

COOPER UNION AERIAL VEHICLE

PRELIMINARY DESIGN REPORT

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THE COOPER UNION FOR THE ADVANCEMENT OF SCIENCE AND ART

1. SUMMARY

The Cooper Union Aerial Vehicle (CUAV) team is decomposed into five different subsystems: Aerodynamics led by Kameron Wang, Navigation and Autonomy led by Alsu Flare, Controls led by Andrew Kim, Structures led by Ginger Lau, and Fabrication, which will be a shared responsibility. Each system lead is responsible for the design and validation of their respective systems, as well as for collaboration with other systems to ensure cohesive design decisions.

Within the realm of aerial vehicles, small-scale vertical take-off and landing (VTOL) drones provide advantageous capabilities — long range efficient flight, exceptional speed and maneuverability, payload capacity, and autonomous navigation — all without requiring a runway. These capabilities enable VTOL aerial vehicles to quickly transfer payloads in areas difficult to access without a runway, for emergency military, medical, or search-and-rescue situations . Therefore, CUAV has joined the 2022-2023 VFS Design-Build-Vertical Flight Competition in hopes to explore and innovate VTOL technologies through a competitive environment.

The competition features a flight course for electric aircraft to navigate through, completing as many laps as possible within a time limit. CUAV aims to design, fabricate, and test a VTOL drone capable of both piloted and autonomous flight, carrying a sufficient payload across the competition course. In order to achieve this, the team must design a suitable aircraft, develop manufacturing and testing methods, and demonstrate technical innovations.

The CUAV team is developing a tilt-rotor tricopter blended wing aircraft for efficient cruise flight and agility during VTOL. Tilt-rotor tricopter configuration allows for stable takeoff and landing while minimizing the weight of avionics and power equipment. Blended wing body (BWB) was developed to maximize forward flight efficiency through reducing parasitic drag and maximizing lift obtained during cruise. The design will also incorporate a reflexed airfoil to improve pitch stability. The CUAV team hopes to innovate the tilt rotor mechanism, BWB body design, and demonstrate a sustainable approach to VTOL design through a conscious choice of materials and fabrication methods. After extensive discussion and research, the CUAV team is currently finalizing design decisions, with clear plans of proceeding onto manufacturing already set. The next steps will involve placing orders for the necessary components, beginning the manufacturing of the airframe, and validating each system along the way until the drone is finished.

2. DESIGN TRADE STUDIES

2.1 MISSION REQUIREMENTS

The mission can be decomposed into several stages of flight — vertical take-off, hover transition, forward flight, turns, and vertical landing. Understanding the mission requirements for the entire flight performance course enables the team to establish subsystem requirements. The aerial vehicle must be able to successfully complete a manual flight performance course and an autonomy course. Both performance courses follow the same route, in which the vehicle must complete as many laps as possible within a 10 minute time restriction. Before take-off, the aircraft must additionally carry at least one 2-lb SoftGrip weight payload. The manual flight performance course is scored based on three criteria: time for the first three laps, total number of laps completed, and payload fraction, each of which is scored out of 50 points, for a total of 150 points possible during this course. The autonomy course is only dependent on a successful completion of the competition route autonomously once. Successful completion corresponds to 150 possible points, but an incomplete mission will result in 0 points.

2.2 SUBSYSTEM DESIGN DRIVERS

CONTROLS: The Controls system aims to optimize the power efficiency and speed of the drone. Responsible for the thrust generation in both the take-off, landing, and forward flight segments, the Controls system contributes to the vast majority of the drone's overall performance. For the best performance in competition, the take-off, landing, and transition to forward flight will have to be optimized in terms of time each stage of flight takes. A balance between fast spin-up time and efficient thrust generation will have to be struck to optimize both the vertical and horizontal flight performances. From selecting motor and propeller combinations, as well as choosing a battery that can support all of these electrical components, the Controls system ultimately dictates the achievable speed and power usage of the drone.

STRUCTURES: The Structures system needs to design the drone airframe such that the moments and vibrations the drone experiences do not violate structural integrity by considering wind loads, vibrations from the spinning propellers, wing loading from aerodynamic forces, etc. This system aims to create a robust design that is as lightweight as possible, while ensuring that the maximum take-off weight (MTOW) is below 20 lb. Furthermore, this system must design around accommodating all components within the airframe such as the required payload, battery, IMUs, etc. within the 10 ft. maximum span.

