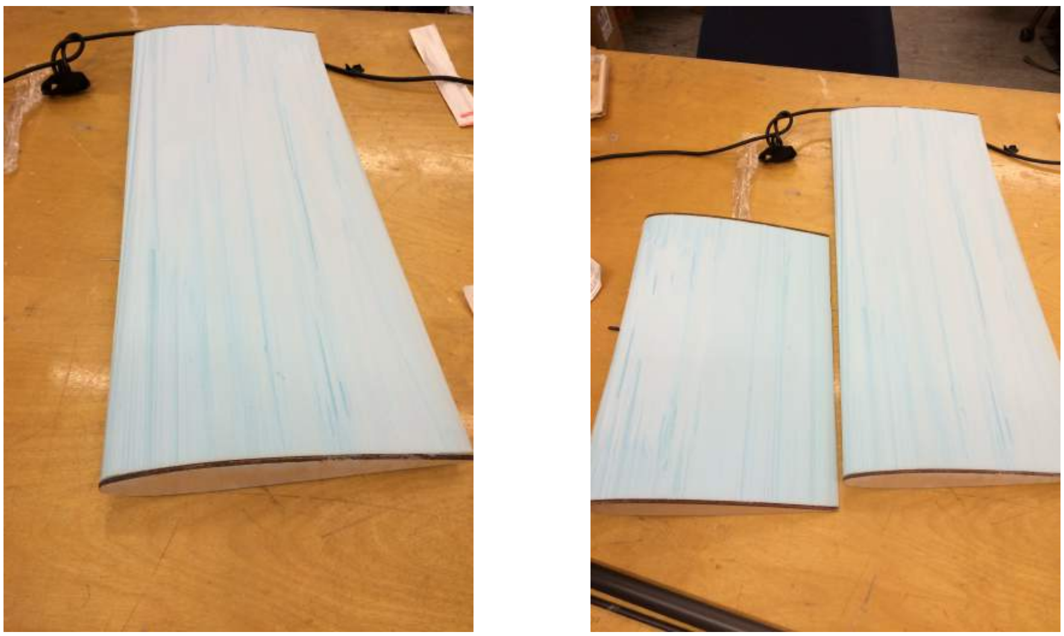


Figure 11: Cores for the elevator and rudder with end profile guides glued on.

The wooden profiles act as a guide for the hotwire cutter. Take time when cutting out the wing profiles, to make sure that the wire travels cleanly around the wooden profile guide.

3.6 Wing Core Construction

The foam wing cores were made in the same way as the elevator and rudder cores; cut the overall shape from 2" foam, create wooden profiles, and use the wooden profiles to guide the hotwire cutter. There is one major difference, however; the wings are too long to create in one piece. The hotwire cutter, as it's currently made, would gain too much slack from thermal expansion if the wire was one meter long. Future wing cores could potentially be made in one piece, if a spring with a lower spring constant is used on the hotwire cutter (allowing the spring to be stretched further before the NiChrome tensile failure, therefore allowing more expansion before loosing tension). Currently, however, the wing cores had to be made in two parts that will later be held together by glue, a wing stab bar, and the carbon fiber skin.

—will insert applicable pictures here. Wings are to be completed later in the build process

The wing stab bars, used here as 5/8" OD x 48" carbon fiber tubes, need to be installed prior to carbon fiber layup. A similar process to that used in embedding the wing bar into the fuselage (see Figure 8) will be used.

3.7 Fuselage assembly

The last step before proceeding to carbon fiber layup is to glue the tail loft to the end of the fuselage. Sand each surface smooth, glue them together, then sand clean the transition between the tail loft and fuselage body.

Figure 12: Sanded foam parts prior to carbon fiber layup. The tail loft has been glued onto the fuselage and the nose has been temporarily attached to test the fit.

4 Carbon Fiber Layup

For additional strength, as well as to bind various parts of the body together, carbon fiber was laid up around the foam cores. A thin unidirectional carbon fiber was chosen for the weight savings offered by a unidirectional fiber mat over a more traditional bidirectional weave; however, wet layup of the thin unidirectional mat proved difficult. Future builds would greatly benefit from using a vacuum bagging technique over the wet layup technique used and described here, and switching to a bidirectional weave may very well prove worth the weight cost for the improved handling, strength, and uniformity; future flight tests with the completed plane will be needed to determine how much more weight can be added without sacrificing in-air maneuverability.

