

T.E.A.R.S. DESIGN TEAM



New River Harrier



OUR HARRIER IS YOUR CARRIER



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Executive Summary

The following report documents team TEARS efforts at designing and constructing an autonomous aerial package delivery system “AAPDS”. This project was an all-volunteer effort from students enrolled in New River community colleges and engineering technology programs. The completed design meets all mission operational and safety requirements of the request for proposals for the American Helicopter Society’s 32nd annual student design competition “Distributed Logistics in an Urban Setting Using Small Unmanned Aerial Vehicles”. The final designs expected productivity is 1950 lb/mi/day. With an operational cost of \$188.4952 per mile.

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List of Symbols

$C_{L_{3D}}$	three dimensional lift coefficient
C_{l_α}	2D lift coefficient slope
AR	Aspect Ratio
α	Angle of Attack (radians)
L	Lift-force (lb)
ρ	Air density (slugs/ft ³)
S	Planform Area (ft ²)
V	Velocity (ft/s)
C_L	Lift coefficient
C_D	Drag Coefficient

Engineering Report

RFP Compliance

Design Requirement	Compliance	Reference
Primary mission	✓	Sections 4.8, 4.6
Payload Capacity	✓	Section 4.8
Environmental Impact	✓	Section 6
Mission Profile	✓	Section 5.2
Avionics	✓	Section 4.7
Maintainability	✓	Section 4
Productivity	✓	Section 5.2.2
Safety	✓	Section 4.11

1 Introduction

The New River Harrier vertical-take-off-and-landing (VTOL) Unmanned Aerial Vehicles (UAV) is being submitted in response to the 32nd annual American Helicopter Society Undergraduate Student Design Competition “Distributed Logistics in an Urban Setting Using Small Unmanned Aerial Vehicles.” The AHS request for proposals addresses an innovative thought in today’s parcel delivery sector. The core of the request is to seek a novel solution for quick, efficient, and economical point-to-point delivery of commercial packages.

In the not too distant past, the mobilization and delivery of commercial products and personal packages was done either by horseback, foot carriers, stagecoach, trains, or boats. Though some of the same methods are still used today — foot carriers must still go door-to-door, technological advances have had a profound effect on delivery systems. As a technologically advanced society, we have striven to reduce inefficiencies in global transportation. In doing so, we have been able to increase significantly the efficiency of delivery. With the evolution and continual emergence of technological advances through the means of engineering and design, we have also been able to reduce greatly labor cost and increase the efficiency of delivery systems.

Things considered miraculous in one era may be merely ordinary in another. Over the last half century, the development and computational understanding of the physical phenomena of flight has enabled more efficient long-distance transportation. The United Parcel Service (UPS), for example, allows customers the option to ship items by next day air. With their commitment to excellence, parcels can be shipped via end of business day and arrive the following day. It is also startling to think how efficient the post office has been throughout the years, especially considering the fact that someone has to be sent every single day to either a home or business throughout the entire United States [7]. The Post Office has been fantastically good at operational improvements. Literally billions of items are processed every week. Approximately 700 million items per day are

picked up, sorted, and distributed across one of the physically largest countries in the world [7]. The distance from Anchorage to Miami covers a staggering 5,000 miles, yet the cost of shipment per mile works out to a miniscule of 0.009 cent/mile for a first class letter [7]. Overall the Postal Service has been very good at reducing its inefficiencies, especially when you consider that it is a union based company. The U.S. postal service has done all that it can to reduce cost and increase efficiency. Still, because of changes in technology and competing delivery systems, they themselves understand that they are a “hedgehog concept” and are rapidly becoming irrelevant [7].

The first attack on the postal service came in the 1980’s with the invention of the fax machine [7]. Since then the postal service has taken an even greater hit as our society has become more tech savvy and has shifted towards a more environmentally friendly approach [7]. We have pushed for paperless billing, faster emails, faster delivery, and more efficient forms of mail delivery. In the near future, we may decrease door-to-door delivery workers and replace them with point-to-point drone delivery systems. Drone systems offer an alluring alternative to overhead cost reduction. Companies such as Amazon, whose profits rely heavily on the shipment of commercial goods and services, have begun to seek novel ways of decreasing the overall cost of delivery by establishing their own distribution networks and technologies.

The engineering design and technology department at New River Community College has used its ingenuity to satisfy this Request For Proposal. This report presents an innovative design called the *New River Harrier*, a hybrid vertical take off and landing aircraft that utilizes a ducted fan lifting system combined with an efficient medium aspect ratio forward flight lifting body. This design is unique in that it utilizes new technologies in 3D printing, it incorporates the use of advanced lithium-air (Li-O₂) batteries, and capitalizes on advanced mechatronics. The design also meets all of the RFP-requirements for operation safety, payload capacity, flight endurance, and maneuverability in an urban environment.

2 Request For Proposal Requirements

2.1 Operating Concept

“Continuing advances in microprocessors, microelectronic sensors, electric motors and batteries point to emerging opportunities to provide rapid aerial delivery of small cargos over the “last-mile” directly to the point of need. These small UAS logistics vehicles, when working together with larger cargo air vehicles, can form a complete aerial shipping system that rapidly take goods from a factory or warehouse all the way to the individual consumer. Such a system of vehicles has been seen as having positive impacts both in the commercial marketplace, where on-demand delivery is a premium service, and in the military, where getting supplies to the point-of-the-spear quickly and efficiently by air has been shown to improve military effectiveness and reduce soldier exposure to enemy forces. This RFP explores the design of such a small, distributed logistics, delivery vehicle and its role in a large logistics system concept.”

2.2 Specific Objectives

2.2.1 Primary Mission

The vehicle shall be capable of carrying a logistics payload of 13 lb an unrefueled distance of 10 statute miles (mi) from a central supply location to the point-of-need and then return to the central supply location without a payload. The mission shall include a 1 min hover at the start the mission and an additional 1 min hover at the point-of-need followed by landing and unloading the payload. Hover shall be assumed to occur 10 ft above the ground, measured from the lowest point of the combined vehicle and payload. As a margin on maneuver performance, the propulsion system shall be designed to generate a sustained vertical lift force of at least 110% of the max take-off gross weight in hover. Hover and forward flight performance shall be calculated in a 6000 ft / 95° F atmosphere (ISA + 57.4° F). Flight shall be limited to 500 ft AGL with ground level of 6000 ft.

2.2.2 Logistics Payload

The vehicle shall accommodate a logistics payload of 13 lb and 12 in x 8 in x 12 in in dimension in an enclosed, weather-proof payload container or fairing. The payload container or fairing shall include provisions to allow for the rapid (<1 minute) loading and unloading of the payload. Unloading of the payload shall be automated. Additionally, the vehicle shall be capable of carrying oversized payloads of up to 13 lb externally, using a cargo carrying net (or similar) attached via a single point to the vehicle. When carrying an external load, the payload container or fairing may be removed from the vehicle.

2.2.3 Environmental Impact

The vehicle shall be designed to minimize impact on the environment with respect to energy consumption, emissions, and acoustic signature.

2.2.4 Precision Departure, Approach, and Hover

The vehicle shall be capable of operating to and from a landing spot by transiting an unimpeded airspace region defined by a cylinder 10 ft radius and 50 ft in height as depicted in Figure 1. The vehicle shall also be capable of hovering for 1 minute, while remaining within that cylinder, and placing the payload within 95% circular error probable of not more than 2 ft radius of the designated delivery point, with winds at 10 knots gusting to 15 knots.

2.2.5 Avionics

The vehicle shall be capable of autonomous flight operations using the customer-furnished avionics package specified. Continuous contact with a central ground control center shall be maintained, providing aircraft telemetry data and ability to dynamically re-task the vehicle.

2.2.6 Maintainability

A modular system design shall be utilized such that the time to replace any component shall not require more than 1 person-hour of labor to accomplish.

2.2.7 Productivity

The vehicle's productivity shall be defined as the total lb-mi achieved in one day (number of missions in 10 hr x 10 mi x 13 lb). Turn-around time between two missions, for a single vehicle, shall be not more than 15 minutes. A single system shall be defined to include all the provisions necessary to achieve the number of missions used to in determining the system productivity as defined above.

2.2.8 Safety

The vehicle shall be designed such that given a loss of power, during any phase of flight and at 50 ft AGL or higher, the aircraft and payload shall be able to accomplish a safe landing on level terrain. Using the customer provided avionics package, the vehicle shall be capable of autonomously operating in an urban obstacle environment. Segments of the mission operated between 100 ft AGL and 500 ft AGL may be assumed to be free of stationary obstacles, below 100 ft AGL forward speed shall be limited such that the vehicle can come to a stationary hover in not more than 400 ft horizontal distance, with no change in vehicle altitude. The safety requirements apply to the vehicle when carrying either an internal or external payload.

3 Configuration Selection

The primary design decision was to find a multi-rotor configuration that would best achieve the desired load capacity and endurance. The design that was selected is shown in Figure 1. This concept incorporates three Electric Ducted Fans (EDF) positioned vertically for takeoff, hover, and landing and one EDF positioned horizontally for forward flight.

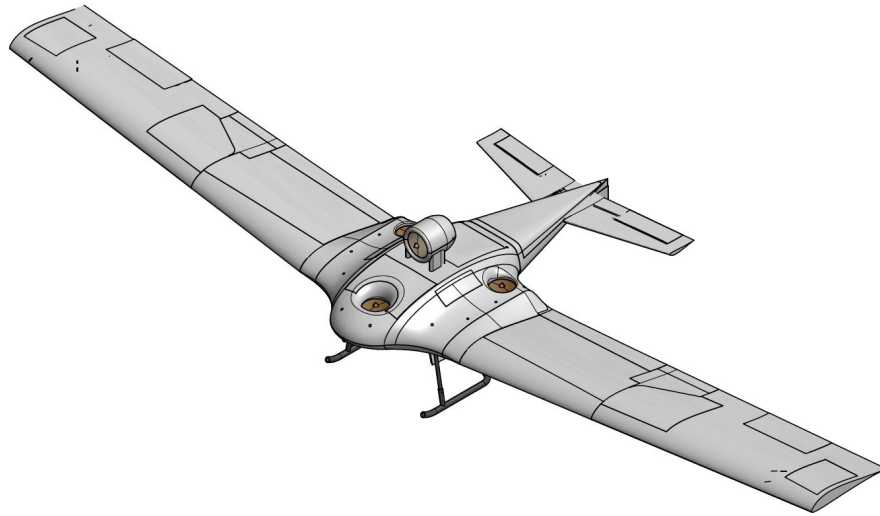


Figure 1: Isometric View of the *New River Harrier*

3.1 Design Requirements

The design constraints considered for proposed configurations were:

- **Safety:** The chosen design must be safe to operate remotely over long distances in an urban environment.
- **Efficiency:** The chosen configuration should maximize efficiency in forward flight to increase endurance.
- **Weight:** The configuration should be as lightweight as physically possible to increase payload capacity for a given thrust rating as well as increase the endurance of the power supply.
- **Mechanical Simplicity:** The chosen design should be mechanically simple to reduce failure points and decrease repair times.
- **Modularity:** The configuration should be simple to break down.
- **Cost:** The chosen design should incorporate off-the-shelf components and technologies to reduce production costs.

3.2 Standard Multi-Rotor (SMR)

This style of Vertical Takeoff and Landing (VTOL) craft is the standard craft currently in use today by hobbyists and aerial photographers. The various standard arrangements can be seen in Figure 2. In current applications, such as aerial photography, hexacopters and octacopters are the usual choices for reasons including lifting capacity, endurance, and built-in redundancy. Currently,

hexacopters and octacopters are capable of lifting large DSLR cameras for extended periods of time, up to 30 minutes in some cases. These large multi-rotors also have built in redundancy in that they are capable of controlled flight even after losing a rotor or two. These designs typically have a low bodyweight because they consist of just a skeleton frame with no aerodynamic skin. However, due to the fact that there are no airfoils built into these designs, they are constantly having to support their entire weight with the thrust of the rotors. This is extremely draining on the batteries, reducing flight time. The other disadvantage is that conventional multi-rotors use large unshrouded props that would be dangerous to use in an urban environment.

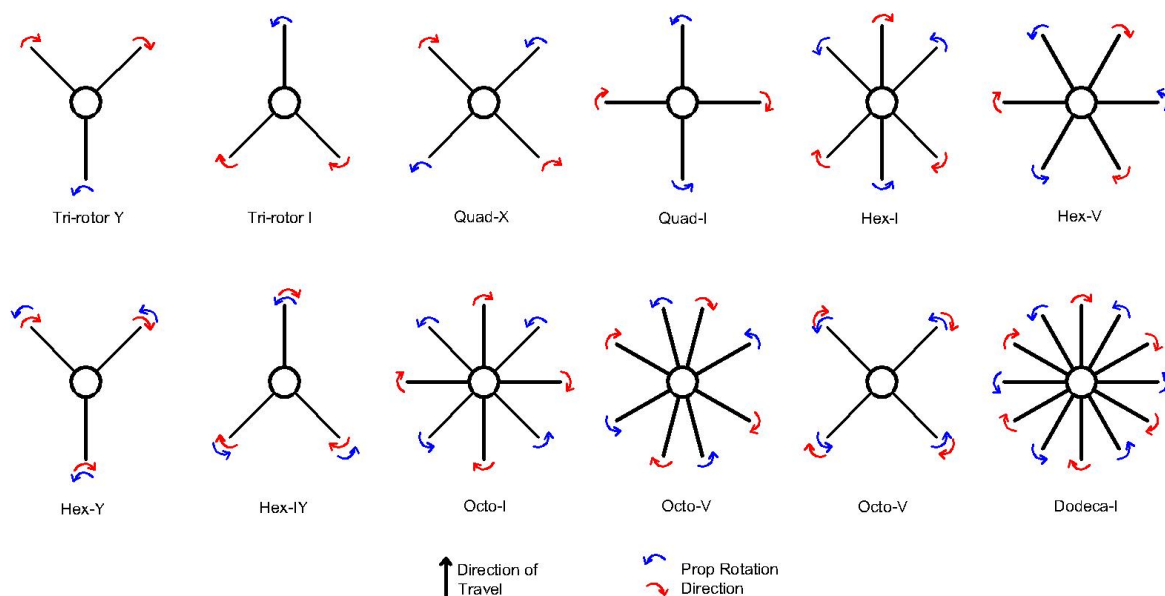


Figure 2: Multi-rotor Configurations

Table 1: Comparison of Current Heavy-lift Multi-rotors

Drone	Body Weight (kg)	Max Load (kg)	Configuration	Prop Diameter (cm)	Flight Time ¹ (min)	Cost (\$)
XPX Heavy Lift Quadcopter ²	x	.9	Quad-X	35.56	9 - 30	1,899.00
CarbonCore ³	3.3	4	Octa-X	40.64	25 ⁴	4,999.99
Turbo Ace Infinity 9 ⁵	4.5	8.164	Octa-V	43.18	8 - 20	10,897.95
Versa Heavy Lift Octocopter ⁶	x	6	Octa-I	38.10	8 - 30	12,276.33
Turbo Ace Infinity 9Pro ⁷	12	9.071	Octa-V	43.18	8 - 15	15,097.95
Dronera 8HL ⁸	8.5	12	Octa-I	45	14 - 50	20,990.00
Dronera X8U ⁹	11	50	Octa-X	55	20 - 35	34,990.00
Dronera X12U ¹⁰	15	100	Dodeca-I	65	20 - 40	39,990.00

