NAVAL POSTGRADUATE SCHOOL

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DEVELOPMENT OF A CROSS-FLOW FAN POWERED QUAD-ROTOR UNMANNED AERIAL VEHICLE

by

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June 2015

Thesis Advisor: Anthony J. Gannon
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DEVELOPMENT OF A CROSS-FLOW FAN POWERED QUAD-ROTOR UNMANNED AERIAL VEHICLE

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The research presented is dedicated to the advancement of construction techniques in order to implement new designs of a vehicle suited for cross-flow fan propulsion. This is accomplished by designing a quad-rotor cross-flow fan that incorporates lessons learned from previous generation models as well introducing novel new construction concepts tailored to cross-flow fan propulsion vehicles. The current vehicle design was built using both custom and standard sections. Commercially available drivetrain and control components are used. The new design focused on three key areas of improvement: airframe simplification, gross takeoff weight reduction and structural rigidity improvement. At all phases the construction and emphasis on using readily available technologies or minor modifications to these was maintained. Novel techniques in construction are presented that allow these technologies to be leveraged. Finally, a new vehicle was built and tested and shown to be able to take-off vertically and be fully controllable in pitch, yaw, and roll.

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LIST OF ACRONYMS AND ABBREVIATIONS

BEC	Battery eliminator circuit
CFD	Computational fluid dynamics
CFF	Cross-flow fan(s)
CNC	Computerized numerical control
COTS	Commercial-off-the-shelf
ESC	Electronic speed controller
GTOW	Gross take-off weight
HVAC	Heating ventilation and air conditioning
LiPo	Lithium-ion polymer
PLA	Polylactic acid, 3-D printer filament
PVA	Polyvinyl alcohol
PREPREG	(Carbon fiber) pre-impregnated with resin
QR	Quad-rotor
STOL	Short take-off and landing
TPL	Turbo Propulsion Laboratory
UAV	Unmanned Aerial Vehicle(s)
VTOL	Vertical take-off and landing

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I. INTRODUCTION

A. BACKGROUND

Cross-flow fan (CFF) geometry is unique in comparison to other common turbomachinery such as axial fans, or turbines. These are typically longer in relation to their diameter and rotate about a longitudinal axis. Cross-flow fans are comprised of many long blades placed in a circular pattern at a constant radius from the longitudinal axis. The working fluid passes radially through the fan, and thus passes each blade twice. As a result, a cross-flow fan is able to achieve equal pressure differences with the same flow rate at lower rotating speeds in comparison to other fans [1]. While this comparison is favorable, perhaps the most useful aspect of cross-flow fan technology in certain applications is the flat sheet of air that is exhausted from the fan. Figure 1 is an example of cross-flow fans used in heating, ventilation and air conditioning industry. The Naval Postgraduate School has been developing [2], [3], [4] CFF technology as a means to power vertical take-off and landing aerial vehicles (VTOL). An example of a thrust optimized CFF is shown in Figure 2.

Figure 1. Modern HVAC cross-flow fan by Pelonis Technologies, from [5].

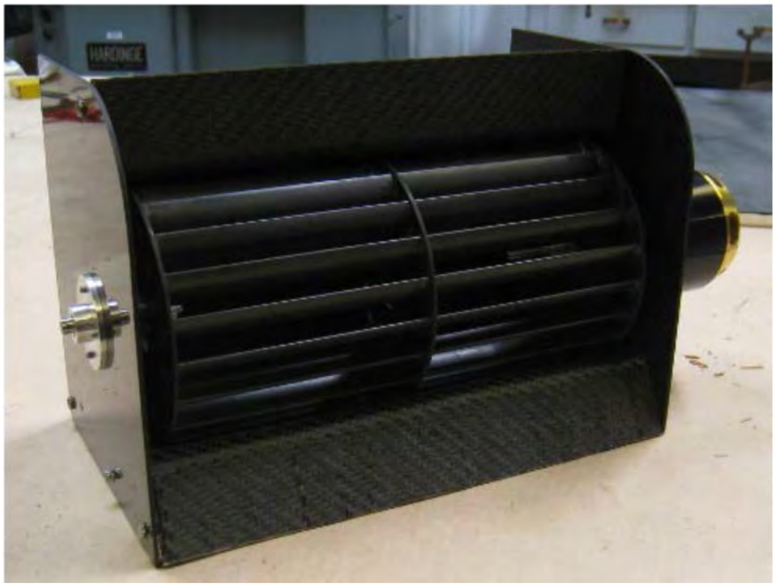

Figure 2. Carbon fiber cross-flow fan and housing unit, from [4].

B. OVERVIEW

There are many types of propulsion techniques currently used in military applications. On aircraft carriers, for example, jet and propeller driven aircraft are able to take off and land on the flight deck due in part to the relative length of an aircraft carrier in comparison to other naval ships, and also due partly to the catapult system which helps propel the aircraft to the necessary speeds to enable transition to flight. The military also employs vertical take-off and landing technology, in the form of rotary wing aircraft such as an SH-60 helicopter, tilt-rotor aircraft such as the MV-22 Osprey, and short take-off and landing (STOL) and vertical landing jet propelled aircraft such as the Harrier, or the Joint Strike Fighter. It is proposed that cross-flow fan technology is a viable technology that is applicable to similar applications and may be superior to helicopters and the Osprey in certain respects.

As previous research on cross-flow fan technology has shown, these types of fans produce similar thrust, lift coefficients, and high-pressure coefficients in comparison to conventional VTOL and STOL designs [6]. An advantage over previous designs comes in the potential to transition to conventional forward flight using lifting surfaces for efficient cruise, and by not having any open rotors reducing the danger of striking external objects. The geometry of a cross-flow fan has a large length to diameter ratio and as a result the flow can reasonably be assumed to be two-dimensional [3]. Cross-flow fans have already been implemented into a wing to achieve conventional flight [6], [7]. The potential exists for such aircraft to take off vertically and then transition to forward flight [2].

Cross-flow fan propelled quad copters share a similar airframe shape to conventional quad copters and also have the potential ability to use the same controllers.

C. LITERATURE REVIEW

Cross-flow turbomachinery technology was first patented by Paul Mortier [8] in 1893. Although the design of cross-flow turbomachines has evolved over time, the concept of operation from Mortier's original turbine design as show in Figure 3 remains the same.

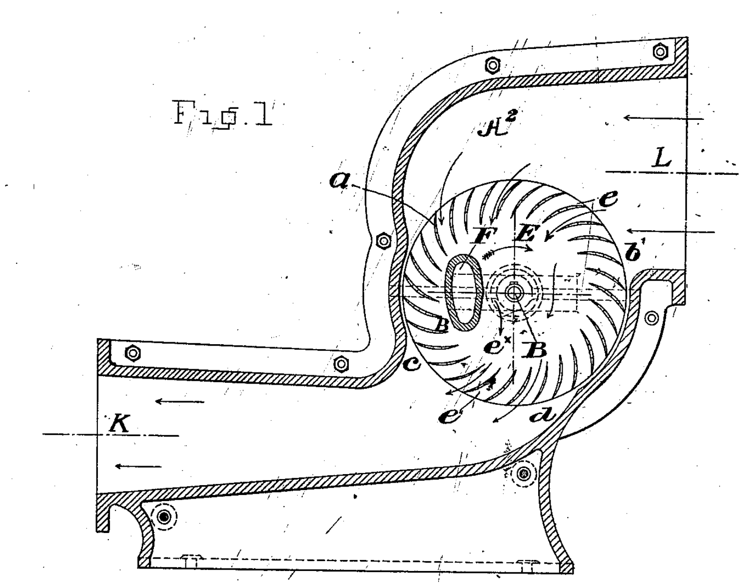

Figure 3. Original cross-flow turbo machine, from [8].

Cross-flow fan technology has been widely used in the heating, ventilation and cooling industry. Cross-flow fans are the fan of choice for this industry as they are relatively inexpensive to produce due to their simple design and the large flat sheet of air that they produce [5]. Pelonis [5] prefers this fan design in the HVAC business and claim that cross-flow fans provide exceptional aerodynamic properties, they operate efficiently, are durable, easy to maintain, and are highly versatile. The fan is typically enclosed in a rectangular housing unit that can be easily adapted to fit in many commercially available spaces more easily than a traditional axial fan. In the early 2000s, NASA stimulated resurgence interest for cross-flow fan technology to be utilized in aircraft [9], and as a result, much research has been focused on optimization and implementation of this technology for this application.

Gossett [9] showed the viability of cross-flow fan technology implemented in a single seat light weight VTOL aircraft.

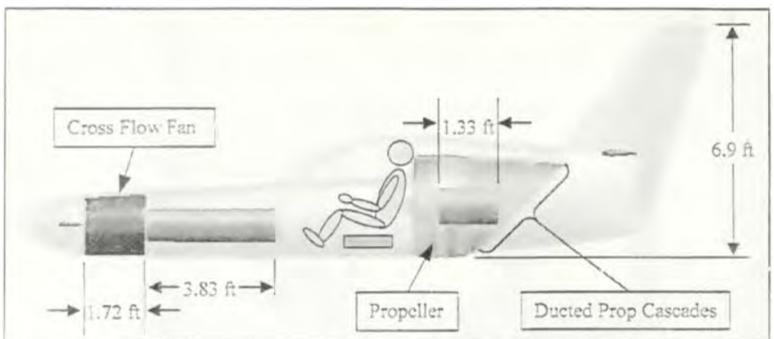

Figure 4. Conceptual design of VTOL Aircraft, from [9].

Seaton [10] further developed the concept of cross-flow fan propelled aircraft by designing a unique fan-in-wing installation that he claimed would increase lift produced by the wing by pressure reduction in the low-pressure region of the upper surface of the airfoil.

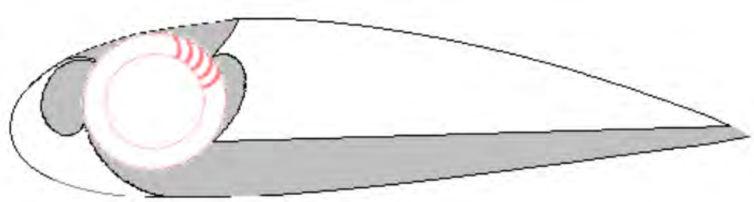

Figure 5. Conceptual fan-in-wing installation, from [10]

Delagrange [3] developed a more optimal fan housing unit for a commercial-off-the-shelf rotor, using CFD software [3]. The housing unit was fabricated and paired with a commercial fan. CFD results were experimentally validated using results from this test rig; the experimental apparatus is shown in Figure 6.

Figure 6. Experimental test rig, from [3].

Kwek [11] predicted a thrust-to-weight ratio improvement of nearly 40 percent from 0.616 to 0.861 over the straight-bladed CFF used by Delagrange by utilizing a helical blade design. Kwek used CFD software to model a helical blade design, shown in Figure 7.

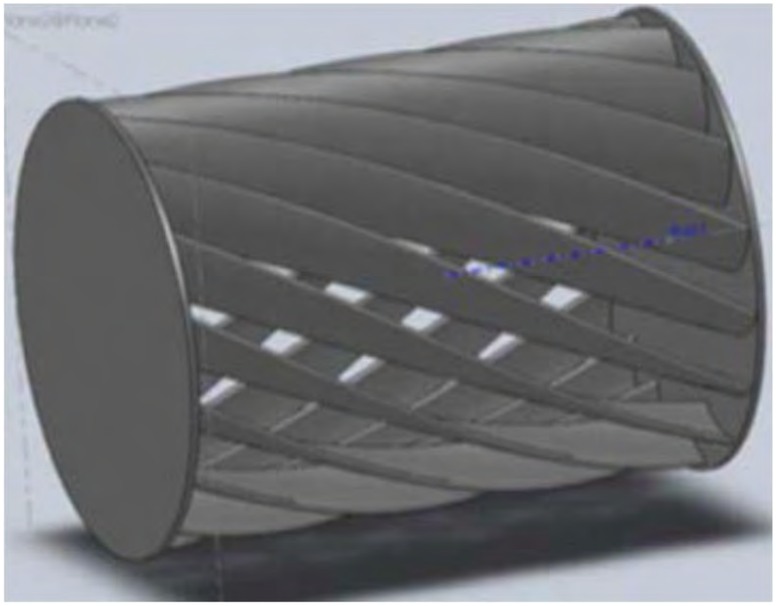

Figure 7. Helical fan blade model, from [11].

Yeo [12] showed that putting two fan units back to back did not necessarily improve lift over a single fan design. Furthermore, the researched proved that the elevation of the exhaust with respect to the ground could adversely impact thrust due to backflow.

Martin [4] determined the optimum number of blades for a fan rotor diameter of 102 mm (4 inches). He showed that his rotor produced a thrust-to-weight ratio greater than one, which is critical for VTOL aircraft. This research also experimentally validated CFD results using working models of three different rotor designs at a range of speeds; see example in Figure 2.

Jones [2] built a carbon fiber airframe and integrated four cross-flow fans powered by two motors and proved through testing that the design generated sufficient thrust for vertical take-off, shown in Figure 8.

Subsequent to Jones' work a full CFF quad-rotor was built and successfully flown in tethered mode. The summary of all previous work was presented by Hobson et. al, [13] during which a audio visual recording of the flight was shown. Figure 9 shows a screen shot from the video.

Figure 8. Airframe with four fans powered by two motors, from [2].

Figure 9. Successful tethered vertical take-off and landing, from [13]

Commercially, Kummer and Allred, the proprietors of Propulsive Wing LLC, have had the greatest success implementing cross-flow fan technology into an aircraft. These researchers invented a STOL aircraft with an extensive list of design features that enhance the flight characteristics of their aircraft, shown in Figure 10.

Figure 10. Propulsive Wing 4, from [7].

Kummer and Allred patented a cross-flow fan propulsion system [7]. The following quote from Kummer and Allred's patent showed the advantages of the propulsive wing concept compared to conventional systems.

> The propulsion system includes a combined propulsor, flow control device, and cargo-carrying platform with large thickness-to-chord ratio cross-section (ranging from 20% up to 50% or more), which provides a compact, cost-effective short takeoff and landing (STOL) or vertical takeoff and landing (VTOL) solution. With its unique thick-wing design, the cross-flow propulsion mechanism within a distributed cross-flow fan wing can carry 3 times the payload weight and 10 times the internal payload volume of conventional systems. For this reason, the aircraft is considered an aerial utility vehicle, or AUV. The platform is also highly maneuverable, generates low noise, and offers a high degree of user safety due to the elimination of external rotating propellers. The present invention includes several improvements to cross-flow fan propulsion technology, including improved control, a dynamically adjustable vortex wall and internal housing, a vortex tube, vertical takeoff and landing rotorcraft configurations, the inclusion of an optimized oscillating blade fan, a wavy vortex wall, power plant refinements, dual leading and trailing edge configurations, stability improvements, tip plates, tapered wings, tapered fans, a fan construction method and underwater applications. [14].

The propulsive wing greatly improved lift, and resulted in angles of attack up to 60 degrees and lift coefficients greater than 10 at takeoff and landing [14]. This is visualized in Figure 11.

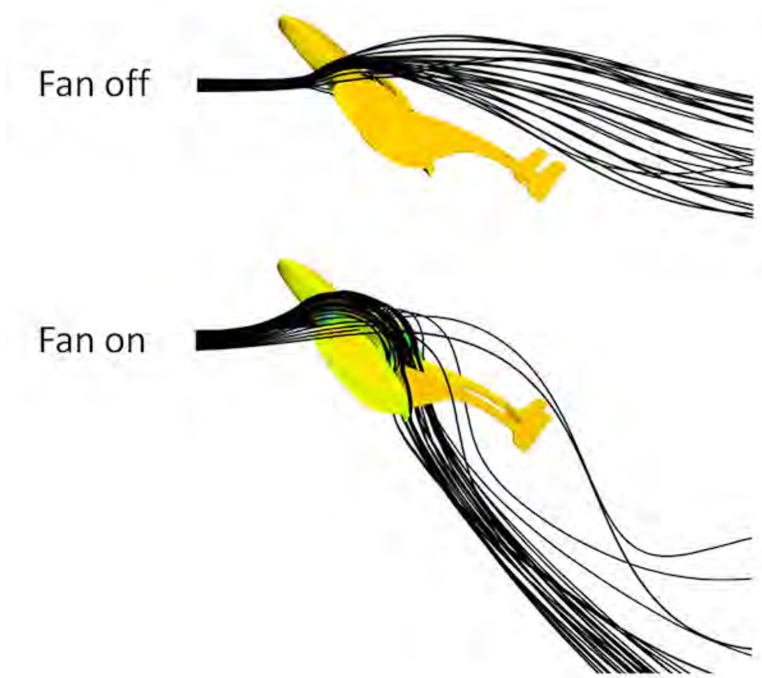

Figure 11. Streamlines at high angle of attack, from [7].

D. OBJECTIVES

The primary objective of this project was to create a completely new quad-rotor cross-flow fan UAV capable of vertical take-off and controllable flight by developing new construction techniques, and by implementing the strengths and improving upon the weakness of the previous quad-rotor cross-flow fan UAV design created at the Turbopropulsion Laboratory [2]. In order to achieve the primary objective, three improvement areas were identified. They were; airframe simplification, gross takeoff weight reduction and structural rigidity improvements. These will be implemented using more modern off-the-shelf technology and are detailed in subsequent sections of this report. In summary, new designs were created that resulted in marked improvements over the previous generation of vertical take-off cross-flow fan aircraft.

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II. DESIGN

A. FIRST AND SECOND-GENERATION BACKGROUND

Jones' [2] vehicle proved that vertical flight was achievable. This design relied on a configuration with two motors and four fans. The SolidWorks model is shown in Figure 12. This platform was tested by tethering the airframe to multiple cinder blocks, and by running cables directly from electronic speed controllers on the airframe to the potentiometer control station [2]. This provided a simple method to control the speed of both motors. Vertical flight was proven with this design, resulting in a thrust to weight ratio of 1.79 [2]. The successful vertical flight was previously shown in Figure 9.

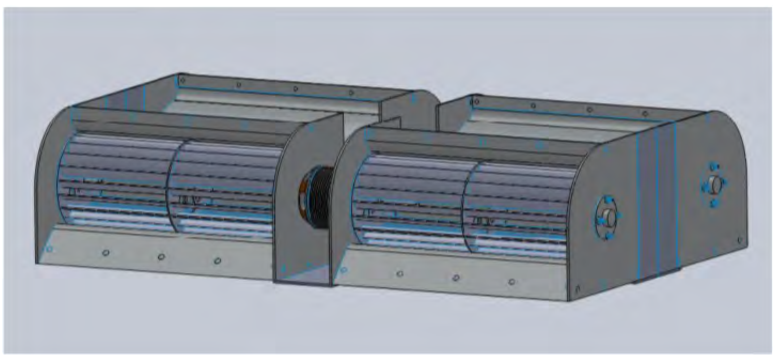

Figure 12. SolidWorks design, Generation 1. From [2].

The second quad-rotor cross-flow fan UAV was assembled at the Turbo Propulsion Laboratory following the work by Jones [2], and her design proved that vertical flight was indeed readily achievable but had no method to control flight. The main objective of the second design was to prove the new airframe design could be controlled. Notable changes incorporated into the second design were a configuration with four motors, increased length and width of the airframe footprint, landing feet, upper and lower stiffening members, and lastly a radio control system; see Figures 13 and 14. The construction of this airframe relied heavily on mechanical connections that vibrated loose during relatively short test flights. This created a significant vibration problem that limited the controllers' ability to function properly and thus the remote pilots' ability to control flight. As a result, significant time was spent constantly adjusting the connection points to ensure no spinning parts rubbed against airframe components and cross-flow fan housing panels. The second-generation design proved vertical flight with control was achievable. As a result of testing with this airframe, it was realized the potential existed to improve upon the design's structural weaknesses and further improve the controllability.