4.1 Items Needed

In addition to the carbon fiber, foam parts, and epoxy resin (+ hardener) the following items will also be needed for the carbon fiber layup:

- Large work area: wet carbon fiber layup can be a messy business, a large workbench is needed to keep everything at hand and leave parts to cure after they're been coated.
- Brushes: dollar store paint brushes work well. The brushes will likely be destroyed after being used to paint on the epoxy resin, so keep a few on hand.
- Mixing container: waxless Dixie cups work well, but any similar disposable cup should do fine.
- Disposable gloves: the epoxy resin tends to get everywhere, gloves help immensely.
- Glue spreader: used to smooth the carbon fiber into place, but any similar semirigid block will work. Also useful for mixing the resin and hardener.
- Scissors: used to cut carbon fiber before laying it onto the foam parts as well as trimming excess after the resin cures.
- Heater: helps to speed curing times. Depending on the resin used, UV lamps can also help with this.

Mould release wax would also be helpful for future builds; an impregnated piece can be safely laid onto a plastic sheet to cure if mould release wax is first applied onto the sheet.

4.2 Procedure

The nosecone, fuselage, and elevator all follow the same basic layup procedure described below. The rudder and wings, however, use a Kevlar strip sandwiched between the foam and carbon fiber as a hinge; this Kevlar strip needs to be cut and laid down before any of the carbon fiber layup. Do not impregnate the Kevlar with resin, as it will act as a flexible hinge.

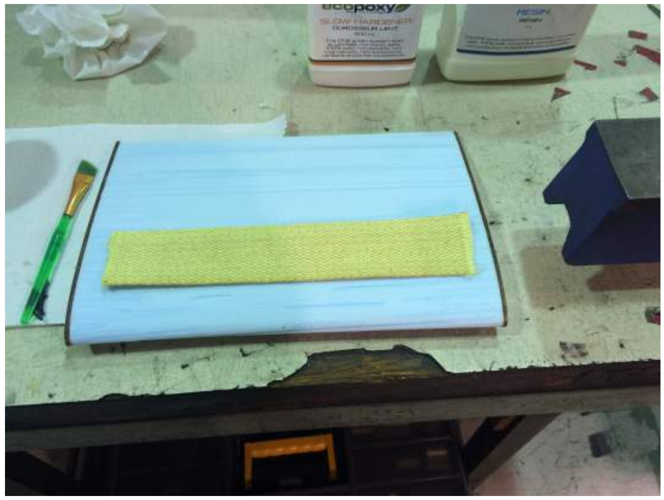


Figure 13: Elevator with Kevlar strip laid down prior to carbon fiber layup. The Kevlar strip will act as a hinge, by cutting a line through the carbon fiber and foam down to the Kevlar.

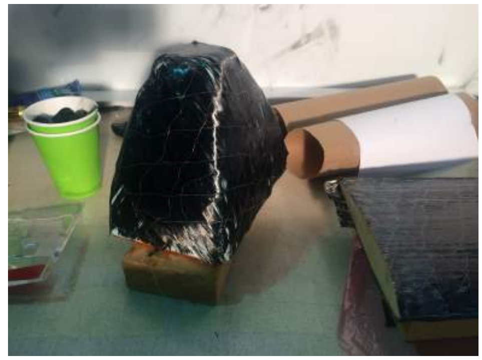
Measure out the correct size of carbon fiber you need to apply to your part. Note that unidirectional carbon fiber is only strong in the direction of the fibers, so lay down the fiber such that it reinforces along your primary force axis. Cut out the appropriate size using scissors. You can later add another layer of unidirectional carbon fiber after the first has cured to gain strength in two directions.

