The DORIS Project

Engineering Calculations Summary

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Project Sponsor: The Boeing Company

Instructor: Professor James Clark

Faculty Advisor: Professor David Willy

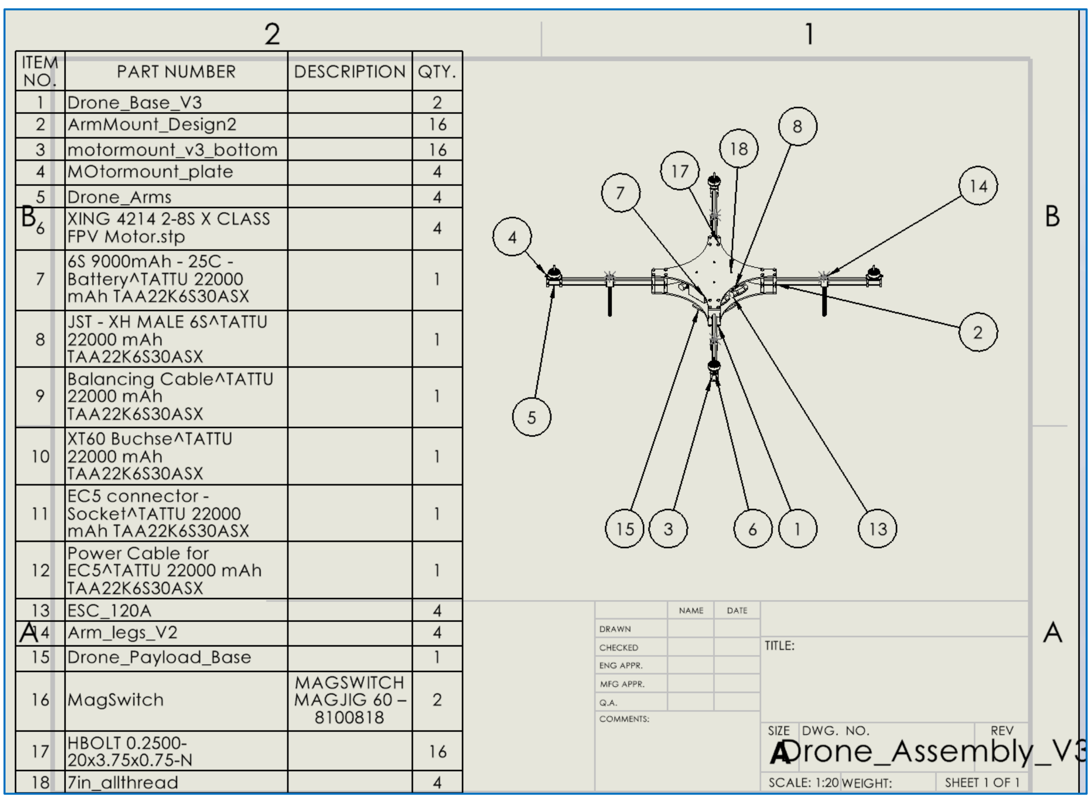
1. Top Level Design Summary

1.1 Problem Summary

Our team was tasked with designing and creating a drone utilizing commercially available parts. The drone must be able to engage and deploy different payloads while remaining airborne. These payloads will include a camera for potential surveying, a payload that must be equal or greater in weight to 30% of the drone's empty weight, and a 3D-printed cruise missile that must be able hit a target after being deployed. The drone must be able to complete a predesignated course where it will take off, deploy the cruise missile, fly to the first payload, pick it up, fly across the field, drop the payload, fly to the next payload, pick it up, fly across the field, drop the payload, pick up a camera, fly to the team, take a picture, and land safely.