Figure 13. Second-generation, front perspective.

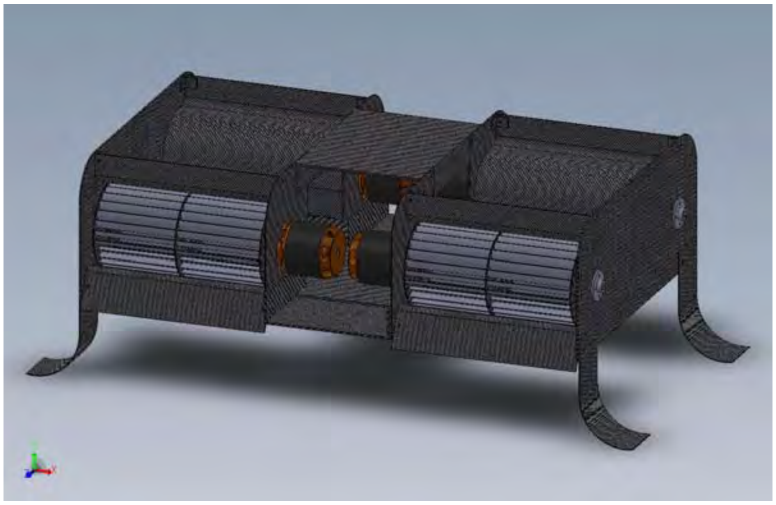

Figure 14. Second-generation, top perspective.

B. THIRD-GENERATION VEHICLE DESIGN OVERVIEW

As mentioned the third-generation vehicle design program focused on three key areas; airframe simplification, gross takeoff weight reduction and structural rigidity improvements. These will be implemented using more modern off-the-shelf technology

The orientation of the fans was changed in the third-generation vehicle design. Firstly, the cross-flow fans were rotated 90 degrees with respect to both adjacent fans. This effectively changed the footprint from rectangular to square. The majority of commercially available quad-copters employ a similar fan arrangement, with rotors placed at four corners and each fan equidistant to the center of geometry. Secondly, in order to minimize the effects of pitch and roll inherent in the first- and second-generation designs, the third-generation vehicle benefited by fans placed further apart. As a result, the polar moment of inertia was increased as was the thrust moment arm of each cross-flow fan. The intent of these two aforementioned design features was to improve the flight controllability.

The design of the third-generation vehicle reduced the dependence on small nuts and bolts. Instead, permanent epoxy connections and semi-permanent clamp-style connections were implemented whenever possible. The design was intended to be easily maintainable with simple disassembly. This design feature provided two advantages. Firstly, reducing the number of nuts and bolts lowered the gross take-off weight (GTOW) and simplified assembly. Secondly, structural rigidity improved by replacing the nut-bolt connections with permanent and semi-permanent clamp-style connections. Figure 15 shows the initial SolidWorks model.

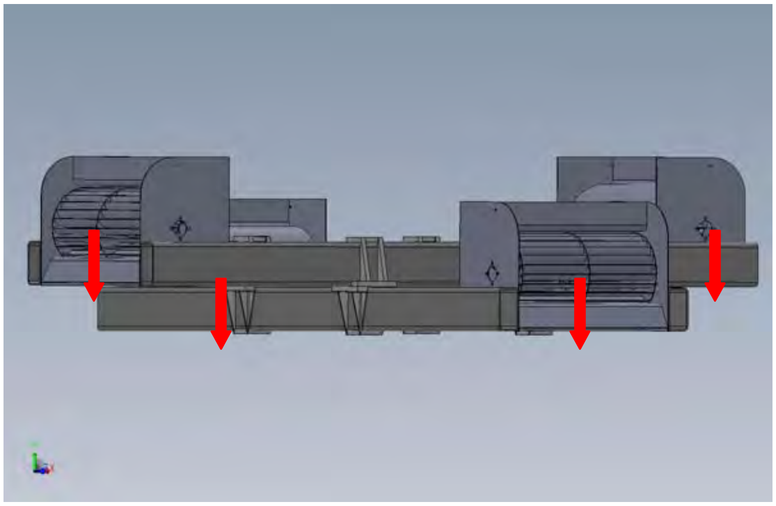

Figure 15. Initial design, quarter perspective.

As can be seen in Figure 15, the initial design did not have yaw control. In order to remedy this design flaw, yaw control was gained by rotating each fan clockwise or counter-clockwise as appropriate; see Figure 16.

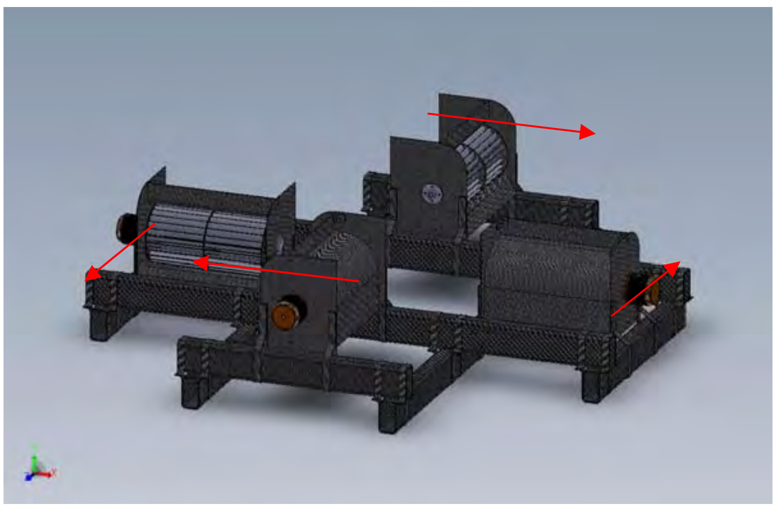

Figure 16. Generation 2, with yaw control, trimetric perspective.

1. Airframe Simplification and Structural Rigidity

As mentioned, the previous designs were complex, and warranted a redesign. To eliminate previous design problems, structural carbon fiber tubing was chosen as the design centerpiece; see Figure 17 as these are commercially available. The custom built CFF housings are manufactured with five layers of carbon fiber versus the previous three to improve their stiffness. The method of fastening the cross-flow fan housing units to the airframe was improved using carbon fiber clamps. Carbon fiber clamps were the joining member between the housing units and airframe. Epoxy was used when possible, and nuts and bolts were used as required to facilitate disassembly for maintenance and repair.

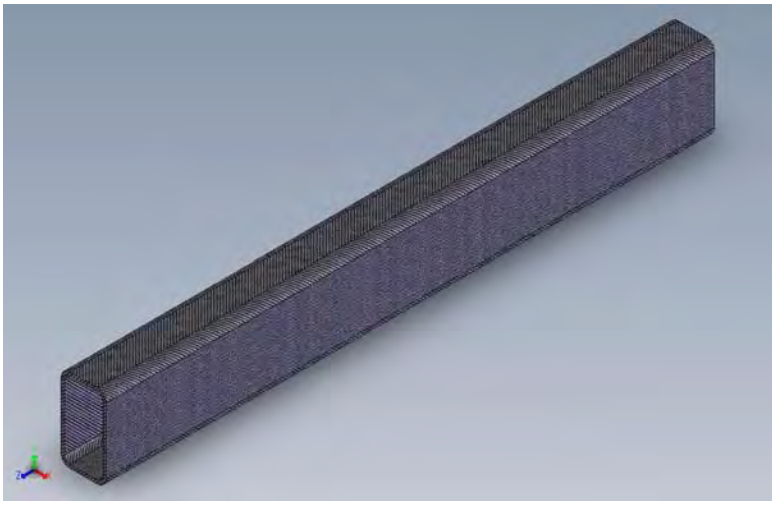

Figure 17. Rectangular cross-section carbon fiber tubing.

2. Carbon Fiber Frame Clamps

A precise, quick, and simple method to fabricate airframe clamps was used. A three-inch length of the carbon fiber tubing was cut and then bolted to an aluminum base plate to form the clamp mold; see Figure 18.

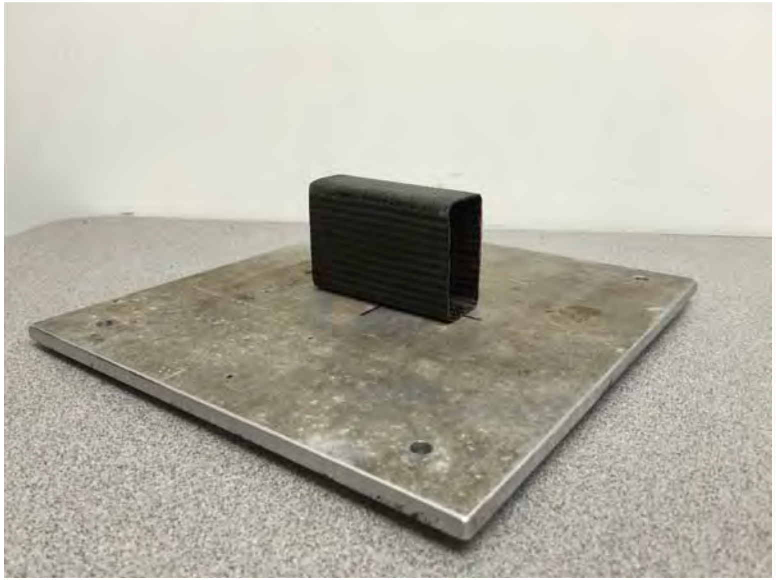

Figure 18. Tubing mold assembly used to make carbon fiber frame clamps.

A larger mold was made to increase production. The final clamps were rigid, lightweight, and precisely fit in unison with the rectangular cross-section carbon fiber tubing; see Figure 19.

Figure 19. Carbon fiber clamp before cut.

3. Carbon Fiber Frame-Housing Clamps

The frame-housing clamps have to provide a rigid connection between the fan housing unit and the carbon fiber framing tubes. Two design options were investigated. In the first a custom clamp was developed; shown in Figure 20. The second design was ultimately chosen and uses commercially available carbon fiber angle, shown in Figure 21.

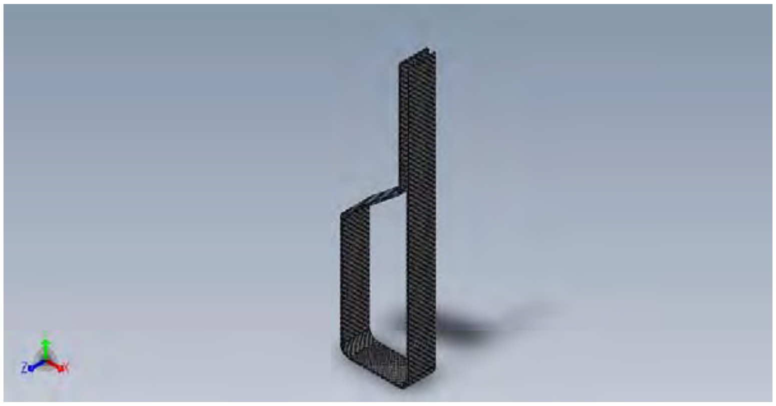

Figure 20. Frame-housing clamp option 1.

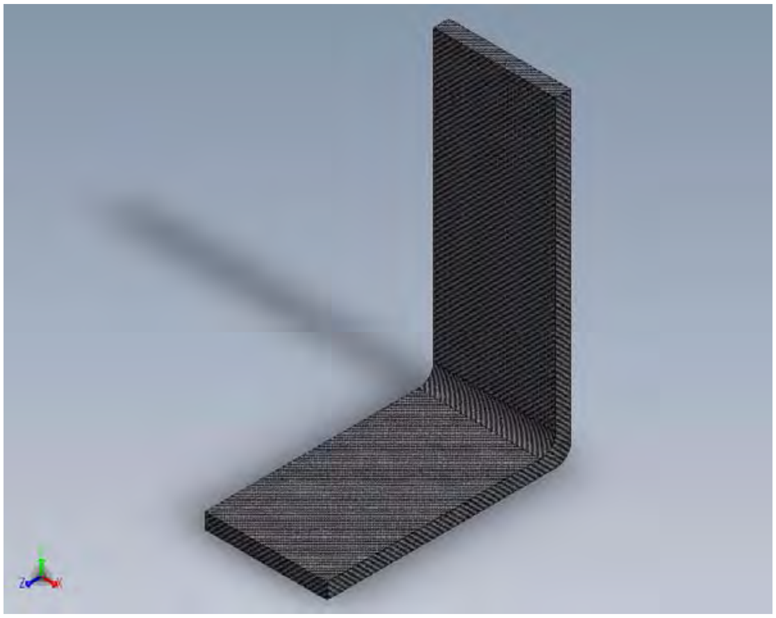

Figure 21. Frame-housing clamp option 2.

4. Intake Housing

Intake housing plates were made utilizing carbon fiber lay-up and vacuum bag techniques. The shape of the airfoil was designed in SolidWorks. The SolidWorks file was exported into the CNC cutting machine, and multiple wood forms were cut. The form for the intake housing was assembled previously at the TPL. For this mold, the wood parts were cut by a CNC machine, were clamped together on a metal plate, and then underwent the same processing steps detailed previously; see Figure 22 for the final product. Using this mold, intake housing plates were laid up, vacuum bagged, and baked to fabricate the final product, shown in Figure 23.

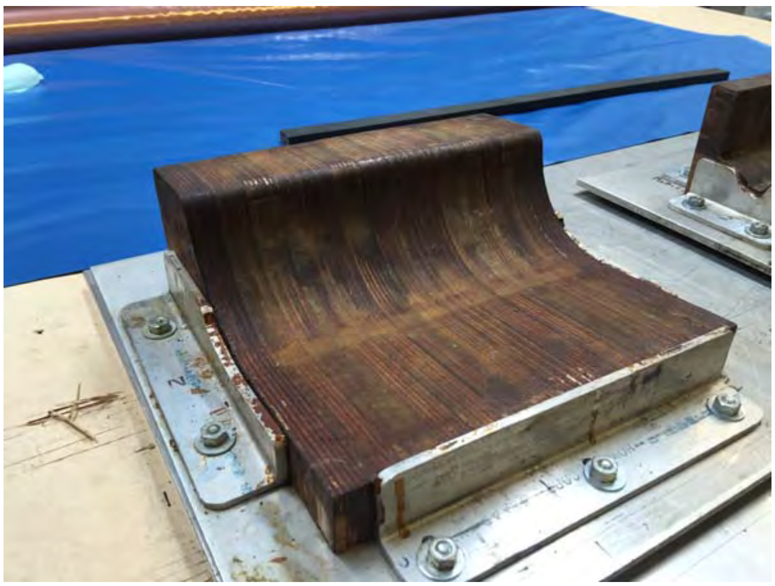

Figure 22. Intake housing mold.

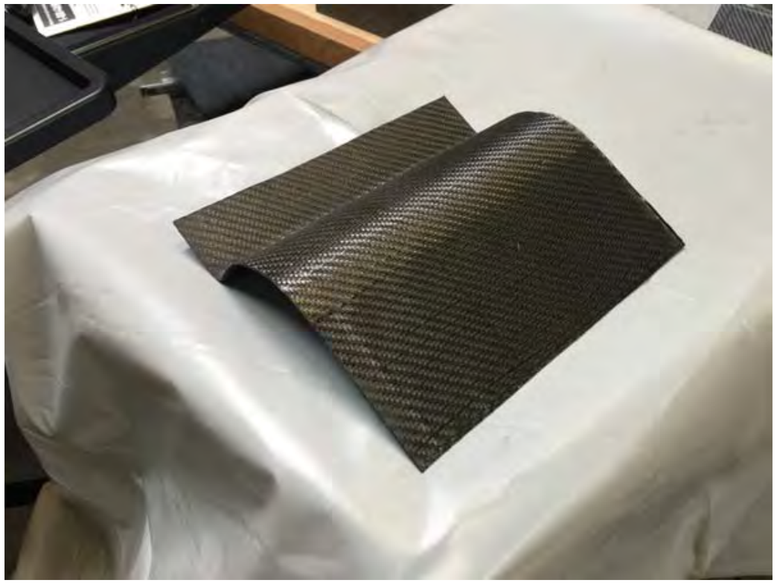

Figure 23. Carbon fiber intake housing.

5. Exhaust Housing

The process for making the exhaust housing was the same used for the intake housing; see Figure 24. The geometry of the exhaust housing had smaller radius curvatures than the intake housing. This made the vacuum bagging process more challenging. The best method found to avoid punctures in the vacuum bag was to significantly increase the size of the bag. To prevent excess vacuum bag material from touching oven heater elements, the excess was folded on top of itself and secured using yellow sealant tape. Once this method was perfected, the lay-up and vacuum bag processes consistently produced usable carbon fiber parts; see Figure 24 and 25.

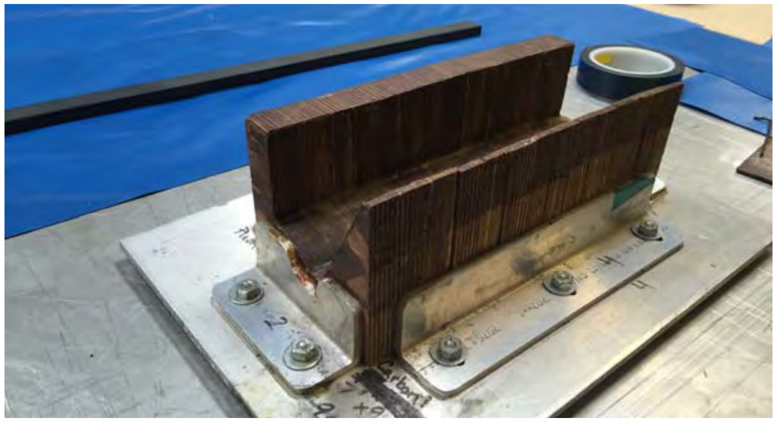

Figure 24. Exhaust housing mold.

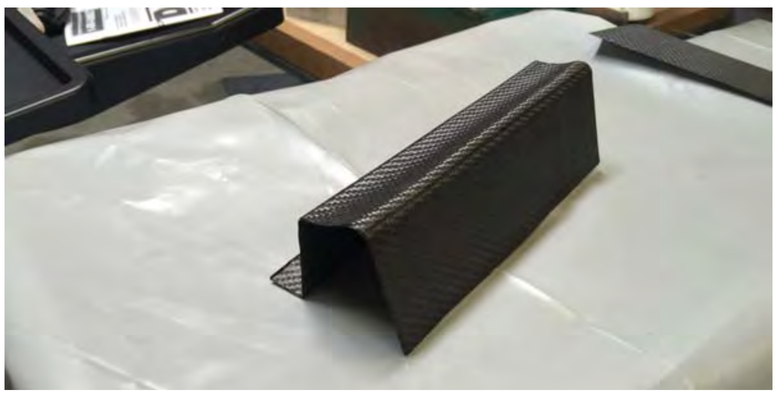

Figure 25. Carbon fiber exhaust housing.

6. Rotors

The rotors were originally developed by analytical (computational) and experimental optimization by Martin [4]. Four rotors of Martin’s design were manufactured by the company Allred and Associates, Inc. Figure 26 shows an example 26-bladed rotor.

