Design and Prototype of an Autonomous UAV

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Interest in lightweight and cost-effective lifting drones for military and commercial uses has increased dramatically over the last few years. This paper introduces an efficient method for the design and development of such a drone, or Unmanned Aerial Vehicle (UAV). The UAV must demonstrate the ability to carry 30 simulated passengers (represented as eggs) and a model rocket booster while having an endurance of five minutes. Such a UAV must be designed to interface a mounting mechanism for the passengers and the rocket booster and be able to follow different preprogrammed waypoints in aerial missions. The first mission involves evaluating the UAV's autonomous flight capabilities without payload, examining performance metrics and endurance under standard operational conditions. The second mission focuses on testing a secure rocket booster attachment, assessing the feasibility of integrating booster systems through controlled flights to evaluate in-flight dynamics. Lastly, the third mission aims to demonstrate the UAV's ability to autonomously transport 30 simulated passengers in the form of eggs through a predefined path, showcasing its adaptability in real-world scenarios. With a budget constraint of $1250 USD and deadline of design-to-prototype of three months, this study aims to highlight the ability for small teams to design and construct drones affordably and efficiently. This will be achieved by using commercially available components and cost-effective manufacturing techniques such as 3D printing while simultaneously focusing on safety, versatility, and autonomous capability.

I. Nomenclature

CAD	=	computer aided design
UAV	=	unmanned aerial vehicle
ESC	=	electronic speed controller
GPS	=	global positioning system
RC	=	remote control / radio controlled
FBS	=	functional breakdown structure
FFD	=	functional flow diagram
FAA	=	Federal Aviation Administration
NFPA	=	National Fire Protection Administration
AUW	=	all up weight, mass of craft upon takeoff
AAD	=	average amp draw
FC	=	flight controller

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II. Project Planning

In response to the escalating project requirement for a cost-effective and versatile lifting drones in both military and commercial sectors, this paper introduces a pragmatic approach to the design and development of an Unmanned Aerial Vehicle (UAV) that excels in versatility, affordability, and autonomous capabilities. Tasked with carrying 30 simulated passengers (represented as eggs) and a model rocket booster, the UAV aims to demonstrate its adaptability through predefined aerial missions. The study's focus is on achieving this within a stringent budget of $1250 USD and a tight three-month design-to-prototype deadline, underscoring the potential for small teams to construct drones effectively. Employing commercially available components alongside cost-effective manufacturing techniques like 3D printing, the UAV's design is geared towards safety, autonomy, and adaptability, reflecting a broader trend in the industry towards efficient and affordable drone solutions.

The proposed project plan for the current development cycle will be discussed in this section. The team's current standing is presented in Fig. 1. To optimize the utilization of available resources and time, it was determined that the workload would be divided between two distinct teams, each concentrating on specific objectives within the designated work period. The research team and CAD team were assigned specific responsibilities during this time frame.