AERODYNAMICS: The Aerodynamics system will mainly focus on optimizing the forward flight portion of the competition. Although the wing design of the aircraft may induce some drag for the vertical takeoff portions of flight, the benefits of passive lift generation outweigh these downsides. Additionally, the Aerodynamics system must be designed with stable forward flight in mind, which includes considering center of pressure with respect to the center of gravity, as well as pitch stability. Finally, this system must consider similar factors that the Structures system faces when designing the wing.

AUTONOMOUS: The Autonomous system has to optimize the GPU, IMU, and GPS system readings to provide an accurate description of the drone's state. From these readings, the drone's remote flight controller and specified flight parameters will allow the drone to perform the programmed actions.

2.3 BACKGROUND RESEARCH

Legal requirements were examined to ensure that drone regulations were acknowledged during the design

process. The Federal Aviation Administration (FAA) has strict regulations on unmanned aircraft systems, in which our drone would qualify under the recreational flight category, since it will weigh under 55 lbs. as per Part 107. Recreational drones must be flown strictly for hobby or educational use and should follow all recognized safety guidelines. Additionally, recreational drones must fly below 400 ft. in controlled airspaces, and all pilots must be certified by the Recreational UAS Safety Test (TRUST). This initial study of drone regulations is important because the project will require public flight testing methods in the future.

2.4 CONFIGURATION SELECTION PROCESS

Seven traditional categorizations of drones were considered for this project, based on the background research. The configuration selection was evaluated using the design criteria for each subsystem. An initial design matrix noted in Figure 5 was created to quantify the value of each criteria. Parameters were assigned weights depending on their importance to the competition. Ethics is an additional criteria because it is important to address the impacts of engineering on the real world. Ethics involves evaluation of sustainability, environmental impacts, safety, and space for innovation.

			Configurations						
	Criteria	Weight	Tricopter	Quadcopter	Hexcopter	Octocopter	Tilt Rotor	Tailsitter	Fixed-wing Hybrid
Controls	Stability	4.5	9	13.5	15.75	15.75	18	15.75	22.5
	Pilot Familiarity/ Experience	3	6	9	9	9	9	4.5	9
	Ease of Control Implementation	5	15	20	20	20	12.5	12.5	20
Aerodynamics	Takeoff Speed	3.5	10.5	12.25	12.25	12.25	14	7	10.5
	Landing Speed	3.5	10.5	12.25	12.25	12.25	10.5	7	17.5
	Maneuverability	2	8	8	8	8	6	4	6
	Power Efficiency	4	18	16	14	12	14	16	14
	Forward Flight Performance	4	13.5	11.25	9	9	20.25	18	22.5
Structure	Payload Capacity	3	7.5	10.5	10.5	10.5	10.5	7.5	12
	Ease of Transportation	2	6	6	6	6	5	5	5
Fabrication	Manufacturability	5	22.5	20	17.5	15	15	15	15
	Reparability	3.5	14	14	14	14	8.75	8.75	8.75
	Safety	4	12	14	14	14	8	8	12
	Cost	3.5	14	14	10.5	7	14	10.5	10.5
Ethics	Sustainability / Env. Impact	1	4	4	3	3	3	3	3
	Space for Innovation	3.5	8.75	7	7	7	14	12.25	14
	Total		179.25	191.75	182.75	174.75	182.5	154.75	202.25

Figure 1. Configuration Matrix

The configuration matrix demonstrated that a fixed-wing hybrid drone would best fulfill the competition requirements. Fixed-wing hybrid aircraft offer better forward flight performance, as airfoils can provide lift and reduce battery usage. In addition, the fixed-wing hybrid aircraft has more space for innovation which is a highlight of the competition. Lastly, the mission requirements prioritize overall speed, and fixed-wing hybrids offer the stability of a multicopter with the forward flight performance of a plane. Since the weights were chosen based on competition objectives and realistic goals, the configuration matrix was used as a starting point for a more educated design selection, opening up the potential for incorporating elements from multiple configurations.

2.5 FINAL CONFIGURATION SELECTION

The selection of a fixed-wing hybrid aircraft configuration involves specification of propeller orientation, aircraft shape, and an evaluation of flight performance.

The working preliminary design features a **tilt-rotor tricopter blended wing design**. This incorporates the lightweight tricopter orientation with the aerodynamic and power-efficient fixed-wing hybrid design. Unlike traditional tilt-rotor drones, this design features a tilting rotor axis placed through the nose of the drone to prevent undesirable wing loading and aerodynamic effects. This nuanced mechanism allows for a reduction of motors used as it only requires one motor to change the orientation of the front two rotors, rather than two separate servos.

