Final Technical Report (UMD AMAV)

1. Executive Summary

1.1. Objective Statement
Under the VFS Design-Build-Vertical Flight Competition guidelines, the University of Maryland Autonomous Micro Air Vehicle (AMAV) team’s overall objective is to develop and fabricate an unmanned aerial vehicle capable of completing a maneuverability course, a maximum range course, and an autonomous flight challenge. The UMD AMAV Eagle Coaxial X8 design is shown to the right.

1.2. Purpose of Design
The design of the vehicle is to be as maneuverable and efficient as possible, with autonomous flight capabilities while remaining under strict competition guidelines such as weight limit, payload requirement, dimensions, and overall design quality. Component and flight testing processes also inform and validate the overall design process.

1.3. Planned Approach
Our team’s plan for the VFS DBVF Competition involved a multistep process to create a successful and innovative design. We began with a detailed schedule that was consistently updated as necessary with every step of our design, manufacturing, and testing processes (Section 2). At the start of the design process, we began by outlining the mission requirements to create our own design plan (Section 3.1). We narrowed down the major priorities for our design to maximize the chances of being successful in the competition and to receive the highest points possible (Section 3.2). From the breakdown of the main design priorities, we developed a number of configurations to determine the best fit for this competition (Section 3.3). From our previous criteria and higher priority competition requirements, we selected our final design configuration to be a co-axial X-8 configuration (Section 3.4). While the overall goal of the design is to be successful in the competition, a large priority is to be unique and to develop new ideas and technologies. A part of our design process also included unique technical innovations into the design, both in the physical aspect and the autonomous capabilities (Section 4). To move forward from this preliminary design to the final design (Section 5), 3D drawings were developed that allow traceability of the design process as well as a simpler replication in the event of successful design (Section 6). Our manufacturing process includes a variety of different fabrication methods available at the University of Maryland, as well as surrounding areas (Section 7). At the termination of the final design stage, we performed a plethora of tests for every component and sub-components of our vehicle to ensure its feasibility and identify any
possible failure modes so that appropriate adjustments to the vehicle can be made (Section 8 and 9). The completed tests validate the overall performance of the vehicle developed for the competition. Additional tests and full mock mission tests will continue up until the final presentation (Section 9) and flight exhibition, as appropriate.

2. Management Summary
2.1. Team Organization
The AMAV team is composed of undergraduate and graduate students from aerospace engineering, computer science, and robotics. The team is guided by advisor, Prof. Derek A. Paley, Director of the Maryland Robotics Center, and co-advisor, Dr. Krishna Kidambi, Maryland Robotic Center Postdoctoral Research Fellow. The team is led by Animesh Shastry, Ph.D. student in the Aerospace Engineering department. The AMAV team has 3 working groups.

Vehicle Analysis: This subgroup is led by Animesh Shastry and consists of two other team members Gregory Miller and Eashwar Sathyamurthy. This team is responsible for analyzing the vehicle performance capabilities, using tools such as FEA, CFD, and rotocraft theory.

Design and Manufacturing: This subgroup is led by AE undergraduate Qingwen Wei, who is also our designated pilot. This subteam is responsible for designing all the parts, fabricating, and assembling the overall UAV. The subgroup consists of 3 other undergraduates; Madeline Brode, Radu Teodorescu, and Patrick Passarello.

Autonomy and Flight Testing: This subgroup is led by Achal Vyas, a graduate student in the Master of Engineering in Robotics program. This subgroup consists of 2 other graduate students Karan Sutradhar and Arun Dhandayuthabani. Their responsibilities include designing flight test procedures and analyzing the overall performance of the vehicle during the autonomous flight.

2.2. Organizational Chart

![Organizational Chart]

2.3. Schedule
We created our project schedule using prior competition experience and also considering the new design specifications, to achieve the optimal design output. We had to adapt and modify our plan on the go to accommodate for delays in manufacturing and building due to COVID. A Gantt chart showing the complete design, build, and flight test timeline is provided below.
3. Design Trade Studies

3.1. Problem Statement

The design of the vehicle is to conform to each of the mission requirements: maneuverability, range, and autonomous flight capabilities. Specific competition guidelines with regard to the overall design specifications also influenced the design activity such as major design drivers, various aircraft configurations, and the overall selection process.

3.2. Mission Requirements

For the fly-off portion of the competition, the aircraft must perform sufficiently in 3 different courses: maneuverability course, maximum range course, and the bonus autonomous challenge course, during which points are awarded using the scoring metric mentioned in the RFP.

**Maneuverability Course:** For the first fly-off portion of the competition, the vehicle is required to maneuver an obstacle course and complete a UAM simulated course, while carrying a 2lb payload. The drone can be pre-programmed to fly the mission autonomously based on the provided details of the course. At the start, the drone must take off to 5-6 ft and then complete the predetermined course, stopping at every waypoint. Near the completion, the drone must land at the predetermined landing point.