Take care to mix the epoxy resin in the correct proportions; any deviation from this could cause your epoxy resin to not cure at all, cure very slowly, or perhaps even cure very quickly. Particularly if using a 1:1 resin and hardener, some brands will arbitrarily label one of the chemicals as the hardener (so adding more of the 'hardener' won't necessarily speed up the cure rate). Throughout this section, 'epoxy resin' may also be shortened to simply 'epoxy' or 'resin'.

Figure 14: Epoxy resin used in the ENPH layup.

After thoroughly mixing the two parts, use a brush to apply a thin layer of resin directly onto the foam. Gently lay the carbon fiber on top, avoiding creasing or folds. Around curved surfaces were folding is unavoidable, cut along the folds until you can lay all the sections down flat. Use the brush to apply another layer of resin to the top of the carbon fiber, both brushing it smooth and dabbing to drive the resin into the fibers. After the top resin coat has been applied, smooth everything using a glue spreader to eliminate bumps or air bubbles- otherwise you'll be sanding them out later.

(a) First layer of carbon fiber applied.

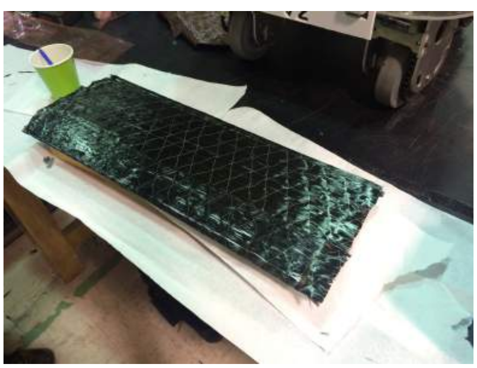


(b) Excess trimmed off after drying.

Figure 15: Nosecone immediately after carbon fiber layup and after trimming.

Let the resin dry. Heat or UV light typically speed the cure time. Use scissors to trim off any overhanging ends or stray fibers. Note that with unidirectional carbon fiber, you'll inevitably get blank spots forming where fibers clumped during curing and revealed the foam underneath. If the clumping is severe, they can be covered up by an additional layer of carbon fiber but generally they won't affect the integrity of the skin.

Extra coats of resin can be applied after the first is cured. Take care when adding extra layers of resin, they can strengthen the carbon fiber but add weight. High spots can be sanded smooth after the last coat is dried.



(a) First layer of carbon fiber applied.

(b) Excess trimmed off after drying.

Figure 16: Elevator immediately after carbon fiber layup and after trimming.

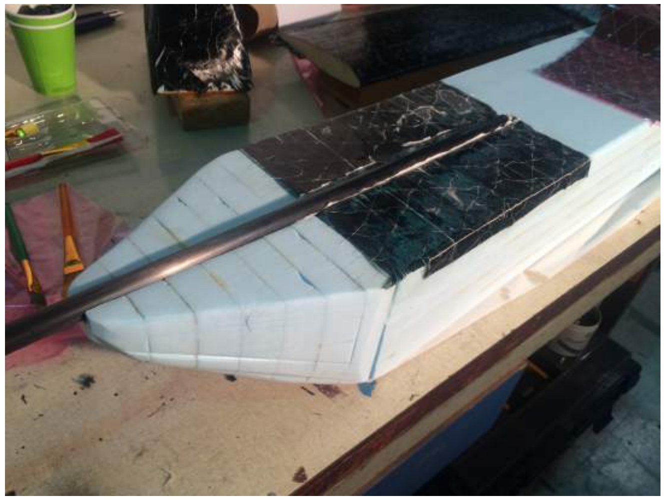


Figure 17: A small section of carbon fiber is laid horizontally where the tail bar connects to the fuselage, to reinforce the area from shear loads and bending.

—will insert more pictures from later in the carbon fiber process, including layup around the fuselage and sanding, once done.)

5 Mechanical Sub-Assembly Creation

5.1 Rear Motor Tilt-Actuation Assembly

The rear motor tilt-actuation assembly allows control of the rear tricopter motor's left-right tilt during hover-mode. The actuation is performed by a Turnigy TGY-306G servo. The assembly was constructed from 3D-printed brackets and waterjet-cut aluminium plates. #2-56 and #4-40 screws were used throughout the assembly, with threads female threads cut into the aluminium plates. M3 screws used to attach the motor, which has its own female-threaded holes. Two clamps on the bottom of the assembly allow it to be securely attached to the carbon fiber rod between the aircraft's body and tail sections. Although not necessary for hover-flight, 3D-printed cowlings for the assembly would decrease its drag during forward (fixed-wing) flight.