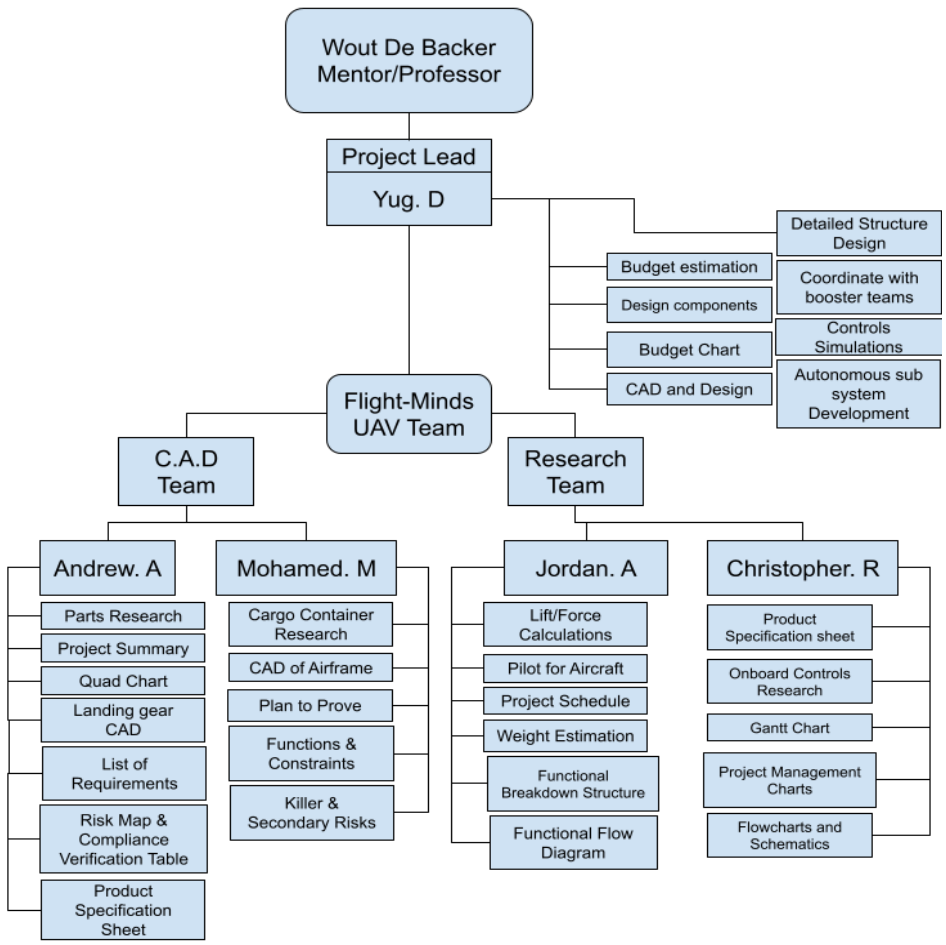

Fig. 1 Project organigram.

The chart in Fig. 1 represents the workload dispersed about the team, directed by our project lead for detailed design phase of our design process.

Moving forward, a decision was made to list constraints in both the Project Objective Statement and the Mission Needs Statement to gain a thorough understanding of what could and could not be achieved with the project. Due to significant concern that a functional Unmanned Aerial Vehicle (UAV) could not be constructed, the project objective was defined as follows:

- The project is required to meet the requirements for a UAV design by developing, prototyping, programming, and testing a flying vehicle within a budget of 1250$ USD, designed by a team of five students within thirteen weeks.

In accordance with the mission needs statement, the team verified the parameters of the UAV and established straightforward objectives that the mission had to fulfill to accomplish its diverse goals while maintaining operational functionality.

- The UAV is required to fly three separate missions lasting five minutes while carrying various payloads: empty cargo, 30 eggs and a rocket booster. The aircraft is to stay airborne for five minutes and is not permitted to damage or alter any available cargo.

A. UAV Systems

The UAV systems must have multiple systems that collaborate effectively for optimal functionality. The ESC is utilized for power regulation of various motors. The ArduPilot system coordinates the ESC and receives GPS data from the GPS module. The GPS module facilitates data transmission and reception with the ArduPilot module regarding the aircraft's speed, rotation, and intended trajectory. Batteries are connected to all systems, with power supplied through the ESC to manage the power output to the GPS, ArduPilot module, and all six motors. Additionally, an external manual connection to the ArduPilot module is established through an RC controller, enabling wireless override for manual takeoff and landing. The diagram shown in Fig. 2 shows dependencies between components and how they will interact with one another within the final construction.

Batteries	Energy Source	Energy Source	Energy Source	Energy Source	Energy Source
Energy Usage	Motors	Power Usage			
Energy Usage	Power Regulation	ESC	Speed Data		
Energy Usage		Direction Control	Ardupilot Flight Controller	Waypoint Control	
Energy Usage			Position	GPS Module	
Energy Usage			Manual Control Override		RC Controller

Fig. 2 N^2 chart.