**Maximum Range Course:** In the second fly-off portion of the competition, the vehicle will be evaluated based on its range as well as its overall endurance. The course begins with the vehicle taking-off to 5-6ft above the original starting point. The aircraft then must complete as many laps of the course as possible in 10 minutes. In the event of low battery, the vehicle must land. Near the completion of each lap, the vehicle must land at the landing spot to mark the end of a lap. The aircraft must land successfully in order for the points of the lap to count.

**Bonus Challenge Course:** For the final fly-off portion, the drone must complete an autonomous mission. It must take-off to 5-6ft above the landing spot and hold its position for 10 seconds. The drone must then fly the outlined course autonomously and, at every waypoint, land and take off successfully. At the final waypoint, the drone must take off, fly to the landing zone, and land.
3.3. Aircraft Design Parameters

The aircraft design parameters were selected based on our team’s collective experience and the guidance from our advisors. Reliability, cost, and performance also informed our choices. Additionally, we performed a design study on four popular multicopter configurations and compared the pros and cons of each design choice to find the optimal configuration.

3.4. Major Design Drivers

Endurance and Maneuverability: For the range test, our primary goal is to fly as fast as possible to maximize the number of laps within the allotted 10 min flight time. Approximately 77% of the overall fly-off points comes from the endurance and maneuverability of the design. Hence, we sought a design with a greater motor thrust or a design with a higher number of motors to increase our ability to accelerate quickly and minimize turning radius.

Weight/Dimensions: For the aircraft design, one of our goals was to make the best use of the provided hard dimensional constraints. The competition presents us with a 6.5 ft maximum span and a maximum weight of 20 lb including the 2 lb payload. Since 15% of the overall points come from our payload fraction, part of our team’s design process involved leaving some room for additional payload weight, but it was not our top priority.

Cost and Reliability: While cost is not a major concern for our team, the cost of components was factored into our overall decision process. In areas where we could lean for a lower-cost alternative, we attempted to do so. However, for the design and components of our drone, we valued reliability much more than cost.

3.5. Configurations Considered

We focused exclusively on the multicopter designs shown in Figure 1 due to their simplicity and maneuverability. The maneuverability aspect is very important due to the short distance and tight turns of the range and maneuverability course. Another important aspect considered was that the range course is only 400 feet long and only has 200 feet from turn to transition to landing, which is something a fixed-wing VTOL design may struggle to accomplish.

Quadcopter: This configuration features four motors and propellers and is a design frequently found in most drone applications. The T-Motor U8 Lite 190 kV motor and the T-Motor 29x9.5in propeller were selected.
Hexacopter: This configuration features six motors and propellers all in the same plane. The KDE Direct 5215XF-330 brushless motor and the KDE Direct CF215-DP 21.5x7.3in propeller were selected.
Octocopter: This configuration features eight motors and propellers, the highest among all the designs considered. The KDE Direct 6213XF-185 motor and the KDE Direct Dual-EDN 18.5x6.3in propeller were selected for this configuration.
**Coaxial X-8:** This design features four coaxially aligned motor-propeller pairs, placed in a quadrotor arrangement. This configuration uses the same motor and propeller combination as the quadcopter, i.e., the T-Motor U8 Lite 190 kV motor with the T-Motor 29x9in propeller.

3.6. Selection Process and Final Design

3.6.1. Analysis of Alternative Configurations

Before arriving at our final design, we conducted an internal design review between the four considered multirotor designs: quadcopter, hexacopter, octocopter, and a coaxial x8.

**Quadcopter:** The quadcopter had the lowest empty weight out of all designs considered. Due to this low weight, it also featured the highest payload capacity. However, there were two major drawbacks to this design. First, a failure of one motor in flight would lead to a loss of control and crash. Second, the quadcopter featured the lowest thrust to weight ratio out of all designs, which is detrimental to the ability to complete the maneuverability course.

**Hexacopter:** The hexacopter design was able to generate a larger thrust-to-weight ratio than the quadcopter owing to the increase in motors. However, this design’s payload capacity was hindered by a large battery weight as three 6S batteries in parallel are required to power the motors for this configuration.

**Octocopter:** The octocopter configuration was able to generate the largest amount of thrust and featured the largest thrust-to-weight ratio out of all the designs considered. However, the empty weight of the design was so high, that it was unable to accommodate the 2 lb payload without exceeding the 20 lb AUW limit.

**Coaxial X-8:** The coaxial X8 design offered unique benefits of having eight large propellers of equal diameter to the quadcopter while having significantly less weight than the octocopter. Due to the increase in motors, it had the second-highest thrust to weight ratio of the designs considered, almost twice as high as the quadcopter. Additionally, the X8’s lower frame weight allowed for a payload capacity larger than the hexacopter.

![Fig. 2. Experimental thrust data of three motors (from T-Motor and KDE)](image)

![Fig. 3. Comparison of theoretical performance metrics of four considered designs](image)

Compared to the other configurations, the octocopter has a higher thrust-to-weight ratio, but sacrifices too much payload and is not within the 20 lb weight limit. The quadcopter can carry
almost double the payload as the coaxial X-8 but makes big sacrifices in the thrust-to-weight category. Also, the quadcopter configuration lacks redundant motors, which increases safety concerns due to the large size of the aircraft. Even though the coaxial X-8 is not the best performing configuration in any comparison category, it has the best overall performance. It has the second-highest payload capacity while retaining a high thrust-to-weight ratio with a 2 lb payload. This allows for a sufficient payload capacity while providing high maneuverability.