1.2 Solution: Drone System

The design that our team has decided on is a quadcopter with a simplistic carbon fiber frame, octagonal carbon fiber arms, a magnetic payload attachment system that can be turned off using a servo motor, a Pixhawk 6C Flight Controller, iFlight XING X4214 660KV Motors, and HQProp 16X8X3 tri-blade propellers. With this design, we believe that it will be capable of picking up large payloads, have a significant flight time, and being able to resist any damage that may occur. If damage does occur, the design allows for easy repairability.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Drone_Base_V3		2
2	ArmMount_Design2		16
3	motormount_v3_bottom		16
4	MOtormount_plate		4
5	Drone_Arms		4
6	XING 4214 2-8S X CLASS FPV Motor.stp		4
7	6S 9000mAh - 25C - Battery^TATTU 22000 mAh TAA22K6S30ASX		1
8	JST - XH MALE 6S^TATTU 22000 mAh TAA22K6S30ASX		1
9	Balancing Cable^TATTU 22000 mAh TAA22K6S30ASX		1
10	XT60 Buchse^TATTU 22000 mAh TAA22K6S30ASX		1
11	EC5 connector - Socket^TATTU 22000 mAh TAA22K6S30ASX		1
12	Power Cable for EC5^TATTU 22000 mAh TAA22K6S30ASX		1
13	ESC_120A		4
14	Arm_legs_V2		4
15	Drone_Payload_Base		1
16	MagSwitch	MAGSWITCH MAGJIG 60 – 8100818	2
17	HBOLT 0.2500-20x3.75x0.75-N		16
18	7in_allthread		4

Figure 1.2: Balloon Assembly

1.3 Sub-systems

1.3.1 Frame (main body)

This design encompasses a two-plate “sandwich” style body design that has attachment points for arms protruding at 45 degrees from the frame creating a symmetric pattern. Legs will be positioned along the length of the drone’s arms so the drone can land and take off. The frame itself will be two symmetrical plates, spaced apart using brackets, allowing attachment points for the arms a place to house the batteries and electronic speed controllers. The plates will later be optimized for weight reduction once the location of all the mounting locations to the frame have been finalized and the material for the construction of the frame has also been finalized.

1.3.2 Arms

The arm design selected uses carbon fiber tubes (20mm in diameter and 500mm in length with a 6mm wall thickness) and is attached to the main (middle) frame using 3D printed connections. The purpose of this design is to allow the carbon fiber tubes to be replaced easily if they receive damages that compromise their strength. This also allows all electronics to be ran inside the tubes to protect them from the elements. This design incorporates two-piece, clamping style mounting solutions which provide enough clamping force to secure the arms in place to the body, and also secure each motor to an arm.

1.3.3 Flight Control Electronics

The flight control electronics system is designed to be the brains of the drone system. It includes the Pixhawk 6C flight controller, LiPo batteries, power distribution board, RC receiver/controller, and the motors. A robust and stable electronics system is essential to maintain full control over all stages of flight. All these components are specifically chosen based on calculated current loads necessary to drive our powerful motors.

1.3.4 Payload System

This system utilizes 2 magnets that are aligned and pressed fit into a mounting bracket, with servo motors to activate and deactivate the release. The payload for this design is required to have a metal plate for the magnet to attach too. This design was chosen for its simplicity and assured release with minimal contact. The magnet chosen, the Magswitch MAGJIG 60, can support up to 60 lb which will be enough to support a 20 lb payload with a safety factor of 3. (Thrust Ratio 3:1 - - - 20lb x 3 = 60lb).

1.4 Quality Function Deployment

From discussion/deliberation with our Boeing Sponsors/advisors, it was determined that the engineering and customer requirements for our project could remain as they were from last semester, which means that our QFD did not require updating for the new semester.

3 Highest on scale

	Thrust : weight > 3:1	Compact Design under 3'x3'x3'	Complete Course < 10 min	Payload > 30% of weight	Time of flight > 10 min	Total Cost under $3,000	Meets FAA requirements (weight < 55 lbs)
Thrust : weight > 3:1							
Compact Design under 3'x3'x3'							
Complete Course < 10 min	3						
Payload > 30% of weight	1		1				
Time of flight > 10 min	3		1	1			
Total Cost under $3,000		3			1		
Meets FAA requirements (weight < 55 lbs)	3	3		1	3	3	

Customer Needs	Customer Weights: 1-5	Thrust : weight > 3:1	Compact Design under 3'x3'x3'	Complete Course < 10 min	Payload > 30% of weight	Time of flight > 10 min	Total Cost under $3,000	Meets FAA requirements (weight < 55 lbs)
		Technical Requirements						
High mobility	4	5	5	5	1	2	1	
Small	1	4	5	3		5	5	5
Complete Boeing Recon Mission	5	5	3	2	4	2		
Payload Capacity	5	5	1	2	5	1	2	
Battery Capacity for small mission	4	3	2	4	4	5	1	1
Cost Efficiency	3	1	2	3		2	5	4
Thrust Efficiency	4	5	3	5	4	5	2	
FAA Registered	5		3					5
Technical Requirement Units			Feet	minutes	% weight	minutes	USD	pounds
Technical Requirement Targets		3:1	< 3x3x3	< 10	> 30	> 10	>3000	< 55
Absolute Technical Importance		28	24	24	18	22	16	15
Relative Technical Importance		1	3	3	5	4	6	7

Figure 1.4: Quality Function Deployment Diagram

1.4.1 Customer Requirements

High Mobility – The drone needs to be highly maneuverable. Able to turn sharply and easy to control to be able to pick up and drop the payload at the waypoints.