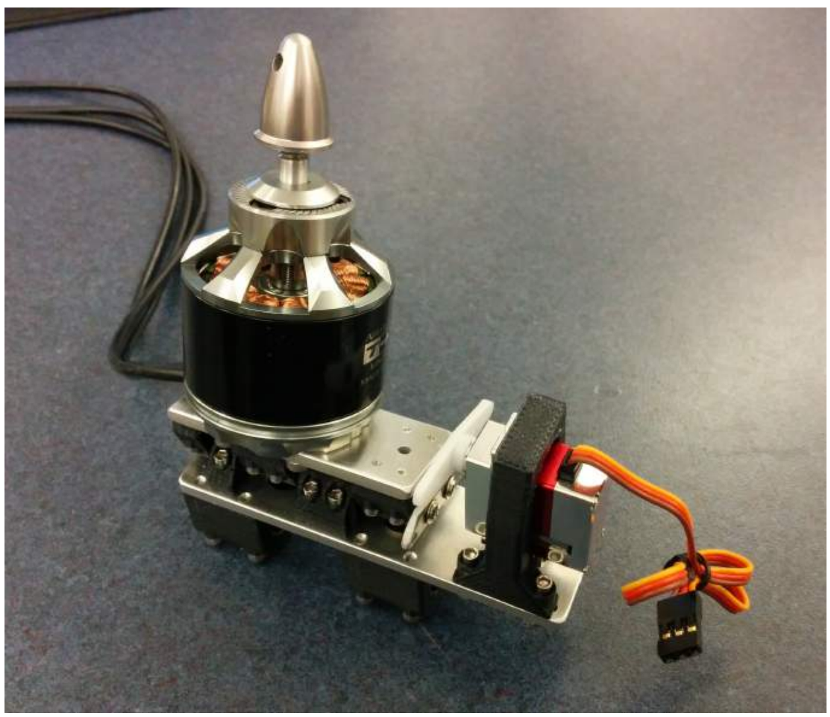


Figure 18: The rear motor's tilt-actuation assembly.

5.2 Front Motor Actuation System

The front tilt actuation assembly allows the actuation of the front motors between forward (flight mode) and upward (hover mode). The actuation is performed by a Turnigy TGY-306G servo. The assembly is to be constructed from 3D-printed brackets and some wires. #1-10 screws are used to clamp the bracket to the carbon fibre tube and wires were used to connect the two brackets.