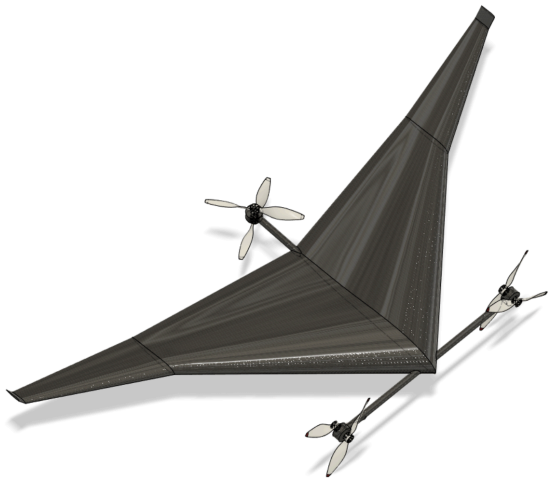


Figure 2. Vehicle CAD model Isometric view

The flight performance and sizing of the design is evaluated by three metrics:

(1) Forward flight performance
(2) Hover performance
(3) Transitional flight performance

A study by Kamal & Ramirez-Serrano (2018) demonstrates how a plot of wing loading and rotor disc loading against power loading during the three modes of flight can generate aid in the selection of correctly sized propellers and motors [1]. Generating this plot involves derivations from momentum theory.

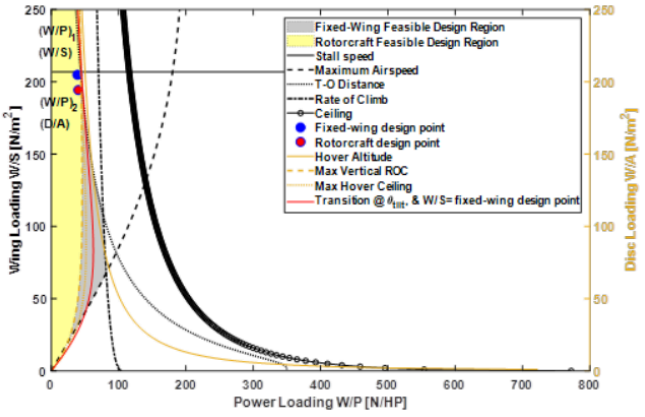


Figure 3. Design Region Sample Plot [1]

Forward flight performance is evaluated using traditional aircraft design methods. This process begins with weight estimations and top level requirements. These defined mission parameters guide the aircraft stall speed, rate of climb, and flight ceiling values, which result in specifications for wing, rotor, and engine design. However, since the aircraft design process is iterative, these parameters are revised continuously.

The transitional flight dynamics are similarly calculated using assumptions that transition occurs at a fixed altitude. Level transition flight, power required to climb, and

induced velocity can be calculated using momentum theory [1].

Hover performance trade studies are evaluated using eCalc and established design methodology for hybrid VTOL design [1]. The eCalc software provides estimates on hover time, hover efficiency, and battery power required based on the multirotor configuration of the hybrid VTOL during hover.

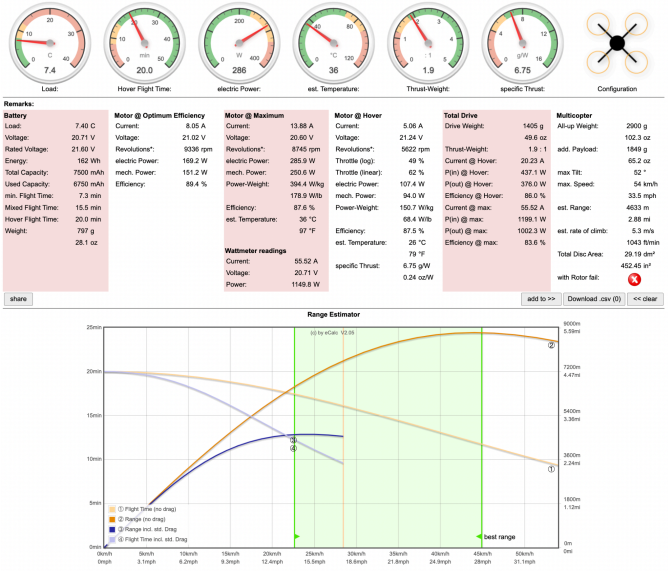


Figure 4. Sample eCalc Metrics

All three mentioned performance evaluation methods were iteratively considered throughout the design process to ensure sensible flight speeds, ranges, and payloads.

3. TECHNICAL INNOVATIONS

The motivation for the competition is to encourage innovation in the small-scale electric VTOL field. Evidently, literature on drones is predominantly dominated by research on quadcopter configurations. This project aims to build on existing knowledge of tricopter drones. The design currently incorporates improved aerodynamics with a reflexed-airfoil blended wing design. The application of reflex airfoils in drones is innovative and can provide power efficiency effects on the overall design.