B. Function Analysis

To better understand the requirements expected for the final design, a functional breakdown (FBS) and a functional flow diagram (FFD) were constructed. These charts visualize requirements for both the mission and design respectively.

A. Functional Breakdown Structure

The main function of a functional breakdown structure is to outline the mission's requirements so that a solution can be developed while ensuring all mission needs are met. For this project a basic FBS, shown in Fig. 3, was developed so that design making decisions could be better tuned and stay relevant to the goal that was trying to be accomplished.

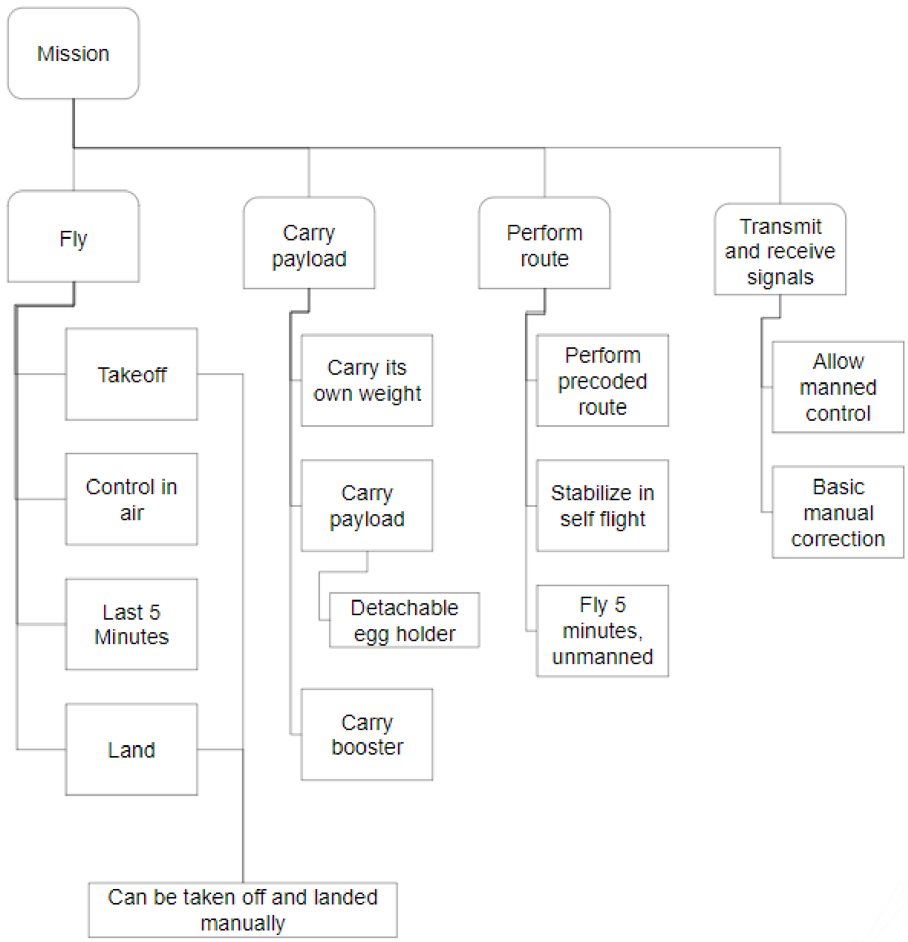

Fig. 3 Functional breakdown structure.

B. Functional Flow Diagram

The functional flow diagram shown in Fig. 4 was also created to outline objectives for the final design. Much like the FBS this chart helps to visualize what dependencies each potential design will have based on the parameters of the mission. For our final design, the FFD was used as a basis for component interaction and conveyed how various components will interact from a removed perspective.