Small – The drone needs to be small and still fit all essential parts such as battery and receivers as well as the payload pick-up system.

Complete Recon Mission – The drone must be able to fly to and pick-up a payload then fly it to another waypoint to drop it off. The drone must also be capable of flying with a camera and taking at minimum one photo of the team below. Lastly, it must be able to carry and launch a steerable cruise missile.

Payload Capacity – The drone can carry a significantly heavy payload, a third of its own weight.
Battery Capacity – The battery must be efficient/large enough to power the full mission and land back at home point.
Cost Efficiency – There is a limited budget for this project, so the team needs to watch their purchases and look for cheaper options if possible.
Thrust Efficiency – The drone should have a high thrust to weight ratio to be able to move easily and lift heavy payloads.
FAA Registered – The team must meet the regulations set by the Federal Aviation Administration for Unmanned Aircraft Systems (UAS). The most important ones are that the team cannot fly it above 400 ft and the drone must weigh less than 55 lbs. If necessary, the drone should be registered with the FAA.

1.4.2 Engineering Requirements

Thrust to Weight Ratio – The goal ratio is for the thrust to be at least 3 times the weight of the drone. This goal was set so that we can lift the payload and still fly with high mobility.
Compact Design – The drone should be under 3 feet in height, width, and length. If the drone gets too large it will become heavier which gets harder to counter with thrust. Also, maneuverability will be more difficult.
Complete Course in Time Limit – The time limit is 10 minutes. The team must operate the drone to complete all tasks within this time constraint.
Payload Weight – The payload must be at least 30 % of the weight of the drone. To do this the drone needs to have powerful motors with efficient propellors to give it high thrust.
Time of Flight – The minimum requirement for the time in the air is 10 min. This test will be done with a full battery and keeping the drone at a hover.
Total Cost – The budget is $3,000 so all purchases must be tracked to make sure the spending does not exceed the limit.
Meet FAA Requirements - The team must meet the regulations set by the FAA for UAS. The drone cannot fly above 400 ft and it must weigh less than 55 lbs.

2. Summary of Standards, Codes, and Regulations

Summary of Standards, Codes, and Regulations

The Federal Aviation Administration (FAA) rules outlined in CFR Title 14 Chapter 1 Subchapter F Part 107 provide guidelines for small, unmanned aircraft, describing requirements for safe recreational drone operations such as pilot certification, maximum altitudes, airspace restrictions, and operational guidelines. These regulations will be managed by Dylan, our flight engineer, to ensure safe and legal operation.

The ASM Handbook: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials offers detailed insights into nonferrous alloys and materials. It focuses on mechanical properties like strength, stiffness, and durability, along with corrosion resistance, weight considerations, and manufacturability. These aspects were crucial in selecting lightweight and structurally sound materials, such as carbon fiber and alloys, for the drone frame.

ASTM F2910-14 provides guidelines for the design and construction of small, unmanned aircraft systems (sUAS) to address reliability and safety. It emphasizes structural integrity to withstand operational stresses, compliance with weight limits, and flight stability for smooth, predictable performance. This is especially important when dealing with payload capable drones, such as the one our team is designing. Additionally, ASTM Aerospace Material Standards ensure that materials used in aerospace applications meet tested benchmarks for thermal stability, mechanical strength, corrosion resistance, and electrical conductivity, which are essential for the drone's performance.

The FAA requires small, unmanned aircraft, the category we are creating , to weigh between 0.55 lbs and 55 lbs (0.25 kg to 25 kg). This regulation defines the maximum allowable weight for registration and ensures compliance for payload operations. With a project goal of carrying at least 30% of the drone's dry weight as payload, the total system weight must remain under 42.25 pounds (19.16 kg) to keep within the legal weight range.