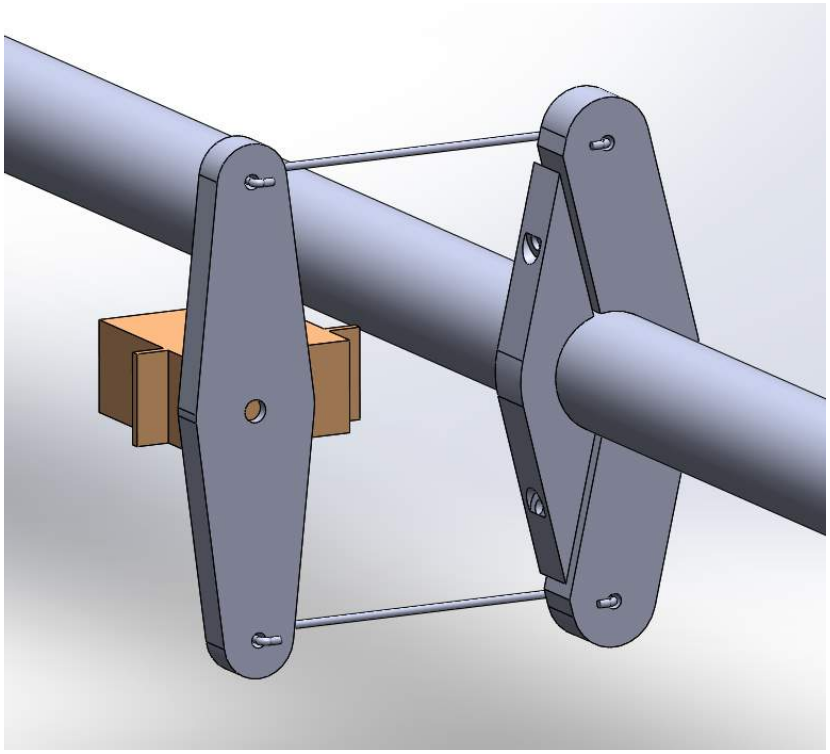


Figure 19: The tiltrotor actuation assembly.

Separately, the motors are clamped to the front tilt assembly using two custom printed parts and some screws. For simplicity, assembly of this motor clasp is shown below and the steps are listed below.

Motor Clasp Components

- Ø1.6mm Wire
- Custom Printed Parts
- 4 M3x10 Socket Head Screws
- 2 M3x30 Socket Head Screws
- 2 M3 Nuts (Locknut Preferred)

Motor Clasp Assembly Procedure

1. Thread M3x10 screws through upper printed component into the Turnigy motor, ensuring side holes are oriented parallel to the motor wires.
2. Attach the two printed components together
3. Thread wires through holes in the side of the printed components and bend them so they are secure

4. Thread M3x30 screws through printed lower component and through holed in carbon fibre tube and use M3 Locknuts to secure.

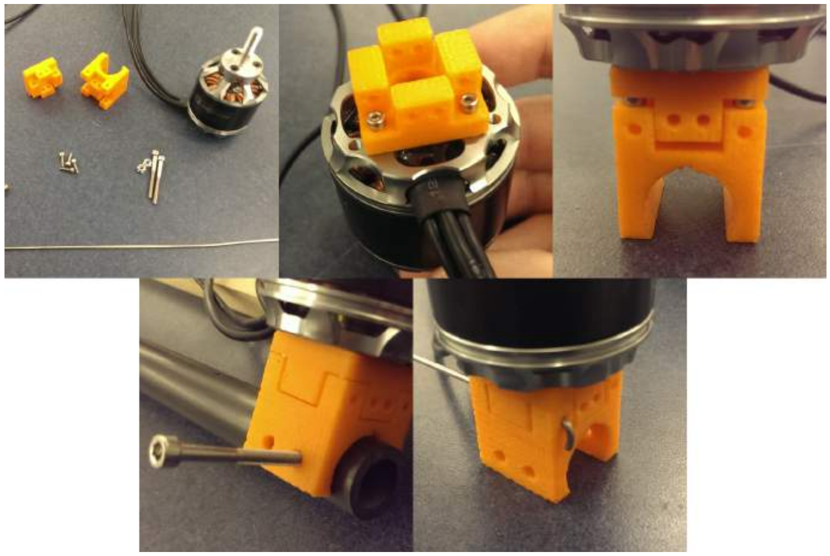


Figure 20: Tiltrotor clasp assembly. Top-left clockwise: Components and steps 1 through 5

6 Assembly

As of Sunday, January 10, construction of the plane is still stalled at the carbon fiber layup process. Resin cure times of 12+ hours, instead of the 2-3 hours indicated on the resin label, stretched layup dates from the estimated two days (January 7 & 8) to over four days (ongoing at present). All steps outlined from here on are preliminary, the planned processes as of January 10 but before actual construction. This section will be updated with pictures and accurate descriptions as additional portions of the plane are completed.

6.1 Servo Installation for Control Surfaces

After carbon fiber layup, sanding, and polishing is complete the next steps are the installation of servos to actuate the ailerons, rudder, and elevator.

The ailerons and elevator use a Kevlar strip sandwiched between the carbon fiber and foam as an internal hinge. This hinge must first be freed; this is done by cutting through the carbon fiber skin and foam down to the Kevlar, from both sides, and clearing away material until the aileron (or elevator) can move freely through at least 30 degrees of motion. Cutting out a wedge-shaped portion of carbon fiber and foam should allow for this motion with only minor damage to the skin of the wing. The internal Kevlar strip should act as a robust hinge, with significantly longer expected life than a traditional pin-attached hinge (as will be used on the rudder).