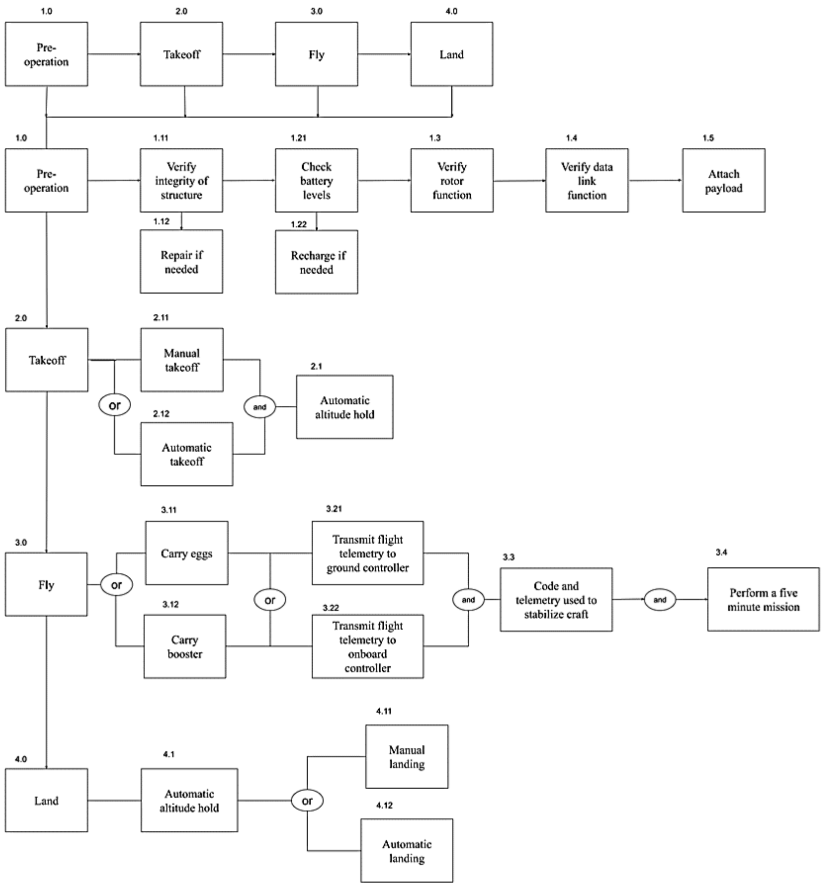

Fig. 4 Functional flow diagram.

C. Concept Generation

To satisfy the requirements outlined in the mission statement the team was tasked with generating different concepts that used unique methods, materials, and designs. Three distinct concepts were chosen for further analysis and comparison; A conventional fixed wing airplane with propellers and landing gear and two multirotor designs: a quadcopter and hexacopter.

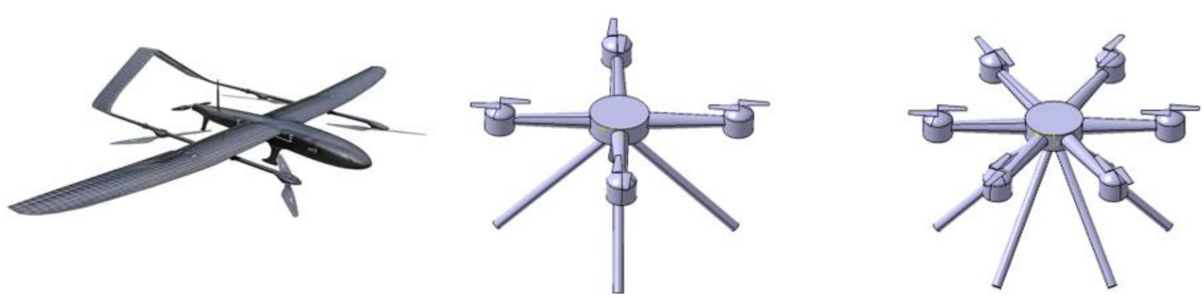

Fig. 5 Concepts for UAV, from left to right; fixed-wing aircraft, quadcopter, and hexacopter [1].

Using these three design concepts, risk heat maps are developed to determine the shortcomings and advantages of each design. Risks evaluated were according to the complexity, cost, development, and testing of each concept. The one shown to have the least amount of risk involved in its design was chosen for continued development, in this case the quadcopter. The selected quadcopter design was also evaluated to be the cheapest and easiest to manufacture of all designs, making it a desirable pick for a short development time. A compliance matrix (shown below in Table 1) was created to further prove the selected design capable of achieving its goal.