IEEE UAS Standards, including IEEE 1937.1 and IEEE 1939.1, provide the frameworks for modularity, interoperability, and system integration. IEEE 1937.1 enables integration with various payloads, seamless upgrades, and reliable communication protocols. IEEE 1939.1 focuses on secure and efficient data transmission, critical for real-time information exchange and payload reliability, such as camera feeds and sensor data.

ANSI UAS Standards from the Unmanned Aircraft Systems Standardization Collaborative (UASSC) emphasize structural integrity, maintenance protocols, and risk assessment strategies. These guidelines enhance safety and usability, supporting diverse applications such as emergency supply delivery. The IEEE Approved Draft Standard for Drone Applications Framework outlines steps for drone registration, ensuring regulatory compliance.

Carbon fiber, with its properties of lightweight density, strength, and thermal resistance, was selected based on data from material-specific sources. This material supports the structural integrity and durability requirements of the drone's arms and base. The ASME Y14.6 standard for screw thread representation ensures precision and consistency in the fasteners used in the drone's construction.

The motor selection was guided by "The Ultimate Guide to Heavy Lift Drone Motors" (JOUAV), which emphasizes power, thrust-to-weight ratio, and efficiency for stable payload operations. The selected iFlight XING 4214 motor, specifically designed for X-Class (large drone) Racing, offers good performance, delivering up to 7.9 kg thrust at 660 kV with high efficiency between 50% and 90% throttle. Its durable construction and heat dissipation design are ideal for sustained flights under load.

IEEE 115 provides standardized test procedures for evaluating electric motors, ensuring consistent metrics for efficiency, power output, and thermal performance. Similarly, ISO 1940-1 addresses the balance quality of rotating components like motor rotors, minimizing vibration and wear while improving efficiency and stability during high-speed operations.

In summary, the drone's design follows a comprehensive set of standards and regulations, ensuring safety, efficiency, and compliance. Key equations and requirements include a thrust-to-weight ratio of at least 3:1, a minimum payload capacity of 30% of the dry weight, and compliance with the FAA's weight range of 0.55 lbs to 55 lbs. Material properties like carbon fiber density (1.9 g/cm³) and motor performance metrics were integral to the design process, ensuring a robust, high-performing, and compliant drone.

3. Summary of Equations and Solutions

3.1 Sub-system 1: Frame to Arms

Assuming the total weight of the drone is 22 lbs or 10 kg, the total maximum thrust from the motor and propeller on one arm is 73.5 N to reach a 3:1 thrust to weight ratio, and the mounts are 12.7 mm thick and spaced 50 mm apart, we can use our force and moment equations to find the resulting stresses on the arms at the contact points. We are also assuming that the distance between the center of mass and the seconds support is 12.31 inches or 312.674 mm. The red dot is the focal point of the calculations (See Figure 1 in Section 4 – Flow Charts and Other Diagram). This calculation needs further updating because the team added another battery, which in turn, changes the weight of the drone.

Solving for the weight force we use the equation

$$\text{Weight (N)} = ma = mg = 10(\text{kg}) * 9.81\ (\text{m/s}^2) = 98.1\ \text{N} \qquad (1)$$

Because we are looking at only a fourth of the drone, we will use that the weight is equal to 24.525 N

For static equilibrium the sum of the forces in the y direction must be equal to zero because of newtons laws of motions so,

$$\Sigma F_y = 0 = T - W - R_1 + R_2 - R_3 + R_4 = 73.5 - 24.525 - R_1 + R_2 - R_3 + R_4 \qquad (2)$$

This means that,

$$R_1 - R_2 + R_3 - R_4 = 48.975\ \text{N} \qquad (2\ \text{simplified})$$

Because R_1 and R_3 should be the same and R_2 and R_4 should the same, this equation simplifies to,

$$2R_{13} - 2R_{24} = 48.975\ \text{N} \Rightarrow R_{13} - R_{24} = 24.4875\ \text{N} \qquad (3)$$

Next, we can move to moment calculations. As with the force calculations, the sum of the moments must add to zero as well. So,

$$\Sigma M = 0 = T(.3946\text{m}) + W(.312647\text{m}) - R_4(.0754\text{m}) + R_3(.0627\text{m}) - R_2(.0127\text{m}) \qquad (4)$$