This design is also capable of incorporating material and fabrication innovations. Traditional eVTOL drones of similar sizing to the design criteria are often designed using plastic foams or carbon fiber spars and ribs. However, it is possible to replace the plastic materials with other structurally equivalent and sustainably sourced materials such as bamboo or flax linen. Bamboo can be used as a leading edge structural support or as a material for spars and ribs. Flax linen is a natural fiber that offers dampening properties and high strength [2]. Finite element analysis is required to verify the possibility of incorporating bamboo in place of traditional carbon fiber methods.

Material	Young's Modulus (GPa)	Tensile Strength (MPa)
Carbon Fiber	99	918
Class 1 Petung Bamboo	11.51	260
Epoxy Flax Linen Composite	6	100

Table 1. Comparison of sustainable innovative material replacements [3][4][5]

The suggested material innovations must also consider the required structural properties as well as availability. The material and fabrication method will ultimately be determined by the ease of access to material.

4. DESIGN DEFINITION

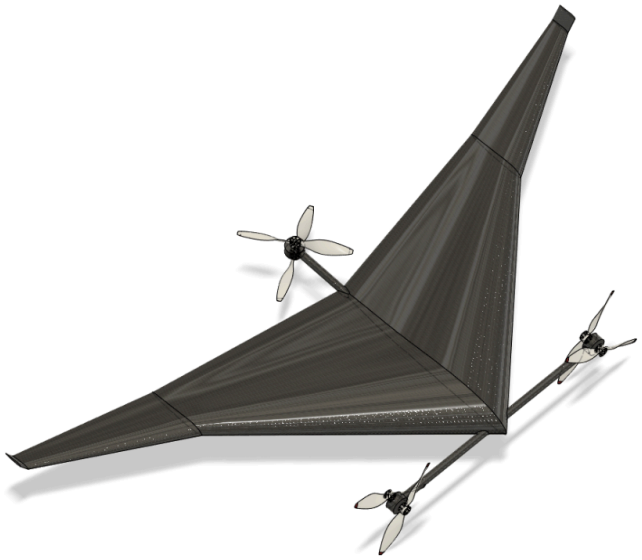


Figure 5. Blended-wing tricopter tilt-rotor (image shows the forward tilted rotors)

The design chosen is a **blended-wing tilt-rotor** design that features a **tricopter** layout for its three motors, combining the advantages of each configuration component. The blended-wing design minimizes parasitic drag effects that a fuselage on a traditional aircraft would have. The tricopter layout allows for a stable take-off/landing without adding the unnecessary weight and battery power draw that would come with more traditional quadcopter/hexacopter designs. Finally, the tilt-rotor feature allows for no wasted components, as the front two motors can tilt forward to give the drone horizontal thrust for forward cruise flight.

4.1 DRAWING PACKAGE

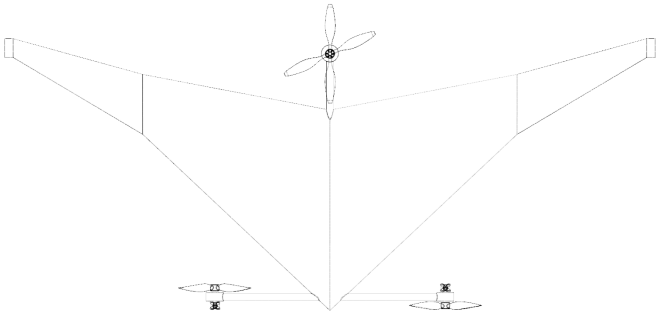


Figure 6. Vehicle CAD model Top view

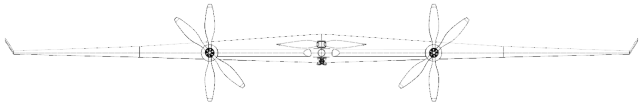


Figure 7. Vehicle CAD model Front view

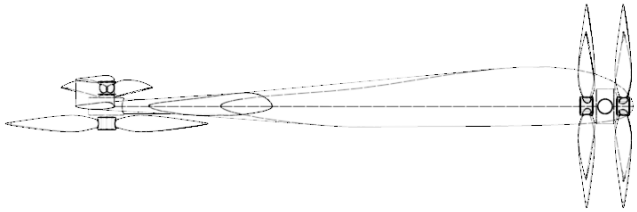


Figure 8. Vehicle CAD model Side view

4.2 MISSION MODEL

A preliminary mission model was estimated using calculated flight speeds from the eCalc software. During take-off, the tricopter's estimated rate of climb is 5.7 m/s. During forward flight, the estimated maximum optimal cruise speed is 54 mph, or 24 m/s. Using these estimations, an approximate mission model was created with assumptions for transition and turning times.