Table 1 Compliance matrix for the quadcopter design.

Requirement/Constraint	Compliance Level	Compliance Document
Endurance of 5 minutes	Achievable	Experiment, simulations
Autonomous predefined path	Achievable	Experiment, simulations
Payload compliance with FAA regulations	Compliant	FAA website [2]
Payload compliance wirh NFPA	Compliant	NFPA website [3]
Efficient passenger loading	Achievable	Experiment
Able to transport rocket booster	Achievable	CAD design
Weather Sensitivity	Achievable	Design review
Cost	Within budget	See table 2 in section IV
Able to fit in mid-sized sedan	Achievable	CAD design

III. Detailed Design

A quadcopter design was chosen to fulfill the requirements in the project as there is a lot of existing documentation out there on automating and building quadcopters, making it simpler for a relatively inexperienced team to follow.

All the aspects of the detailed design such as structural soundness, aerodynamic performance, and various subsystems will be discussed in this section. Some of these design decisions are subject to deviations as implementation of the design into a physical aircraft takes place. The preliminary design for quadcopter is shown in Fig. 6 and serves as a visualization, however, will not be the final manufactured design as the iterative design process continues.

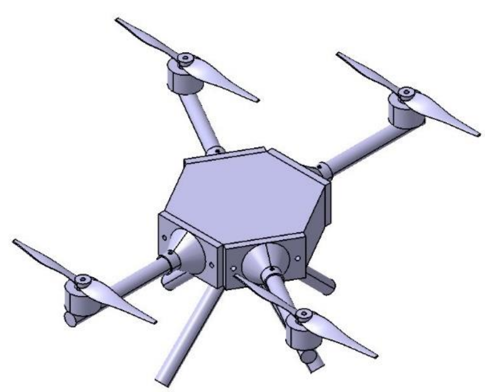

Fig. 6 Preliminary quadcopter design.

A. Structural Soundness

The physical stresses on the UAV's structure encompass a range of forces and conditions encountered during its flights. These stresses include aerodynamic forces such as lift, drag, and thrust, which vary based on the UAV's design, speed, and altitude. Additionally, the structural components must withstand gravitational forces during takeoff, flight, and landing.

Specifically, the aircraft's arms, the legs (landing gear) and the bottom of the control unit which carries the payload are the aircraft's highest loaded components.

Arm Loading

The load carried by each arm is demonstrated in Fig. 7, with circular cross-section with 1 inch diameter where the lift generated by the rotor is shown by an upward force at the tip and the contribution of the weight taken by each arm shown by a downward force at the root of the arm. Both values are determined to be 1/4 of the maximum weight of the aircraft because of the quadcopter design. It is assumed that the weight of the payload and the control unit is evenly distributed among the arms.

Fig. 7 Arm loading.

This results in the shear force and bending moment diagrams are shown in Fig. 8 and Fig. 9, respectively. Once the external loads and reactions of the structural beam were identified. The beam was then cut at a location on the arm, and one portion was isolated for examination. Each arm is identified as a cantilever beam under the influence of a constant shear force of 64 N, the shear force diagram reveals a horizontal line with a magnitude of 64 N along the beam's length. Simultaneously, the bending moment diagram depicts a linearly increasing trend, starting from zero at the fixed support and reaching its maximum at the free end. This relationship is in accordance with the fundamental principles of structural mechanics, where a constant shear force induces a linear change in bending moment. The shear force remains uniform, exerting a lateral force throughout the beam, while the bending moment progressively intensifies, reflecting the internal moments experienced by the cantilever. The maximum bending moment is calculated to be 16 Nm at the tip of each arm.