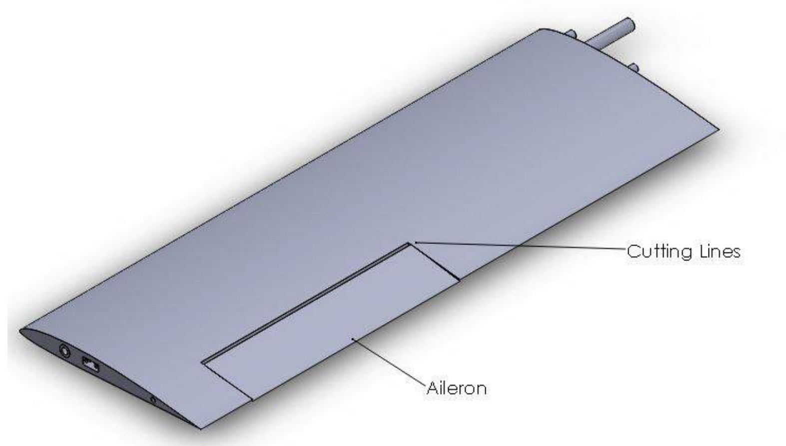
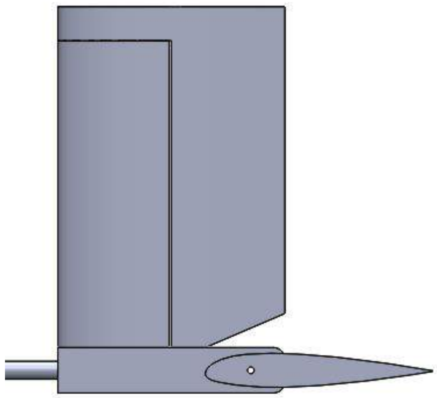


Figure 21: Visualization of the cut-out aileron.

The rudder, however, will use a traditional pin hinge. The rudder will need to be cut cleanly as shown in Figure 22a, then a pin mount will be installed similar to Figure 22b.



(a) Visualization of the rudder cuts.The rudder sits above the elevator.

(b) Example of the pin mechanism used to actuate the rudder. Image via `http://www.modelflying.co.uk/forums/postings.asp?th=100544`.

Figure 22: Rudder visualizations.

The servos will then need to be installed. Holes will need to be cut out from a fixed area near the control surface (e.g. into the wing near the aileron, or into the forward section of the rudder) into which the servos will be glued. Once the glue is set, connect the servos to the pins via a lightweight metal tube.

6.2 Mechanical Sub-Assembly Installation

The mechanical sub-assemblies outlined in Section 5 will also need to be installed. Since these sub-assemblies are all attached via clamped fittings and/or glue, this section will simply outline where these sub-assemblies are to be attached.

The rear motor tilt-actuation assembly, required for tricopter control, is installed by clamping it onto the bar connecting the fuselage to the tail. Screws into the tapped portion of the metal baseplate hold the assembly onto the tube by clamping down through the 3-D printed sections.

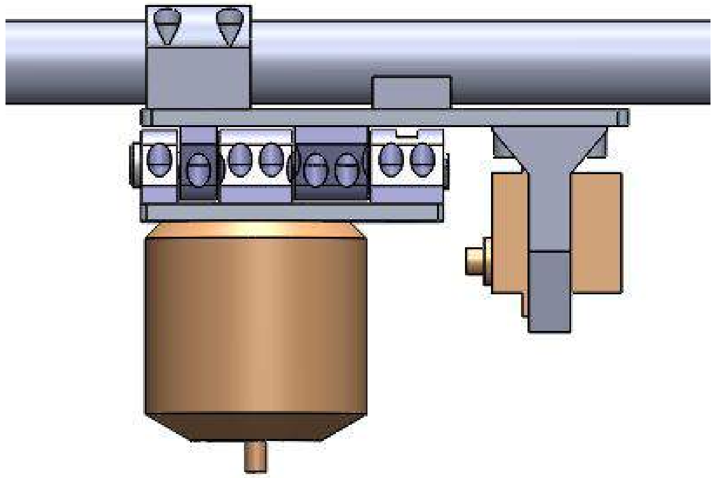


Figure 23: Installation of the rear motor tilt-actuation assembly on the carbon fiber tube connecting the fuselage to the tail of the plane.