Flight Task	Estimated Time (sec)
VTOL 5 ft Take-off	5
Forward Flight Transition	3
Forward Flight (400m)	400m / (24 m/s) = 17
Turn	3
Forward Flight (500m)	500m / (24 m/s) = 21
Turn	3
Forward Flight (100m)	100m / (24 m/s) = 4
VTOL Landing	5
Lap Total	61

Table 2. Estimated Flight Path Times

This preliminary estimation results in a complete lap time of 61 seconds, totaling about 10 laps in the 10 minute time frame.

4.3 AIRFRAME

The aerodynamic forces were analyzed via XFLR5, a software that performs calculations based on a given airfoil and wing planform. For better accuracy from the software, the effects of a fuselage and other miscellaneous components (motors, propellers, etc.) were not modeled. However to properly factor those components in, separate coefficients of drag were compiled based on textbook approximations (cylinder in crossflow approximation of a motor). The subsequent contributions these components had on drag were added to the XFLR5 results, and then an additional factor of 50% was applied to consider potential viscous effects. Before the finalized design is completed, computational fluid dynamics will be used to evaluate the viscous effects that XFLR5 cannot.

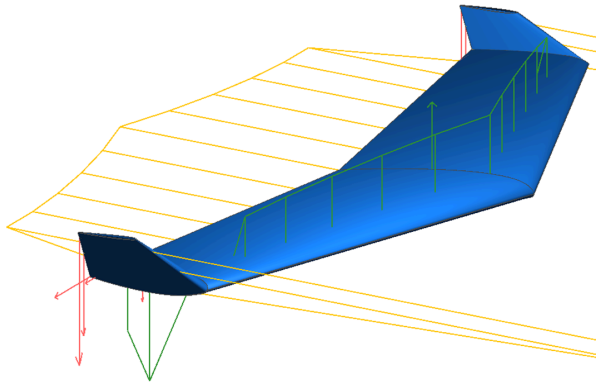


Figure 9. XFLR5 Analysis (green = lift, red = downwash, yellow = induced drag)

From the XFLR5 analysis, at a cruise speed of 25 m/s, the wing design is capable of generating just over 100 N of lift at an angle of attack of +3.75° angle of attack. The drag generated from just the wing is slightly under 5 N, however adding an additional factor of at least 50% to account for unmodeled effects equates to a total drag of 7.5 N. Additionally, the wing features winglets that are tilted 90° from the wing to reduce the effect tip vortices have on the aerodynamics. By reducing tip vortices, the effect downwash has on generating induced drag is lessened. The parameters of the wing are listed below.

4.4 WING PARAMETERS

Wing Span	1.9 m = 6.2 ft
Wing Area	0.73 m^2 = 7.86 ft^2
Aspect Ratio	5
Taper Ratio	0.3
Sweep Angle	24°
C_L	0.3625
C_D	0.01709

Table 3. List of Wing Parameters and Coefficients

For stability considerations, careful airfoil selection was performed. For a sleeker, lower drag design, the team has chosen the flying wing design, a tailless design. The benefits of the flying wing design can be seen by the high lift-to-drag ratio as detailed above. However, it comes at the cost of pitch stability usually provided by a horizontal tail on traditional configurations. Especially in the case of a VTOL flying wing, there is additional weight in the front of the aircraft, which shifts the center of gravity in front of the center of pressure. Therefore, a positive coefficient of moment is necessary for pitch stability. To remedy this, a reflexed airfoil design is utilized.

The NACA 22112 provides a region of positive camber towards the trailing edge of the airfoil, translating into a positive moment coefficient compared to negatively cambered airfoils. This specific airfoil profile was selected after using XFLR5 analysis of a set of reflexed and non-reflexed airfoils. The results of this analysis are shown below.