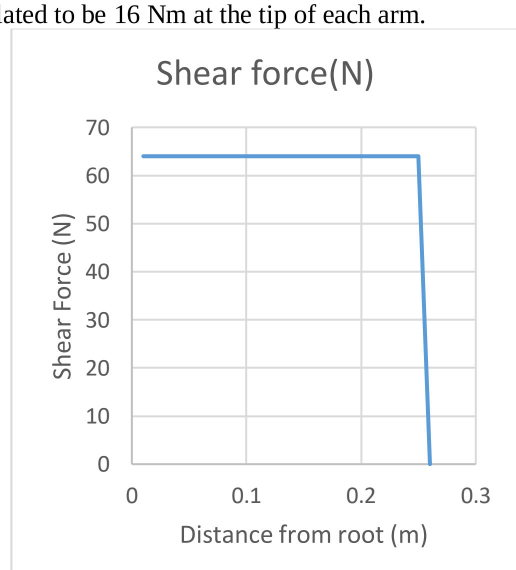

Fig. 8 Shear diagram.

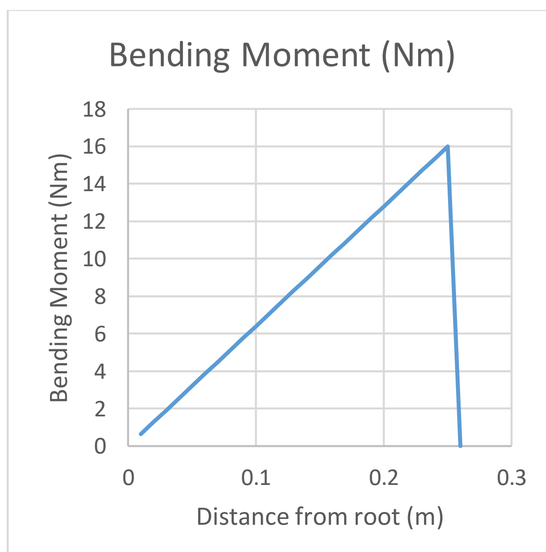

Fig. 9 Bending moment diagram.

Bending stress at the point of highest bending moment were calculated to be 9.95 MPa using Eq. (1). In Eq. (1), moment of inertia, I, for a circular cross section was calculated using Eq. (2). Coupling the highest bending stress experienced by the arm with the yield strength of the material of the arm, Acetal Copolymer, of 66 MPa [4], results in the minimum safety factor of 6.6 for the arm.

$$(My)/I \tag{1}$$

$$A = (\pi D^4)/64 \tag{2}$$

Load from Payload Mounting

Since the payload will be mounted underneath the control unit and the heaviest component of the aircraft, the battery is mounted inside it, the control unit needs to be stiff enough to carry the weight without deformation and strong enough to not fail under the combined load of the payload and the parts that the control unit is housing. The maximum weight that the control unit will support is 5.5 kg. Using 1/8th inch think sheet of aluminum (6061) for this part should suffice due to a high yield strength of 241 MPa, which should be orders of magnitude higher than the expected load.

Landing Gear Impact

The landing gear of the aircraft will use the same rods as the arms, complemented by a support system of tennis balls to absorb impact during rough landings, contributing to a practical and resilient design. It was not realistic to account for emergency situations or crash landings because of the lack of budget and time.

B. Aerodynamics and Performance

Due to the nature of quadcopters and other multirotor craft rather than lift or drag the performance can be estimated using a set of equations based on the power output of the motors and battery. For this paper, average power usage during different stages of flight was used based on information from others on drone hobby forums. An average value of 250 W/kg was decided upon for calculating our maximum allowable payload and endurance. Mass of maximum mission payload and craft was found to be approximately 6.58 kg. The voltage of the battery selected is 22.2 V as per the manufacturer specifications and maximum discharge was assumed to be 80% of full to safely operate the LiPo battery. Using Eq. (3) and (4) an average amp draw and minimum battery required was found to be 74.1 A and 9260 mAh respectively. Using Eq. (5) a flight endurance of 12.9 minutes was calculated with our maximum payload attached.

$$AAD = m \times \left(\frac{average\ power\ usage}{V}\right) \tag{3}$$

$$Minimum\ battery\ capacity = \frac{(t \times A)}{usage} \tag{4}$$

$$Flight\ Endurance = \frac{(battery\ capaciy \times usage)}{A} \tag{5}$$

C. Autonomous Subsystem

The Autonomous Controls Subsystem of the aircraft revolves around the APM 2.8 flight controller and the uses ArduPilot flight control software [5]. Design considerations, implementation strategies, and selected options for achieving autonomous capability are discussed in this section.