Bearings as well as the front tiltrotor bar need to be inserted before the front motors or internal tiltrotor assembly can be installed. The front tiltrotor bar is a 5/8" OD x 32.5" carbon fiber tube.

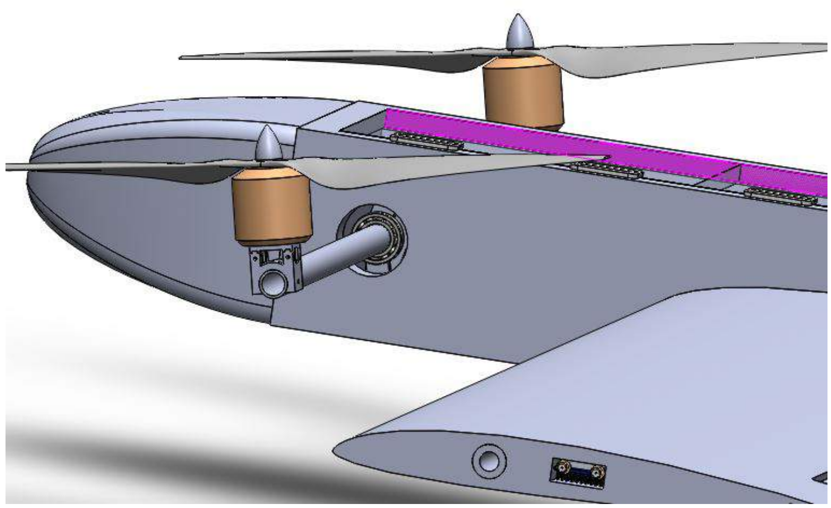


Figure 24: Front of the plane, showing the location of the bearings as well as carbon fiber tiltrotor bar.

After the bar is placed, the motor clasps outlined in the latter part of Section 5.2 can be installed along with the forward motors. Lastly, the tilting actuation assembly itself will be installed. The tilting assembly as well as the motor clasps both hold onto the tiltrotor bar via clamping force and supplemented by glue.

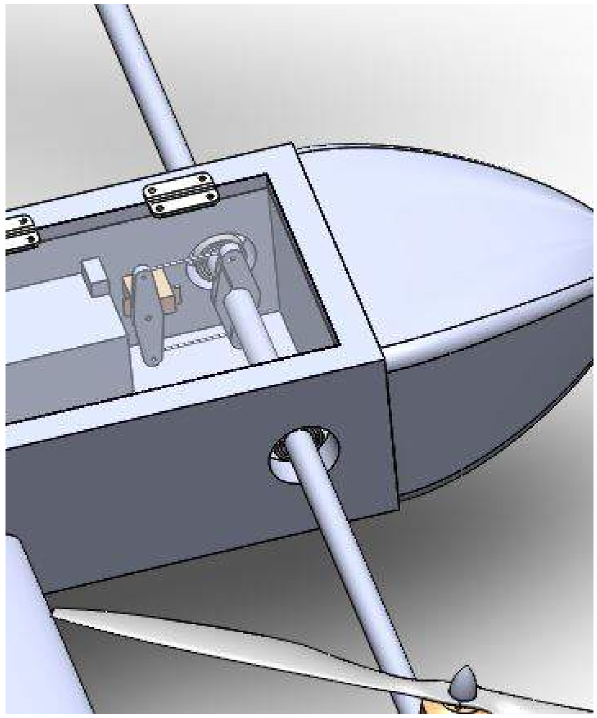


Figure 25: Location of the tilting actuation assembly in the front of the fuselage.

7 Final Notes

This area is reserved for future notes, supplemental to the Recommendations section of the ENPH 479 Final Report, that arise during the final stages of construction of the VTOL plane.