¹variance due to battery configurations and load²ProHELI. <http://xproheli.com/products/xpx-heavy-lift-quadcopter>³Autonomous Avionics Custom UAVs <http://autonomousavionics.com/products/carboncore-cortex-heavy-lift-by-autonomous-avionics>⁴with 16000mAh 6S battery and no payload⁵WOW Hobbies http://www.wowhobbies.com/turboace.infinity_9_octocopter_bundle.aspx⁶VERSA Drones <http://www.versadrones.com/#!heavy-lift-octocopter/c20v1>⁷TerboACE http://www.turboace.com/infinity-9pro_octocopter.aspx⁸Dronera Unmanned Aerial Vehicles <http://www.dronera.no/product/dronera-8hl-heavy-lift-rtf/>⁹Dronera Unmanned Aerial Vehicles <http://www.dronera.no/product/dronera-x8u/>¹⁰Dronera Unmanned Aerial Vehicles <http://www.dronera.no/product/dronera-x12u/>

3.3 Multi-rotor with Rotating Pusher Props (MRRPP)

The second design that was considered was a modified multi-rotor that included wings and one or two props that could be swiveled horizontally for forward flight. A concept design using this configuration is shown in Figure 3. This configuration combines the vertical lifting capacity of a standard multi-rotor with the forward flight efficiency of a regular plane. To use fewer props, the prop diameter must increase, resulting in extremely large props which, while quieter due to lower RPMs, pose a safety concern to people and animals around the landing areas. This danger can be reduced by putting shrouds around the props. Due to the mechanical complexity of rotating the props horizontally (added failure points), and the safety concerns of the large props, this idea was deemed unsuited for use in an urban environment.

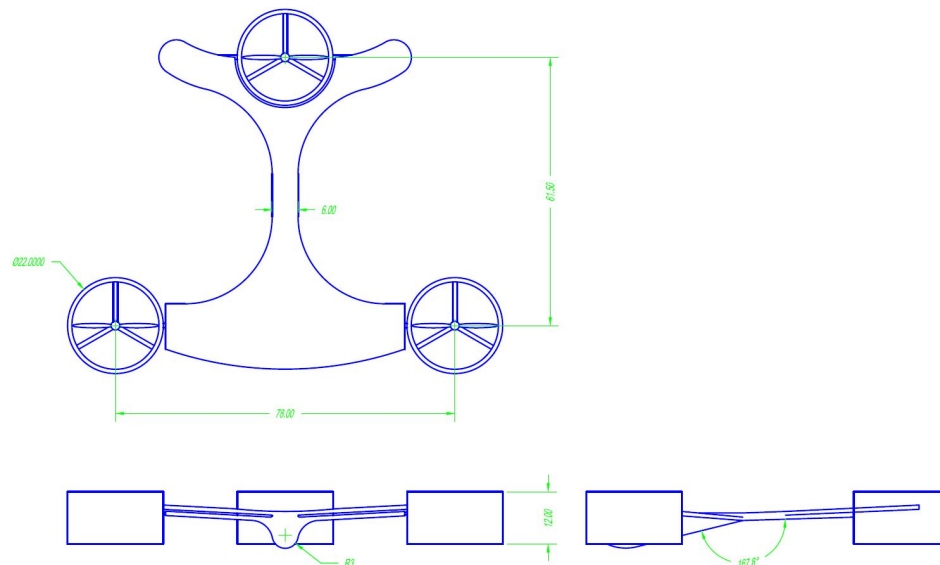


Figure 3: Multi-rotor with rotating props. In this concept design, all three props rotate 90° for forward flight. Note the large prop diameters.

3.4 Multi-rotor with Fixed Pusher Props (MRFPP)

This was a variation of the MRPP design (Figure 4) and shares the same advantages with the addition of reducing the mechanical complexity by having one or more rotors fixed in the horizontal position. It also requires a large prop size and thus poses the same safety concerns as the MRRPP design.

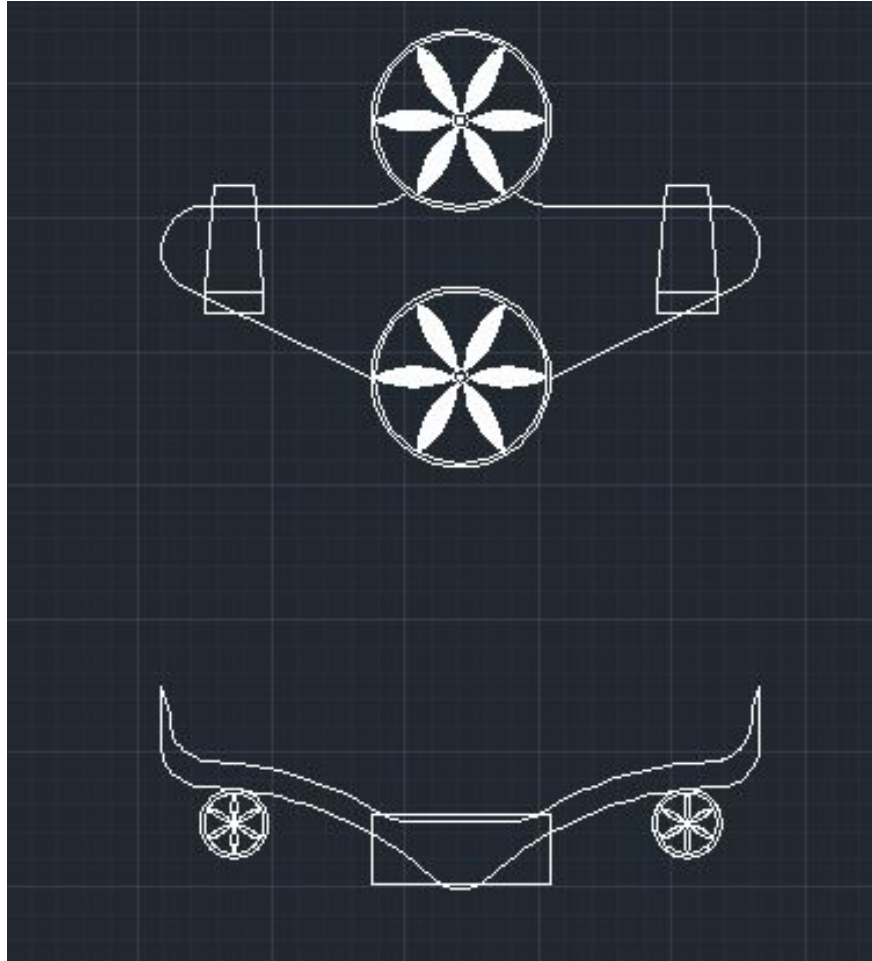


Figure 4: Multi-rotor with fixed, underwing, pushing props.

3.5 Multi-EDF with Rotating Pusher EDF (MERPE) and Multi-EDF with Fixed Pusher EDF (MEFPE)

During the team's research into possible configurations, Electric Ducted Fans were discovered that could produce thrust similar to the large rotors of the SMR, MRRPP, and MRFPP designs but with much smaller rotor diameters. This led to design variations of the MRPP and MFPP designs with the rotors replaced by EDFs. These designs have the additional advantage over the standard prop designs of increased safety due to smaller rotor size and built-in shrouds. However, EDFs have very high power requirements and are much louder than standard props due to the extreme RPMs of the rotors. They are also much more expensive due to the tight tolerances needed between the rotor tips and the interior of the duct.

3.6 Conclusions

The Multi-EDF with Fixed Pusher EDF was chosen as the best configuration to meet the RFP design requirements (Figure 1). This configuration offers a mechanically simple design and increased

safety from small rotor diameters and shrouds. The additional expense of the EDFs is offset by the increased efficiency.

3.7 Configuration Selection Summary

Table 2: Motor Configuration Pros and Cons

Motor Configuration	Pros	Cons
Standard Multi-rotor	Readily Available Lifting Capacity	Props unsafe Inefficient in forward flight Large prop size
Multi-rotor with Rotating Pusher Prop	Lifting capacity Efficient in forward flight	Mechanical linkage for rotating prop Props unsafe Large prop size
Multi-rotor with Fixed Pusher Prop	Lifting capacity Efficient in forward flight Mechanical simplicity	Props unsafe Large prop size
Multi-EDF with rotating EDF	Lifting capacity Small prop size Shrouded Prop Efficient in forward flight	Extremely high power requirement Mechanical linkage for rotating EDF Limited Technical Data Available EDF Cost
Multi-EDF with Fixed EDF	Lifting capacity Small prop size Shrouded Prop Mechanical simplicity	Extremely high power requirement Limited Technical Data Available EDF Cost

4 Unmanned Aerial System Design

4.1 Design Tools

The following tools were used in the design and testing of the *New River Harrier*.

Table 3: Tools used for the design of the *New River Harrier*

Tool	Type	Use
Autodesk Inventor 2015	CAD/Solid Modeling	Develop solid model of NRH
Autodesk Inventor 2015	FEA	Stress and displacement testing on NRH components
x-Plane 10	FAA Approved Flight Simulator	Flight test simulations
Autodesk CFD	CFD	Airfoil and efficiency testing

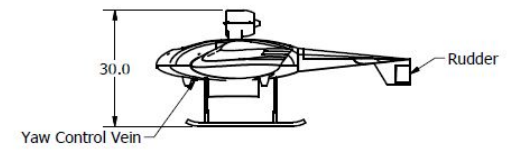
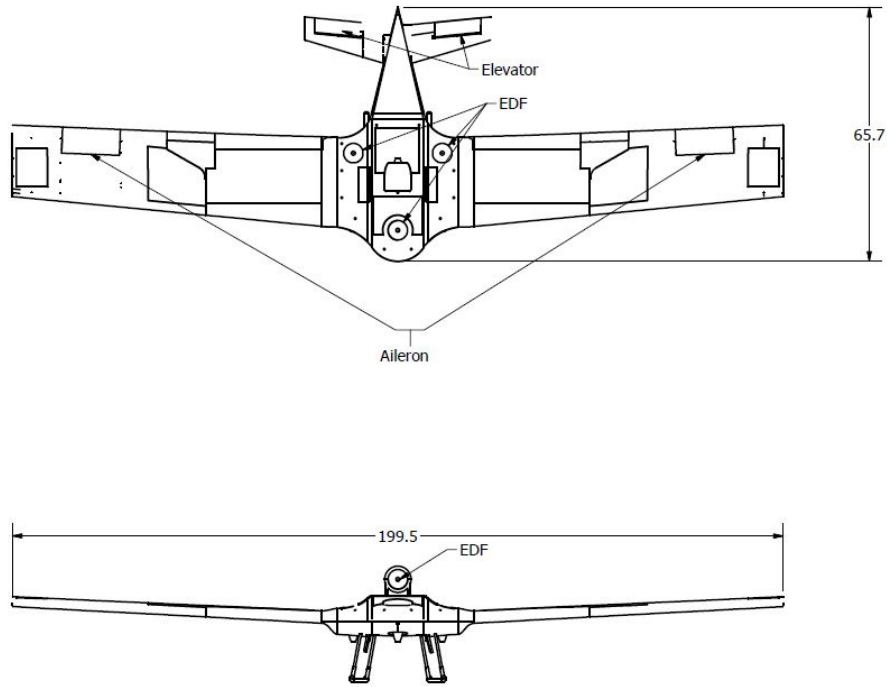


Figure 5: *New River Harrier* primary dimension. All units are in inches.

Table 4: Frame Material Properties

Material Property	CFRP	Aluminum 2024	Aluminum 7075-T6
Poisson's Ratio	0.39	0.33	0.33
Shear Modulus (<i>psi</i>)	7.687×10^6	3.751×10^6	3.920×10^6
Thermal Expansion Coefficient ($^{\circ}F^{-1}$)	5.517×10^{-6}	1.311×10^{-5}	1.311×10^{-5}
Density (<i>lb/in</i> ³)	0.052	0.101	0.098
Thermal Conductivity (<i>btu/(in · sec · ° F)</i>)	1.404×10^{-3}	3.300×10^{-3}	3.300×10^{-3}
Specific Heat (<i>btu/(lb · ° F)</i>)	0.270	0.214	0.214
Tensile Strength (<i>psi</i>)	8.369×10^4	6.500×10^4	8.270×10^4
Yield Strength (<i>psi</i>)	4.351×10^4	3.989×10^4	7.320×10^4

4.2 General Overview

The *New River Harrier* is designed as a Tri-rotor I and powered-glider hybrid design. Figure 5 shows the full dimensions.

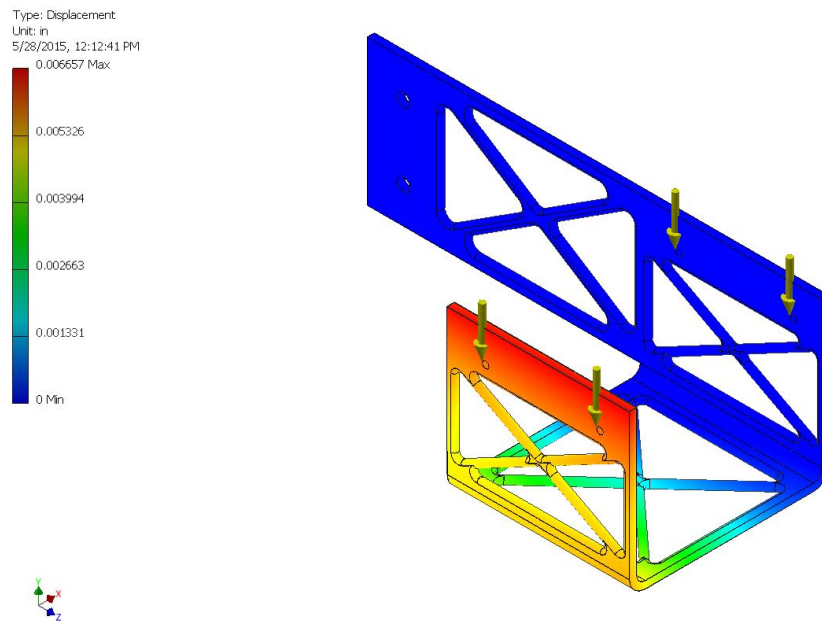
4.3 Frame

The frame for the *New River Harrier* is made out of carbon fiber resin composite (CFRP). This material was chosen after comparing FEA results of various frame components using CFRP and aluminum 2024 (Table 4 lists material properties). As verified by FEA, CFRP produces a stronger frame (less displacement under load) while also reducing weight. An example of the testing is shown in Figure 6.