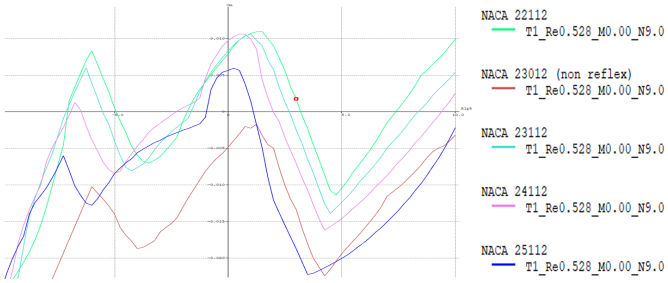


Figure 10. Coefficient of Moment vs Angle of Attack for several airfoils (the red marker indicates the cruise angle of attack)

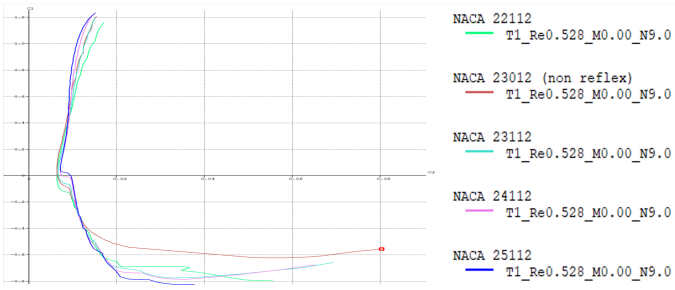


Figure 11. Coefficient of Lift vs. Coefficient of Drag for several airfoils

From the 2D airfoil results above, the NACA-22112 has the best coefficient of moment (most positive) for the angle of attack range the drone will fly at. In terms of the best lift to drag coefficient, all the airfoils perform relatively similarly at low to mid range angles of attack. The NACA-22112 has slightly higher drag at higher angles of attack, but those angles of attack are generally outside of the operating range for cruise so they are not as impactful.

4.5 PROPULSION SYSTEM

Based on market research, a range of motor, propeller, and battery specifications were established for VTOL hybrid aircraft with a MTOW of 10-20 lb. Vertical lift motors were found to be between 100-1000 KV, which makes sense because for larger drone sizes at this scale, lower KV values deliver greater torque as opposed to higher KV motors, which are suited for small drones. The propellers used were between 12-20 in., which differs based on hybrid configuration and MTOW. Batteries were either 4S or 6S, meaning that the nominal output voltage was either 14.8V or 22.2V, and capacities ranged between 5000-25000 mAh depending on the application. This research provided useful baseline estimations when selecting motor and propeller configurations.

Assuming that the final aircraft MTOW will meet the maximum of 20 lb, the thrust required for a tricopter configuration to achieve a 2:1 thrust-weight ratio is approximately 6048g. This means that any selected motors must exhibit a minimum of about 6000g of thrust at 100% throttle. A 2:1 thrust-weight ratio was selected because this enables the drone to hover at 50% throttle. Even if the final aircraft is less than 20 lb, additional thrust is desirable for greater speeds and maneuverability.

Six motors of varying sizes and KV were considered for this year's design, from motor manufacturers KDE Direct and T-Motor. Three KDE Direct motors were compared with the same recommended propeller pairing, a 18.5x6.3 dual-blade. Three T-Motor motors were also compared with the same recommended propeller pairing, a 22x6.6 dual-blade. An important metric to observe regarding propulsion is the thrust-to-power ratio, which can also be observed through the thrust-to-current ratio for a given voltage source, taken to be a 6S battery.

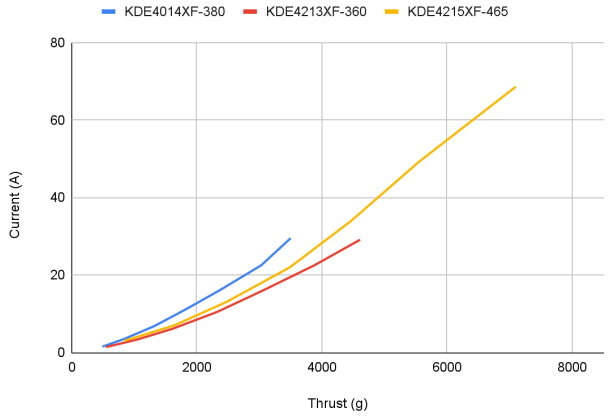


Figure 12. KDE Direct motor comparison for 18.5x6.3 dual-bladed propeller

These three KDE Direct motors were specifically observed because they were the most cost-effective options for the desired KV range. Although the KDE4215XF-465 has the lowest maximum thrust-to-current ratio, it achieves the most amount of thrust. Although the KDE4213XF-360 is more efficient, the maximum thrust output is 4610g, which is only enough for a 15 lb MTOW, not a 20 lb MTOW. The KDE4215XF-465 was selected as the most viable option in this comparison due to its significantly higher thrust output despite a minor weight increase.