3.6.2. Selection and Customization of Final Design
The chosen configuration for the competition this year is the coaxial X-8 configuration, named Eagle, which provides the best balance of payload capacity and power between the various multi-copter configurations considered. The coaxial X8 configuration provides the weight-saving benefits, smaller form factor, and propeller size of a quadcopter configuration with the thrust provided by eight total motors. By having fewer arms and the corresponding support material, it allows the weight to be reallocated to carry more payload. Also, having only four of the rotors on the same plane allows for much larger 30” propellers to be used, leading to lower disk-loading and higher efficiency. But due to the coaxial configuration of the rotors, a small efficiency loss in comparison to a standard non-coaxial configuration is present. A propeller of a similar size in a coaxial configuration is about 77% as efficient as in a standard isolated rotor setup when operating under normal circumstances\(^1\). However, this is compensated by the larger and more efficient propellers, which give a much higher efficiency factor, pulling about 25A less than the other motors considered for the hexacopter and octocopter.

The weight of the airframe and motors for the coaxial X8 configuration is 5.4 kg. After factoring in an estimate of all the components required to be on the aircraft for the competition as well as the efficiency loss, the estimated maximum thrust is approximately 45 kg or 99 lb. This results in a thrust-to-weight ratio of 5.23 with a 2 lb payload and 4.98 at the maximum 20 lb weight, carrying an estimated maximum 3.6 lb payload.

4. Technical Innovations
4.1. Design Innovations
**Custom Frame:** Our first technical innovation was the use of a double-level custom frame in order to make effective use of the weight requirement. The frame has exact mounting points for only the electronic components we need for the competition without any excess. It also allows better integration of the specialized portions of the frame to meet competition requirements, specifically, the shunt plug and the payload mounting points.

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**Spring Landing Gear:** Another technical innovation is the creation of custom spring landing gear. The motivation behind the design of this gear versus a fixed gear was to cushion landing impacts, increasing the overall safety of the heavy design should a motor failure occur during landing. The Spring landing gear is made up of five components: (1) a retaining ring for the carbon fiber landing leg; (2) a holder that prevents the components from falling out; (3) a carbon fiber landing leg; (4) a spring; and (5) a bottom cap. The retaining ring, holder, and bottom cap are all made of ABS plastic due to its low density and good resistance to large shocks.

**VIO+GPS Localization:** Navigation using only the GPS for aircraft positioning is unsuitable when higher localization accuracy is needed for autonomous missions. Measurements from GPS are unreliable, have higher variance, and lower feedback rates. Real-Time Kinematic (RTK) GPS uses an IMU to fuse data and increases the localization accuracy considerably. However, since it is dependent on communicating with a ground-based module, the vehicle’s operational range is limited. The state-of-the-art for localization in GPS-denied or mixed-GPS environments involves the fusion of visual feedback from cameras along with GPS and IMU. The fusion typically occurs in two stages. First, using a synchronized camera and IMU, their data is fused to generate visual-inertial odometry (VIO). This is then fused with the primary aircraft IMU along with GPS measurements. The Pixhawk microcontroller selected for this design already has the capability to perform the fusion of VIO data with its own internal IMU. For generating VIO data, we selected the Intel-Realsense T265 tracking camera based on our past experience deploying it on quadrotor drones. Figure 5 shows the overall architecture of the VIO+GPS Fusion process.

![Diagram](image)

**Fig. 6.** The position data obtained from realsense-ros node from Intel Realsense T265 is processed by the vision_to_mavros node and sent to the MAVROS node via the topic /mavros/vision_pose/pose. The MAVROS node performs the East-North-Up (ENU) - North-East -Down (NED) frames transformation and sends it to ArduPilot through MAVLink.
4.2. Mission Model

Maneuvering flight for rotorcrafts involves aerodynamic interactions of unsteady wind and analyzing their power requirements is beyond the scope of this report. Hence, we will describe the model used for power prediction in hover and forward flight only.

**Assumptions and uncertainties:** Standard rotorcraft flight assumptions include 20% propulsion efficiency loss, 30% power loss due to co-axial configuration, flight at ISA+15°C conditions (air density $\varrho=1.224$ kg/m$^3$), and canceling of rotor in-plane forces and moments due to symmetric placement of rotors. The rotor-blade is assumed to be rectangular, untwisted, and rigid. Additionally, uniform inflow conditions are also assumed for simplicity. Table 1 lists the parameters and assumed numerical values based on empirical and manufacturer data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Efficiency Scaling Factor</td>
<td>$\eta$</td>
<td>1.56</td>
</tr>
<tr>
<td>Motor Force Coefficient</td>
<td>$k_f$</td>
<td>2.52e-4 N-s$^2$/rad$^2$</td>
</tr>
<tr>
<td>Number of Propellers</td>
<td>$N_{propa}$</td>
<td>8</td>
</tr>
<tr>
<td>Rotor Blade Profile Drag Coefficient</td>
<td>$C_{d(\theta)}$</td>
<td>0.015</td>
</tr>
<tr>
<td>Rotor Blade Radius</td>
<td>$R$</td>
<td>0.3556 m</td>
</tr>
<tr>
<td>Rotor Blade Solidity</td>
<td>$\sigma$</td>
<td>0.0895</td>
</tr>
</tbody>
</table>