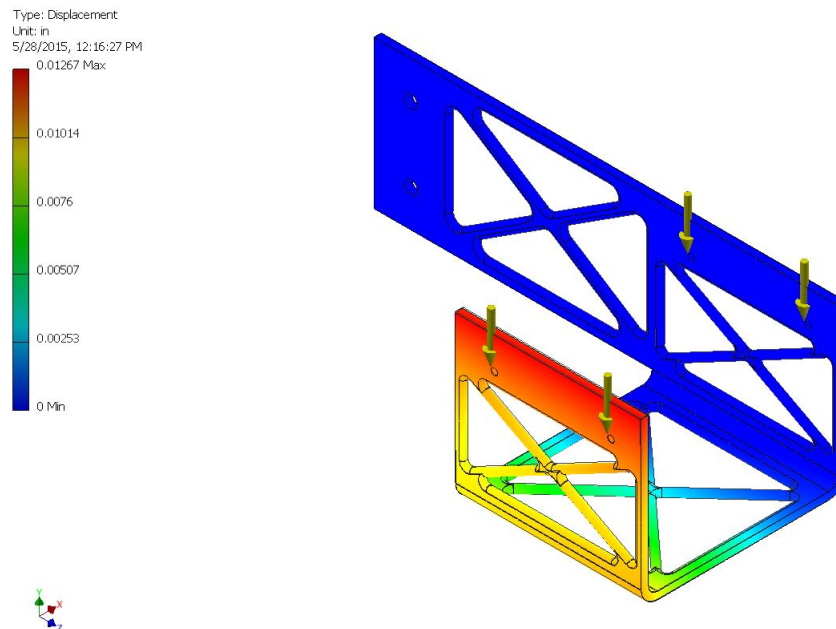
The fasteners used on the *New River Harrier* are made of aluminum 7075-T6. This reduces the total weight of the fasteners used to 0.6 lb from 1.75 lb with Stainless Steel AISI 317 and 0.97 lb with Titanium 6Al-4V.

4.4 Skin

The skin of the *New River Harrier* was designed to be 3D printed. It consists of panels up to 36in² that are designed to slide over the frame members. The material chosen was ABS plastic, however the effective density of the 3d printed ABS plastic is different due to the fact that the printer can print a honeycomb structure on the interior of parts that reduces the total weight, but they retain the majority of their structural properties. The benefits of this production method are covered in greater detail in Section 6.1.1.



(a) FEA displacement test of the front-right electronic speed controller bracket using CFRP. Maximum displacement under load is 6.657×10^{-3} in.



(b) FEA displacement test of the front-right electronic speed controller bracket using Aluminum 2024. Maximum displacement under load is 1.267×10^{-2} in.

Figure 6: Material Comparison using FEA

4.5 Wings

4.5.1 Airfoil Selection and Planform Area Calculation

Airfoil selection is a critical—if not the most critical part—of the overall design of an aircraft. The type of airfoil selected will have a direct impact on the capabilities and performance of the aircraft. The challenge for the aircraft designer is one of selecting an airfoil that gives an acceptable balance of properties for an aircraft to meet the mission objectives.

According to Sadrey et al. [12] selecting an airfoil begins with a clear understanding of the flight requirements. Taking into consideration the design requirements stated in Section 3.1, the airfoils researched were limited to glider-like airfoils that would yield a high endurance at our target weight of 80 lb. The *New River Harrier* was designed with a larger than normal planform area to increase safety as described in Section 4.11.

Each airfoil has a lift coefficient (C_l), which is an indicator of how much lift it will generate relative to other airfoils at a given angle of attack (α). All else being equal, the higher the angle of attack, the more lift an airfoil will generate. The maximum lift coefficient (C_{lmax}) is the C_l at the angle of attack that generates the most lift. The ideal lift coefficient (C_{li}) is an average of lift coefficients where the drag is minimized. By basing the airfoil selection on these values the previously selected glider style airfoils selection was narrowed to four airfoils: NACA 4424, NACA 63(3)-618, NACA 65(3)-618, and MH83-iL. Figure 7 shows the comparison of C_{lmax} and C_{li} for these airfoils.

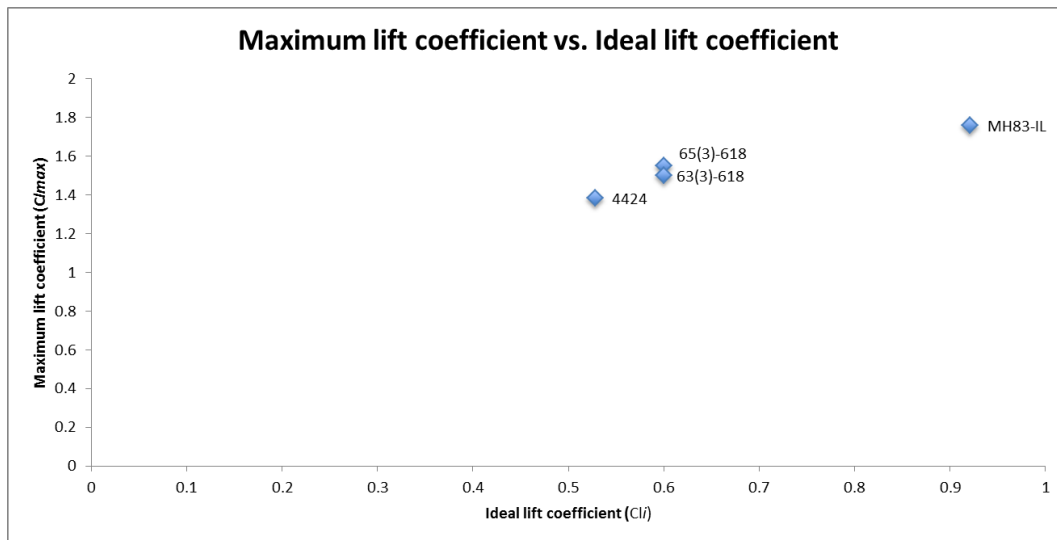


Figure 7: Comparison of C_{lmax} and C_{li} for selected airfoils

Once the airfoil selection was restricted to these four airfoils, they were then evaluated using the following criteria and graded on a scale of 1-10 as seen in Table 6.

1. Highest lift to drag ratio (L/D)
2. Smallest coefficient of drag (C_d)
3. Largest C_l/C_d

4. Largest α before stall
5. Highest C_l before stall
6. Highest C_l at $\alpha = 0$
7. Smallest C_d at $\alpha = 0$
8. Smallest coefficient of moment (C_m)

The MH83-il airfoil was selected based on these criteria and its compliance score of 93.4%. This airfoil provides an excellent lift to drag ratio.

Using the Lanchester-Prandtl wing theory (Eq. 1), the most efficient wing design based on the airfoil geometry was calculated using Microsoft Excel. Using Equation 1, the $C_{l_{3D}}$ was calculated on the AR-interval of 0.1 to 100. Based off of this data, an aspect ratio of 7.7 was selected to give the most efficient wing shape while still keeping the total wingspan under 20 ft to satisfy RFP objective 2.2.1.4.

$$C_{l_{3D}} = C_{l_{\alpha}} \left(\frac{AR}{AR + 2} \right) \alpha \quad (1)$$

$$L = C_l \rho S V^2 \quad (2)$$

To calculate the planform area of the wing, an aircraft weight of 69 lb to 82 lb and a speed range of 30 - 100 mph were used. Using Eq 2, the set of optimal planform areas for the range of aircraft weights and speeds were generated in Microsoft Excel. In these calculations, $C_{l_{3D}}$ was substituted for C_l , the lift force was set to the aircraft weight, and ρ was set to 0.002 slugs/ft³. The resulting optimal planform areas are shown in Table 5.

Table 5: Calculated Planform Areas (ft²)

Speed		Aircraft Weight	
MPH	ft/sec	PA (ft ²) at 82 lbs	PA (ft ²) at 69 lbs
30	44.0	35.57	29.93
40	58.7	20.01	16.84
50	73.3	12.81	10.78
60	88.0	8.89	7.48
70	102.7	6.53	5.50
80	117.3	5.00	4.21
90	132.0	3.95	3.33
100	146.7	3.20	2.69

The final dimensions of the wings are shown in Table 7

Table 6: Graded rankings of the four selected airfoils.

Criteria	MH83-iL	Compliance Ranking	NACA 4424	Compliance Ranking	NACA 63(3)-618	Compliance Ranking	NACA 65(3)-618	Compliance Ranking
C_l at best $\frac{L}{D}$	1.476	10.0	1.1196	2.5	1.2252	3.0	1.173	3.5
Minimum C_d	0.01192	8.0	0.01521	8.0	0.0092	9.0	0.00889	9.0
$\frac{C_l}{C_d}$	123.8	8.0	73.6	2.0	133.1	10.0	131.946	9.0
C_m	-0.0654	10.0	-0.529	10.0	-0.1188	7.0	-0.1191	7.0
Stall α (deg)	19	9.75	19.25	10.0	17.75	7.0	17.75	7.0
C_l before stall	1.7595	10.0	1.3825	6.0	1.50	8.0	1.55	8.5
C_l at $\alpha = 0$	0.4633	9.0	0.186	2.0	0.518	10.0	0.518	10.0
C_d at $\alpha = 0$	0.00849	10.0	0.00997	10.0	0.00721	7.0	0.00721	7.0
Compliance Total (80 max)		74.74		50.5		61.0		61.0
Compliance %		93.4		63.1		76.3		76.25

Table 7: Final Wing Dimensions

Planform Area (ft ²)	24.10
Root Chord Length (in)	23.18
Tip Chord Length (in)	19.18
Single Wing Length (in)	80.00
Total Wing Span (in)	199.5

4.5.2 Pivot System

To meet the RFP requirement that the drone must stay within a 20 ft diameter cylinder during hover (RFP Section 2.2.1.4), the wingspan of the *New River Harrier* was limited to just over 16.6 ft. However, this gives the drone only 1.5 ft of clearance off of either wingtip. To increase this clearance and make it easier for the flight controller to compensate for wind gusts, a hinging mechanism was designed for the middle of each wing. With this hinge, the outer 50 inches of the wing can swivel back 60° towards the tail. This can be seen in Figure 8. This reduces the effective wingspan by 3 ft and thus increases the clearance between the wingtip and the edge of the hover cylinder. The horizontal nature of the hinge prevents the wing from acting like a sail in the folded configuration.



Figure 8: The *New River Harrier* in hover with wings folded back. Note the moveable panels in their retracted position on the underside of the inner wings.

The hinge is located two thirds of a chord length back from the leading edge of the wing and is activated by a linear actuator located in the inner, stationary, segment of the wing. In the forward position, the outer portion of the wing locks into place by slotting the two front spars into sockets

on the corresponding inner spars (Figure ??). This provides a mechanical connection to support the wing during forward flight and reduces the strain on the hinge. To provide the outer segment of the wing space to pivot into, but without having to sacrifice lifting surface, the segment of the wing directly behind the hinge is split into two panels that separate vertically when the outer wing pivots back as seen in Figure 8. These panels are springloaded so that they sit naturally in the closed position when the wing is extended, but can be separated easily by the wedge on the trailing edge of the outer wing segment.

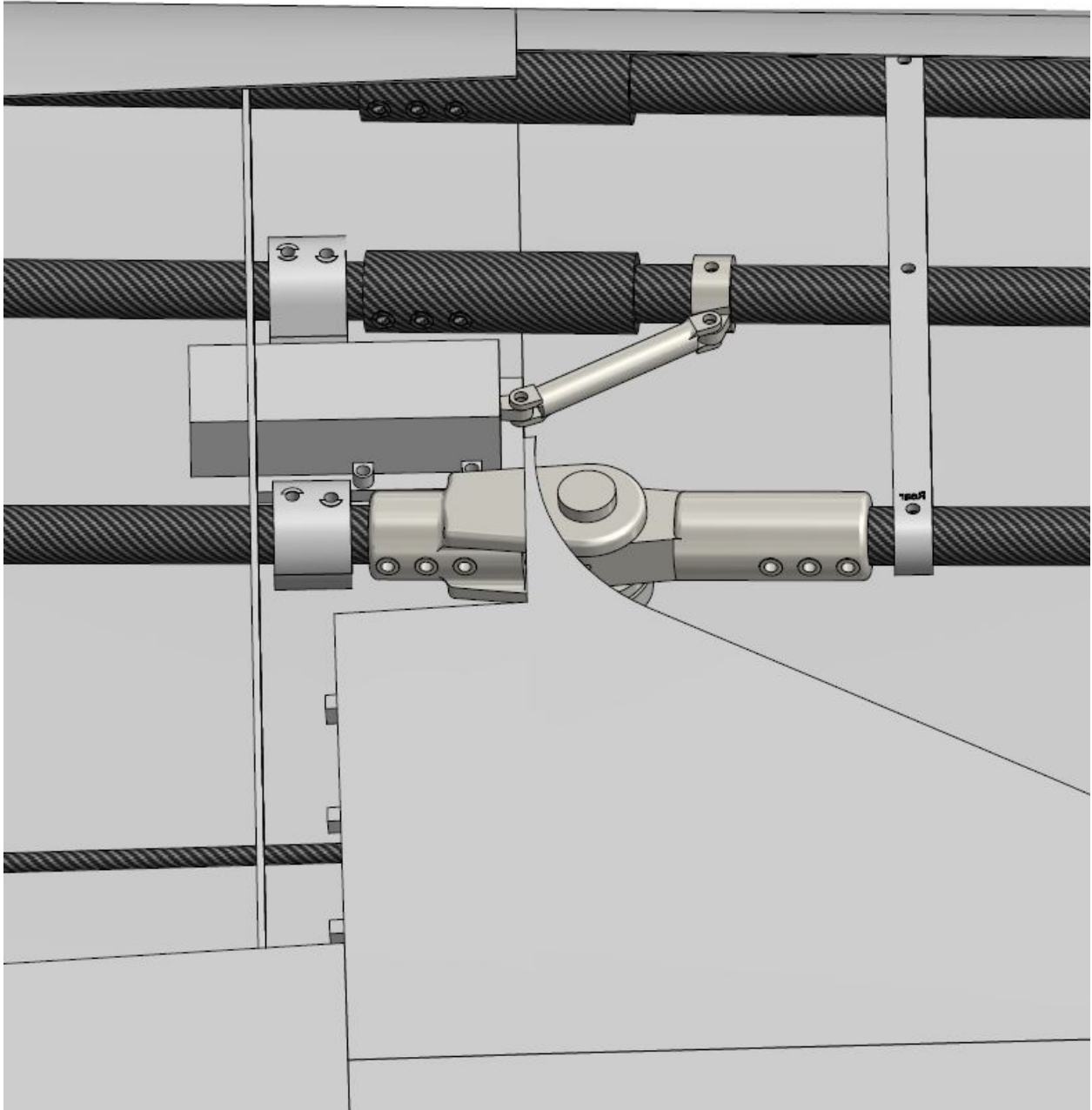


Figure 9: The wing extended and the outer forward spars are slotted into the sockets on the inner spars. The leading edge of the wing is at the top of the figure.