Figure 26. Complete manufactured 26-bladed rotor, from [4].

7. End Plates

End plates for the fan housing units were essential. These plates provided motor mounting, bearing mounting for the fan axles and the end plates supported the entire airframe structure via the frame-housing clamps as detailed in Section 3. The end plates were adapted from Delagrange's initial design [3]. A model of the end plate was created in SolidWorks, shown in Figure 27. The end plate drawing file and the carbon fiber plates were sent to Advanced Laser & Waterjet Cutting Inc. The final product returned by Advanced Laser and Waterjet Cutting Inc., was cut to a tolerance of 0.005 inches and was ready for the build process; see Figure 28.

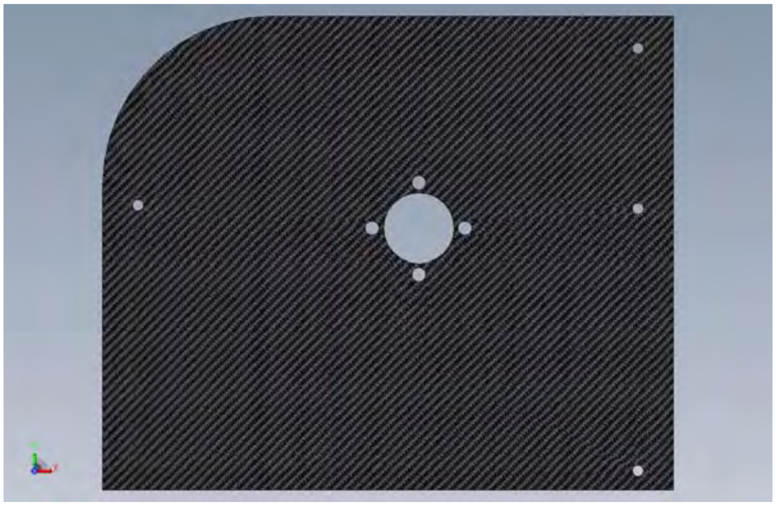

Figure 27. End plate SolidWorks model.

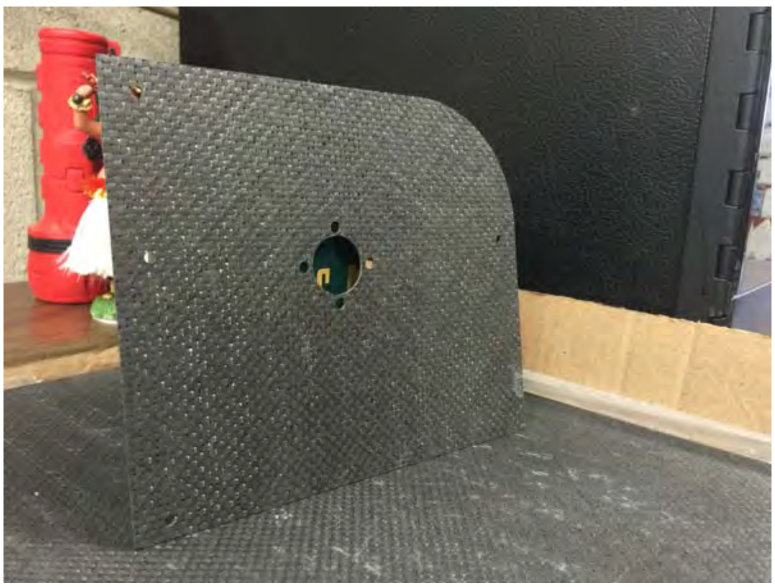

Figure 28. Carbon fiber end plate.

III. THIRD-GENERATION VEHICLE BUILD AND TESTING

A. STRUCTURAL COMPONENTS

Full details of the third-generation vehicle assembly process are included in Appendix A. It was essential that accurate jigging was used to ensure that the assembly was rigid, ensuring alignment of the rotors. The extensive use of epoxy required overnight cure time at a minimum before any further work could commence. Accurate measurements were made before cutting, drilling, and mounting components. This method helped to ensure dimensional accuracy, proper bolt-hole alignment between adjoining parts, and the same axis of rotation for opposing fans. When possible, the center of gravity was kept low to aid in stability and to improve the moment of inertia about the vertical axis to help produce optimal control response. For this reason, the fan housing units were integrated with the motors oriented inwards. Similarly, the batteries were secured to the lowest tube in the center of the airframe, and all other electronic components were routed low along central airframe tubes and on the carbon fiber component plate that spanned the center of the airframe. Figure 29 and 30 visualize the aforementioned description.

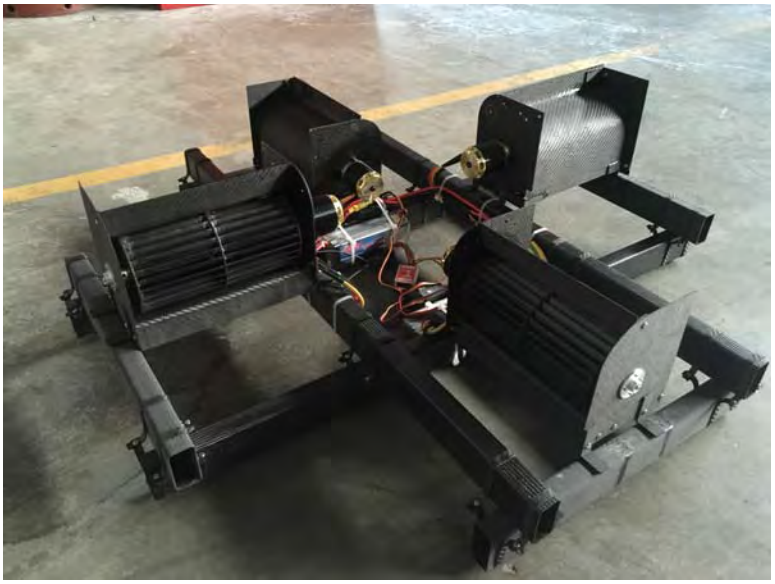

Figure 29. Third-generation, isometric view.

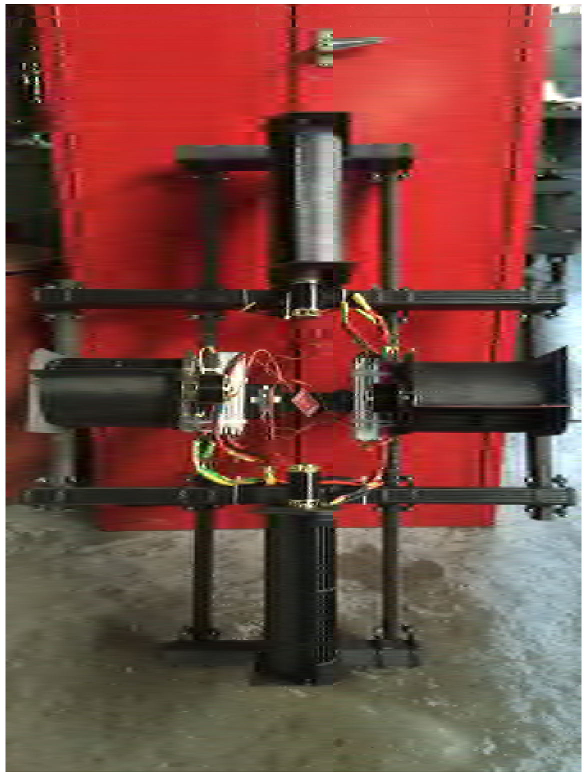

Figure 30. Third-generation, top view.

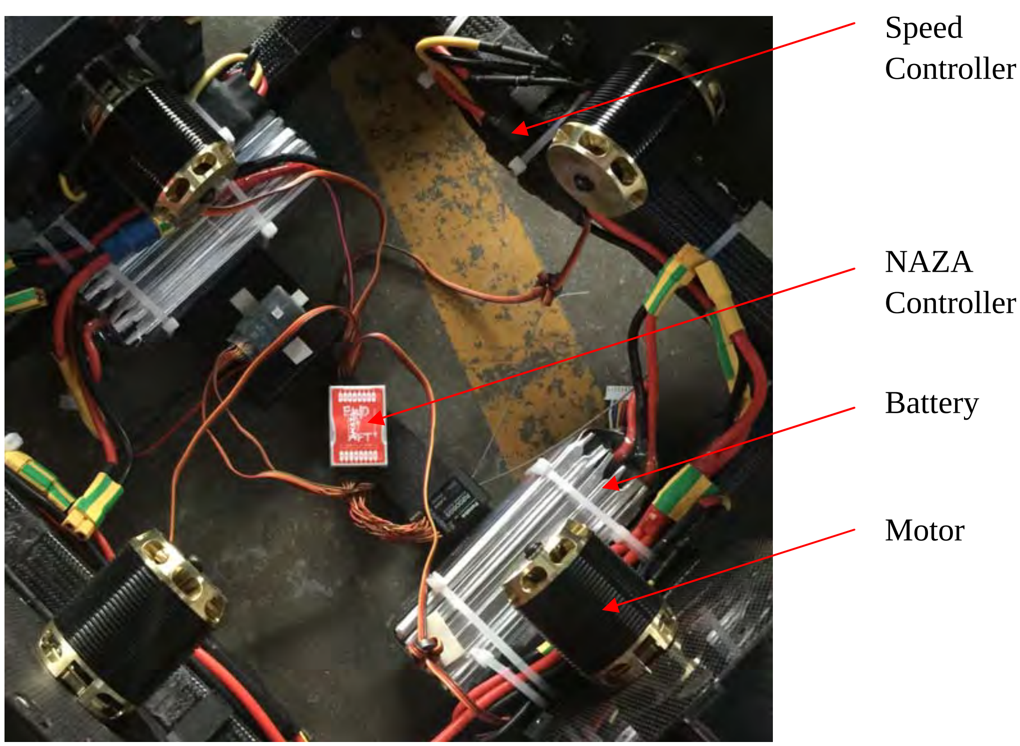

Figure 31. Third-generation wiring harness layout.

B. POWER AND ELECTRONICS

Controller: Two controllers were chosen as options for the third-generation vehicle design. They were the Pixhawk and the NAZA-M. Initially, both controllers appeared to be suitable and were readily available [15]. Ultimately the NAZA-M was chosen. The Pixhawk was tried, but it did not work. The NAZA-M had been used at the Turbo Propulsion Laboratory on previous generation airframes, and as a result there was a fair amount of corporate knowledge regarding NAZA-M operational characteristics, and how to tune the controller. It was unknown how the Pixhawk functioned, and how to implement it into a new airframe. To gain insight into how the controller performed a fully assembled X8+ quad copter and a do-it-yourself quad-kit were purchased. NAZA-M and Pixhawk controller specifications are provided in Table 1 and Table 2.

3DR Pixhawk				
Options	**Microprocessor**	**Sensors**	**Interfaces**	**Power System**
PPM Encoder	32-bit core	3-axis 16-bit gyro	5x UART (serial ports)	Ideal diode controller
Ext USB and LED module	168 MHz / 256 KB RAM / 2MB Flash	3-axis 14-bit accelerometer	2x CAN	Servo rail high-power / high-current ready
Digital airspeed sensor	32-bit failsafe co-processor	3-axis accelerometer/gyro	Satellite compatible input	Peripheral outputs over-current protection
Telemetry radios		Barometer	S.BUS compatible I/O	Inputs ESD protected
GPS with compass			PPM sum signal	
			RSSI input	
			I2C	
			SPI	
			3.3 / 6.6 V ADC inputs	
			External microUSB port	

Table 1. Pixhawk controller specifications, from [16].

NAZA - M	
Dimensions	45.5 x 31.5 x 18.5 [mm]
ESC Output	400 [Hz] refresh frequency
Transmitter	PCM
Working Voltage Range	4.8-5.5
Yaw Angle Velocity	200 [deg/2]
Max Tilt	45 [deg]
Built-in Functions	Three mode autopilot
	Enhanced fail-safe
	Low voltage protection
	S-bus receiver support
	2-axle gimbal support

Table 2. NAZA – M controller specifications, from [17].

X8+: The premise behind procuring a fully assembled commercially available drone, shown in Figure 32 was to gain an opportunity to see how the Pixhawk controller functioned in flight, as well as how the controller was set up in a known working package. As a result, valuable insight was gained by flying the X8+. Also, the X8+ provided a fully assembled example of how to properly connect all peripheral components to the controller.

Figure 32. 3DRobotics X8+.

Motors and Batteries: Various motors were tried and the ones that were sufficiently powerful were the Scorpion Power System HKIII-4035–560KV motors. The most recent motors tested that were not powerful enough were the Scorpion Power System HKIII-4025–330KV motors. The batteries chosen were Thunder Power RC TP5000–6SM70. Previous generation airframes relied on four batteries, each one independently powering one motor. Testing proved that two batteries wired in parallel provided sufficient power to match the demand of all four motors. The wiring diagram is presented in Figure 50. Parallel wiring of the batteries also provided some redundancy in the case of a single battery loosing charge during flight. The motor and battery specifications are provided in Table 3 and Table 4, respectively.

HK-III-4035-560KV	
Motor Kv	560KV [RPM/V]
Max Continuous Current	100 [A]
Max Continuous Power	4200 [W]
Weight	460 [g]
Drive Frequency	8 [kHz]

Table 3. Motor specifications, from [18].

TP5000-6SM70	
Max Charge	12 [C]
Max Charge Current	60 [A]
Max Continuous Discharge	70 [C]
Max Continuous Current	350 [A]
Max Burst	140 [C]
Max Burst Current	700 [A]
Weight	796 [g]

Table 4. LiPo battery specifications, from [19].

Electronic Speed Controllers: Cobra 150 ampere electronic speed controllers were chosen. Previous work proved the Cobra 150 Amp ESC capable of handling the electrical load of the cross-flow fan propulsion system. The electronic speed controller specifications are shown in Table 5.

Cobra 150 Amp ESC Specifications	
Weight (Without Connectors)	82 grams (2.89 oz)
Max Continuous Current	150 Amps
Burst Current rating (15s)	188 Amps
Operating Voltage Range	6 to 26 Volts
Number of Li-Po cells	2 to 6 cells
Number of Ni-XX cells	6 to 20 cells
Number of Li-Fe cells	2 to 7 cells
Switching BEC Output	6 amps @ 5.5 Volts

Table 5. ESC specifications, from [20]

C. FLIGHT TESTING AND RESULTS

All flight testing was conducted indoors at the Turbopropulsion Laboratory. Flight tests were conducted with an arrestor line in the case of loss of control.

As was previously mentioned, the Pixhawk controller was tried, but ultimately the third-generation design implemented the NAZA-M controller. Initial testing with the Pixhawk was problematic. The issue was resolved by disabling certain preflight checks built into the Pixhawk controller. This enabled the Pixhawk controller to initialize and spin the rotors; however throttle curve settings prevented the rotors from spinning fast enough to generate minimum thrust required for vertical take-off. Next, the NAZA-M was implemented into the design. With this hardware, the third-generation vehicle design spun up on the first attempt, and troubleshooting was not necessary.

Power was sufficient with a hand tethered flight proving this; shown in Figure 33.

Figure 33. Third-generation hand-tended test flight.

Following several hand-tended test flights, a tether line suspended from above was connected. The result was a violent flat spin. Power to the engines was immediately cut, and damage to the airframe was avoided. The cause of the flat spin and apparent lack of yaw control was potentially due to two issues. First, it was suspected that the yaw gain setting for the third-generation vehicle was not ideally calibrated. Second, two of the fan housing units (opposing fan housing units) were situated closer to the ground, which might have caused the thrust vectors to undesirably interact with the ground and dominate the thrust produced by the other two fans, thus inducing a flat spin. Several controller settings were tried to stop the flat spin including reorienting the controller, changing motor pin connection spots, and changing yaw gain values for the controller.

None of the aforementioned approaches remedied the problem, which ultimately guided the project to design and build a fourth-generation airframe.

IV. FOURTH-GENERATION VEHICLE BUILD AND TESTING

As a result of the problems encountered with the third-generation vehicle during flight testing (detailed in Section III.C), an entirely new airframe was designed and built, similar in footprint to the first and second-generation airframes (detailed in Section II.A). The purpose of this additional redesign was multifaceted. Firstly, it was desired to use the NAZA-M in the fourth-generation design. The NAZA-M worked well in first- and second-generation models [21], and as a result and previously mentioned, there was a fair amount of corporate knowledge regarding the NAZA-M controller at the Turbo Propulsion Laboratory. Secondly, it was desired to reconfigure motor orientation in the fourth-generation design so that they more closely matched the available motor assignments of the NAZA-M controller. Lastly, first- and second-generation airframe designs achieved a slightly greater degree of success with flight testing as evidenced in Jones' report [2] than the third-generation vehicle design. Thus it was desired to revert back to proven airframe geometry. The motor assignment option that most closely resembled the motor configuration of the fourth-generation model was the Quad-rotor X, shown in Figure 34.

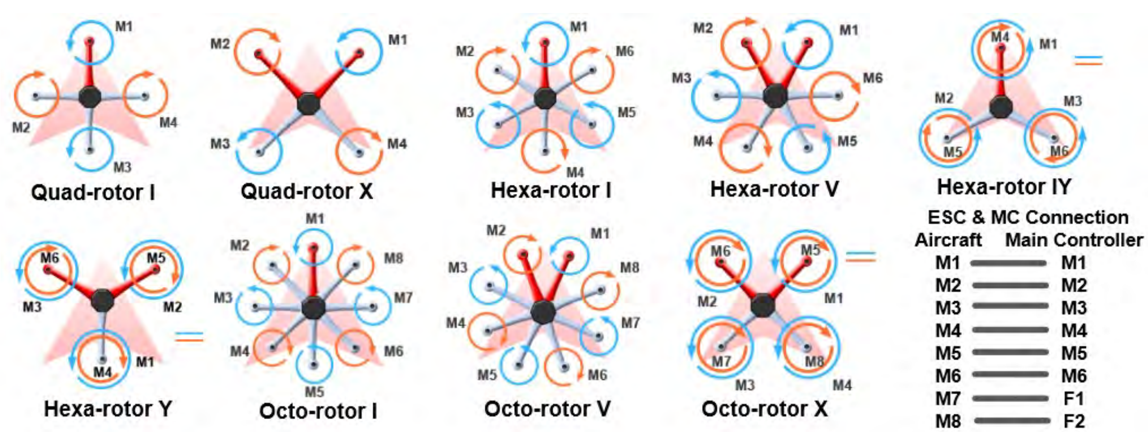

Figure 34. NAZA-M motor configuration options, from [22]

The fourth-generation SolidWorks design is shown in Figure 35 and the fully assembled vehicle is shown in Figure 36 and 37.