APM 2.8 Flight Controller

The APM 2.8 flight controller, shown in Fig. 10, is central to the Autonomous Controls Subsystem and effectively manages electronic signals for navigation. Its seamless integration with ArduPilot aligns conveniently with our system, contributing to enhanced control precision through its versatile support for various flight modes.

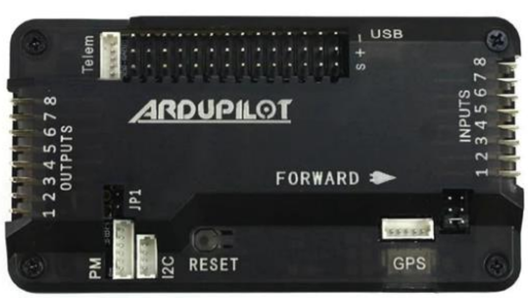

Fig. 10 JMT APM 2.8 controller [6].

ArduPilot Software

The ArduPilot software plays a central role in the Autonomous Controls Subsystem, efficiently managing electronic signals for precise navigation. Defining an autonomous path is ArduPilot will be done by utilizing the tools on the ArduPilot mission planner such as defining waypoint, takeoff, landing, and loiter points in the software which are then uploaded to the APM 2.8 flight controller.

Waypoints are defined through mission planning tools integrated into the ArduPilot ecosystem, enabling the drone to autonomously follow a predetermined route. During take-off, ArduPilot ensures a seamless ascent, considering factors such as altitude, wind conditions, and specific mission requirements. Loiter points, where the drone hovers over designated locations, are managed by ArduPilot, controlling the drone's position, altitude and orientation. Similarly, defining landing points involves a coordinated descent to designated locations, accounting for variables like altitude and terrain. Mission planner screen is shown in Fig. 11.

Fig. 11 ArduPilot mission planner [5].

In essence, ArduPilot serves as a reliable foundation for autonomous flight, ensuring precise navigation and mission execution across diverse scenarios. The integration of ArduPilot into the system exemplifies an effective control mechanism for the drone's autonomous capabilities.

Design Option Tree

Design decisions were made for the choosing software to program autonomous paths and the flight controller which would help the drone follow these paths. The chosen flight controller hardware was APM 2.8, highlighted in green in Fig. 12, over Pixhawk because it was a budget friendly option as it was available to use from the senior design project from the previous year and was otherwise a perfectly viable option for a flight controller for a simple autonomous mission of taking off, loitering at a few points and landing. Since APM 2.8 was chosen as a flight controller hardware, iNAV had been discarded as an option for flight controller software, and ArduPilot was chosen, highlighted in green in Fig. 13, which is a great option as it provides simple waypoint navigation using GPS.

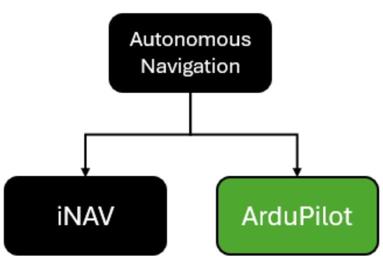

Fig. 12 Design options: hardware.

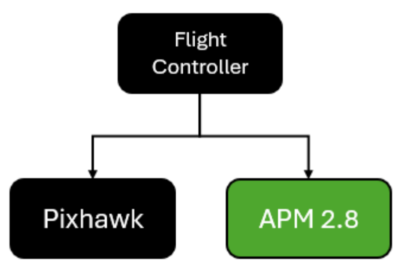

Fig. 13 Design options: software.