4.6 Power System

The design of the power system is the major limiting factor in the design of the *New River Harrier*. Due to the VTOL nature of the design, the power system must generate enough thrust to lift the entire drone and package weight. As such, the use of only three fans in the vertical sections of flight

placed a hard limit on the maximum weight of the drone.

4.6.1 Electric Ducted Fan

The Schübler DS-94-DIA HST with a DSM6745-700 motor¹¹ was selected for the propulsion system due to its light weight, relatively small rotor diameter, and rated thrust (Table HV.1 and Figure HV.1). The maximum thrust generated by a single DS-94-DIA HST is 29.22 lb-f (130N) so the total hover capacity of three EDFs is 87.66 lb. Taking into account the maximum payload weight of 13 lb and the RFP requirement of generating a vertical lift force of 110% of the max take-off gross weight, the maximum empty take-off weight of the *New River Harrier* was calculated to be 66.69 lb. The power vs. thrust curves of these EDFs were necessary to perform endurance and efficiency calculations, but were not available from the manufacture, Schübler Composites. Thus the team decided to use the Hardware Validation optional section to generate the thrust curves. This procedure is covered in the Hardware Validation Addendum of this report.

4.6.2 Electronic Speed Controller

In multi-rotor aircraft, Electronic Speed Controllers (ESCs) are necessary to translate throttle and control inputs into required RPM for each motor. For the *New River Harrier* the ESCs are the MGM COMPRO TMM 25063-3 (seen in Figure 10) recommended by Schübler Composites to run their EDFs. The specs for these ESCs can be seen in the following table (Table 8).

Table 8: ESC Specifications

Max Continuous Power (kW)	15.75
Weight without cables (lb)	.551
Feeding Voltage (V)	15-63
No. of Feeding cells Li-ion/Li-Pol	4-15
Max Continuous Current (A)	250
Max Burst Current (A)	360

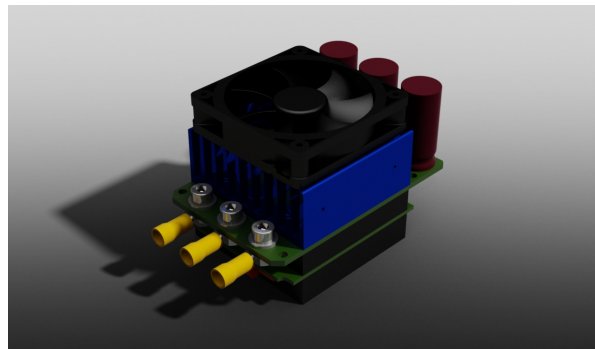


Figure 10: ESC recreated in Inventor 2015

4.6.3 Power Supply

When deciding on a power supply for the *New River Harrier*, the design team considered three options: gas power hybrid, Lithium-Polymer Batteries, and Lithium-Air Batteries. The advantages and disadvantages of each are shown in Table 9.

¹¹<http://www.schuebeler-jets.com/en/hst-fans-en/ds-94-dia-hst.html>

Table 9: Power Supply Option Advantages and Disadvantages

Power Supply	Advantages	Disadvantages
Gas Power Hybrid	High energy density	More Parts
		More Weight
		Combustible material
		CG changes with fuel consumption
		Lots of heat generated
		CO ₂ emitted
Li-Poly Battery	Easily Obtainable	Weight
	Hobby RC proven	Special charging unit required
	Moderate energy density	Highly volatile if damaged
	Constant Mass	
	Easily Swapable	
	Environmentally friendly	
Li-O₂	High energy density	Under Research
	Constant Mass	Large hystereses in voltage capacity curve
	Easily Swapable	High charging potential
	Environmentally friendly	Capacity retention

There are many options when considering an energy storage system, such as flywheels, ultra-capacitors, compressed air, coal, gasoline, diesel, and bio-fuel. However, batteries as a primary energy source are an alluring alternative to these options because batteries are highly efficient with a high energy to weight ratio. Batteries are also considered a "green" or clean technology due to their recyclability and minimal carbon emissions.

Based on these advantages and disadvantages, the lithium-air battery was selected to power the *New River Harrier*. Though still under research, this type of battery has a potential energy density ten to fifteen times greater than that of current lithium-polymer batteries and current studies place the potential energy density of Lithium-air batteries near that of gasoline [8]. According to theoretical studies [8], and current lab results [7, 12, 13, 4], lithium-air batteries have an energy density of 12 kwh/kg.

A lithium-air battery works on the chemical system of a precipitation dissolution reaction as seen in Figure 11. During the course of operation, ambient oxygen that is not stored within the battery reacts with lithium to create a lithium peroxide and electrical energy. Throughout the course of operation, the lithium within the battery is nucleated and a lithium oxide phase is created during electrical discharge. As the battery is recharged the lithium oxide phases created during the discharge react with an electrolyte and decompose back into their original phase. The much higher energy density of lithium-air batteries compared to conventional lithium-polymer batteries is due to this electrolyte reaction within the discharge and recharge phase of the battery cycle.

The electrode reactions within a general lithium-air battery can be summarized as follows:

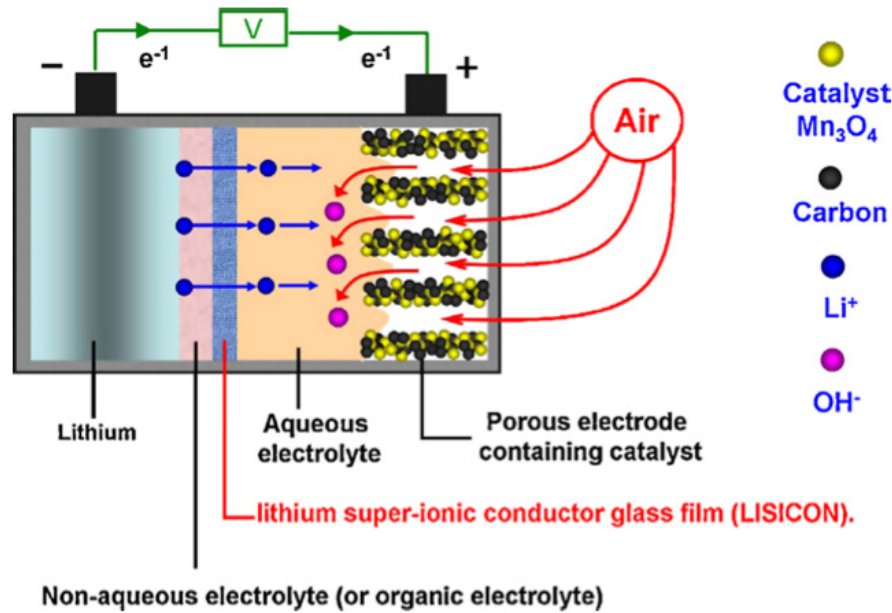


Figure 11: Schematic representation of a developed lithium- O_2 battery

1. Positive electrode: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$
2. Negative electrode: $Li^+ \longrightarrow Li^+e^-$
3. Battery reaction: $4Li^+O_2 + 2H_2O \longrightarrow 4Li^+ + 4OH^-$

While the standard lithium-polymer battery is the power source of choice for popular consumer electronics, it is not suited for use in sustainable electrified transport [7]. The development of advanced, higher energy-density, lithium batteries is essential in the establishment of the electric, long distance transport [7]. Owing to its exceptionally high energy-density, the lithium-air battery is a very appealing candidate for fulfilling this role [7]. Researchers such as Hung-Gi Jung et. al. in “An improved high-performance lithium-air battery” have reported a lithium-oxygen battery that can operate under capacity levels as high as $5,000 \text{ mAhg}_{carbon}^{-1}$ with an average discharge voltage of 2.7 V, leading to a very high theoretical energy density of $13,500 \text{ Wh Kg}^{-1}$. It is also important to note that other researchers, such as Yonggang Wang et al. in “A lithium-air battery with a potential to continuously reduce O_2 from air for delivering energy” have reported a 500 hour continuous discharge performance with a capacity of $50,000 \text{ mAhg}_{carbon}^{-1}$. This is one of the highest discharge studies reported [12].

4.7 Flight Control

The flight control for the *New River Harrier* consists of two modes, one for each realm of flight. In both cases, the drone is controlled by the customer supplied flight controller (RFP Section 2.2.1.5, Table 1). In vertical flight, the flight controller uses the three vertical EDFs and controls pitch and roll by adjusting the thrust (RPMs) and yaw by operating the control vein located in the exhaust of the front EDF as seen in Figures 5 and 12. In horizontal flight, control is maintained by standard flight control surfaces.

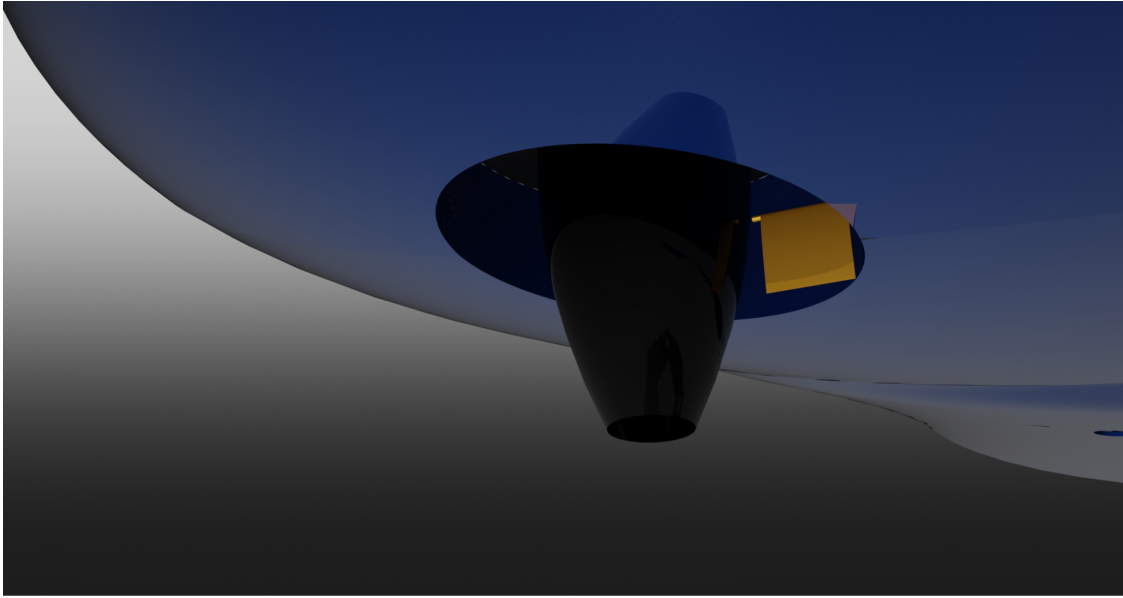


Figure 12: Close up of Yaw Control Vein

4.8 Cargo Attachment and Deployment

4.8.1 Internal Cargo Bay

The internal cargo bay of the *New River Harrier* measures 12.25 in x 12.25 in x 8.25 in internally to provide room for the straps to connect the package to the pully system. In internal carry mode, the package is protected from the elements by cargo bay doors.

4.8.2 External Cargo Carry

For oversize packages, the cargo bay can be easily reconfigured. In this mode, the cargo bay doors are removed by releasing the bolts holding the 3 axle parts together. The cargo cable can then be extended so that the package dangles below the cargo bay during flight. This mode imposes drastic reductions in performance due to the increased drag of the open cargo bay and the suspended package.

4.8.3 Cargo Deployment

The process to unload the package at the point-of-need does not involve a standard landing. Instead, the *New River Harrier* is designed to remain in hover, 10 ft above the ground, and lower the package via a wench and 50 lb-test monofilament line. Once the package is in contact with the ground, a cutter (similar to a cigar cutter) is used to separate the package and line segment from the drone. Both these features, remaining in hover and cutting of the package line, are designed to increase the safety of the drone and will be explained further in Section 4.11.