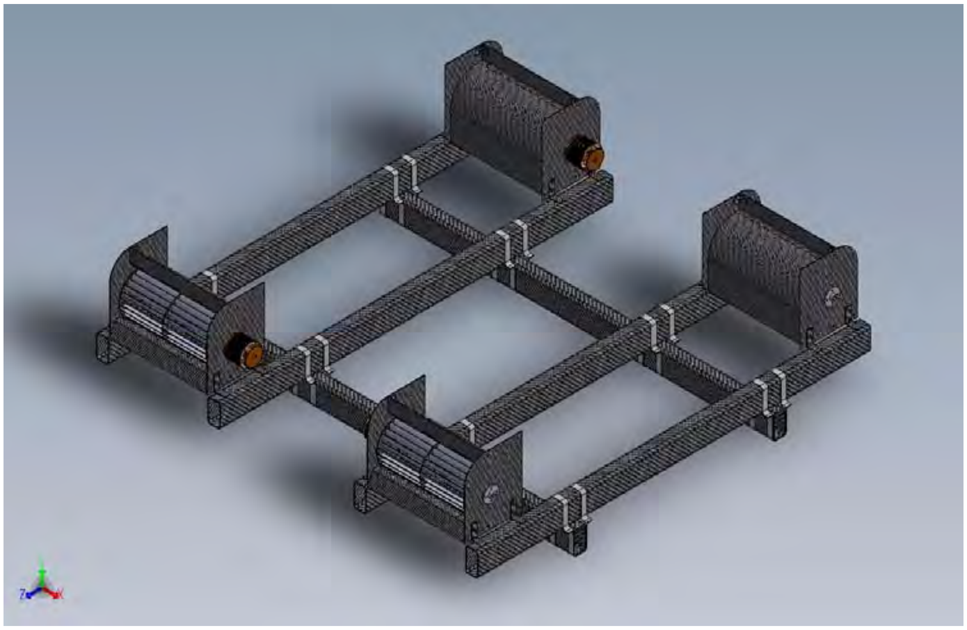

Figure 35. Fourth-generation SolidWorks model.

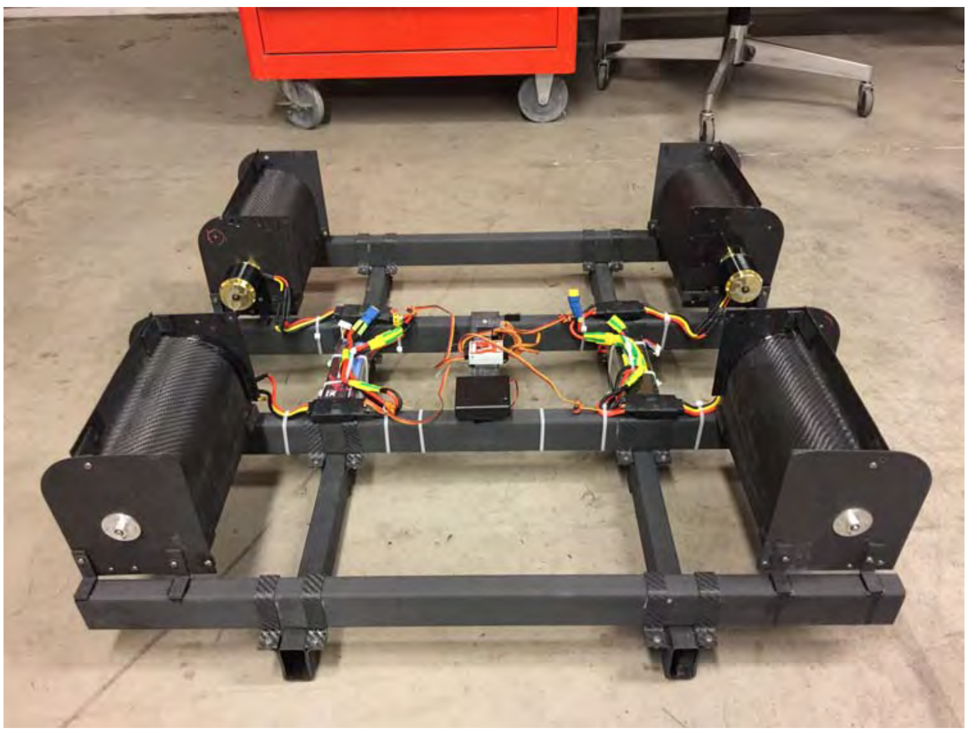

Figure 36. Fourth-generation vehicle.

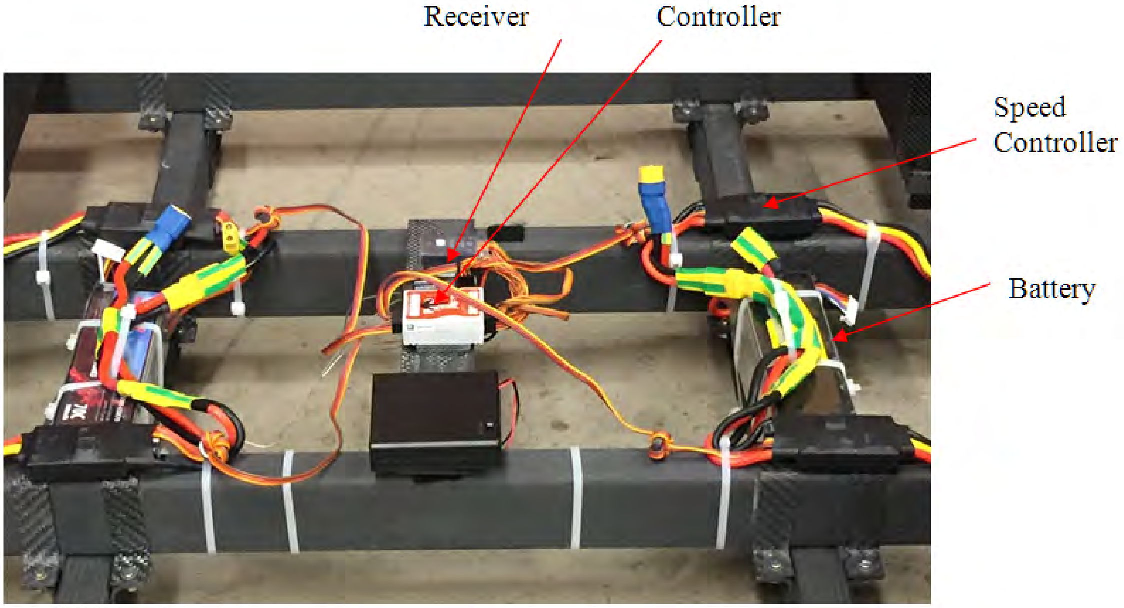

Figure 37. Fourth-generation vehicle, control and power set up.

Flight testing was immediately successful with the new design and the NAZA-M controller. The fourth-generation design proved vertical take-off and controllable flight; shown in Figure 38.

Figure 38. Fourth-generation, vertical take-off and controlled flight.

The fourth-generation vehicle weighed 7.81 kg. The maximum measured thrust was 5.015 kg per motor, for a maximum total airframe thrust of 20.06 kg. Thrust measured at 9,000 RPM was 4.15 kg per motor, for a total airframe thrust of 16.58 kg. The maximum achievable thrust to weight ratio of the fourth-generation airframe was 2.57. The thrust to weight ratio at 9,000 RPM was 2.12.

Figure 39. Untethered flight of fourth-generation UAV.

V. CONCLUSIONS

A VTOL cross-flow fan powered vehicle capable of full pitch, yaw and roll control was built and tested. This airframe was developed by implementing novel construction techniques tailored to cross-flow fan propulsion vehicles as well as incorporating lessons learned from previous generation airframes. The fourth-generation vehicle design was built using both custom and standard sections. Commercially available drivetrain and control components were used. The new design focused on three key areas of improvement: airframe simplification, gross takeoff weight reduction and structural rigidity improvement. At all phases the construction and emphasis on using readily available technologies or minor modifications to these was maintained.

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VI. RECOMMENDATIONS

Implementing 3-D printed parts have the potential to completely change the way quad-rotors are designed and constructed. Follow on research should focus on exploiting the Turbo Propulsion Laboratory's new carbon fiber 3-D printer. A new type of adhesively bonded fastening system was demonstrated at the Turbo Propulsion Laboratory during this project [23]. Any system such as the Weld Mount System implemented into future airframes would contribute to further weight reduction by eliminating more nut/bolt connections. Any system of this type would also improve airframe stiffness and rigidity by using larger areas to bond parts together and by avoiding drilled holes in key structural components necessary to route bolts. As mentioned in Section I.B, the potential exists for such aircraft to take off vertically and then transition to forward flight [2]. Future research should build upon the success of vertical take-off and landing and controllable flights of the fourth-generation airframe achieved by this project and incorporate lifting surfaces to enable transition to conventional forward flight after taking off vertically. Lastly, given the type of thrust devices used, future research should expand to incorporate a control system designed by Naval Postgraduate Students specifically tailored to leverage cross-flow fan propulsion.

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APPENDIX A. THIRD-GENERATION VEHICLE ASSEMBLY PROCESS

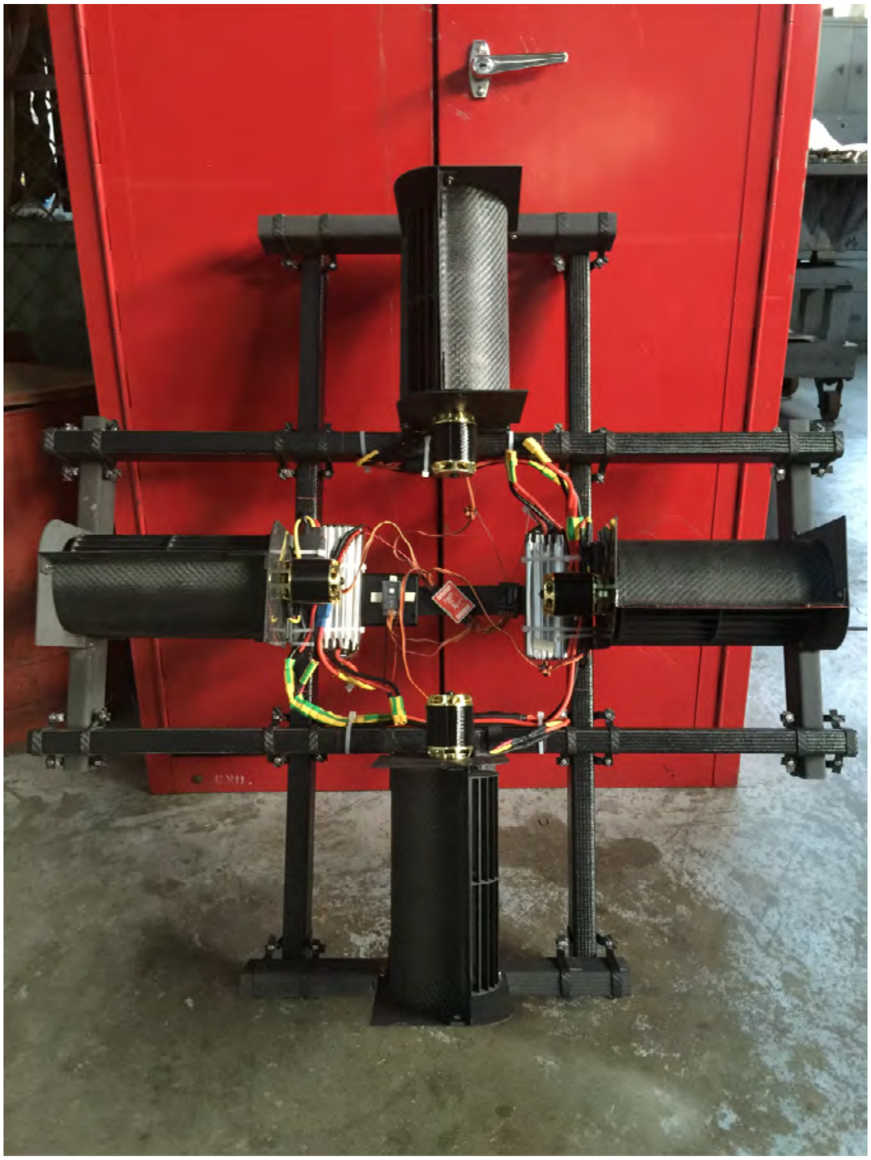

Figure 40. Third-generation vehicle.

Intake and **Exhaust Housings:** These parts must be measured and cut accurately to ensure fan housing units had consistent dimensions. Specifically, the height and width of the housings were most important. These dimensions were important because the height and width of the intake and exhaust housings were the driving factor for symmetry between the four fans, and they also drove square dimensionality in the airframe. This focus on accurate measuring and cutting helped maintain weight-scale and length-scale symmetry about the centroid of the airframe, which ultimately would contribute to the controllable flight characteristics of the third-generation vehicle.

Rotor Assembly: To save time, rotor fabrication was outsourced to Allred and Associates. Upon receiving the rotors from Allred and Associates, aluminum brackets were installed on the ends. Each bracket had an inner slot through which the drive shaft and non-drive side axel would pass and be secured using a set screw. This was accomplished using hex head bolts and a matching hex key.

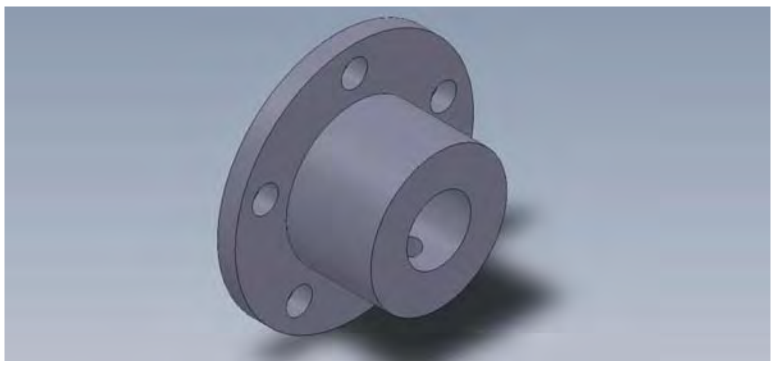

Figure 41. Aluminum rotor brackets

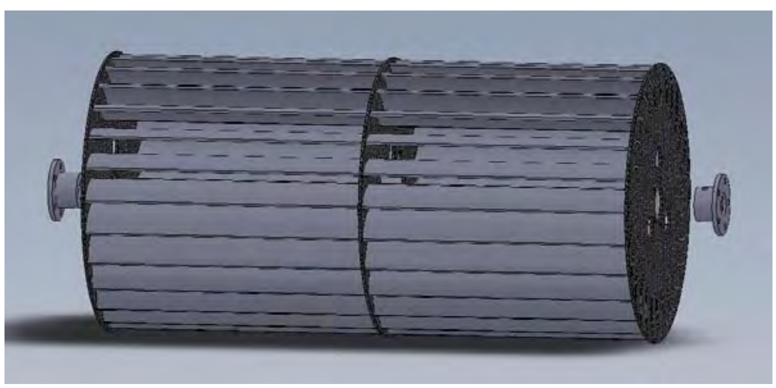

Figure 42. Rotor and bracket exploded view.

End Plates: There were two endplate configurations. The drive side end plate required the installation of the motor. This was accomplished by inserting the drive shaft through the center hole of the end plate and aligning the pre-drilled holes in the end plate with the motor mount holes. Once aligned, bolts secured the motor to the end plate. The non-drive side end plate required the installation of an aluminum bearing mount bracket, the bearing, and an axel. Hex head bolts and a hex key were used to accomplish this portion of the build.

Fan Housing Assembly: The fan housings were mocked up in an incremental manner to ensure proper rotor alignment with respect to opposing end plates and to achieve the desired spacing between the intake/exhaust housings and the rotor. First, “L” shaped carbon fiber brackets were epoxied to the intake and exhaust housings. Next, spring clamps were used to secure the intake and exhaust housings to the drive side end plate. With the non-drive side end plate unattached to the housing, the rotor was connected to the motor shaft to make sure there was no abrasion between the rotor and intake/exhaust housings. Once optimal alignment was achieved, the location of the tabs with respect to the end plate was outlined with a marker and epoxy was applied to permanently connect the drive side end plate with the intake and exhaust housings, shown in Figure 43.

Figure 43. Fan housing epoxy process.

After drying, the rotor was installed on the drive shaft, and the non-drive end plate was installed in a similar manner to ensure proper alignment, only screws were used instead of epoxy to provide future access to the rotor and motor bolts, shown in Figure 44.

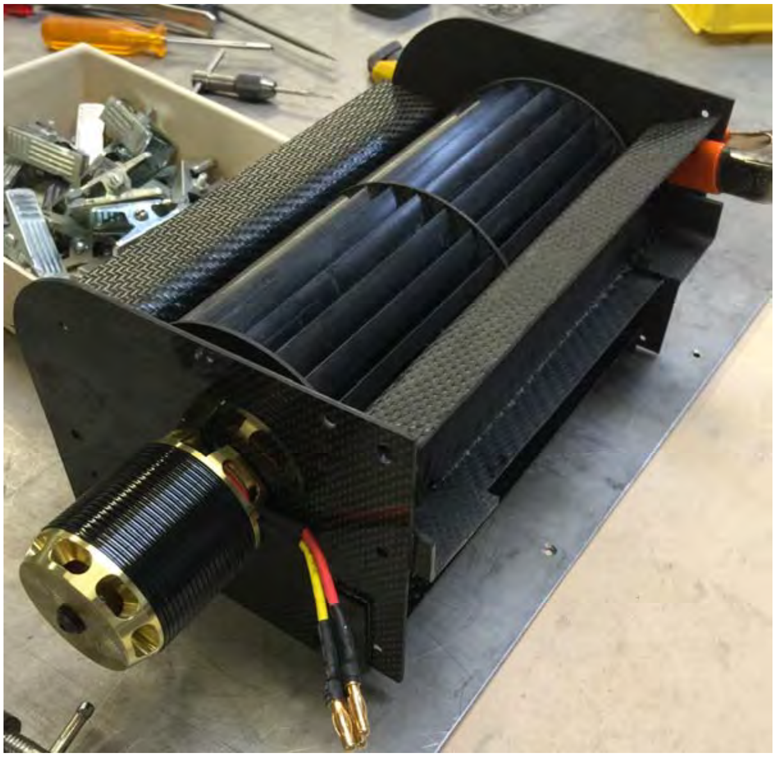

Figure 44. Fan housing finished product.

Airframe: Building a square airframe was critical for several reasons. Weight and length scale symmetry were important to provide in-flight balance. Additionally, the manner in which rotor thrust was vectored from each rotor was carefully considered in the design process, and small deviations from the intended thrust vector alignment could potentially have a large impact on how the airframe responded to control input.

To ensure the frame was square, special clamps were designed in SolidWorks, and then printed using the 3-D printer. A geometric key and slot scheme was designed on clamp mating surfaces, as shown in Figure 45. Appendix B details the 3-D printing process.

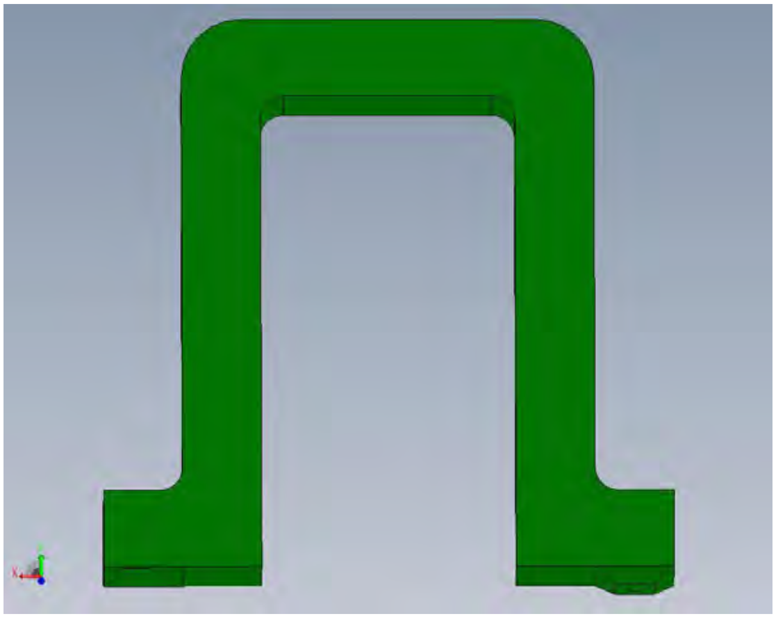

Figure 45. SolidWorks model shows clamp interlocking shape.