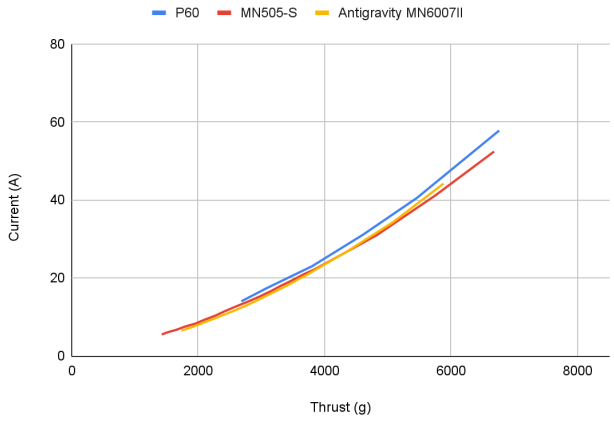


Figure 13. T-Motor motor comparisons for 22x6.6 dual-blade propeller

These three T-Motor motors were selected from a variety of the company's flagline options, looking for the most cost-effective options that met the propulsion criteria. All three motors perform similarly, but the Antigravity MN6007II produced the lowest maximum thrust at 5882 g. As for the MN505-S, not only is it more efficient than the P60, it also weighs 40% less, making it the superior option. Between the KDE4215XF-465 and MN505-S, although the MN505-S weighs 30g more, it produces a comparable thrust output and efficiency while costing about $100 less.



Figure 14. T-Motor MN505-S KV320

Since the selected configuration is a tilt-rotor aircraft, servo motors must also be examined in the near future to ensure accurate control of the selected motors and propellers.

4.6 ELECTRONICS

The primary duties of the aircraft's controls system is for sensing, controlling, and communicating data. The aircraft must be capable of measuring position and speed using a GPS, controlling the motors through a flight controller and electronic speed controllers (ESCs), and communicating all sensor information to the pilot during manual or autonomous flight. Previous students who have worked on drones have left behind several of the required electronics, so CUAV will be utilizing these functioning items. The main item of the controls system is the flight controller, which will be a Holybro PixHawk4 due to its advanced autopilot capabilities and flexible connectivity. Paired with ArduPilot, an open source autopilot software, implementing a VTOL control system on the aircraft is simplified with the already developed framework and commands.

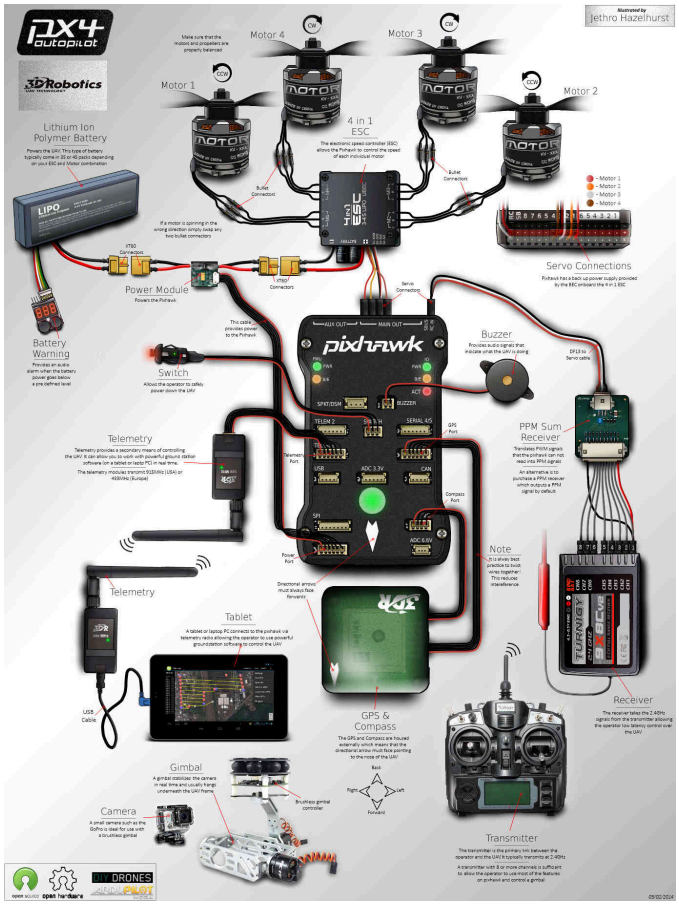


Figure 15. PixHawk4 Control System Diagram

This simplified diagram depicts each integral component to the controls system with the flight controller at the center, acting as the brain of the drone. For propulsion, the system requires a battery, XT90 power connectors, a HobbyMate 3-6S power distribution board, Hobbywing Skywalker 80A ESCs, and an external GPS and compass. For remote control capabilities, the system requires a telemetry receiver and transmitter in addition to a transmitting radio controller that can be used to send pilot controls and inspect drone telemetry in real-time. The telemetry system selected is the FrSky X4R-SB 3/16 Receiver. The only item that the team does not have currently is an external GPS and compass, but there are many cost-effective options readily available that are compatible with the PixHawk4 and ArduPilot that must be evaluated for minimal noise and accurate measurements. The servo selected for the drone is the Hiwonder LD-20MG Digital Servo.