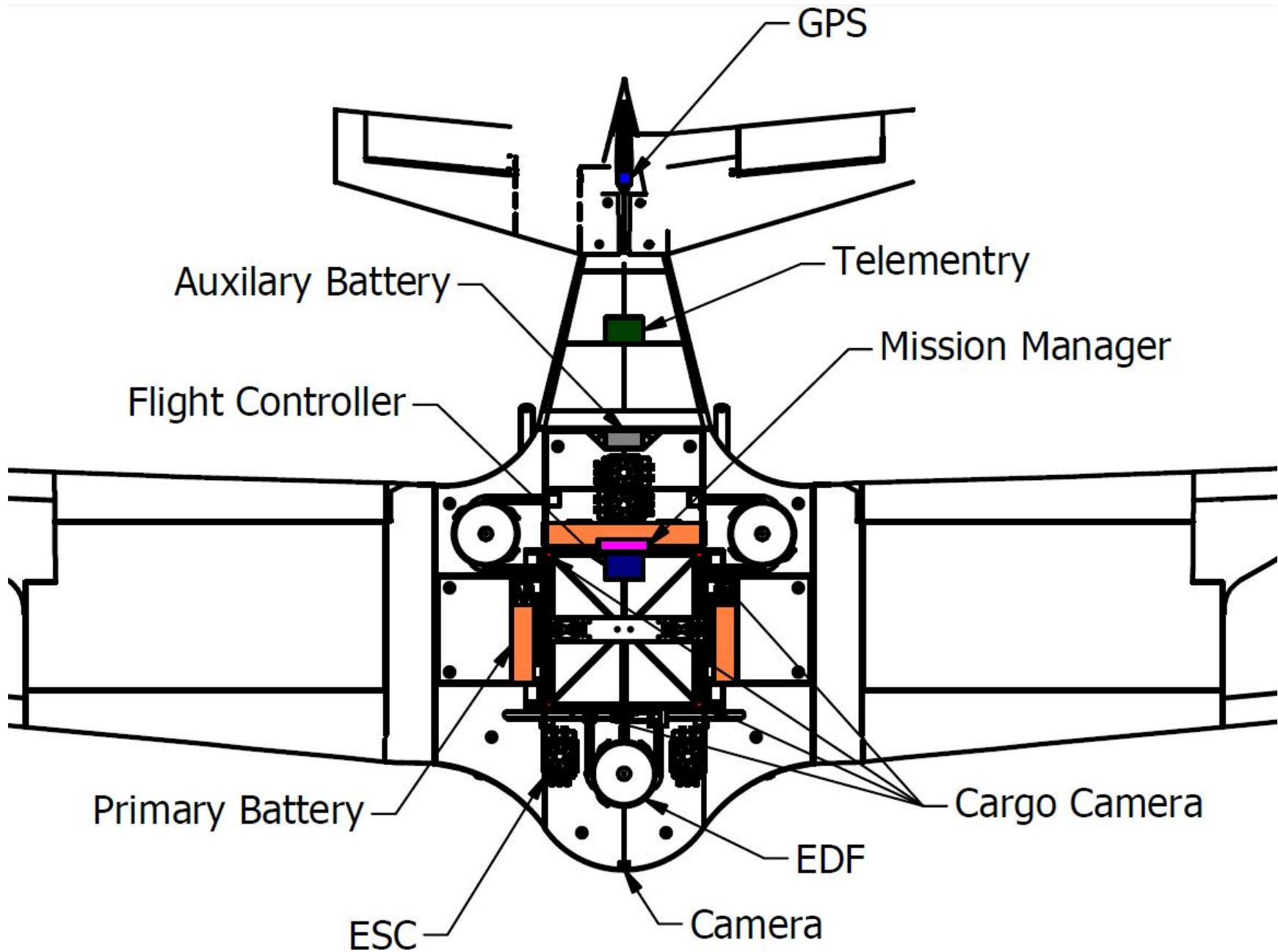


Figure 13: Locations of Major Electronic Components

4.9 Navigation and Hover Localization

The *New River Harrier* utilizes a combination of technologies to navigate to the specified point-of-need. In a commercial setting, the customer would sign-up for the same day delivery service with the delivery company. This would involve localizing their address and then generating the coordinates of the landing area. The customer would then receive a brightly colored, rubber landing zone mat that is 4ft by 4ft and has a unique QR code printed on the top.

For a delivery, the coordinates of the customer would be uploaded to the drone and it would fly to the general area using the GPS module located in the tail. It would then switch to landing zone locator mode and, using the downward facing camera, locate the landing mat. Once the QR code on the mat is verified, the drone then enters a hover over the landing mat. As described in Section 4.8.3, the drone then proceeds to lower the package to the landing mat. To keep the drone centered over the mat and to compensate for wind, the *New River Harrier* is outfitted with four visual sensors on the inside top of the cargo bay, as seen in Figure 13. These cameras provide a stereo view of the top of the package and the landing mat. The landing mat and package box are designed to have contrasting colors on the top sides so that when the drone sees the same amount of landing pad color around the boxtop color, it knows that it is centered over the mat. When the drone and package are buffeted by wind, the amount of landing pad color visible around the package will change and the drone can tell that it is drifting and will then compensate in the other direction.

4.10 Telementary

The data link for the *New River Harrier* is located in the tail of the drone along with the GPS unit in order to limit electromagnetic interference from the EDFs, ESCs, and batteries that are located in the central body. The telemetry unit is the standard customer supplied unit listed in Table 1 of RFP Section 2.2.1.5. This unit provides a realtime visual feed from the drone's forward and downward facing cameras as well as the ability to dynamically retask the drone in mid-mission. This retasking also possible due to the powerful long-endurance of the Li-air batteries discussed in Section 4.6.3.

4.11 Safety

There are several safety features that are incorporated into the design of the *New River Harrier* that have been mentioned in earlier sections.

1. **EDFs** - By their nature, EDFs are shrouded and due to their small size, they are located in the central body of the *New River Harrier* which provides a natural shroud and also dampens the acoustic signature.
2. **Large Planform Area** - As discussed in Section 4.5.1, the planform area of the *New River Harrier*'s wings is larger than what is normally designed for this weight and the cruising speed of 50 mph. This design allows the drone to operate as a glider even if all four motors fail.
3. **Redundant Batteries** - The design of the *New River Harrier* assumes that the customer supplied flight controller can be operated in a similar way to the Pixhawk flight controller available from 3dRobotics. This allows the flight controller to draw power from up to three

different sources in case one or more sources fail. In the case of the *New River Harrier*, the flight controller typically draws power from the auxillary battery that powers the control surface servos and other electronics. If the auxillary battery fails, the flight controller can then draw power from the primary batteries.

4. **Point-of-Need Hover** - The unusual package deployment at the point-of-need is designed to limit the danger to people or animals in the vicinity. The 10 ft hover prevents inquisitive children or pets from being caught in the blades of the EDFs.
5. **Package Deployment** - The cutting mechanism is designed so that the drone can not become stuck from a person or animal jumping on it (in the case of a full landing) or grabbing hold of the package and/or cable.

4.12 System Weight Summary

Table 10 breaks down the total weight of the *New River Harrier*. The most significant contributions to the total weight are the batteries and skin. The weight of the batteries is actually greater than that of the frame.

Table 10: System Weight Summary

	Weight (lb)	Percentage of Max Gross Take-off weight
Frame	16.91	27.26
Skin	18.69	30.13
Batteries	17.09	27.55
Electronics	8.74	14.09
Fasteners	0.60	0.97
Total	62.03	100

5 Performance

5.1 Flight Testing

The FAA certified flight simulator software package, X-Plane 10, is a very useful engineering tool for assessing an aircraft's flight performance. This section of the report details the flight-testing that was used to calculate the endurance of the *New River Harrier*.

Essentially the flight simulator hardware was used to determine:

- The total amount of energy that could be stored onboard the aircraft. The amount of energy stored is a function of the energy densities of various energy sources i.e. Li-po vs Li-O₂ batteries.

5.1.1 Endurance

The team used X-Plane 10 to simulate realistic missions for the RFP, a package was attached to the flight simulator model of the *New River Harrier*, and according to RFP rules the model was flown out 10-miles to a delivery point and the package was delivered. The *New River Harrier* then was flown back to the simulated warehouse and landed under a number of different cruising speeds and weather conditions as listed in Table 11.

Table 11: X-Plane 10 Simulation Conditions

Test Number	Airspeed (knots)	Windspeed (knots)	Gust Strength(knots)
1	30	0	0
2	30	10	15
3	40	0	0
4	40	10	15
5	50	0	0
6	50	10	15

X-Plane recorded the pilot's commanded thrust of each engine motor on the *New River Harrier* on each flight in 100 ms increments. This data was then analyzed using MathWorks MatLab software to convert the thrust required for the mission at any given interval into the electrical power that was required to complete the mission. This was done using data collected from the hardware validation test, see Section 3.

Once the power draw from the electrical system is known using this conversion process, the power used over the entire flight can be summated and that summation is the total energy required to complete the mission.

Seen below is the time history of the *New River Harrier*'s propulsions systems for each simulation that was flown. The energy total for each of these simulations is provided in Table 12. It can be seen that the most efficient flight regime is to cruise the *New River Harrier* at approximately 40 knots. However, it may not be the most efficient use of the drone in terms of productivity.

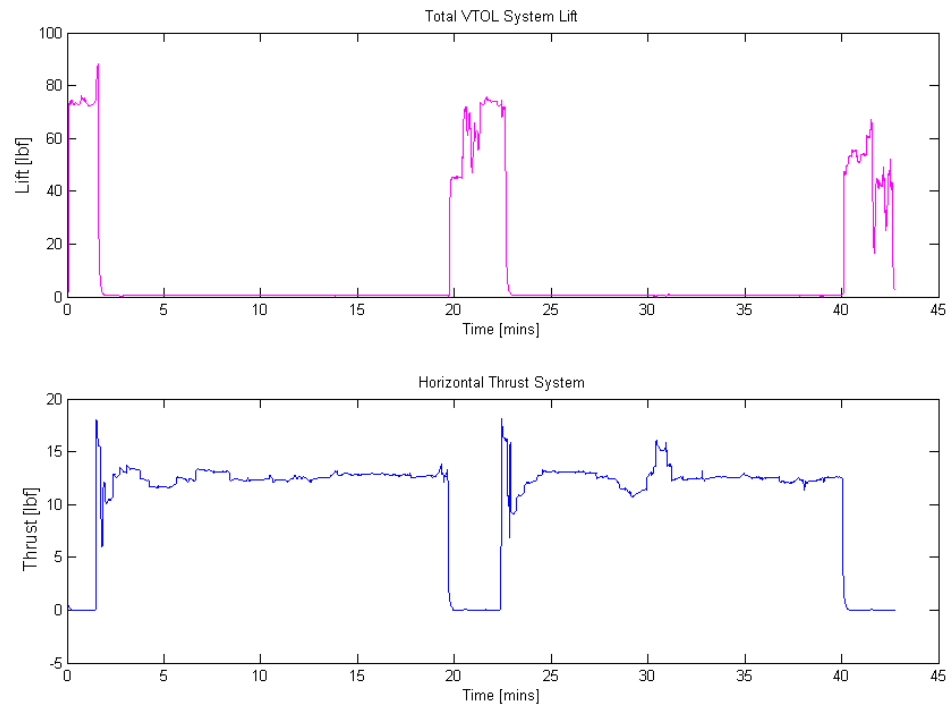
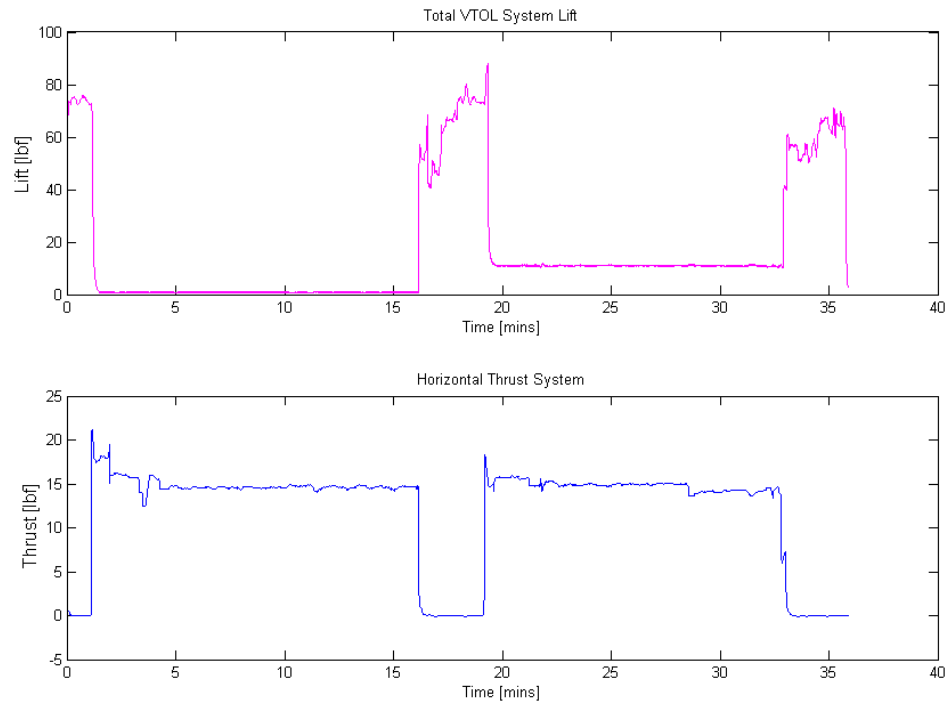
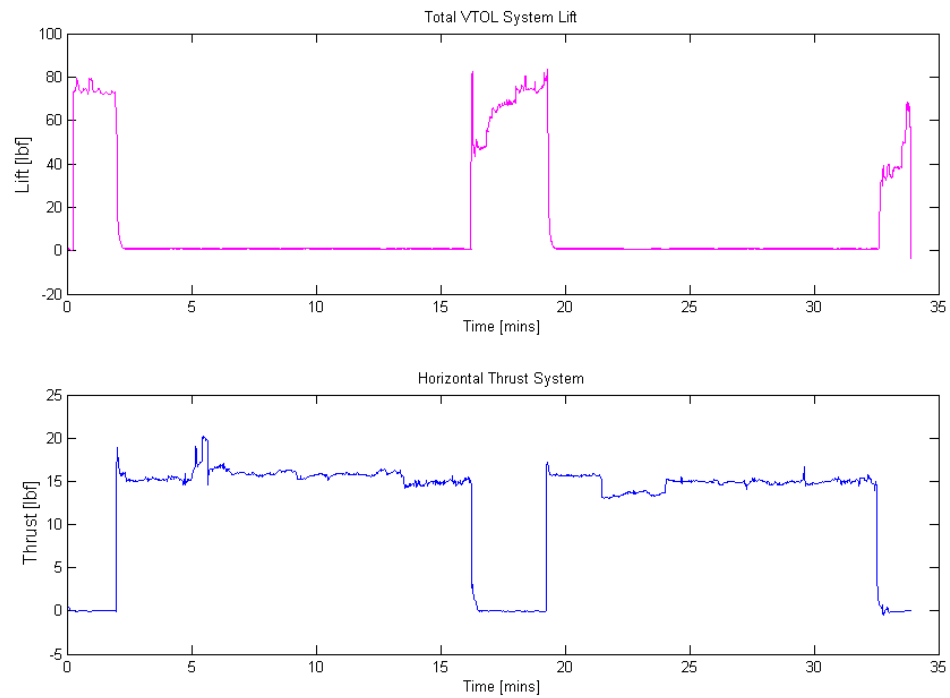


Figure 14: Test 1 Thrust Logs. Test 2 data was corrupted.