**Source of inputs:** In addition to the vehicle model parameters described in Table 2, the only other input to the mission power estimation model is the aerodynamic force model. The aerodynamic lift and drag force model on the body is obtained via CFD simulation, whose process is described in Section 5.4 in detail. The 2nd-order lift and drag polynomial coefficients were normalized by the square of the inlet airspeed to obtain a generalized lift and drag expression as a function of vehicle pitch orientation and airspeed. Motor thrust and rpm is automatically calculated during the trim process. Environmental effects of external wind, moisture content, etc. are ignored.

**Detailed model description:** The power estimation model given in Algorithm 1 is based on the rotorcraft trim procedure with uniform-inflow assumption. The derivation and the theory behind this procedure are based on helicopter aerodynamics$^2$.

5. Design Definition

5.1. Overall vehicle design

The Eagle Coaxial X8 consists of eight motor/propeller pairs in a quad configuration. The dual opposing motors on each arm give the vehicle its characteristic coaxial X8 configuration. Each propellor is 30.2” in diameter, which was determined to be the maximum allowable size to avoid internal interference and satisfy the design constraint of a 6.5’ span (Figure 7). Using the maximum propellor size for this configuration gives the thrust necessary to execute maneuvers.

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Algorithm 1 Vehicle Power calculation

1: Initialize vehicle model parameters
2: for Forward Speed \( V \in [0, 30] \text{ m/s} \) do
3: Lift and Drag: \([L, D] \leftarrow \text{AerodynamicModel}(V)\)
4: Thrust and Aircraft Pitch angle:\[T, \theta] \leftarrow \text{solve}(T \cos(\theta) + L - W, T \sin(\theta) = D)\)
5: Motor angular speed: \( \omega \leftarrow \sqrt{\frac{Tk_f}{N_{\text{prop}}}} \)
6: Blade Tip Speed: \( V_{\text{tip}} \leftarrow \omega R \)
7: Advance Ratio: \( \mu \leftarrow \frac{V}{V_{\text{tip}}} \)
8: Thrust Coefficient: \( C_T \leftarrow \frac{T/N_{\text{aggregate}}}{\rho V_{\text{tip}}^3} \)
9: Parasite power: \( P_{\text{parasite}} \leftarrow \eta DV \)
10: if \( \mu = 0 \) then
11: Induced inflow: \( \lambda _i \leftarrow \frac{C_T}{2} \)
12: else
13: Inflow: \( \lambda \leftarrow \text{solve} \left( \lambda = \mu \tan(\theta) + \frac{C_T}{2\sqrt{\mu^2 + \lambda^2}} \right) \)
14: \( \lambda _i \leftarrow \frac{C_T}{2\sqrt{\mu^2 + \lambda^2}} \)
15: end if
16: Induced Power Coefficient: \( C_{P_i} \leftarrow \lambda _i C_T \)
17: Profile Power Coefficient: \( C_{P_0} \leftarrow \frac{1 + 4.65(\mu^2)}{8} \frac{C_{T_{\text{ull}}}}{S} \)
18: Rotor Power Coefficient: \( C_P \leftarrow C_{P_i} + C_{P_0} \)
19: Rotor Power: \( P_{\text{rotor}} \leftarrow \eta \rho A V_{\text{tip}}^3 C_P \)
20: Total Power: \( P_{\text{total}} \leftarrow N_{\text{props}} P_{\text{rotor}} + P_{\text{parasite}} \)

Result: \( P_{\text{rotor}}, P_{\text{parasite}}, P_{\text{total}} \)

with the payload added. The top and bottom plates of the airframe are cut from carbon fiber and are each roughly 15\"x15\", the maximum allowable size for our CNC capabilities. These plates were designed to be as lightweight as possible, with material removed strategically from places that will not experience relatively high loads and kept along the axes to retain structural integrity. The final total weight of the drone came out to be 17.8 lbs, higher than originally predicted but fully capable of carrying the minimum 2 lb payload for the maneuverability and range courses.

Fig. 7. External dimensions of the final design of Eagle Coaxial X8
5.1. Vehicle sub-system design

5.1.1. Airframe

**Motor Mounts/Arms:** Each arm features two motor mounting plates, which are cut from 3 mm thick carbon fiber sheets. The ESC mounting plates are 3D printed, and allow the two ESCs to be easily and compactly fastened to the ends of each arm via two zip-ties. This structure was designed with as little material as possible to minimize the loads at the ends of each arm, which would already carry a lot of stress from the weights of the motors and propellers.