For the battery, a 6S battery has been selected over a 4S battery. This is because it includes two additional cells, allows for increased longevity, and enables a faster and more agile performance. The capacity and discharge rate have not been selected yet, but will be iteratively selected using eCalc to allow for sufficient flight times and responsive control of the vehicle. Further testing will be done to test and tune the collective use of these electronic components together.

5. FABRICATION METHODS

The manufacturing plans for the CUAV drone design currently have two unique fabrication plans. The first is a more traditional method, which involves carbon fiber wings. For manufacturing carbon fiber wings, the process begins with the creation of the mold. After the CAD model of the wing is complete, the negative of it will be carved out of a medium density foam. After sanding and post-processing the surface to have no imperfections or rough spots, the mold will be coated in epoxy resin and cured to ensure a glassy, smooth surface that the carbon fiber layup will not adhere to. Next, a release agent is spread across the surface, on top of which sheets of dry carbon fiber (or prepreg carbon fiber) will be placed to fill the shape of the mold for epoxy resin to be applied until the carbon fiber is saturated. Finally, a vacuum seal will completely press the loose carbon fiber into the final shape of the mold. Once cured, one half of the shell of the wing is completed, and the process is repeated for the opposing half.

To join the two halves of the carbon fiber shells, the inner frame of the drone will either be composed of low density foam (EPO Foam) or bamboo wood spars. Both options will give the carbon fiber shell the strength and rigidity that is desired for the drone. Spars offer the benefit of free space within the wing for easier wiring and component placement, but at the cost of higher difficulty in assembling with perfect tolerance. Foam offers the benefit of a more precise shape, as the shape can be carved out on a CNC machine or wire cut, but may cause issues with wiring and component placement. Both options should be sufficiently light enough to not cause a significant increase in structural weight.



Figure 16. Example of Rib and Spar method with Carbon Fiber layup [5]

The second option offers a more sustainable approach, at the cost of some nuanced manufacturing methods. The application of sustainable materials will be more intricate as there is limited literature on bamboo and flax linen. FEA models and costs will ultimately determine if sustainable materials are a sufficient replacement for industry standard EPO foam and carbon fiber.

Carbon fiber spars within the wing will connect to linear rail shafts capable of supporting the servos and motors.

6. SCHEDULE

The project is organized by three competition deliverables. Design is an iterative process and involves constant revision. In addition, fabrication and testing often involves more time than expected. Therefore, the remainder of this project has a generous timeline to follow, such that progress can be guided with ample time for iterations.

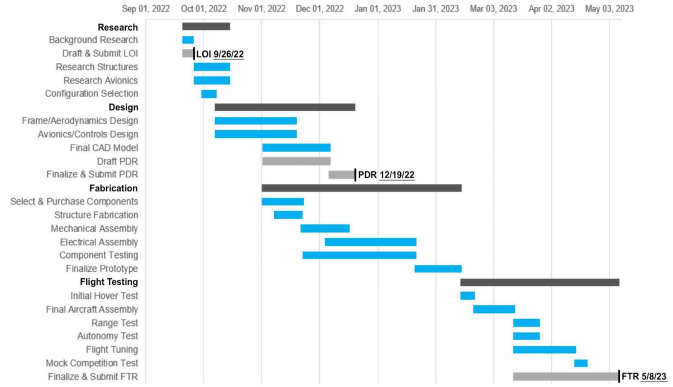


Figure 17. Gantt Chart - Project Deadlines

The upcoming tasks for the team emphasize more intense design and prototyping in order to accelerate the testing and troubleshooting process.

6.1 METHODS OF TESTING / VALIDATION

To validate the design beyond calculations and simulations, the components will be tested through physical means. To test the structural integrity of the carbon fiber shell with either spar/foam supports, a smaller test section will be created to be analyzed under an Instron under the expected load configuration. For motor and propeller validation, combinations can be mounted to a test thrust stand we will either build or purchase, in which a thrust load cell measures the motor's thrust through a pivot that transfers the force. Initial flight tests will be performed in the school's Drone Control laboratory, in which there is a safe flight zone for testing. Finally, as the design becomes more flight-ready, full test flights will be conducted in FAA legal zones to both ensure the design is working as intended and to train the pilots. These test flights will closely examine hover and cruise endurance, in addition to simulating the actual competition both manually and autonomously.

7. REFERENCES

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