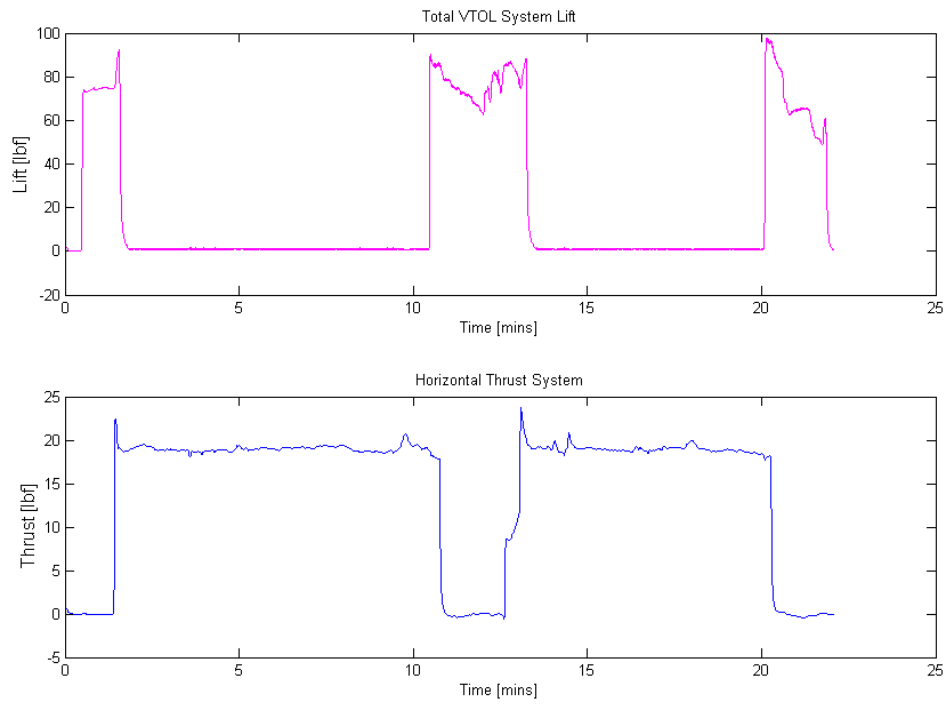


(a) Calm Air

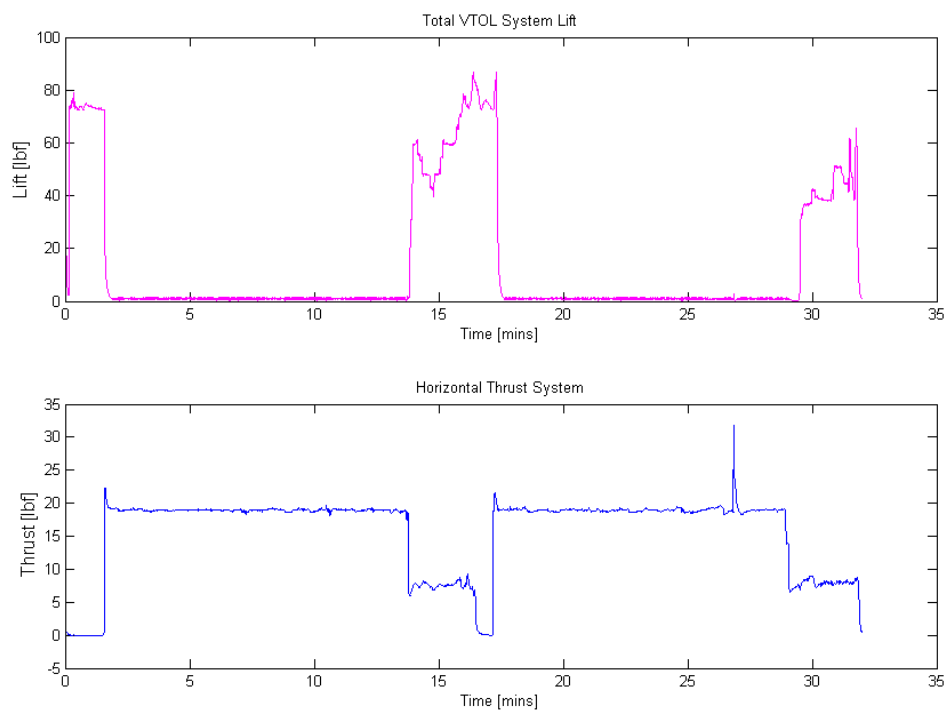


(b) 10 Knot wind with 15 Knot gusts

Figure 15: 40 knot Airspeed test logs



(a) Calm Air



(b) 10 Knot wind with 15 Knot gusts

Figure 16: 50 knot Airspeed test logs

Table 12: Simulation Energy Totals

Test Number	Total Energy MJ	Li-Po Battery Capacity mAh
1	15.111	81,028
2	19.548	104,831
3	13.875	74,402
4	17.168	92,066
5	10.172	54,548
6	16.245	87,117

At the present time the most advanced commercially available batteries that can be purchased are lithium polymer batteries. If these were to be used in the *New River Harrier*, only 30% of a 10-mile mission could be flown; however, the *New River Harrier's* design calls for lithium-air batteries, which will allow the storage of approximately ten to fifteen times the amount of energy that a lithium polymer battery can store. In this case the *New River Harrier* will be able to fly three to four 10-mile missions on a single charge.

5.1.2 System Reliability

Due to the mechanically simple nature of the *New River Harrier*, the probability of a mission abort due to mechanical failure is low. The primary points of failure are the batteries, EDFs, and the wing pivot mechanism. If the drone is operated for long periods of time or in a hot environment the EDFs have a risk of overheating and losing magnetization causing them to fail. The batteries, especially lithium-polymer batteries, are highly susceptible to shock from hard impacts such as a rough landing. The major problem here is that the damage could be to one of the internal cells so it is not visible until the entire battery fails. In both of these cases, the *New River Harrier* is designed to land safely in glider mode if it loses power in flight.

The wing pivot is another primary failure point. In forward locked configuraion, the outer leading spars are physically connected to the leading edge spars in the inner wing so that the wing is structurally sound. The potential failure is when the wing is swept back and the only mechanical connections to the inner wing are the hinge and the linear actuator. In this mode, a bird strike or some other strong impact on the wing could cause the hinge to fail.

5.2 Mission Profile

5.2.1 Turn-around Timeline

The mission turn-around timeline for the *New River Harrier* is a very simple procedure as follows:

1. Drone lands at warehouse

2. Ground crew checks battery voltage level and remaining cable on winch spool (2 minutes)
 - 2.1. If voltage and cable are within operational limits, drone is dispatched again
 - 2.2. If either voltage or cable length are low, the battery or spool is disconnected and replaced (3 minutes)
3. New package is attached and drone dispatched (2 minutes)

The total elapsed turn-around time is estimated between four and seven minutes.

5.2.2 Productivity

As stated in the RFP, productivity is the total lb-mi achieved in one day (number of missions in 10 hr x 10 mi x 13 lb), with a 15-minute turn around time. The team calculated productivity using the previous formula for each simulation flown in X-Plane 10. Those numbers are listed in Table 13. The peak productivity from the simulations was found to be 1,950 (lb-mi)/10-hr-day.

Table 13: Productivity Results

Test Number	Round Trip Time (min)	Trip Time Including Turnaround (min)	Missions per day	Productivity (lb-mi/day)
1	31	46	13	1690
2	23	38	15	1950
3	37	52	11	1430
4	33	48	12	1560
5	55	70	8	1040
6	42	57	10	1300

6 Production and Operating Costs

6.1 Production Costs

Based on the development cost given in RFP Section 2.2.2.3 of \$200,000/lb of weight empty, the development cost for the *New River Harrier* is estimated to be \$13,800,000.

The production costs are estimated in the following table and are based off of the design team's experience with additive manufacturing and machining.

Table 14: Production Cost of the *New River Harrier*

Component	Material	Cost (\$)
Skin	3D printed ABS	13,000
Frame	Carbon Fiber	20,000
Batteries	Lithium-Polymer	4,000
EDFs		8,500
Electronics		2,000
Fasteners		500
Total		48,000

6.1.1 Additive Manufacturing

The practice of additive manufacturing (3D printing) is a key element in the design and production of the *New River Harrier*. The skin of the *New River Harrier* is the primary component that is designed to be 3D printed along with the cargo box. Printing these parts greatly reduces the cost and time of production while allowing them to be lighter and have a more complex geometry than if they were produced by injection molding or machining. The benefits of 3D printing are as follows:

1. Designer is able to print part, no machinist is needed
2. Part file can be used to generate replacement parts
3. Changes can be made to the part and printed without re-tooling
4. Replacement parts can be made quickly in house
5. Very little waste material is created during printing. Only waste material is support material that can be minimized by print orientation

6.2 Operating Costs

The operating costs for running one drone for a year (as described in RFP Section 2.2.1.9) are shown in the following table:

Table 15: Operating Costs based on values in RFP Section 2.2.2.3

Expenditure	Rate	Cost/month/drone
Space	100 ft ² × 15 \$/month	\$1,500
Liquid Fuel	NA	0
Energy Cost	\$853/hour	\$255.90
Repair Labor/maintenance	\$100/hour	\$20,100

Based on these calculated costs, the projected cost for operating a drone for three years is \$848,228.40.

7 Feasibility and Path to Production

In the design of the *New River Harrier* the design team decided to use as many readily available parts as possible to reduce development time and production costs.

7.1 Feasibility

The maturity levels in the following table are defined in the DOD Deskbook 5000.2-R as follows:

1. Basic principles observed and reported
2. Technology concept and/or application formulated
3. Analytical and experimental critical function and/or characteristic proof of concept
4. Component and/or breadboard validation in laboratory environment
5. Component and/or breadboard validation in relevant environment
6. System/subsystem model or prototype demonstration in a relevant environment
7. Actual system and qualified through test and demonstration
8. Actual system proven through successful mission operations

Table 16: Feasibility Assessment

System Component	Technology Maturity	Comments
3D-printed skin	8	Printers are readily available, but currently have small print areas
EDF & ESC	9	In use on hobby aircraft
Carbon-fiber frame	9	CFRP is currently used in a variety of frames
Lithium-air Battery	4	Currently being researched

Table 17: Production Timeline

Component	Time (year)
Skin	1
EDF	1
Frame	1
Lithium-air Battery	2

7.2 Path to Production

The RDT&E phase for the *New River Harrier* is expected to be relatively short. As seen in Table 16, the limiting technology is the lithium-air batteries. All of the other technologies are readily available. The TEARS design team has already begun prototyping the *New River Harrier* using off-the-shelf parts and substituting the central carbonfiber frame with Aluminum 2024. Table 17 shows the expected timeline.

8 Conclusions

In response to the 2015 AMERICAN HELICOPTER SOCIETY Student Design Competition Request for Proposal “Distributed Logistics in an Urban Setting Using Small Unmanned Aerial Vehicles”, the New River Community College’s undergraduate team entry, the *New River Harrier*, has been presented.

Lightweight Design: The *New River Harrier* utilizes lightweight materials such carbonfiber and low-density 3D-printed ABS plastic to increase the thrust to weight ratio. This allows the UAV to support the maximum weight package of 13 lb in hover and have lifting capacity to spare.

Incorporated Safety Features: Utilizing EDFs, remote package deployment, point-of-need sustained hover, and redundant batteries for operational safety in an urban environment.

Proven Technologies: The only technology used in the *New River Harrier* that is not already in widespread use is the Lithium-air batteries which are currently in the research phase.

The *New River Harrier* is a revolutionary concept that can handle a wide variety of payloads safely in an urban setting.

Hardware Validation

1 Introduction

The *New River Harrier* is a hybrid vertical-takeoff-and-landing aircraft (VTOL) that utilizes electric ducted fans (EDF) in a Tri-roter I configuration (Figure 2) for vertical flight combined with an efficient, high aspect ratio, powered glider design for forward flight. In this design, three EDFs are used to power the aircraft in vertical flight and a fourth EDF is located on top of the aircraft exhausting aftward to provide thrust in forward flight. This design was chosen in order to satisfy the following RFP mission objectives:

1. The vehicle shall be capable of carrying a logistics payload of 13 lb. an unrefueled distance of 10 statute miles (mi) from a central supply location to the point of need and then return to the central supply station without the initial payload. (RFP Section 2.2.1.2)
2. The system shall include a 1 minute hover at the start of the mission followed by an additional 1 minute hover at the point of need followed by landing and unloading of the payload. (RFP Section 2.2.1.1)
3. The propulsion system must be designed to generate a sustained lift force of at least 110% of the maximum take off gross weight in hover. (RFP Section 2.2.1.1)

The design team selected a Schübler EDF, model DS-94-DIA HST, as the propulsion system that would be used (See Table HV.1 and Figure HV.1). This motor is a carbon fiber, electric ducted fan, and was primarily selected due to its light weight of 2.93 lb (1250 g), as well as its rated thrust output range of 22.48 - 29.22 lb-f. This particular motor was also designed with an internal ventilator system, so that no interior cooling system would have to be designed within the *New River Harrier*.

One of the largest engineering hurdles in designing the *New River Harrier* was determining the total amount of time the aircraft could spend in both vertical and horizontal flight. As such, it was imperative to accurately gauge the amount of power (in wattage) that would be required to generate the necessary vertical lift force and horizontal thrust in their respective realms of flight. In order to calculate this, a power vs. thrust curve was needed.