**Central Body:** The central body consisting of the top and bottom plates were designed around individual components, with space allocated for all electronics and wiring assemblies. The plates are secured together with standoffs on the edges and in the center, with additional support provided on the diagonal axes by each arm. The central body also supports the 7” shunt plug tower with incorporated 100 Amp fuses for the two main batteries to meet the competition requirements.

5.1.2. Propulsion System

**Discussion of Motor and Propeller Choice:** Two motors were considered for the final design: The KDE 7215XF Kv 135 and the T-motor U8 Lite Kv-190. Table 2 provides a parametric study comparing the weight, cost, maximum thrust, and maximum current draw of the two motors. The performance data for the 7215XF was calculated with the KDE Dual-EDN 30.5x9.7 propeller, and the data for the U8 Lite was calculated with the T-motor 29x9.5 propeller. For this study, the weight of the motor and the maximum thrust produced are the most important factors.

<table>
<thead>
<tr>
<th>Motor</th>
<th>Weight (g)</th>
<th>Cost ($)</th>
<th>Max Thrust (g)</th>
<th>Max Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-motor U8 Lite Kv-190</td>
<td>243</td>
<td>299.99</td>
<td>7334</td>
<td>43.7</td>
</tr>
<tr>
<td>KDE 7215XF Kv-135</td>
<td>555</td>
<td>373.95</td>
<td>7440</td>
<td>33.9</td>
</tr>
</tbody>
</table>

The T-motor U8 Lite Kv-190 was chosen based on its low weight and low cost. The difference in motor weight is large enough that it justifies the use of an additional battery, which accommodates the U8 Lite’s higher current draw. The difference in maximum thrust produced,
about 1.4%, is small enough to be considered negligible and most likely from testing error, thus this parameter was not considered in the decision.

**Batteries:** Due to the size of the aircraft and selected propellers, we used the maximum allowable battery voltage, 6S. The capacity of the chosen Zece battery is 4500mAh due to the 100Wh limit on the battery size. The use of 2 batteries of this size was enough for the aircraft to fly the maximum-range course successfully. Having multiple batteries allowed for redundant power and hot swaps of the main batteries without having to power down the flight controller. The flight controller and FPV gear are powered from a separate 4S battery located on the aircraft. A capacity of 2300mah is sufficient for the selected flight controller and FPV gear.

5.1.3. Electronics

**Pixhawk 2.1 Cube Orange and Here3 GPS:** The Pixhawk 2.1 Cube Orange was chosen for its reliability and autonomous capabilities. This Pixhawk features a triple-redundant IMU that is temperature and shock-resistant. This allows for additional safety as the IMU is the primary sensor needed for manual flight, allowing the possibility of maintaining control of the aircraft in manual mode should other sensors fail. The Pixhawk also allows for dual GPS and power inputs to provide further redundancy for on-board systems. Our Pixhawk is paired with two Here3 GPS.

**DJI HD First Person View:** This system transmits live video footage on the 5.8 GHz band. Compared to analog first-person view systems, it provides a high definition FPV feed at 720p and 120fps allowing for safer operation of the aircraft. Also, using two-way communication, the system has a more robust connection with the video link compared to analog alternatives.

**Advanced Power Drives Electronic Speed Controller:** These ESCs were originally intended for X-class racing drones. They are intended to power large motors at high speeds while performing fast maneuvers. The ESC features an F3 processor that accepts DShot input commands, which create a robust and lower-latency connection between the ESC and flight controller compared to standard PWM. We selected the 80F3[X] series ESC, which supports 8s and 80 amps since the higher rating of the ESC leads to cooler and more reliable operations.

5.1.4. Autonomous Flight Control

We use QGroundControl as our ground control station (GCS) software to configure autonomous waypoint missions. A connection with the drone and the ground station (Figure 11) is established with the help of MAVLink via telemetry radio. The waypoints for each mission are set using the GCS software. Finally, the mission file is uploaded to the Pixhawk through MAVLink via telemetry radio.

![Fig. 11. Aircraft Autonomy Network](image-url)
5.2. Structural Design and Analysis

Arm structure: The arms structure is the primary load-bearing element. It comprises elliptical cross-section carbon-fiber tubes to support the rotor’s static and dynamic loads. Due to the shortened flight duration, emphasis was placed on choosing a very rigid structure capable of withstanding the rotor loads in high acceleration flight, which is the primary flight condition for this mission. We selected off-the-shelf carbon fiber tubes which are typically manufactured for x-class racing drones. Carbon fibers run parallel to the centroidal axis, thereby giving it very high axial and bending stiffness. Helical carbon fiber weave is also present which gives high torsional rigidity. For simulating the loads we applied 100N of force and 5N-m torque (2x higher than the maximum expected force and torque experienced in standard flight conditions) at the motor end of the arms, while the frame end was kept fixed to complete the boundary conditions. The resulting Von-Mises stress on the arm is shown in Figure 12. The maximum stress is observed on the steel screws connecting the top and bottom motor mounting plates.