This was a subtle yet effective solution to ensure the airframe was square when putting all of the parts together. Essentially three of the four main tube cross points were connected using these clamps, and carbon fiber airframe clamps were measured, cut and installed on the fourth tube cross point. This pattern was repeated until all tube cross points had permanent carbon fiber airframe clamps installed. Figure 46 shows the 3-D printed airframe alignment clamps installed on the airframe to facilitate precise measuring, cutting and permanent carbon fiber airframe clamp installation. The clamps bolts were loosely fastened in order to make minor adjustments when fitting the housing units in place.

Figure 46. 3-D printed airframe alignment clamps.

Next, the fan housing mounting tubes were added to the main airframe using the same clamps. Again, the bolts were kept loose. This process is shown Figure 47.

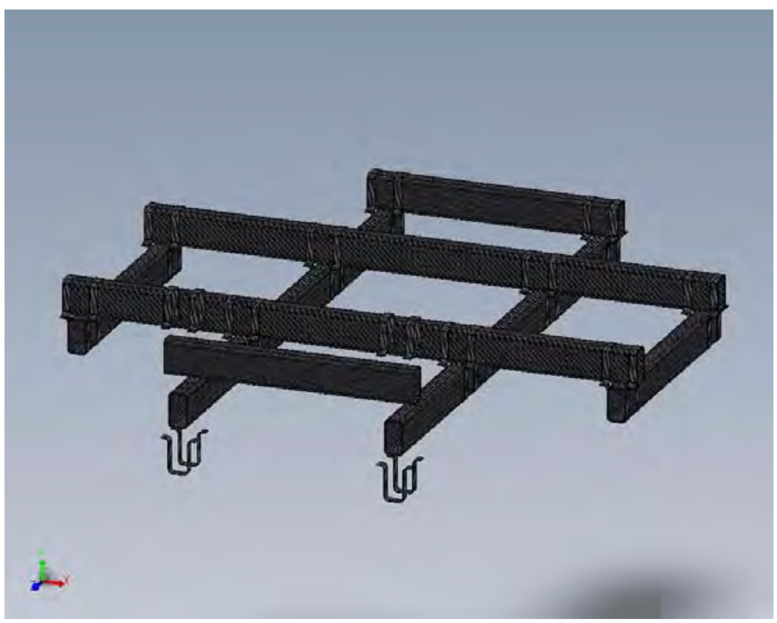

Figure 47. Exploded view, composite airframe.

Next, minor adjustments were made to the composite frame assembly as required to fit each fan between each set of parallel tube sections. Once the proper adjustments were made, the frame clamps were tightened down, and Loctite was applied on each bolt to prevent the bolts from vibrating loose as a result of flight-induced vibrations.

Carbon fiber angle clamps were used to attach the housing units to the frame. In order to determine the precise location of each angle clamp on the frame, the fan locations were mocked up, and then each angle clamp was outlined with marker. The fans were then removed and the angle clamps were epoxied in the appropriate marked location. The fan housings were replaced in their respective locations between each set of angle clamps, holes were drilled and nut/bolt connections were made. The UAV including structural components only is shown in Figure 48. Once the structural assembly process was complete, the focus shifted to incorporating the electronic, power and control components.

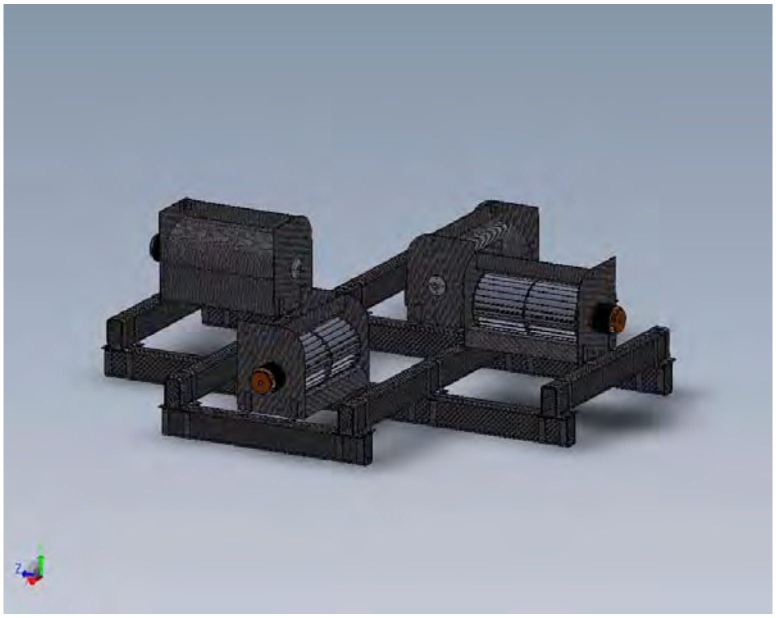

Figure 48. Structural assembly.

The final control packages integrated into the third-generation vehicle design were the NAZA controller and versatile unit, and the FUTABA radio control system. The controller and versatile unit were powered by four AA batteries wired in series. Two 6 cell LiPo batteries were connected in parallel and powered all four electronic speed controllers, and all four electric motors. Figure 49 shows the third-generation vehicle design power and electronic configuration.

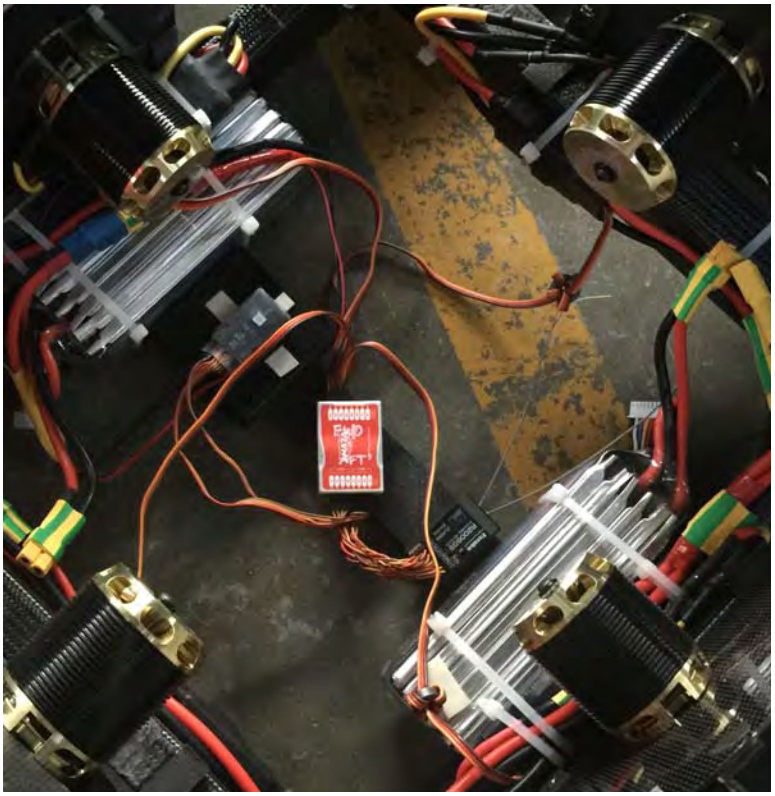

Figure 49. Power and electronic configuration.

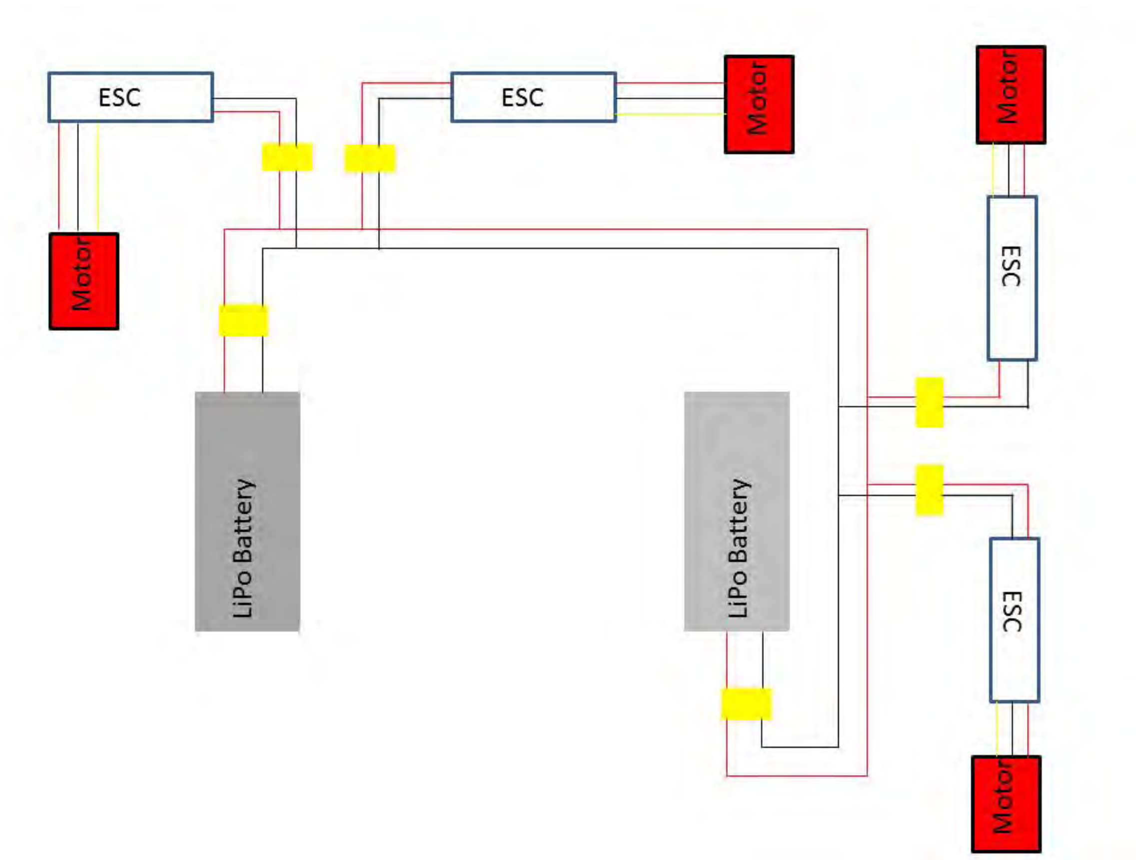

Figure 50. Third-generation vehicle power wire diagram.

APPENDIX B. 3-D PRINTED CLAMPS

3-D Printed Clamps: To ensure airframe geometry remained true, special clamps were designed to hold the carbon fiber tubing in place. The clamp design process went through several iterations. Initially, the idea was to create a top and bottom clamp. Utilizing the computer design tool SolidWorks, a clamp was created that focused on assembly strength in tension and minimizing unnecessary material. The first SolidWorks iteration is shown in Figure 51.

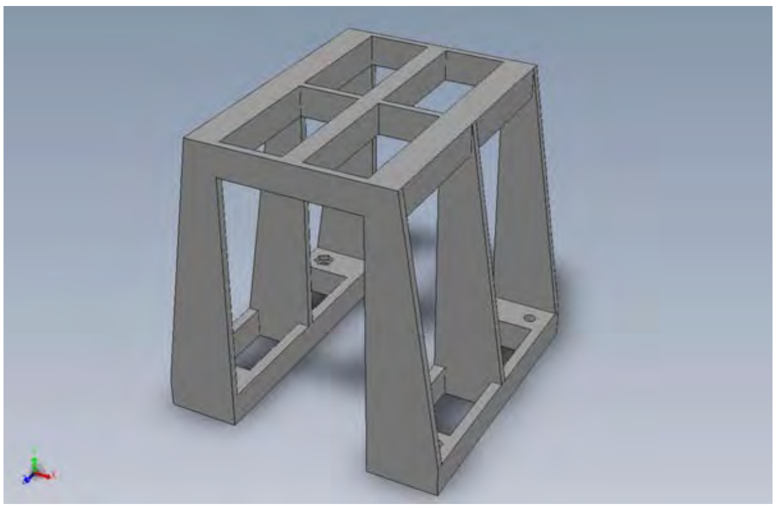

Figure 51. Frame clamp iteration one.

Next, the model file was imported into the turbo propulsion laboratory 3-D printer program and the first attempt to print a clamp began. Problems with the printing process spurred the second iteration, shown in Figure 52.

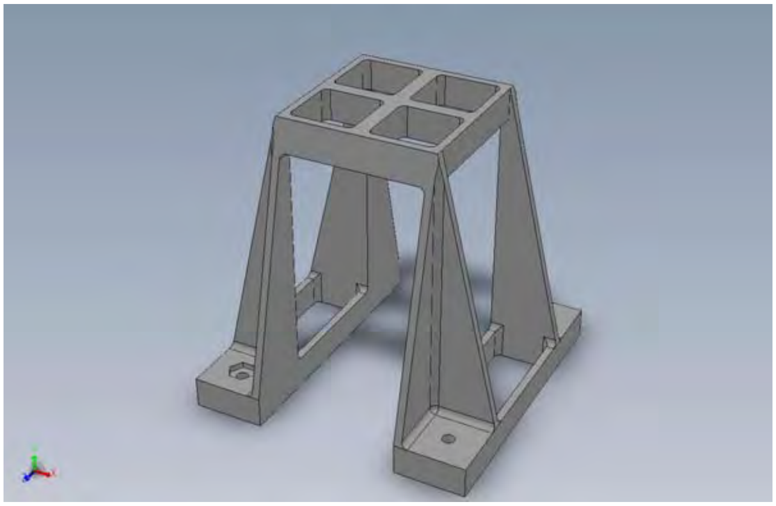

Figure 52. Frame clamp iteration two.

Iteration two removed the middle-rib member in order to simplify the print geometry. Issues with the 3-D printer continued. Iteration three aimed to further simplify the print process by thickening the clamp walls as well as removing the longitudinal ribs on all corners. Iteration three is shown in Figure 53.

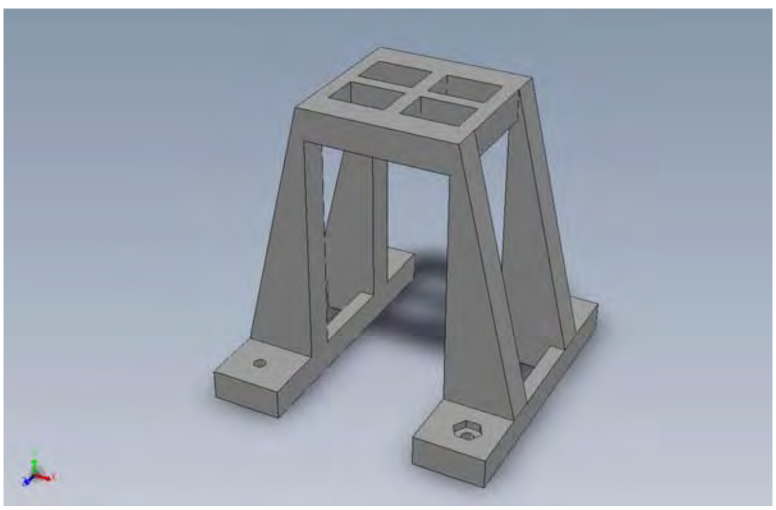

Figure 53. Frame clamp iteration three.

As the previous three figures portray, subsequent designs presented simplified geometry. Irrespective of design simplification, it was clear that the 3-D printing process was a challenge. In order to solve the problems experienced with printing a clamp, the research took a step back and asked a simple question: what was the intended purpose of the clamp? The root answer pointed to the solution, which shifted the design process from printing clamps with the 3-D printer to making molds on which carbon fiber parts could be laid up.

3-D Printed Molds: At this point, the research shifted focus from designing a frame clamp that proved to have relatively complex geometry from a 3-D printing perspective, to designing a solid mold with elementary geometry in SolidWorks, and then printing the mold with the 3-D printer. Inner and outer clamps were designed in SolidWorks. The inner clamp surface matched the shape of the carbon fiber tubing, and was the surface on which the pre-impregnated carbon fiber sheets were laid up; inner clamp shown in Figure 54.

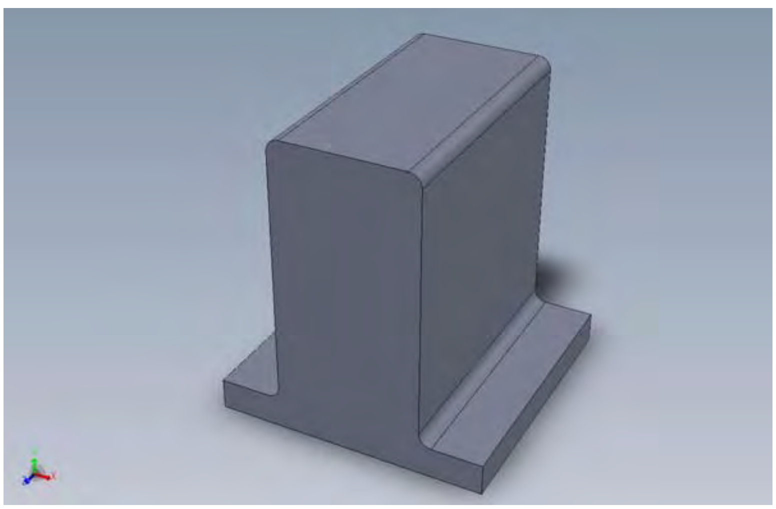

Figure 54. Inner clamp mold.

The outer clamp fit over the inner clamp and left a gap between the two clamps that correlated with the desired thickness of the carbon fiber and release material shown in Figure 55.

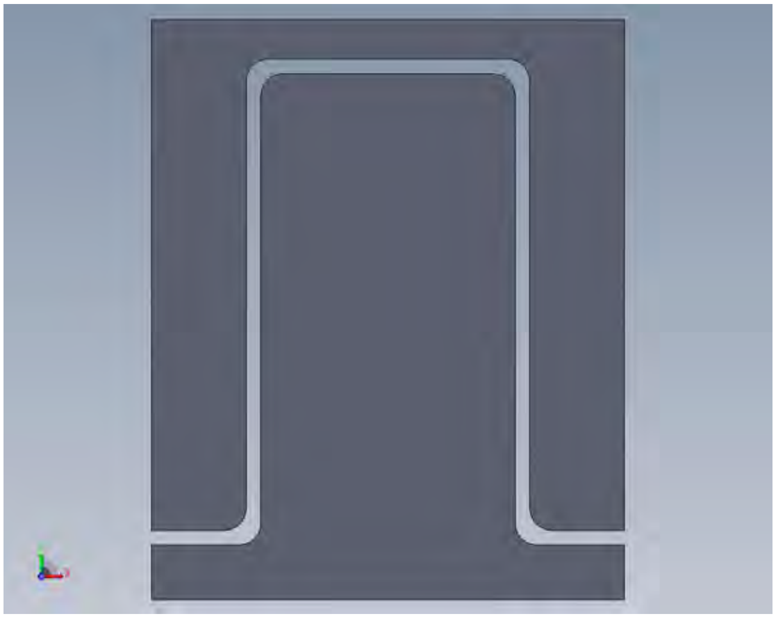

Figure 55. Clamp mold assembly.