A power vs. thrust curve is a graph that shows the amount of power required to generate a given amount of thrust. The curve is based on measurable and verifiable data, where the amount of thrust generated by the motor is measured at various power inputs. Once an accurate and precise curve was standardized, it was possible to determine how much power the two flight configurations would use which then allowed the flight times in the various configurations to be calculated based on the power densities of the standard lithium-polymer (LiPo) and the experimental air breathing lithium-polymer(LiPo-A) batteries. The design team requested supplemental information from Schübler detailing their power vs. thrust tests. The intent was to use their factory specifications and test results as a baseline to validate the experimental testing. However, Schübler was unable

to provide this information.¹²

Schübler DS-94-DIA HST	
Inner Shroud Diameter (in)	5.03
Fan Swept Area (in ²)	14.57
Total Weight ¹³ (lb)	2.93
Thrust (lb-f)	22.48-29.22
Exhaust Velocity (ft/s)	308.39-354.33
RPM Range	28,000-30,500
Input Power (kW)	6.6-9.6
Allowed Battery (S ¹⁴)	12-14
Overall Efficiency (%)	70-71

Table HV.1: Schübler DS-94-DIA HST Specifications

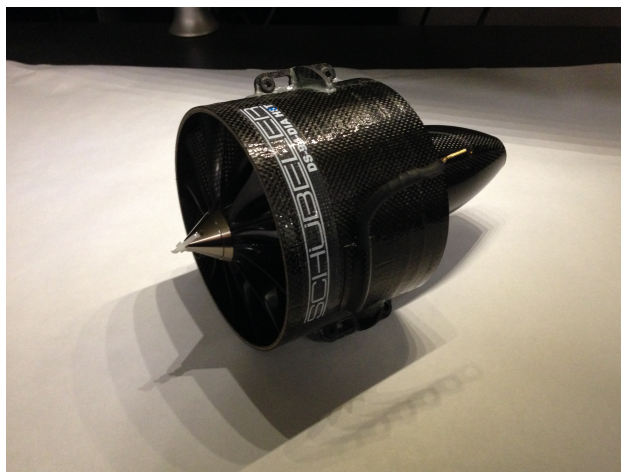


Figure HV.1: Schübler DS-94-DIA HST

The team had to engineer and design a quick and efficient way to analyze the thrust generated by the EDFs at various power inputs. The general idea was to mount an EDF to a sled with one degree-of-freedom and a stationary force gauge. Power to the EDF would then be systematically increased and the amount of thrust generated by the EDF would be recorded at each stage. All data recorded from the test would then be plotted and analyzed using MathWorks MATLAB software.

2 Materials and Methods

The challenge in generating the thrust vs. power curve was to design and build a static thrust test apparatus that would allow the thrust produced by the EDF to be recorded at various power inputs.

2.1 Preliminary Ideas

2.1.1 Unconstrained Motor Sled

The initial idea was to mount the EDF on top of a skateboard or sled with wheels. A force gauge would be placed against a wall and the skateboard would push against the gauge when power was supplied to the EDF. This idea was quickly scrapped because the skateboard would not be securely fastened to the ground and since the thrust generated by the EDF would be greater than the weight of the EDF and skateboard, the assembly had the potential to become a large airborne projectile.

¹²Personal e-mail correspondence with Daniel Schübler, CEO of Schübler Composites

¹³Includes motor, wires, connectors, and secure fan fixture

¹⁴Number of cells in a Lithium-Polymer battery

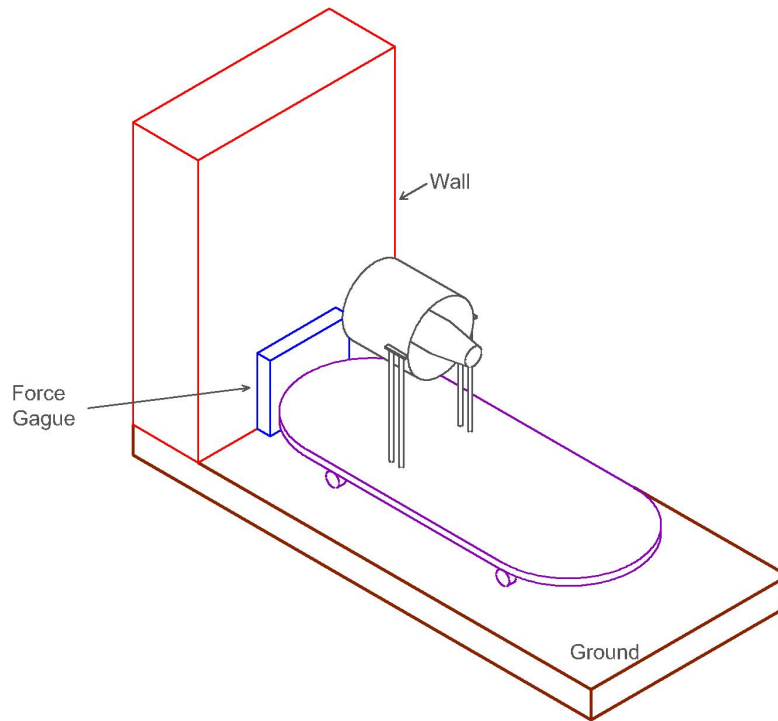


Figure HV.2: Unconstrained Motor Sled

2.1.2 Total Force Plate and Windspeed Probe

The second idea was to mount the EDF to a heavy steel baseplate and aim the exhaust at a vertical force plate. This would allow the exhaust velocity and pressure to be measured using a pressure probe and the force plate (Figure HV.3). Upon further investigation, the design team realized that to account for the total force produced by the exhaust, all of the air molecules being pushed against the force plate, as well as near the outlet of the EDF shroud, would have to be accounted for. It was determined that this would make the variance and standard deviation too high and the idea was scrapped.

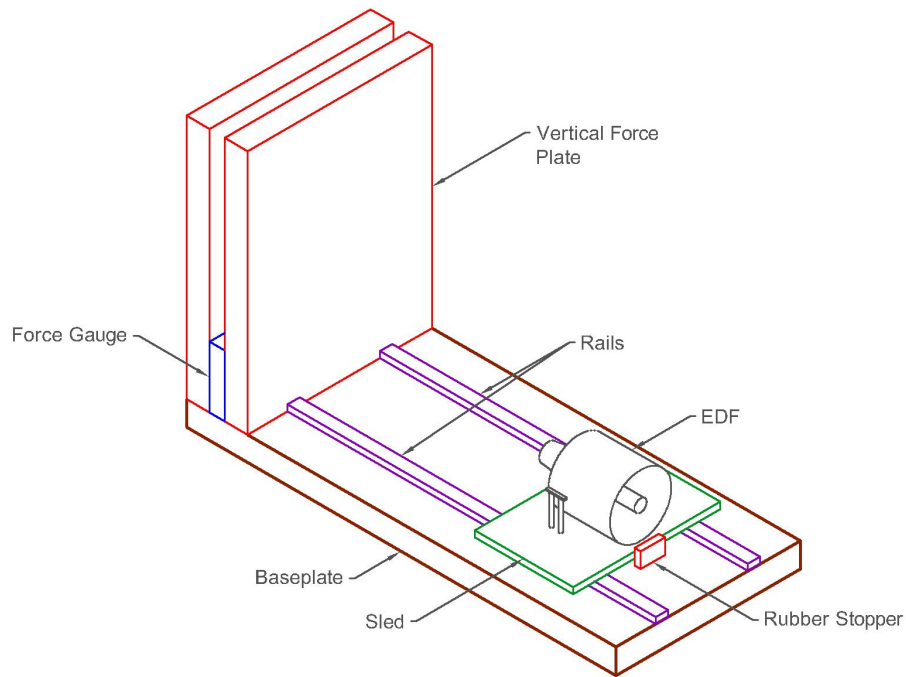


Figure HV.3: Force plate and wind probe set up

2.1.3 Constrained Motor Sled

The final idea incorporated elements of both previous ideas and was selected due to the safety factors that were incorporated into the design. As shown in Figure HV.4, the EDF is mounted to a sled which is constrained in five degrees of freedom by attaching it to a railing system which was, in turn, attached to a large base plate. A stop was attached to the base plate, in front of the sled, to limit the travel of the EDF in the remaining degree of freedom. This eliminates the possibility of the EDF/sled assembly from becoming a projectile. The force gauge could then be placed inbetween the sled and the fixed stop and a windspeed probe would be used to measure the EDF's exhaust velocity.

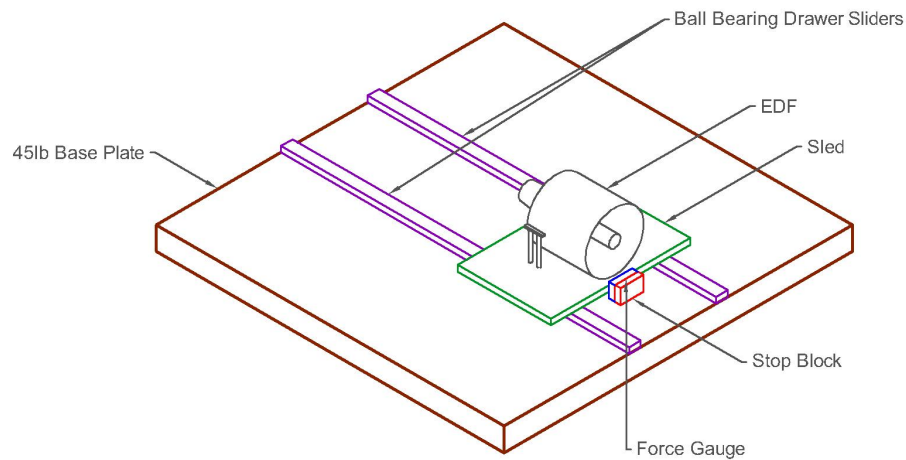


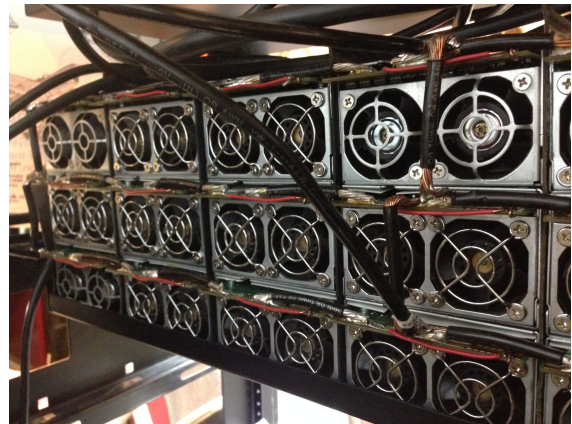
Figure HV.4: Constrained Motor Sled

2.2 Materials List

1. Custom power supply using reclaimed server power supply units (Figure HV.5)
 - (a) 12x HP DP-800GB, each 12.95 V / 82.3 A (max)



(a) Single HP DP-800GB PSU

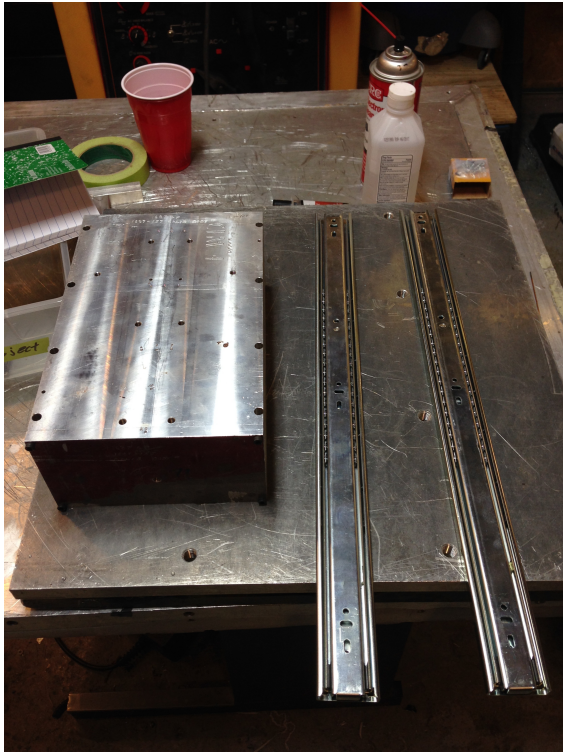


(b) Bank of 12 PSUs

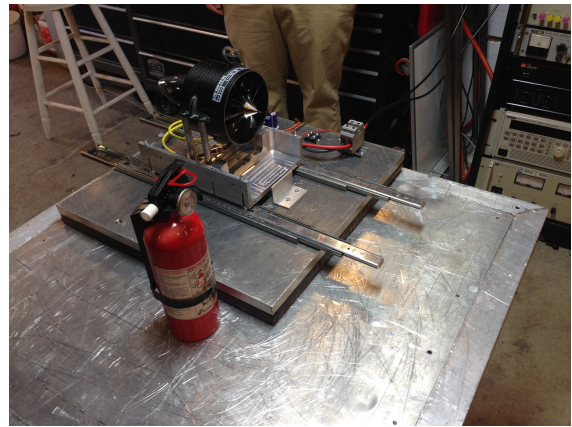
Figure HV.5: Custom Power Supply

2. DC bench power supply
3. 45lb base plate (Figure HV.6)

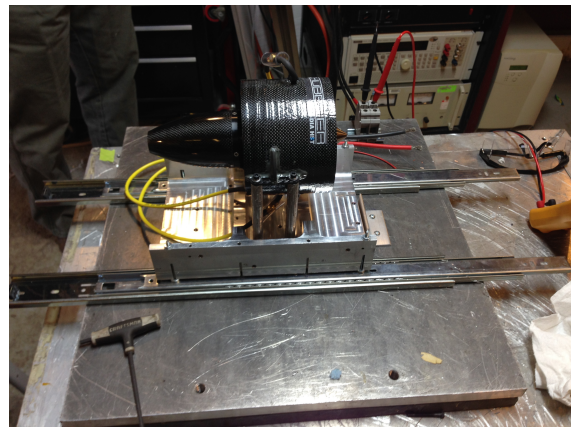
4. Aluminum sled base (Figure HV.6)
5. 18-inch ball bearing drawer slides (Figure HV.6)



(a)



(b)



(c)

Figure HV.6: HV.6a Shows the base plate, drawer slides, and sled (underside) HV.6b and HV.6c) Show the EDF mounted on the test rig

6. Aluminum EDF Standoffs (Figure HV.7)

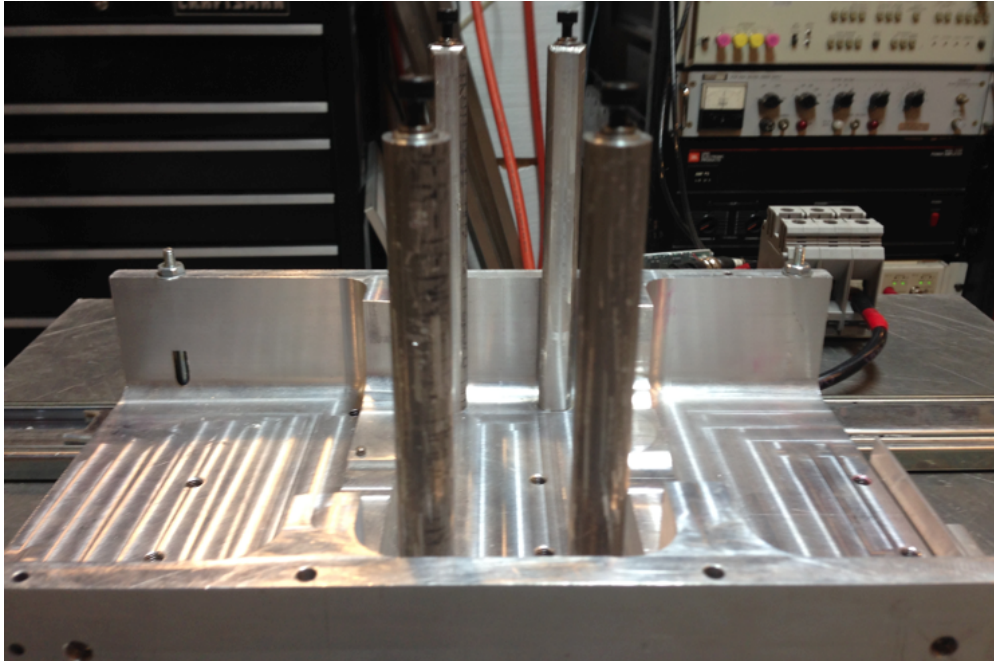


Figure HV.7: EDF mounting Standoffs machined from Aluminum 2024, 0.5 in. diameter rod stock. The machining of the sled base is also visible.