Frame Structure: Under the same loading, but with the opposite arm kept as the fixed point to complete the boundary conditions for the simulation, a structural analysis of the center frame was done. The design of the center plates was made to replicate an I-beam structure. The portions of the frame running from one arm to another are solid to create the horizontal flanges of the I-beam structure and standoffs were added to create the web. Having a flange going from one arm to another without any cutouts provides the best reinforcement to prevent bending from the thrust produced by the motors on each arm. The side structure of the center body was designed to reinforce against twisting in the frame during yaw maneuvers and to prevent bending that could result in the propellers getting too close to each other. The rest of the structure has hexagonal cutouts as a reference to our school mascot, Testudo the turtle, and provides areas to mount the various electronic components. From Figure 13, the majority of the stress is on the screws mounting the arm onto the frame, which is ideal as it provides a failure point that would let us quickly and easily recover from a crash. The rest of the stress is concentrated on the arm connecting the outer structure, with little stress on the hexagonal cutouts in the structure.
**Final Weight and Balance:** The final weight of the drone is 17.8 lbs. This is about a pound greater than what our expected final weight is, most likely due to the unaccounted wires that were added. However, it still lets us carry the minimum 2-pound payload that is required by the competition. Due to the multi-rotor design, it is a very symmetrical design and it almost perfectly balances in the center of the frame.

5.3. Aircraft Performance Analysis

![Surface Aerodynamic Pressure and local airspeed variation](image)

**Fig. 14. Surface Aerodynamic Pressure and local airspeed variation**

**Aircraft lift and drag:** The primary objective of the aerodynamic simulation and analysis is to estimate the lift and drag model for the trim procedure, described in Section 4.2. Batch CFD simulation of the complete vehicle without the propellers was performed using SimScale. Vehicle pitch orientation was varied from 0° to 45° with 5° steps. Inlet freestream velocity was set to be 10m/s and the outlet was kept at 1 bar atmospheric pressure. Figure 14 shows the aerodynamic pressure exerted by the air on the vehicle surface, as well as the local airspeed variation. Figure 15 shows the final lift and drag data that was obtained from the batch CFD process. A 2nd order polynomial was fitted onto the data to get the lift and drag curve as a function of the vehicle pitch orientation.

![Aerodynamic lift and drag model fitted onto batch CFD results](image)

**Fig. 15. Aerodynamic lift and drag model fitted onto batch CFD results**
Aircraft performance analysis: The performance of a multirotor vehicle is measured by its power requirements at different flight speeds. The power estimation model described in Section 4.2 was used to calculate the total power required by the vehicle at different forward flying speeds. The weight of the vehicle was taken as 18.4 lbs (predicted empty weight + 2 lb payload). The total power consists of rotor power and parasitic power as shown in Figure 16. The rotor power decreases with speed initially due to the increase in net inflow. The parasite power increases cubically with speed. At hover, the endurance obtained is 17.1 min. The best endurance is obtained at the minimum power requirement. The best endurance speed is 7.5 m/s and the maximum endurance is 22.28 min. The best range is obtained at the minimum drag condition, which is the point where the power to speed ratio is minimum. The best range speed is 13 m/s and the maximum range is 18.798 miles. The maximum allowable current from the battery is 160A. Hence, the maximum available power at 25V is 4 kW, which indicates that the maximum speed for the vehicle is around 27 m/s, but this will reduce the endurance to 3.3 min.

Range mission analysis: The range course has an approximate lap length of 1000ft. It includes 4 turns, where the vehicle will fly in unsteady aerodynamic conditions. Calculating rotor power in such a flight scenario is beyond the scope of this report. Hence, we assume that the vehicle flies at steady conditions throughout the range mission. The flight time is limited to 10 min. Factoring these assumptions and constraints, the upper bound on the number of laps that the aircraft can achieve as a function of cruise speed for the range mission is shown in Figure 17.

Endurance-Range and Payload Trade-Off Study: For a pilot to make decisions on the cruise speed for any general mission, an endurance-range tradeoff is essential. Figure 18 shows the endurance-range tradeoff for our vehicle with a 2 lb payload. To decide on the payload, that vehicle can carry for a particular mission, Figure 19 provides the complete picture of the aircraft performance. Carrying a heavier payload can be achieved at the expense of endurance and range.
6. Drawing Package

![Fig. 20. Four view drawings of the Eagle Coaxial X8](image)

(a) Motor mounting structure  
(b) Arm mounting structure  
(c) Electrical system layout

(d) Propulsion system layout  
(e) Avionics and electrical system layout

*Fig. 21. Structural arrangement (a, b) and systems layout (c, d, e) drawings*
7. Fabrication Methods

7.1. Manufacturing processes investigated, discussed, and compared

Having participated in previous VFS MAV student competitions we have experience choosing materials and fabrication methods to be able to quickly manufacture and assemble a completely custom drone in the short timeline given by the competition.

7.2. Considered Methods/Materials

CNC Machining: For our main body and structure we considered Dragon Plate, carbon fiber and wood sandwich, and normal carbon fiber. Dragon plate provides a more lightweight option but it loses strength from using a wood core and has a higher chance of delamination. Due to the complexity of the carbon fiber plate components, we investigated automated machining methods such as CNC and waterjet as the primary means of manufacturing.