After both clamps were mated with the carbon fiber material laid up between, the outer lateral surfaces of the clamp assembly were clamped together with strong-backs and G-clamps in order to apply equal and constant pressure during the curing process, shown in Figure 56.

Figure 56. Molds with G-clamps and strong backs.

Failures: The filament used in the turbo propulsion laboratory 3-D printer is 1.75 millimeter polylactic acid. Polylactic acid melts at 315° F (157° C) and the glass transition temperature is 134° F (57° C). This was important information to know when the project attempted to cure carbon fiber in the oven. The pre-impregnated carbon fiber (PREPREG) used in this research had three manufacturer recommended cure profiles. The lowest temperature profile had a target temperature of 270° F (132° C) and a hold time of four hours. The first attempt at curing the carbon fiber laid-up in the 3-D printed mold while adhering to the aforementioned cure profile failed; see Figure 57.

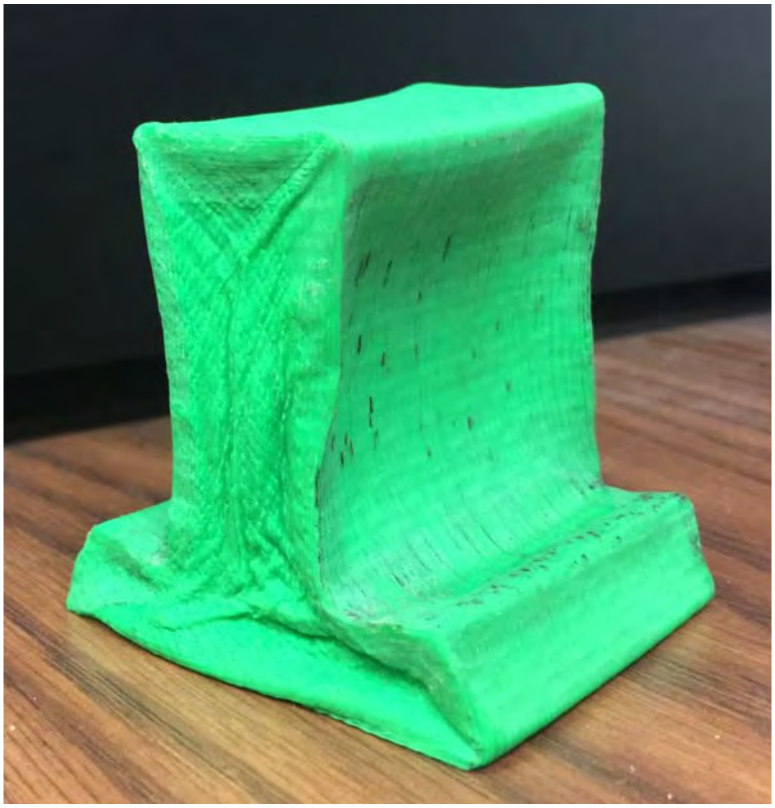

Figure 57. Clamp mold failure.

This failure was a result of baking the carbon fiber and mold at the lowest recommended PREPREG cure profile, as well as using a vacuum bag. As the mold temperature increased beyond the glass transition temperature of 134°F (57°C) the suction inside the vacuum bag caused the mold to deform.

The clamp and strong back method also failed. The research observed that at any temperature above 100°F, the polylactic acid printer filament lost all desired mechanical properties, and the molds would not maintain the proper shape. Additionally, the research observed that when oven temperatures were lowered below the filament glass transition temperature the carbon fiber would not cure even when left in the oven for 20 hours.

Final Clamp Solution: To ensure the frame was square, special clamps were designed in SolidWorks, and then printed using the 3-D printer. A geometric key and slot scheme was designed on clamp mating surfaces. Essentially three of the four tube cross points were connected using these clamps, and then on the fourth tube cross point carbon fiber airframe clamps were measured, cut and installed; as shown in Figure 58.

Figure 58. 3-D printed clamp solution.

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APPENDIX C. PREVIOUS GENERATION ASSEMBLY GUIDE

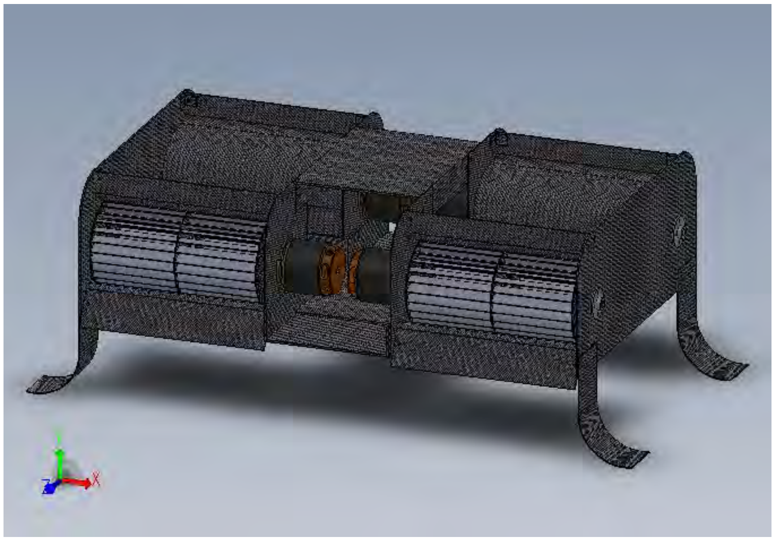

Figure 59. Second-generation model.

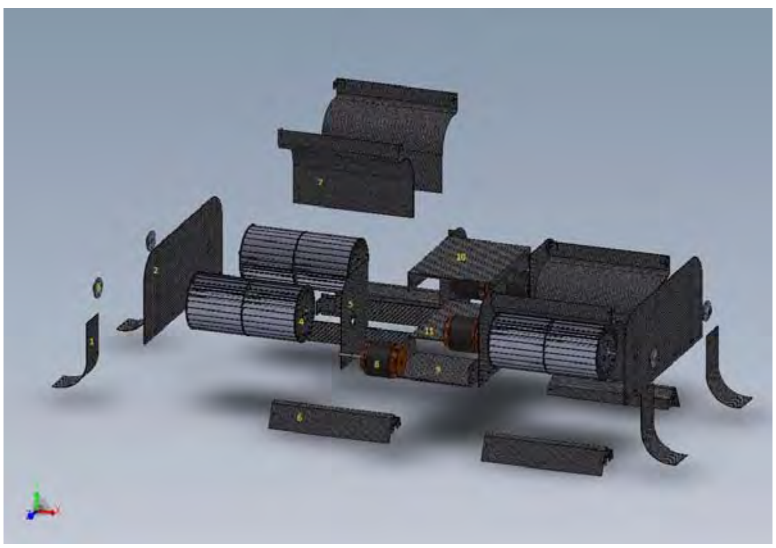

Figure 60. Second-generation, exploded component view.

Parts List: The following items comprise the main structural components of the second-generation vehicle and they are correlated visually with Figure 60. All power and electrical system components are explained later in this appendix.

1. Landing gear

2. Exterior end plate

3. Bearing mount

4. Cross-flow fan

5. Interior motor mount end plate

6. Exhaust housing

7. Intake housing

8. Motor

9. Airframe foundation

10. Bottom plate

11. Top plate

Airframe assembly procedure:

1. **Motor to Interior Motor Mount End Plate:** Bolt the motor to the interior motor mount end plate. Make sure you orient the motor on the plate so that the motor wires point towards the notch on your motor plate (circled in red below). Repeat this step for all motors.

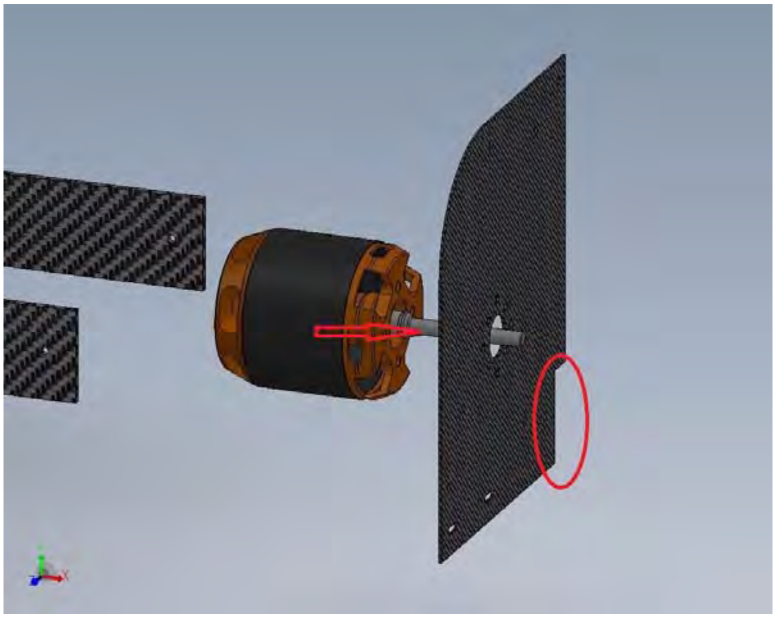

Figure 61. Motor to endplate subassembly.

2. **Airframe Foundation:** Bolt interior motor mount end plate with motor attached to the airframe foundation, as shown in Figure 62. Repeat step for all motor locations.

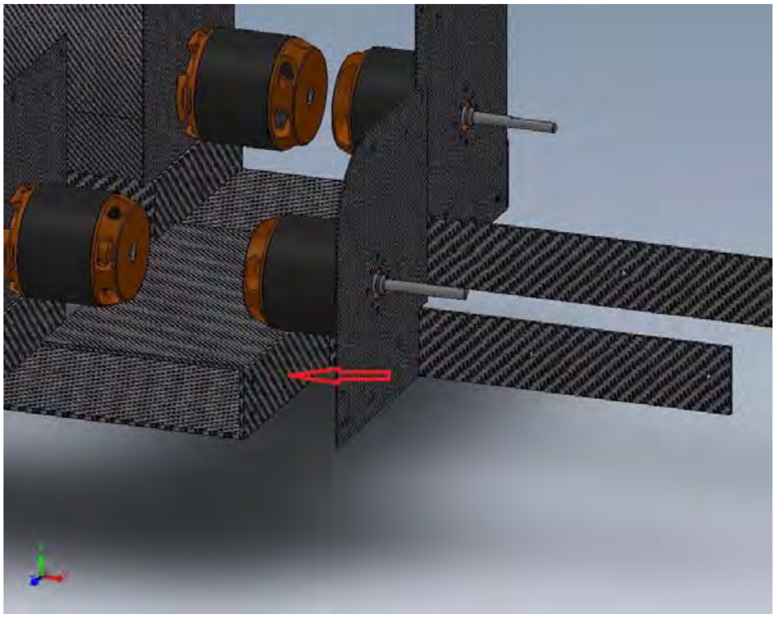

Figure 62. Motor mount plate to airframe foundation.

3. **Exhaust Housing:** Attach exhaust housing to interior motor mount end plate assembly using "L" shaped tabs. Lightly tighten to facilitate precise alignment once airframe is fully assembled.

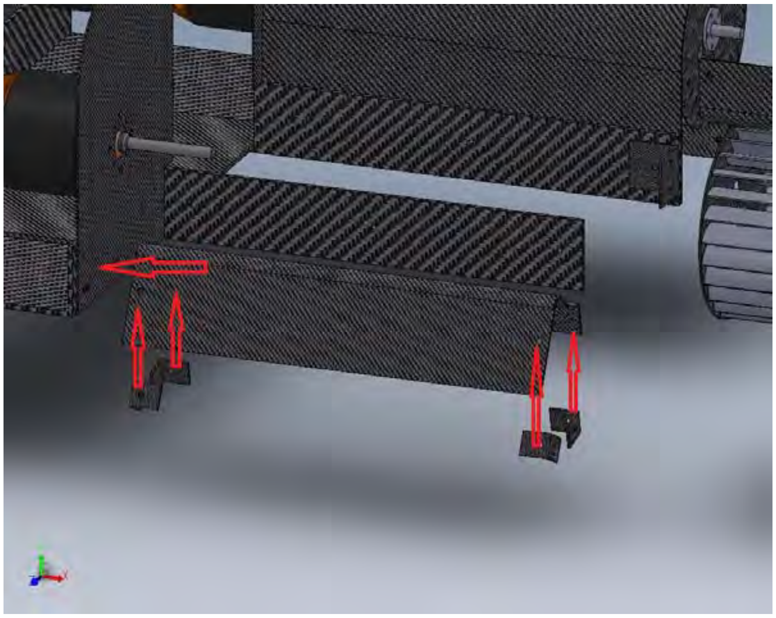

Figure 63. Exhaust housing to airframe foundation.

4. **Cross-flow Fan:** Attach cross-flow fan by sliding motor axel through aluminum bracket on the cross-flow fan. Ensure cross-flow fans are properly oriented concave up. Loosely tighten the set screw located on the aluminum bracket to hold the cross-flow fan in place, but allow for final adjustment.

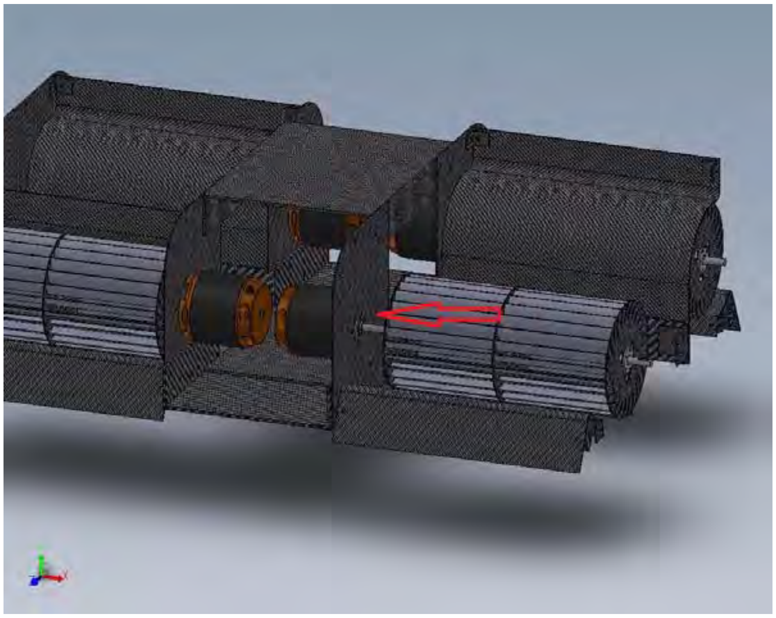

Figure 64. Cross-flow fan.

5. **Intake Housing:** Attach intake housing to the interior motor mount end plate and the vertical surface of the airframe foundation. Use an "L" connector for connection to motor mount end plate and align pre-cut holes on the lower portion of the intake housing with the pre-cut holes on the vertical surface of the airframe foundation.

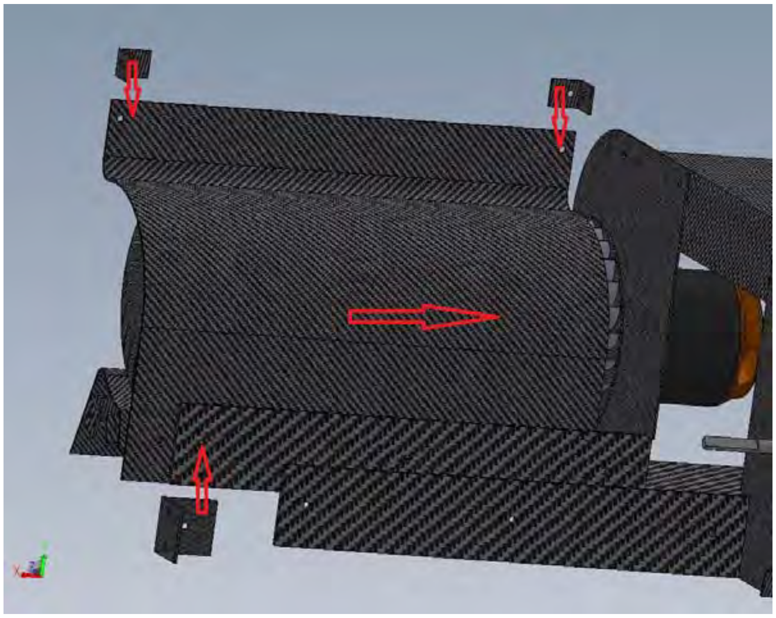

Figure 65. Intake housing to airframe foundation.

6. **Bottom Plate:** Attach the forward and aft airframe foundation assemblies with the bottom plate.

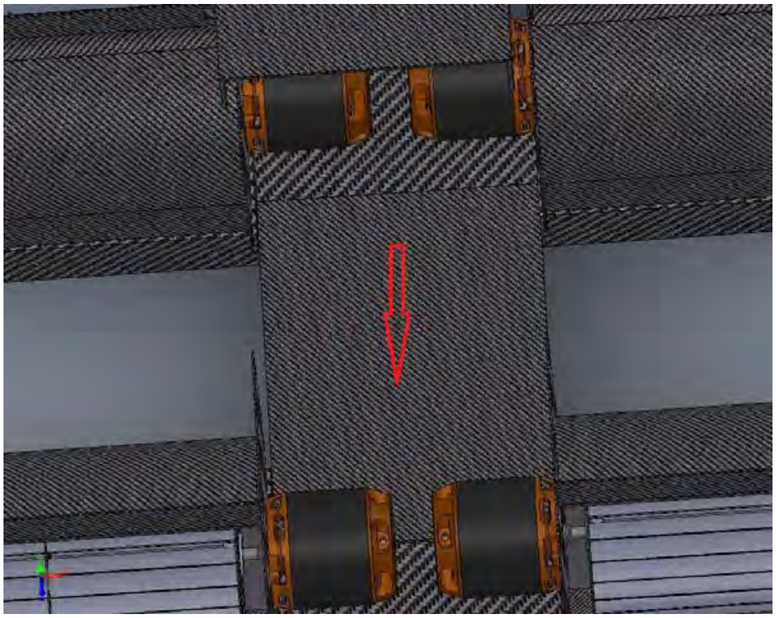

Figure 66. Bottom plate to forward and aft airframe foundations.

7. **Bearing Mounts:** Attach bearing mounts on exterior end plates by aligning pre-cut holes on the exterior end plate with the holes on the aluminum bearing mounts.

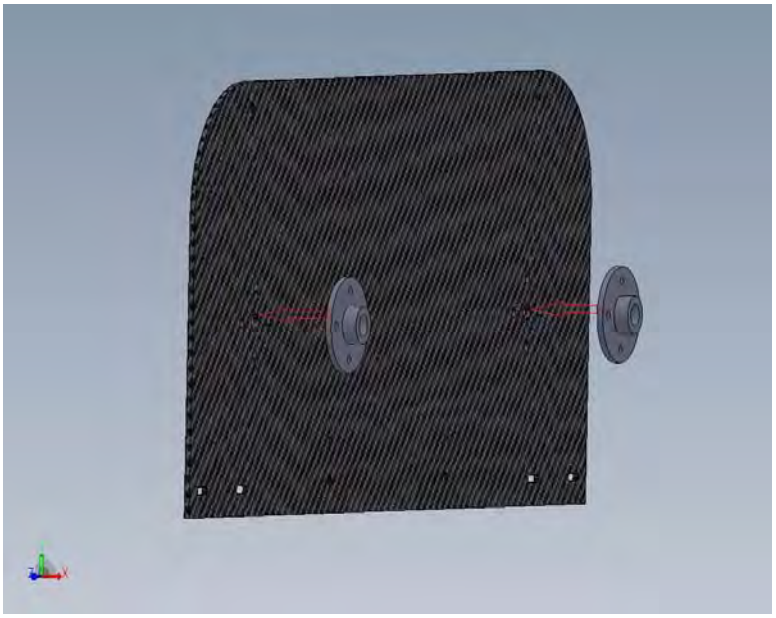

Figure 67. Bearing mounts to exterior end plates.