7. Shunt resistor $2.03\text{m}\Omega$ (Figure HV.8)
8. Electronic Speed Controller Model # MGM COMPRO TMM 26063-3 (Figure HV.8)

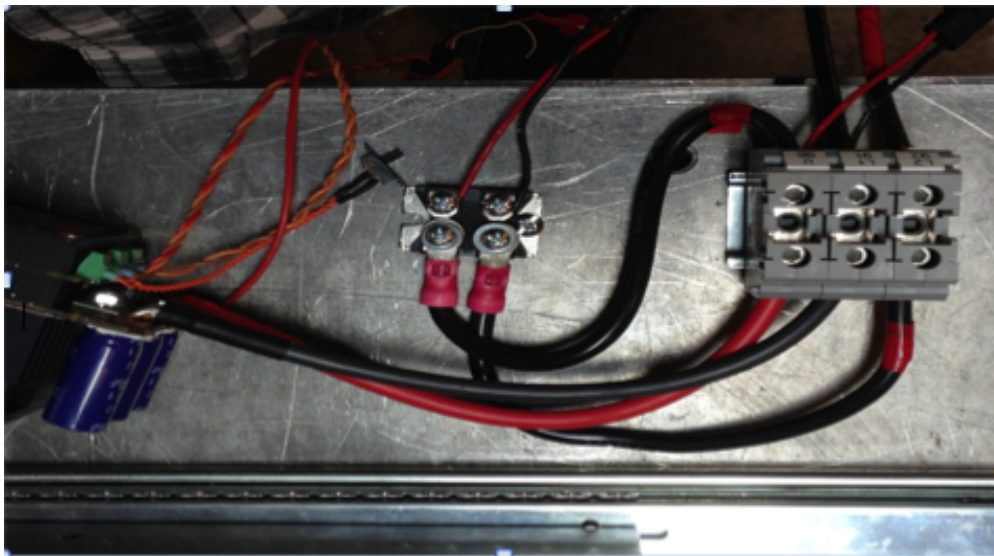


Figure HV.8: Shunt resistor (center) and ESC (left)

9. HP 3457a bench multimeter (Figure HV.9a)
10. Force Gauge (Figure HV.9b)



(a)



(b)

Figure HV.9: HP 3457a bench multimeter (HV.9a) and IMADA load cell (HV.9b)

11. DS-94-DIA HST EDF (Figure HV.1)

2.3 Build Protocol

The following figures (Figure HV.10 and Figure HV.11) show the electrical and mechanical schematics of the test rig. The electrical system was powered off a 240 VAC / 60 A (max) source and was required to output approximately 51 VDC at up to 250 A.

1. Twelve HP DP-800GB, each measuring 12.95 V / 82.3 A (max) were soldered together. Four were soldered in series and three were of those series were connected in parallel. (Figure HV.5b)
2. 18-inch retractable ball bearing drawer slides were mounted onto a 45 lb. base plate. The slides were to be used as a track/railing system for the motor sled.
3. Aluminum motor sled was mounted onto retractable drawer slides. See Figure HV.11 for layout specifications.
4. Force gauge (Figure HV.9b) was placed between stop and front of sled (parts 5 and 3 respectively in Figure HV.11).
5. 2.03 mΩ Shunt and Electric Speed Controller model #MGM COMPRO TMM 26063-3 (Figure HV.8) were mounted onto base plate. See Figure HV.10 for layout specifications .

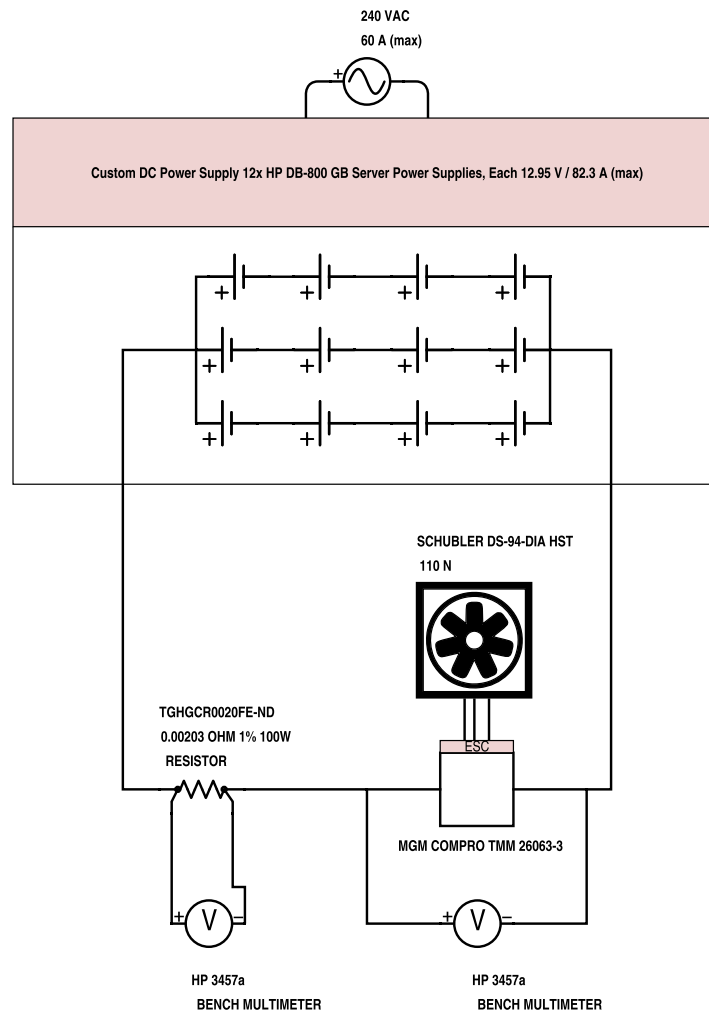


Figure HV.10: Electrical schematic diagram of experimental setup

Figure HV.11: Exploded assembly of test rig”

3 Results

As shown in the electrical schematic diagram, Figure HV.10, a 4-wire measurement system was used to measure the amount of electrical current consumed by the DS-94 DIA HST motor. The DS-94 DIA HST motor was throttled in increments of approximately 1.12 lbf (5N) from 0.224 lbf (1N) to 24.7 lbf (110N).

The data shown in Table HV.2 was generated by staging the DS-94 DIA HST on an interval of 0% power to around 100% power in stepwise increments of 5%, pausing on each step to record the thrust of the motor, the voltage at the input of the ESC, and the voltage developed across the shunt resistor on the high side of the ESC's DC input. Testing was done at 75.92°F (24.4°C) at an elevation of 2,137.7ft.

Using Ohm's law and the definition of electrical power, the following formula can be written:

$$P = \frac{V^2}{R} \quad (3)$$

The input power can then be calculated by

$$P_{input} = V_{ESC} \times \left(\frac{V_{shunt}}{R_{shunt}} \right) \quad (4)$$

which allows the Thrust vs. Power curves, as seen in Figures HV.12 and HV.13, to be generated.

Table HV.2: Data generated with the static thrust sled

Thrust (N)	Thrust (lb-f)	Shunt Voltage (mV)	ESC Voltage	Input Power (W)	Input Power (Hp)
1	0.224	2.8103	51.528	71.3346	0.0957
2	0.449	4.4351	51.474	112.4593	0.1508
4	0.899	6.7145	51.438	170.1382	0.2282
7	1.57	12.3274	51.302	311.5371	0.4178
12	2.69	19.1352	51.218	482.7915	0.6474
15	3.37	25.3985	51.174	640.2674	0.8586
19	4.27	31.858	51.129	802.3979	1.076
23	5.17	38.009	51.086	956.5161	1.2827
29	6.52	51.584	50.985	1295.5715	1.7374
35	7.87	71.58	50.885	1794.2602	2.4061
45	10.1	103.392	50.744	2584.4944	3.4659
52	11.6	132.287	50.559	3294.7283	4.4183
56	12.6	149.039	50.291	3692.276	4.9514
65	14.6	175.385	50.107	4329.072	5.8054
70	15.7	202.307	49.883	4971.271	6.6666
80	18	231.768	49.897	5696.8118	7.6396
86	19.3	259.236	49.655	6341.0658	8.5035
90	20.2	277.02	49.945	6815.6472	9.1399
95	21.4	298.201	49.294	7241.1429	9.7105
100	22.5	318.18	49.294	7726.2881	10.3611
108	24.3	355.93	48.984	8588.6084	11.5175
110	24.7	361.9	48.791	8698.2576	11.6646

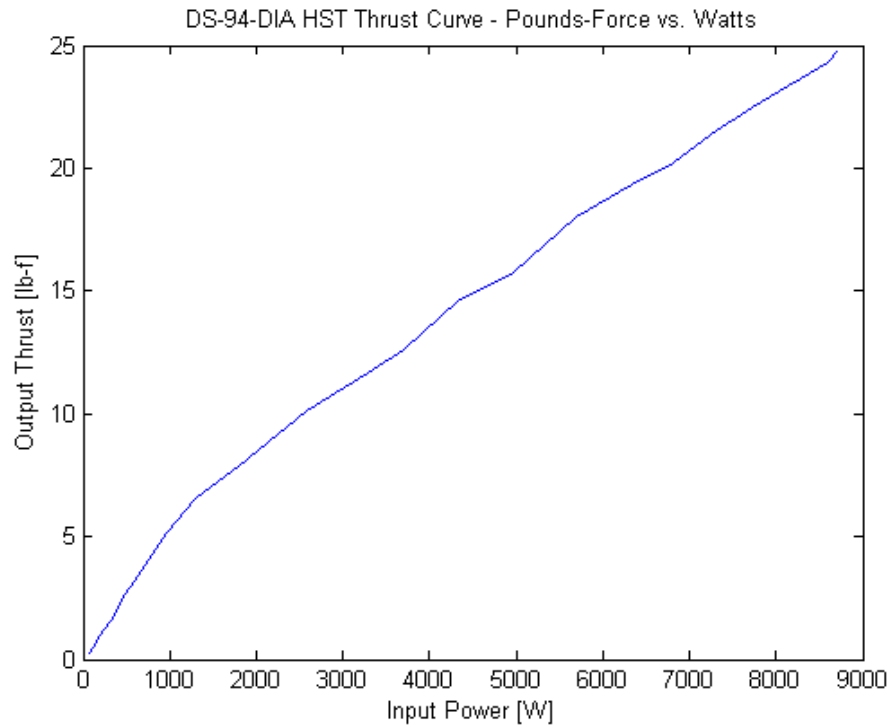


Figure HV.12: Schübler DS-94-DIA HST Thrust vs Power (W)

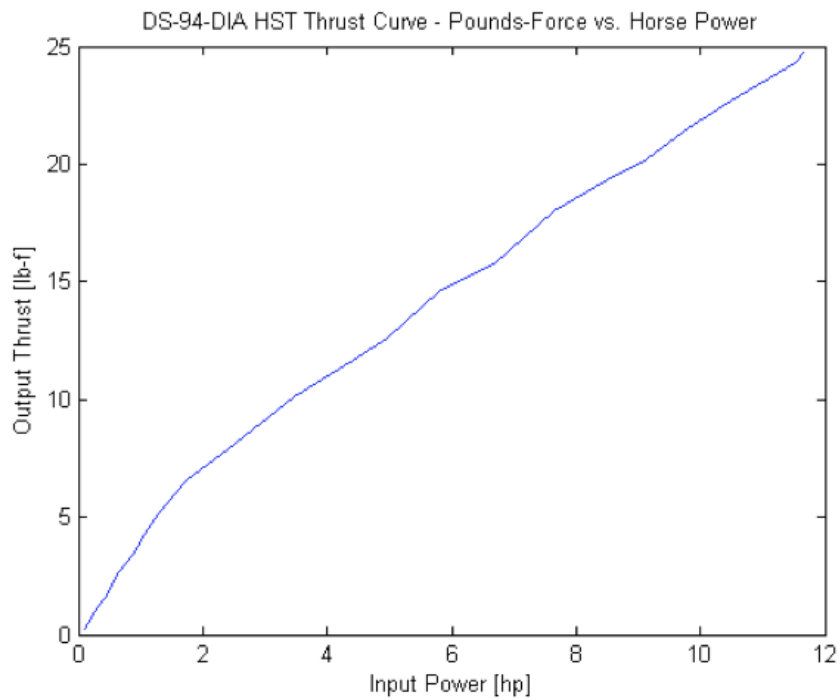


Figure HV.13: Schübler DS-94-DIA HST Thrust vs Power (Hp)

4 Discussion

The information gathered from experimental testing of the Schübler DS-94-DIA HST motor was a critical step in the developmental design of the New River Harrier. This data was used to calculate the flight endurance. In doing so, the battery life of standard RC-lipo batteries and lithium air batteries could be accurately compared and contrasted.

It is also important to mention that during the experimental testing of the Schübler DS-94-DIA HST motor, the team recorded and observed issues with engine over heating, for unknown reasons. According to Schübler, the model motor is safe to run at temperatures below 65 degrees Celsius and has been designed with an internal ventilator system so that no interior coolant is required. As a safety precaution, we used a 4-wire Platinum RTD transducer to monitor the heat generated by the motor. The Platinum RTD transducer was contained in an exceedingly small (0.0177 x 0.0610 x 0.0334 in) surface mount package. This probe was affixed to the aluminum of the motor casing near the back of the coil package. The transducer was also instrumented with a Yokogawa-7563 digital bench thermometer accurate up to 0.01 degree Celsius.

Now that the team knows the test bed is capable of measuring the thrust outputs at various power inputs, the future plan is to use a pitot static probe to measure the velocity of the air at the intake and exhaust.

References

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