IV. Budget Breakdown

Financial and Weight breakdowns of the components used in this project are shown in this section.

A. Financial Breakdown

Financial Breakdown of the components used for this project are shown in Table 2. More components like bolts and L-brackets are to be finalized and added to the budget in the project's manufacturing phase. The total budget spent so far on the project is $932.49.

Table 2 Cost by Components.

Subcomponent	Part	Packs to Order	Price Per Pack	Total	Total + Tax & Shipping	Supplier
Propulsion	DC Motor	4	$74.99	$299.96	$353.05	Cobra Motors
Propulsion	Prop	6	$8.31	$49.86	$58.69	APC
Power Source	6S Lipo Battery	1	$201.59	$201.59	$237.27	Hobby King
Frame	Mount for Props	2	$2.69	$5.38	$6.33	APC
Frame	Arm mounting sockets	1	$9.54	$9.54	$11.23	Amazon
Power Source	Charger	1	$51.99	$51.99	$61.19	Amazon
Power Source	Charger Adapter	1	$7.99	$7.99	$9.40	GetFPV
Frame	Landing gear	1	$21.99	$21.99	$25.88	Amazon
Power Supply	ESC	1	$89.99	$89.99	$ 105.92	T-motor
Flight Controller	APM 2.8	1	$53.97	$53.97	$63.52	E-bay
-	**-**	**-**	**-**	**-**	**$ 932.49**	**-**

B. Weight Breakdown

Weight Breakdown of the components used for this project are shown in Table 3. Total weight estimation of the components ordered so far on the project varies from 5.080-6.495 kg.

Table 3 Weight by components.

Part	Model	Mass (g)
Frame	N/A	950
Motor x 4	Cobra CM-4510/28 Multirotor Motor, KV=420	844
Propeller x 4	APC 16x5.5 MR Prop	176
ESC Flight Control	FLAME 100A 6S Multi-Rotor Uav Drone ESC 4-8S battery	6
Battery	Turnigy High Capacity 20000mAh	2630
GPS	BN 880	3
Wire (1 m)	N/A	21
Landing Gear/Mount	N/A	450
Egg Payload	N/A	1415
Booster Payload	N/A	1500
Total (Egg Payload)	**-**	**6495**
Total (Booster Payload)	**-**	**6580**
Total (Empty)	**-**	**5080**

V. Future Works and Manufacturing

In the forthcoming two months, the team is gearing up for a pivotal phase, focusing on the manufacturing and testing of the designed UAV. The manufacturing process is scheduled to unfold at the University of South Carolina, where the team will take charge, overseeing the intricate assembly of the components. This hands-on phase reflects the team's dedication and technical prowess.

Following manufacturing, the team will shift its focus to rigorous testing, a crucial step to validate the UAV's performance and functionality. The testing procedures are set to transpire at the esteemed Triple Tree Aerodrome, a valued partner in the project. The aerodrome's expansive and controlled airspace provides an optimal environment for comprehensive testing, allowing the team to assess the UAV's capabilities under real-world conditions.

As the project progresses, these imminent manufacturing and testing stages not only signify a critical phase but also represent a thorough evaluation process. The outcomes of these endeavors will inform subsequent refinements, ensuring that the UAV aligns with the stringent standards of performance and reliability. The team remains committed to navigating these upcoming milestones with precision and dedication, laying the groundwork for the successful deployment and application of the designed UAV.

Acknowledgments

The team expresses gratitude for the essential funding provided by the Aerospace Engineering Program and the Mechanical Engineering Department at the University of South Carolina, which was instrumental in the realization of the project's success. Furthermore, appreciation is extended to the previous year's project teams whose insights and experiences have provided valuable perspectives, contributing significantly to the development and execution of their own project. The team would also like to express gratitude to Triple Tree Aerodrome for generously providing a launch site for our project. Their support has been crucial in facilitating the practical aspects of our endeavors, and we are appreciative of their contribution to the success of our project.

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