8. **Exterior End Plates:** Attach exterior end plates to port and starboard sides by pass cross-flow fan axels through the aluminum mounting brackets. There is no set screw on the outboard aluminum brackets. Secure the exterior end plate by aligning pre-cut holes on the end plate with the small "L" connectors on the exhaust housing, and a large "L" connector on the intake housing.

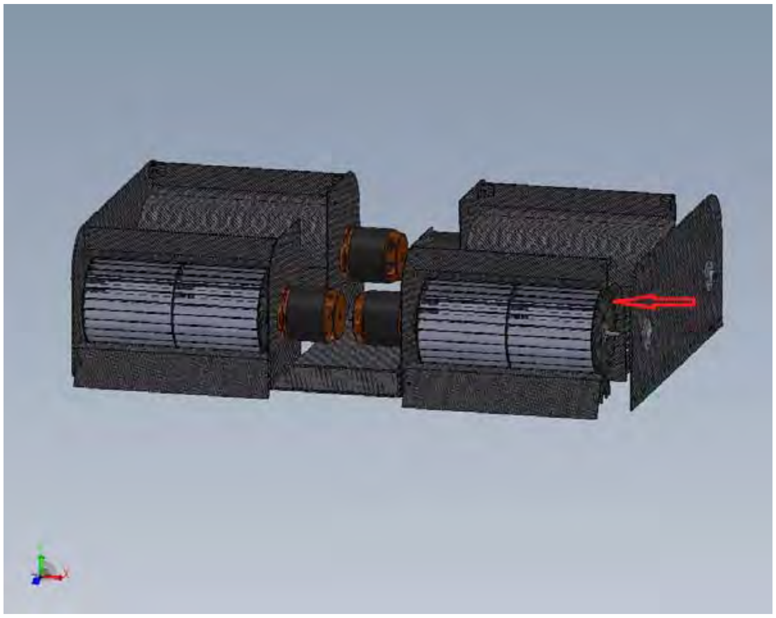

Figure 68. Exterior end plates to airframe foundation.

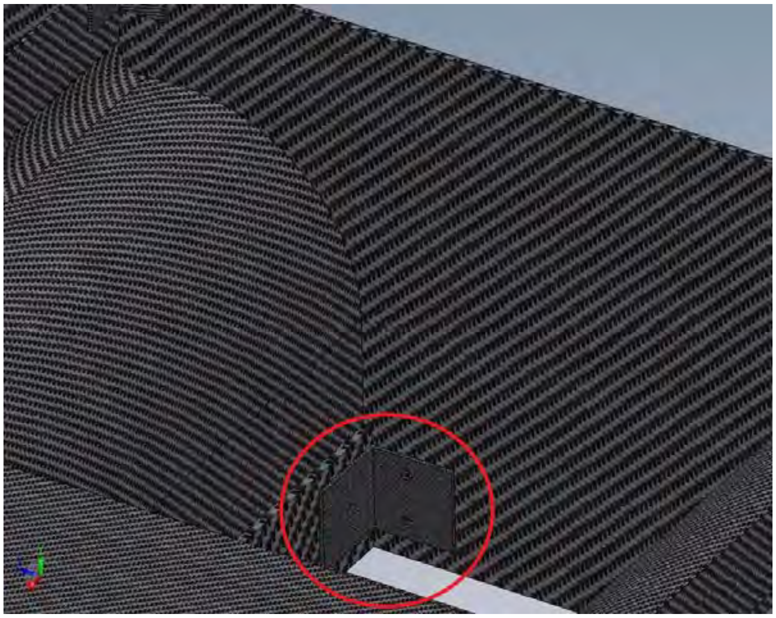

Figure 69. Large “L” bracket connector.

9. **Top Plate:** Attach top plate by aligning pre-cut holes on the vertical sides of the top plate with the pre-cut holes on the top of each interior motor mount end plate.

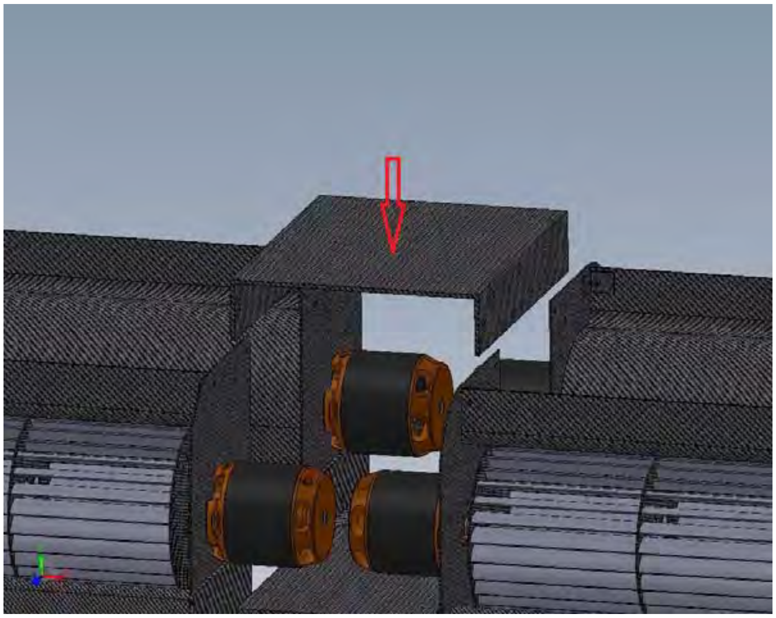

Figure 70. Top plate attachment.

10. **Landing Gear:** Attach the landing gear on the corners of the airframe.

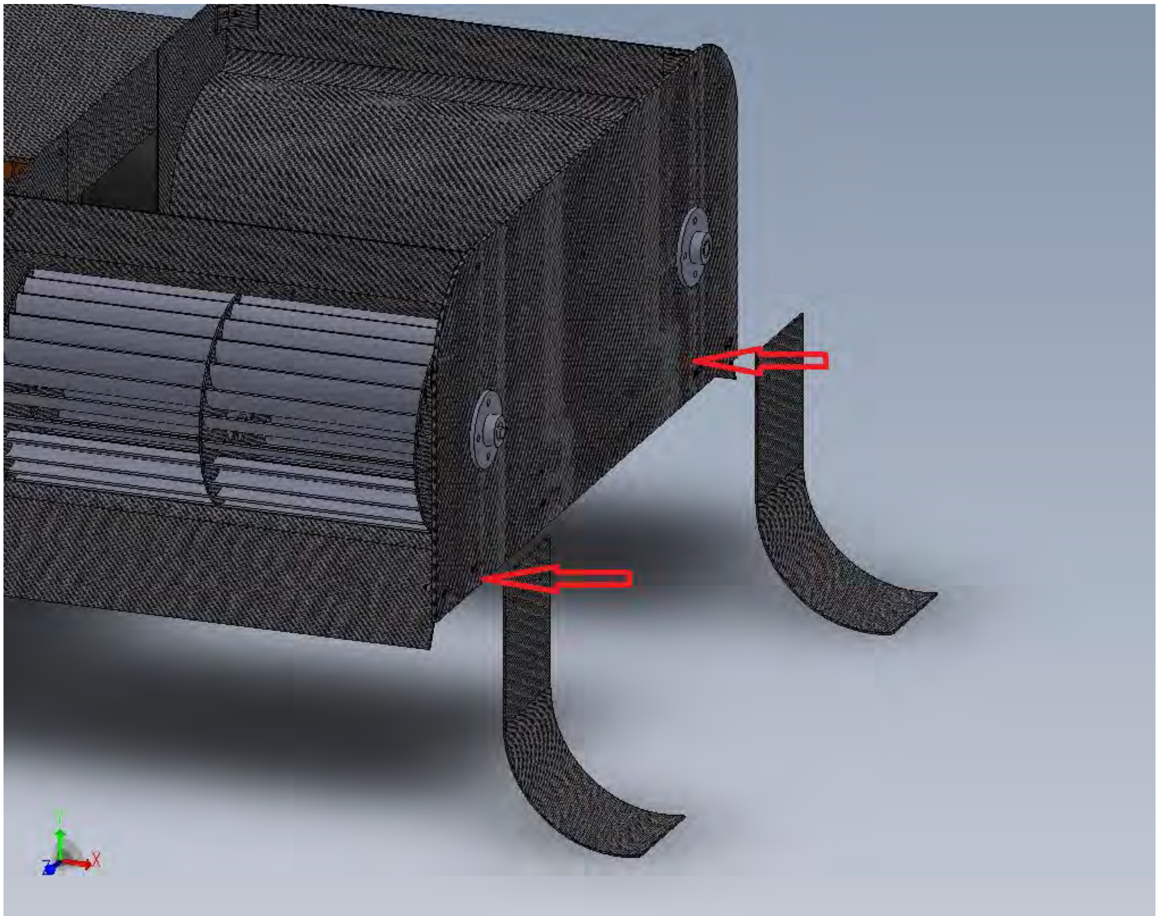

Figure 71. Landing gear.

Power and control systems assembly procedure:

1. **Electronic Speed Controllers:** Secure the electronic speed controllers for each motor behind each cross-flow fan housing unit as shown in the following figure. Ensure all slack is pulled out of the smaller wires so that they easily reach to the center of the airframe.

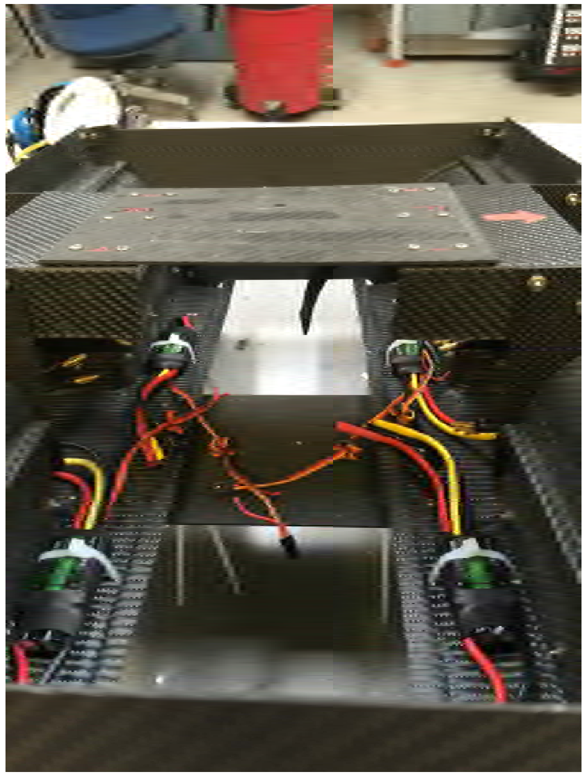

Figure 72.	Electronic speed controllers.

2. **Main Controller:** Centrally mount the main controller oriented so the labeled connections M1 through M6 and F1 and F2 point directly forward. Fans 1 and 2 should be in front of the main controller and fans 3 and 4 should be aft. Connect the small wire from each electronic speed controller to the main controller so that the electronic speed controller for each fan matches the number following the M. For example, the electronic speed controller for fan 1 should be connected in M1. See the following figure.

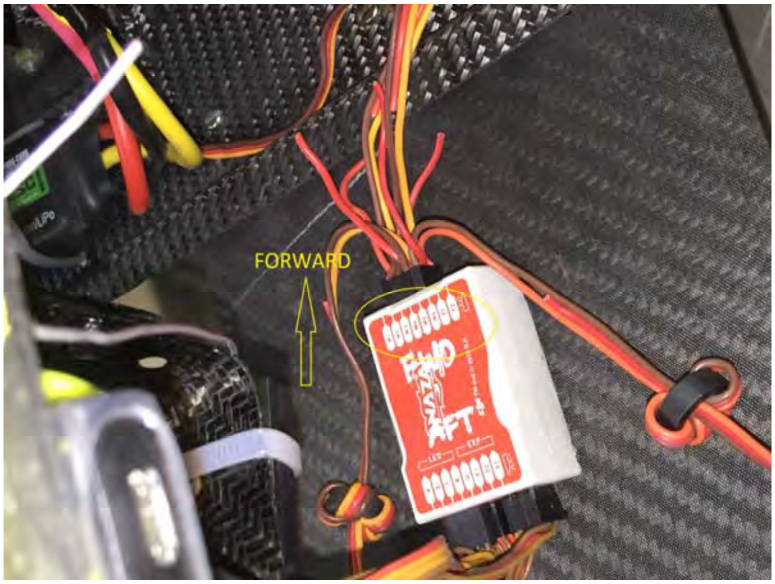

Figure 73. Main controller with proper electronic speed controller connections.

3. **Radio Control and Versatile Unit:** Mount the radio control system and the versatile unit on the underside of the top plate as shown in the following figure.

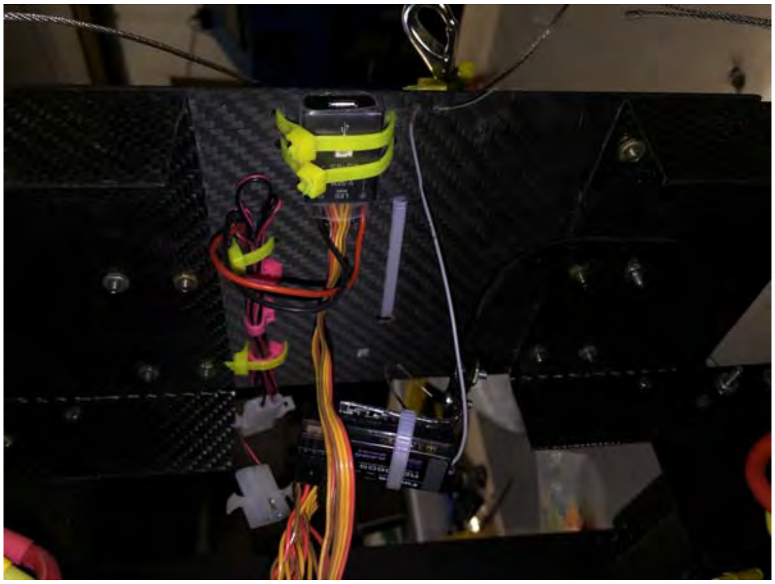

Figure 74. Radio control system and versatile unit mounted with zip ties.

4. **LiPo Batteries:** Mount the batteries on the undercarriage of the bottom plate. Connect the batteries in parallel.

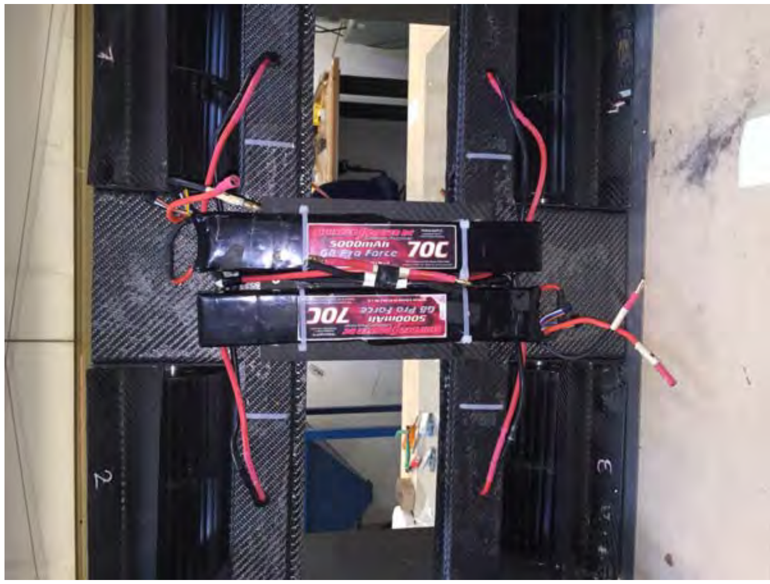

Figure 75. LiPo batteries and parallel battery connector cable.

5. **Power Supply and Tether Cable:** Mount the radio control system power supply on the top plate. Connect the tether cable at the four corners of the top plate.

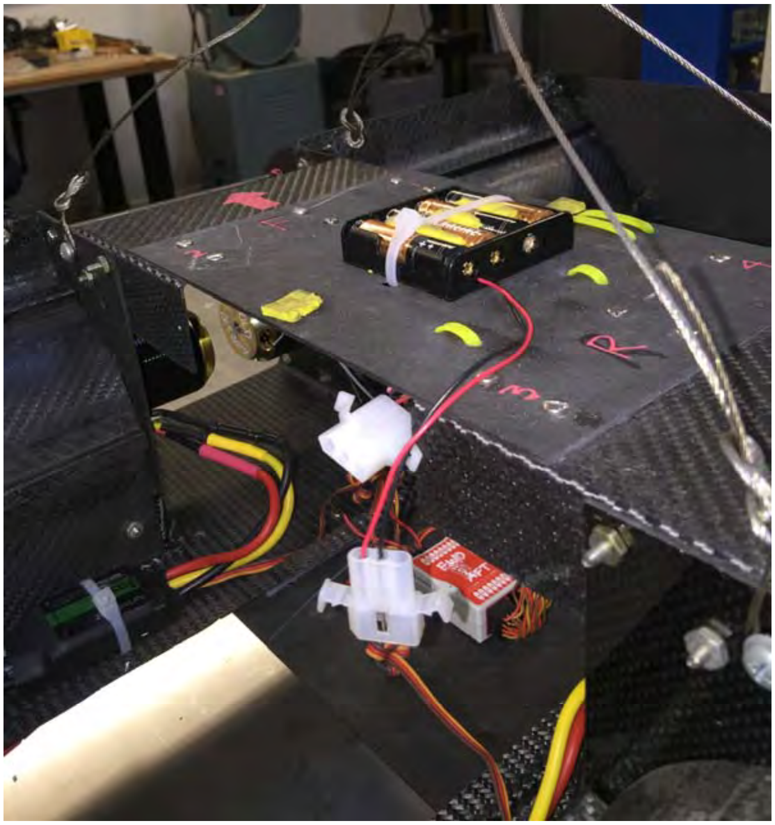

Figure 76. Radio control system power supply and tether cables.

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APPENDIX D. STROBE RIG ASSEMBLY

1) **Purpose: Test cross-flow fan actual speed (RPM).**
2) **Basic wiring diagram:**

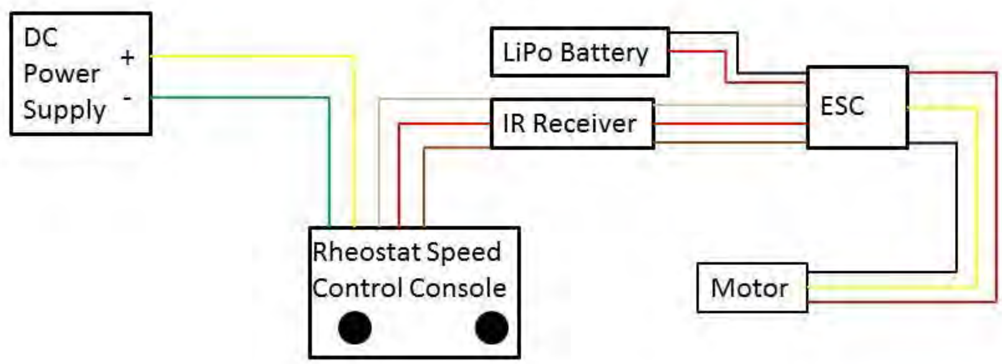

Figure 77. Strobe rig wiring diagram.