This simplifies to,

$$29\ (\text{N*m}) + 7.668(\text{N*m}) - 0.0881R_{24} + 0.0627R_{13} = 0 \qquad (5)$$

$$0.0881R_{24} - 0.0627R_{13} = 36.668\ \text{N*m} \qquad (6)$$

Using equations 3 and 6 we can now solve for the reaction forces. Rearranging equation 3, we know,

$$R_{13} = R_{24} + 24.4875\ \text{N} \qquad (3)$$

So, we can plug this into equation 2.3,

$$0.0881R_{24} - 0.0627(R_{24} + 24.4875) = 36.668 \qquad (6)$$

Solving for R_{24} we get R_{24} = 1504.07 N, which means that R_{13} = 1528.56 N

This leads to the question; can the arms survive this force? The area that touches the arms is 254 mm^2 so the pressure that the arms feel is,

$$\text{Pressure} = F/A = 1528.56 \text{ N} / 0.000254 \text{ m}^2 = 6{,}017{,}952.76 \text{ Pa} = 6.017 \text{ MPa} \quad (7)$$

This means the carbon fiber arms will be ok, because the yield strength of 2,500 MPa

We also know that the yield strength of PLA is 26.082 MPa.

Using this knowledge we can calculate the factor of safeties,

$$\text{FOS(arms)} = \text{fail/allowable} = 2{,}500\text{MPa}/6.017\text{MPa} = 415.5 \quad (8)$$

$$\text{FOS(spacers)} = \text{fail/allowable} = 2{,}500\text{MPa}/26.082 \text{ MPa} = 95.85 \quad (8)$$

The last force that we want to know is the maximum drag force on the arm. To find this we need can use the drag equation,

$$D = (C_D * \rho * V^2 * A)/2 \quad (9)$$

Assuming ρ = 1.337 kg/m^3, C_D = 1, A = .01 m^2, V = .5 m/s,

$$D = (1 * 1.337 \text{ kg/m}^3 * (.5 \text{ m/s})^2 * .01 \text{ m}^2)/2 = .00167 \text{ N} \quad (9)$$

With this number being so small, the drag due to the arms themselves are pretty much negligible compared to the entire drone.

Assuming the inner radius of the carbon fiber tube (d_i) is 0.02m and the outer radius (d_o) is 0.022m:

$$E=250GPa-350GPa \textit{E=250GPa−350GPa} \quad (10)$$

From the engineering toolbox we can solve for the moment of inertia for a hollow rod.

$$I=\pi 4 \ (d4o-d4i)=\pi 4 \ [(0.022m)4-(0.02m)4]=5.832\cdot 10-8 \ m4 \quad (11)$$

Using this, we can solve for the maximum defection.

$$\Delta_{max} = PL33EI=100N\cdot(0.5m)33\cdot(300\cdot 109Pa)\cdot(5.832\cdot 10-8m4)=0.2381mm\approx 0.01in \quad (12)$$

The equations above calculate the maximum defection that the arms will deflect when the motors are maxed using the moment of inertia equation for a circular hollow pipe. This is important to know because if the arms bend too much, it could cause devastating problems for the drone.

3.2 Payload Attachment & Carrier Design Sub-Assembly – Dylan Boeholt & Andre Bonillas

The team needs to understand the limits on the payload weight, the dry drone weight, and the total weight of the drone system. Then from the predicted weight of the drone, the theoretical thrust to weight ratio can be calculated.

For Maximum weight calculations based off of FAA regulations:

$$W_D + W_P = W_s => W_D + 0.3W_D = 25kg => W_D = 19.2\ kg\ and\ W_P = 5.8\ kg \quad (13)$$

Where W_D is the dry weight of the drone, W_P is the weight of the payload, and W_S is the total weight of the drone system, the 0.3 in the equation denotes that the payload will be 30 percent of the drone's dry weight without the payload attached. 25 kilograms denotes that maximum weight measurement for a small, unmanned aircraft from the FAA regulations.

For desired weight calculations based on customer requirements:

$$W_P = 5\ lbs; W_D = \frac{W_P}{0.3} = 16.7\ lbs;\ 16.7lbs + 5lbs = 21.7\ lbs = W_S \quad (14)$$

The desired weight of the drone unloaded will be 16.7 pounds, which means the total loaded weight will be 21.7 pounds.