3D Printing: As almost the entire aircraft is custom for mounting and other hardware parts, we decided to use 3D printing. The main materials considered were PLA, ABS, and TPU. PLA has a tensile strength of 50 MPa and 1.3 g/cm³ density. ABS was the next choice as it has a higher 110 MPa tensile strength and a lower 1 g/cm³ density. However, ABS is harder to print as it requires higher printing temperatures and has a higher chance of warping. TPU has rubber-like properties and could be used for areas that might benefit from flexibility.

7.3. Manufacturing Process

Custom Component Manufacturing: Standard carbon-fiber plate was selected as the primary material for the aircraft due to its low weight, high strength, low cost, and manufacturability. To manufacture the top and bottom plates of the aircraft as well as the eight motor mounting plates we outsourced it to CNC Madness. The primary 3D printing material chosen was ABS and it was used on most of the custom structural/mounting components. The landing gear feet were 3D printed in TPU to provide more grip and cushion during landing.

Assembly: Most of the components on the aircraft are screw-mounted and reinforced with Loctite to diminish the effects of vibration-induced loosening of the screws. All elements of the drone were assembled in the AMAV team’s base in the UMD Brin Family Aerial Robotics Lab. Any components that required soldering or heat shrink tubing were also assembled in the Aerial Robotics Lab soldering stations, and then subsequently integrated into the drone.

8. Test Plan

The majority of tests were done at UMD’s Brin Family Aerial Robotics Lab and the Fearless Flight Facility (F3), due to the 15-mile no-fly zone established by the FAA around Washington D.C. / Reagan International. Compared to the 600-foot diameter of the competition location, F3 (Figure 22) is 100x300x50 feet, which resulted in scaled-down tests compared to the competition.

Fig. 22. The UMD Fearless Flight Facility
8.1. Motor/Propeller Thrust Test

**Test Objective:** Determine the amount of amperage per thrust of our chosen propeller and motor combination. These data are used to compare the specifications given by the manufacturer and also predict the efficiency loss from the coaxial configuration.

**Test Setup:** The test was conducted on a custom-made test stand (Figure 23), which accommodates the individual drone arms. The setup can control and measure the current from multiple motors simultaneously. Thrust is measured by a load cell and an Arduino.

8.2. Hover Endurance Test

**Test Objectives:** Determine how long the drone can hover in place and establish its reliability for the duration of the battery life and its low-speed handling characteristics.

**Test Setup:** The test was conducted inside the netted area of the Brin Family Aerial Robotics Lab as it is a more controlled environment than the outdoor netted facility.

8.3. Landing Gear Drop Test

**Test Objectives:** (1) Determine if the spring landing gear has a lower peak acceleration and/or longer impact duration versus the fixed gear; (2) compare the survivability of fixed and spring landing gear; and (3) qualitatively determine the amplitude of the subsequent vertical oscillations of the testbed post-impact with the spring gear.

**Test Setup:** The landing gear testbed is made up of a carbon fiber plate of similar dimensions to the ones used on the drone, landing legs (spring or fixed) attached to it, and weights to simulate the drone’s maximum weight of 20 lb. Drop tests will occur at three height intervals: 0.75m, 1m, and 1.25m. The impact and duration is measured using an MPU-9250 accelerometer.

8.4. Forward Flight Endurance and Range Test (With/Without Payload)

**Test Objectives:** Determine the total flight time while doing multiple loops around our netted test facility as well as measure the power consumption in steady forward flight.

**Test Setup:** To maintain a constant flight speed, the test is performed autonomously. Steady forward flight occurs along a 450 ft straight line and power consumption is logged onboard. However, we also perform manual loops to better simulate the range course of the competition and to determine the maximum flight time.

8.5. Agility and Speed Test

**Test Objectives:** Determine how well the drone could perform tight/sharp turns and maneuvers.

**Test Setup:** To push the limits of the drone, the drone was flown in Acro mode which disables the attitude stabilization and allows for more extreme pitch and roll angles. Testing was limited due to the size of our netted facility but quick bursts of acceleration and tight turns were possible.
8.6. Autonomous Waypoint Following Test

**Test Objectives:** Determine how accurate the autonomous capabilities of the drone are by programming numerous waypoints in the testing facility.

**Test Setup:** We test the GPS capabilities of the drone by flying in position-hold mode, which is the mainstay prerequisite before testing. Initially, simple waypoint missions like take off, fly 10 feet, and land are tested. Finally, the complexity of these missions is increased to establish reliability, eventually leading up to a mock mission.

8.7. Autonomous Landing Accuracy Test

**Test Objectives:** Determine the range of error using the same autonomous mission and same predetermined landing point to see exactly where the drone lands each time.

**Test Setup:** A simple autonomous mission is created with a landing point and is executed multiple times. After each mission, the landing position of the drone is marked on the ground.

8.8. Battery and Motor Failure Test

**Test Objectives:** Determine how well the drone is able to fly with possible failures such as a battery not working and/or one motor/propellor setup not working properly.