3) Parts required:

a) DC power supply

Figure 78. DC power supply.

b) Rheostat speed control console

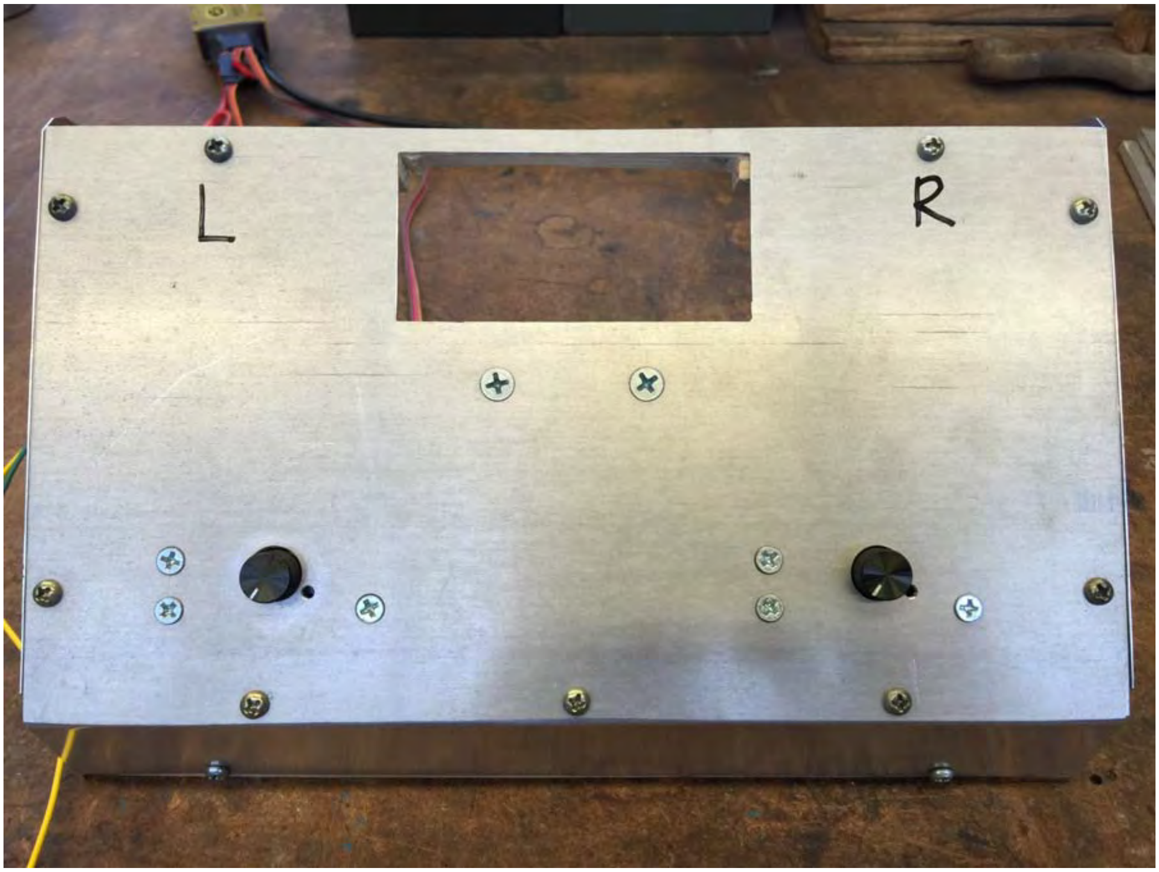

Figure 79. Rheostat speed control console.

c) 6 cell lithium polymer battery

Figure 80. 6 Cell LiPo battery.

d) Motor controller - Cobra Commander V130A ESC

Figure 81. Cobra motor controller.

e) Cross-flow fan with motor attached

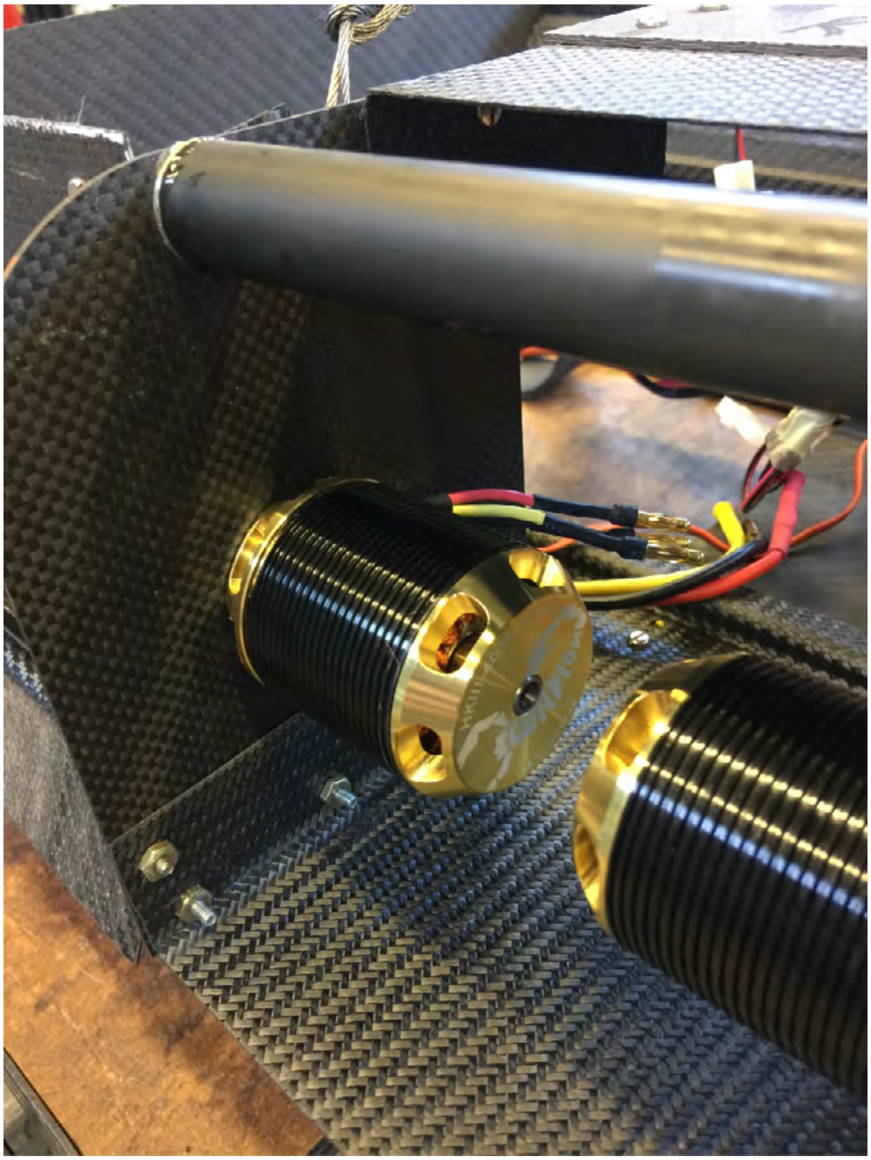

Figure 82. Cross-flow fan with motor attached.

f) Stroboscope

Figure 83. Stroboscope.

4) **Configuration Procedures:**

   a) Connect rheostat speed control console to DC power supply as shown in the following figure:

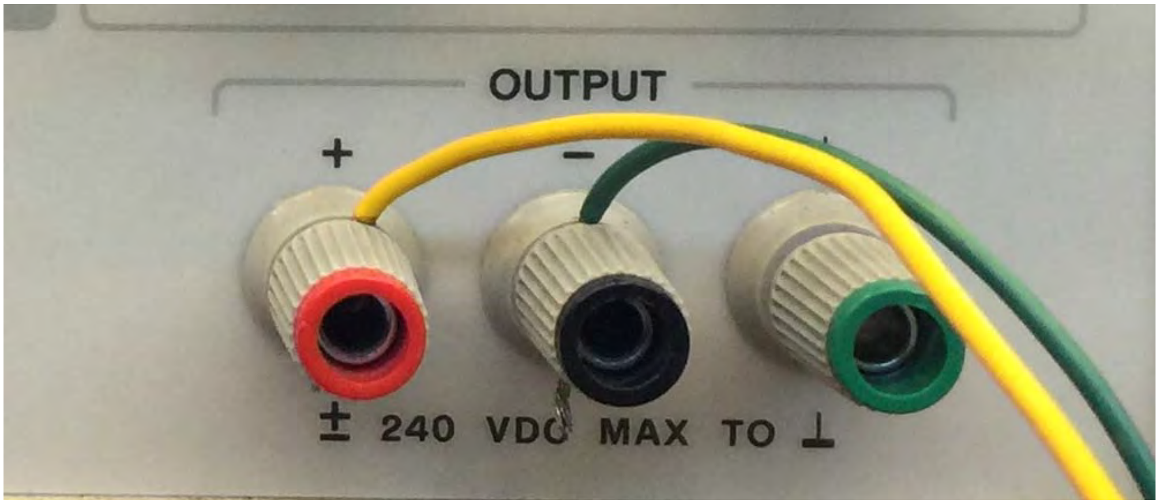

Figure 84. Speed control console to DC power supply connection.

   b) Connect cobra motor controller to rheostat speed control console as shown in the following figure:

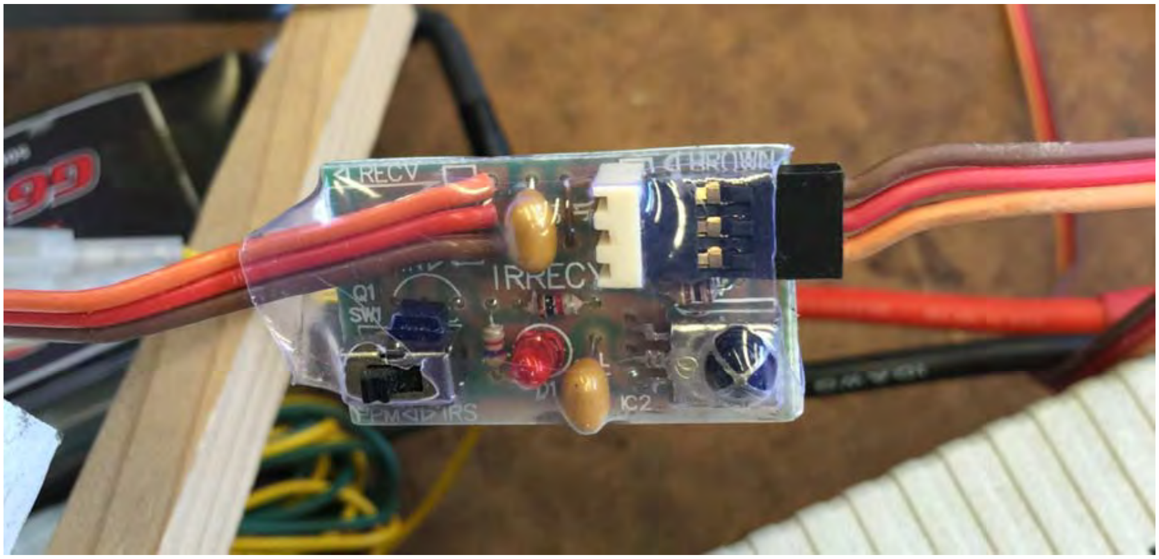

Figure 85. Motor controller to speed control console connection.

c) Connect 6 cell LiPo battery to Cobra motor controller as shown in the following figure:

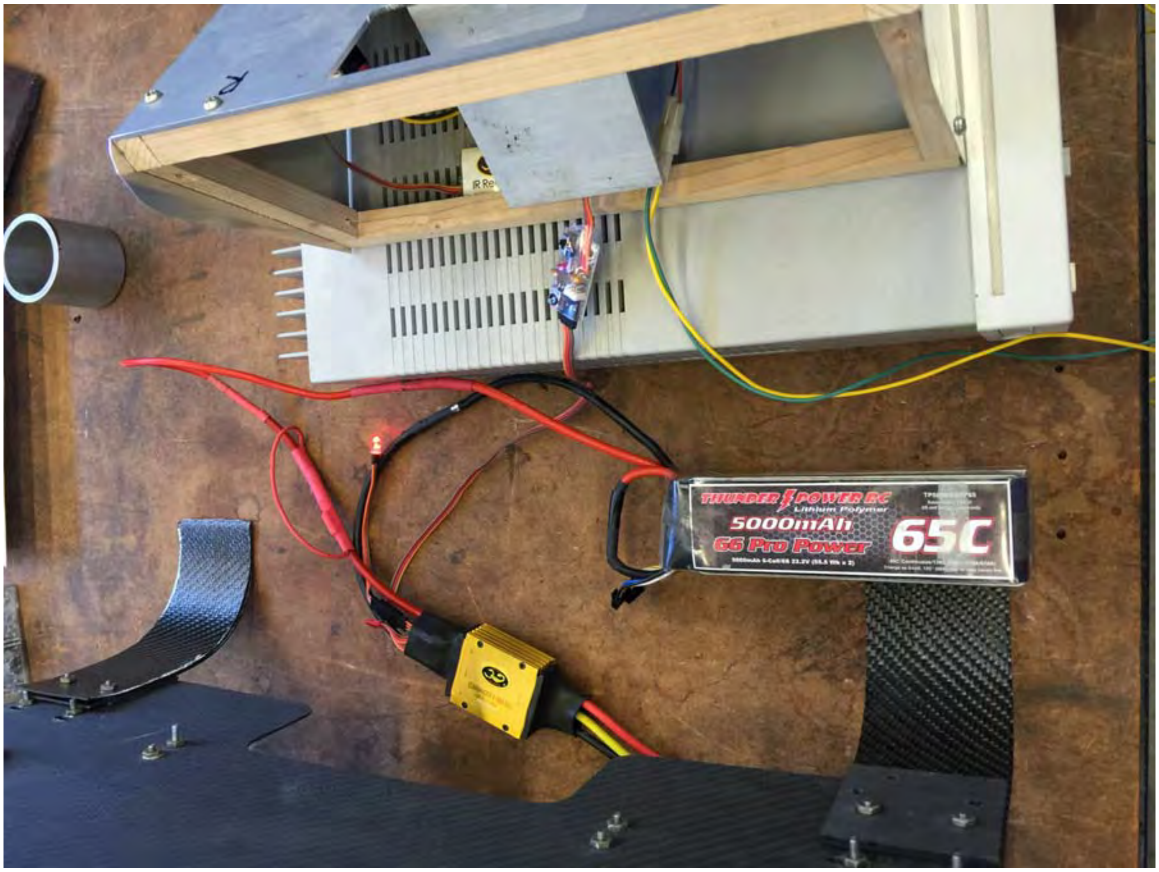

Figure 86. LiPo battery to Cobra motor controller.

d) Connect Cobra motor controller to cross-flow fan motor assembly as shown in the following figure:

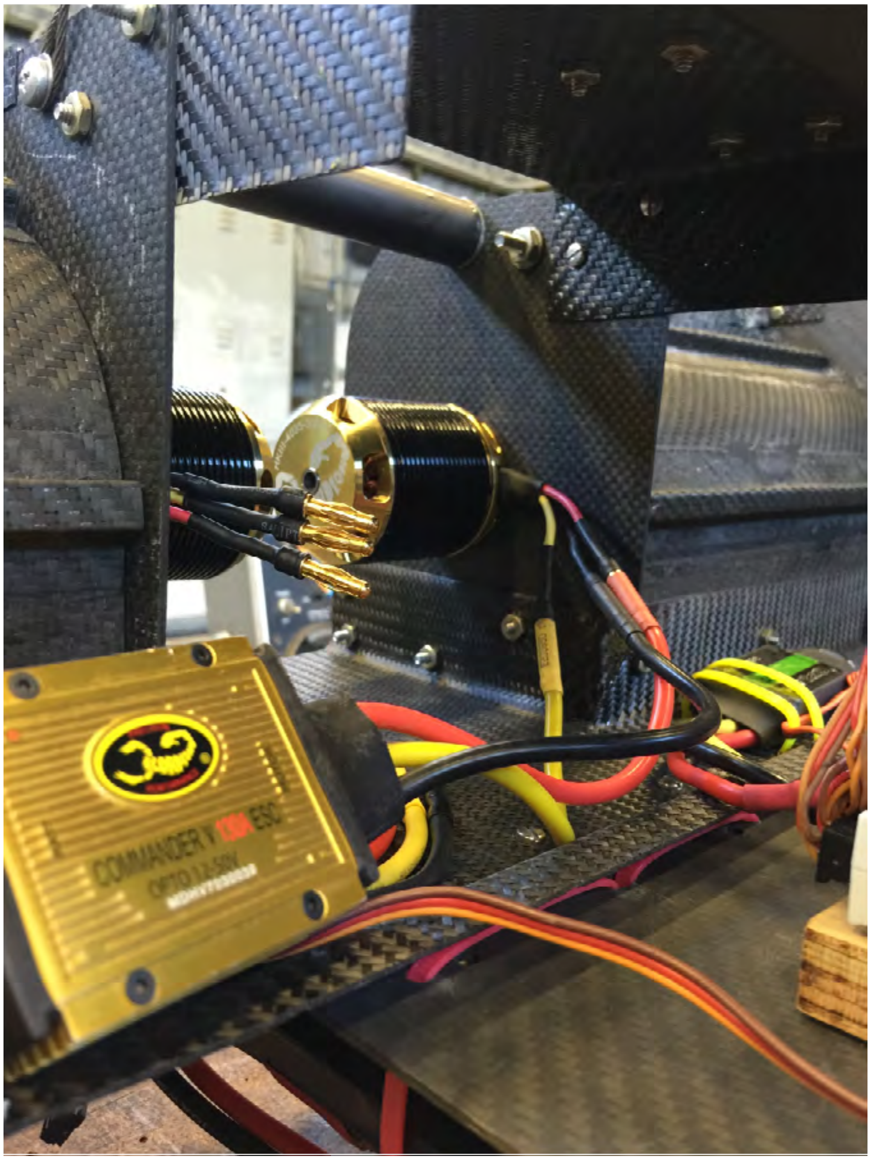

Figure 87. Motor controller to motor.

5) **Operating Instructions:**

a) Energize power supply. Tune power supply output voltage to 5.00 volts using voltage adjustment knob on power supply. (Before doing this, ensure that the speed dials on the rheostat speed control console are turned all the way to the left, in the off position).

b) Energize stroboscope.

c) Energize cross-flow fan to the desired speed by turning the appropriate speed dial located on the rheostat speed control console to the right (clockwise) to increase speed, and to the left (counter clockwise) to decrease speed.
d) Determine cross-flow fan by tuning the stroboscope frequency. Note that a small portion of one blade on the cross-flow fan must be painted white as this will be the spot on which you focus in order to tune your stroboscope frequency.

6) Safety Considerations:

a) When you are using this rig to test the potential of your motor and cross-flow fan assembly, do not ever exceed 9000 rpm, even if your motor is rated to 13,000 plus rpm. Exceeding 9000 rpm may cause the LiPo batteries to overheat.
b) Properly anchor your rig to prevent unwanted vertical take-off.
c) Ensure the immediate area is clear of foreign object debris.
d) Wear personal protective equipment to include double hearing protection and safety glasses.

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