For the force of the payload acting on the connection apparatus:

$$F = m * g,\ 5lbs = 2.268\ kg = m; g = 9.81\frac{m}{s^2}; F = 22.25\ N \quad (15)$$

For thrust calculations

$$Thrust\ to\ Weight\ ratio = 3{:}1; T = W_S * ratio = 21.7lbf * 3 = 65.1\ lbf \quad (16)$$

Where W_S is the total system weight derived earlier in pound-force, 21.7 lbf, ratio equals the desired thrust to weight ratio, 3:1, and the variable, T, is the theoretical thrust force requirement for the drone based off the desired ratio and desired drone weight, which was found to be 65.1 lbf.

3.3 Flight Control Electronics Sub-Assembly – Michael Zielinski

One of the first things the team needed to figure out was how much battery capacity is needed to both complete the flying course and the minimum endurance time limit for flight. Equation 17 is the power formula for determining the number of watts *P* based on the voltage *V* and current (in amps) *I* output of a battery. From that equation, you can then use Equation 18 to find the energy consumption over time in watt-hours *Wh* by multiplying *P* by the time *T* in hours. The battery capacity in amp-hours (Ah) *C* can then be found from Equation 19.

$$P=V\cdot IP=V\cdot I \quad (17)$$
$$E=P\cdot TE=P\cdot T \quad (18)$$
$$C=EVC=EV \quad (19)$$

We originally assumed a 700-watt max draw per motor for 15 minutes of flight from a single 22.2-volt battery to match the motors we selected, which led to the apparent need of at least 31.53 Ah of battery capacity. The team purchased a 22 Ah battery to begin with, and further calculations (see below), a second battery was purchased.

Additionally, the team needed to investigate more into the flight controller that we received from the previous capstone drone team: a Pixhawk 6C. Figure 3.3 shows the graphic from the HolyBro website (where Pixhawk 6C's are sold) demonstrating the overall capability in the number of connections from the flight controller.

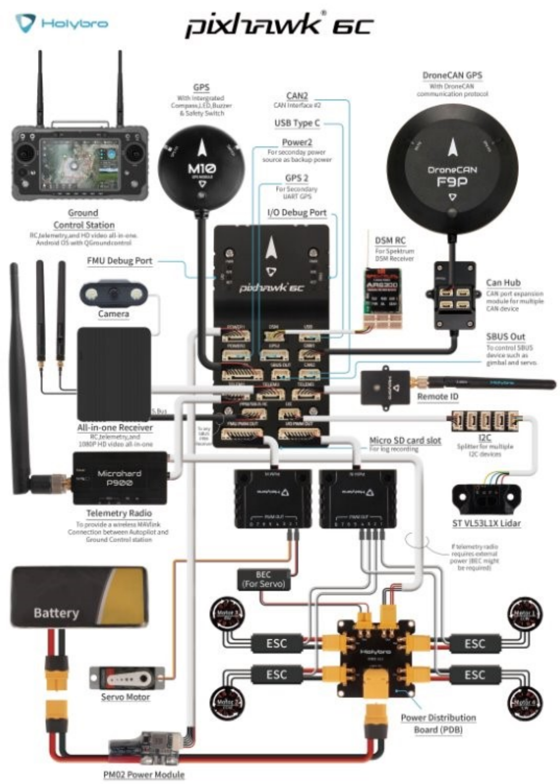


Figure 3.2: HolyBro Pixhawk 6C ecosystem chart [65].

Based on the sensors included (accelerometer, gyroscope, inertial measurement units, magnetometer, and barometer) as well as the number of interfaces (16 Pulse Width Modulated [PWM] outputs, 3 serial ports, 3 telemetry ports, 2 GPS ports, and S.BUS output), the team determined that we can continue to use the Pixhawk 6C as our primary flight controller and avoid having to purchase a new one.

More current calculations based on MATLAB permutations of the above equations were used to draw relationships between the battery capacity and flight time for different throttle settings and battery capacities. The resultant graphs are shown below:

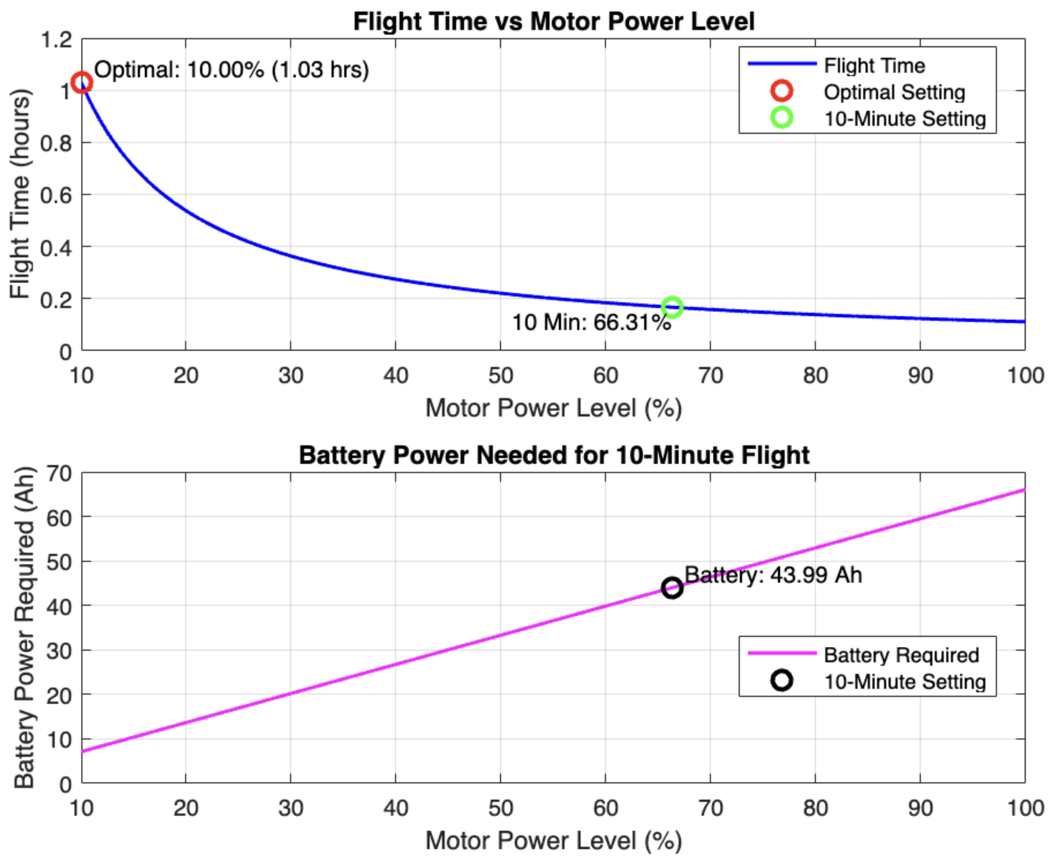


Figure 3.3. Graphs of flight time vs power level and battery capacity.

3.4 Factor of Safety Table

Sub-system	Part	Load Case Scenario	Material	Method of Calculating FoS	Minimum FoS
1: Frame to Arms					1.5
	Frame	Weight of the drone, Aerodynamic Forces	Carbon Fiber or Acrylic Plastic (need material analysis)	By Hand Calculations	Still needed (based on material properties)
	Arm	73.5 N of Force due to the motors, Aerodynamic Forces	Carbon Fiber	By Hand Calculations	415.5

	Arm to Frame Spacers	Reaction Forces and Moments due to the motors and weight of the drone,	3D Printed PLA	By Hand Calculations	95.85
2: Payload Attachment					3
	Mounting bracket (to frame)	Reaction forces and moments due to weight of payload and movement of drone	3D Printed PLA	By Hand Calculations	95
	Magnet (s)	Reaction forces and moments due to the weight of the payload	Material was selected by the manufacturer	By Hand Calculations	11.9
	Mounting plate	Reaction forces and moments due to the weight of the payload	High ferrous steel	By Hand Calculations	11.9