**Test Setup:** The drone employs two main batteries to separately power the top and bottom set of motors. For the test, one battery is removed to see how well the drone is able to fly as a standard quadcopter in the event that one battery is to become disconnected, lose power, etc. In another test, one motor is disconnected to mimic the loss of a motor or propellor failure.

9. Flight Test Results

9.1. Subsystem Performance Testing

**Battery (Hover Endurance Test):** The hover test was performed indoors and resulted in an endurance of 18 minutes until the battery voltage took a significant dip to 18.8 volts near the 18 min mark in Figure 24, resulting in gradual loss of thrust. The spike at the 4 min mark was a quick landing and takeoff to check the ground station, it only had a slight effect and the trend remained the same. The measured endurance is a minute longer than the predicted one.

**Fig. 24. Battery voltage variation**

**Propulsion (Rotor Bench Test):** The results of the motor thrust test described in Section 8.1 are shown in Figure 25. The thrust and current data for the single rotor were multiplied by a factor of 2 to generate the current and thrust profile for 2-isolated rotors. The coaxial rotor configuration needs more power as the bottom rotor is operating under the downwash of the top rotor. We observed that approximately 30% more current is required for a coaxial setup, which is in agreement with the coaxial rotorcraft theory.

**Fig. 25. Thrust vs current for coaxial and 2-isolated config.**
the battery voltage for the forward flight test described in Section 8.4. The measured power was scaled up by a factor of 6 to adjust for the power requirement of the other motors as well the power loss due to conversion efficiency and coaxial setup. Figure 26 compares the measured power consumption with the predicted power derived in Section 5.3. The data almost agrees with the predictions, but more data at higher speeds is required to fully validate the power model.

**Landing Gear Drop Test:** The test results in Figure 27 show the benefits of the spring gear. The fixed landing gear maxed out the accelerometer when dropped from 0.75m, whereas the spring gear only did so when dropped from 1.25 m. Moreover, the spring landing gear was able to reduce the peak acceleration. The testing results for the 1.25 m drop are omitted as all four legs of the fixed landing gear failed. Finally, the amplitude of subsequent vertical oscillations were negligible in all test cases.

### 9.2. Full System Performance Testing

**Forward Flight Endurance Test:** The maximum range course is based on the number of laps that the Eagle Coaxial X8 can complete within the 10 minute allowed time for the course. Since our netted facility is smaller than the full course, our laps result in more turns and less distance in the straightaways, so lap numbers are not comparable to the competition course. We determined that the drone can fly laps for approximately 13 minutes with the 2 lb payload while flying at 30 mph, which meets the competition requirements.

**Agility and Speed Test:** Since we chose a multirotor configuration and not a fixed-wing/multirotor hybrid, the Eagle Coaxial X8 has a much faster transition from hover to forward flight and a tighter turn radius. The drone can perform a U-turn maneuver with a turning radius of a few feet when flying at high speeds ~45 mph (Figure 28). Higher maneuverability is beneficial as there are many stages in the competition that requires multiple take-offs and landings.

**Autonomous Waypoint Following Test:** In our netted testing facility we were able to replicate a scaled version of the bonus challenge course, with a few extra waypoints to avoid obstacles. We took off from a starting point and flew to what would be the first numbered point in the course
and landed, denoted by L (Figure 29) instead of waypoint number, then took off again. The drone proceeded to complete the bonus challenge and landed back at the starting point. This mission demonstrated our ability to fully complete the bonus challenge course.

**Autonomous Landing Accuracy Test:** Using a simple square flight path and re-flying the mission multiple times we tested the landing accuracy. Figure 30 presents the outcome of using QGroundControl’s precision landing feature, which resulted in a landing accuracy of 1 ft with the largest variation in the heading direction. Figure 31 shows the result when the precision landing feature was disabled, which resulted in a landing accuracy of 4 ft. The non-precision landing was expected from a purely GPS-based system with no additional VIO or RTK compensations. However, the precision landing exceeded our expectations. Both of these results show our capability to complete the Autonomous Bonus Challenge portion of the competition. As stated in the RFP, the VTOL start and finish pad are 30 ft in diameter and we have to land in the “general location of each numbered point”, which as demonstrated by the landing tests, can be accomplished by our drone.

**Battery and Motor Failure Test:** An advantage of most multi-rotor designs with more than four rotors is the redundant safety it provides. The Eagle Coaxial X8 configuration has redundant motors, propellers, power distribution, and batteries. Figure 32 shows the aircraft flying without one of the main batteries. Figure 33 shows the aircraft flying with one motor unplugged, to simulate a propeller, motor, or ESC failure. This is the most common failure that could occur due to these parts being the most exposed and with the highest load. Both these tests prove that the aircraft, due to having redundancy in flight-critical systems, can continue its operation even with an occurrence of a major failure.

10. **Conclusion**

The technical report describes the entire procedure by which we designed, built, and tested our aircraft for the VFS DBVF competition. We met or exceeded the design requirements, completed the bonus task, and readied our vehicle in the allotted time. Ongoing and future works seek to further enhance the aircraft’s performance and expand its autonomous capabilities.