4. Flow Charts & Other Diagrams

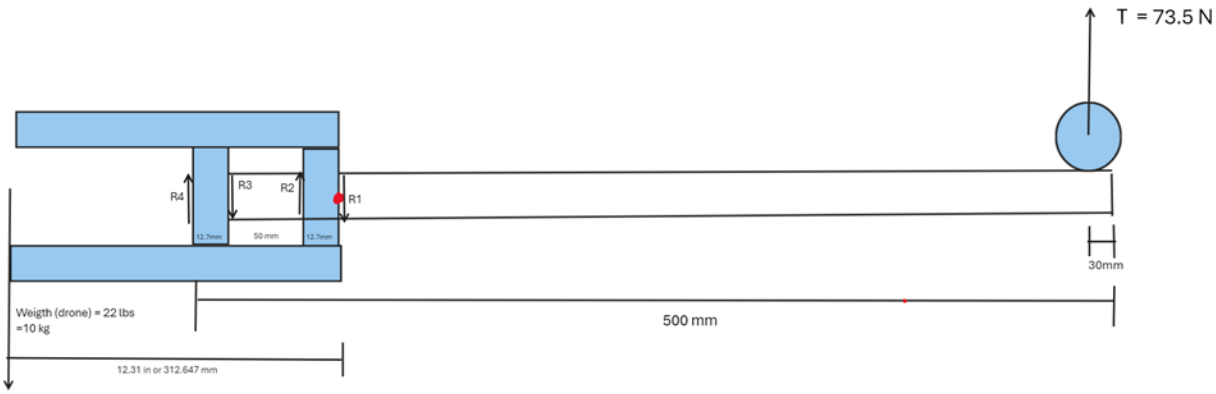


Figure 4.1: Free body diagram of arms

Figure 4.1 shows a free body diagram of the arms to frame sub-system. This diagram was used to help calculate reaction forces and moments on the spacers, the total pressure on the arms and spacers, and factor of safeties for the arms and the spacers

Figure 4.2 shows the electrical system components and connections. This diagram was used to help illustrate on a basic level how each component in the subsystem connects and is physically wired.

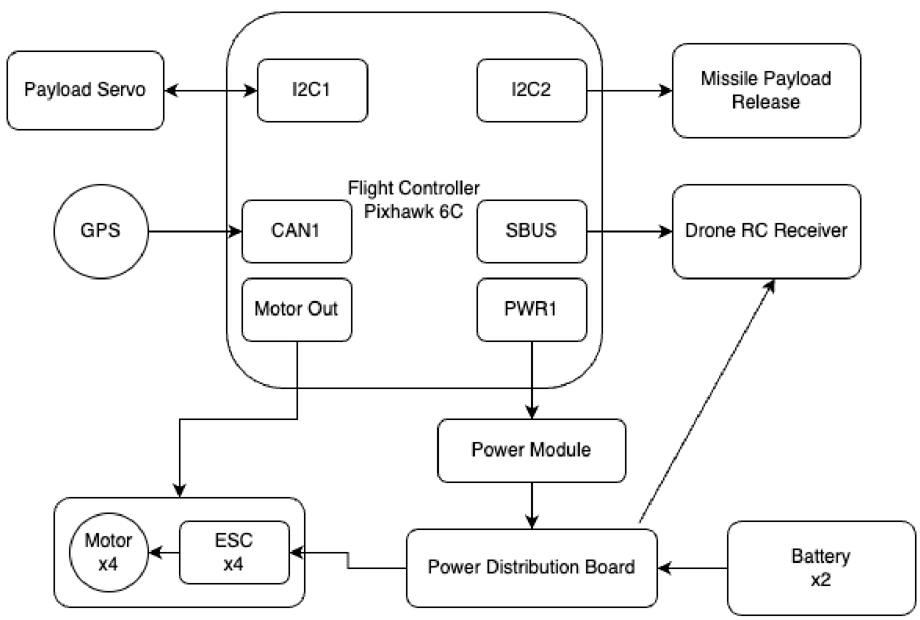


Figure 4.2. Electronics Layout Schematic.

5. Moving Forward

In addition, moving forward, the servo actuators for the magnets in the payload system need to be selected and evaluated. The team did contact the manufacturer of the magswitch, which they informed us that required the torque to actuate the switch is 0.01 N-m, which gives us a starting point, minimum torque requirement for the actuation of the magswitches.

Appendix A

Factor of Safety Calculations for Magnet System:

With the use of two magnets, it can be assumed that the max hold force will remain constant at a value of 60 pounds, or 27.2 kilograms, which can be multiplied by 9.81 m/s^2 to get 267 newtons, the factor of safety can now be estimated for the magnet holding system for use in holding the 5-pound (22 N), weighted payload. Please note that the factor of safety using the cruise missile forces was not conducted as it is not the team's plan to use magnets to secure the cruise missile to the drone, the resultant forces for the cruise missile are not significant enough to use high strength magnets. The cruise missile design schematics came with an attachment solution, which makes the missile not retrievable, but the missile does not need to retrievable, it just needs to be deployable. The factor of safety was conducted using resultant forces under the conditions of a max speed of 10 mph and a maximum forward tilt (negative angle of attack) of 30 degrees. The following calculation also assumes a maximum magnet hold force using 2 magnets of 267 N. The factor of safety for the 2-magnet system used to secure the 5-pound payload.