University at Buffalo

Quadcopter Design

Custom Frame and Power System

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CONTENTS

1 INTRODUCTION

This documentation will act as a detailed guide for the design choices of a custom quadcopter built for UB's airborne network testbed project. It also provides a good deal of technical directions that can be used to build other multirotor designs based on varying mission specifications.

The main focus of this report is on flight characteristics and safety, so there are some components that have not been given any space for discussion. These are components that have no notable impacts on the mentioned focus items, so should cause no concern.

The deliverables for this multirotor design is its flight-time and safe and easy payload carrying capacity. The flight time decided for the project was at least 20 minutes and the ability to protect expensive components as well as have a frame that is easy to build with disposable parts. The main payload is a URSP E310 with its battery pack and the flight battery. The multirotor is designed to be able to adapt to reasonable changes in the payload geometry and weight in the future.

2 PROPULSION DESIGN

Three main components contribute to this aspect of a quadcopter. A battery for energy, the motors for power and the propellers for thrust. There are individual aspects to consider for each to gain the very high efficiency and power that this copter has. The considerations for each will be covered below.

A weight class estimate has to be picked for the copter to start the design process. Then the propulsion system can be picked; which would be a propeller and motor combination. After which, a battery that can power this propulsion system would be decided on. They are generally picked as an optimal combination based on what is in the market and what agrees with theory.

2.1 PROPELLER

The initial weight estimate of this copter came out to be a value of 3kgs. This was then used for determining the thrust per rotor. The general convention in the hobbyist community for a properly responsive multicopter is one that has a maximum thrust that is more than two times its weight (Liang, 2013). This means that the maximum thrust would need to be greater than or equal to 6kgs. Since the copter in this case has 4 rotors, the 6kgs is divided by 4 to get the thrust needed per rotor. The thrust that each motor and propeller combination needs to create can now be seen as at least 1.5kgs. This is where the technical design of the copter begins.

2.1.1 THRUST DERIVATION

The basic propeller thrust equation is as follows (Hill & Peterson, 2010):

$$T = \dot{m}(V_e - V_o)$$

Where $\dot{m}$ is the mass flow rate of air, V_e is the exit velocity of air and V_o is the freestream or aircraft velocity.

$$\dot{m} = \rho A V_e$$

Here ρ is the density of the air and A is the area of the spinning propeller.

$$A = \frac{\pi d^2}{4}$$

Where d is the diameter of the propeller.

V_e can be assumed to equal the pitch speed of the propeller, which can be determined as follows:

$$V_e = V_{Pitch}(m/s) = RPM_{Prop}(0.0254 * pitch)(\frac{1min}{60\text{sec}})$$

The 0.0254 is a conversion factor to convert the inch value to meters.

The theoretical value for the static thrust based on the air density, RPM, propeller diameter and pitch can now be estimated from substituting the equations above as the following:

$$T = \rho \frac{\pi(0.0254 * d)^2}{4} \left[RPM_{Prop}(0.0254 * pitch)(\frac{1min}{60\text{sec}})\right]^2$$

V_o has a value of zero during static thrust so that component of the equation is ignored here.

This derived thrust equation is strictly theoretical and there are many inconsistencies in practice. This project did not have the resources to experimentally determine the correction factors to account for these inconsistencies. However, someone else was able to do so, and provided a detailed article on determining it using empirical data, leading to this modified version that works for all RC propellers (Staples, 2014):

$$\boldsymbol{T = \rho \frac{\pi(0.0254 * d)^2}{4} \left[\left(RPM_{Prop}(0.0254 * pitch)\left(\frac{1min}{60sec}\right)\right)^2 - \left(RPM_{Prop}(0.0254 * pitch)\left(\frac{1min}{60sec}\right)\right) V_o\right] \left(\frac{d}{3.29546 * pitch}\right)^{1.5}}$$

Assuming Standard Temperature Pressure (STP), the air density value can be assumed to be $\rho = 1.225\frac{kg}{m^3}$ for most cases. If the density varies significantly from that at sea level, the ideal gas law could be used to solve for it as shown below:

$$\rho = \frac{P}{RT}$$

P and T are the atmospheric pressure and temperature at the given altitude, respectively. R is the specific gas constant of air which is $287\frac{J}{kg*K}$.

The thrust equation shown was then used to determine a propeller that could generate over 2kgs of thrust using the motor and battery chosen for the project. This process was a trial and error method done using calculation tables similar to Table 1.

The specifications of the propeller that became the final choice for this model is one with a pitch value of 4 inches and a diameter of 12 inches. This working at the maximum RPM possible by the chosen power system will be able to provide between 2.3 and 2.4kgs of thrust per rotor. So the maximum thrust of the system can be up to 9.6kgs which is clearly larger than the needed value of 6kgs and thus the copter will be very responsive in flight. This also provides it with the possibility of increasing the payload size in the future.

2.1.2 ROTOR POWER DRAW

Once the thrust is determined, it is important to determine the power required to maintain that level of thrust both mechanically and electrically. On the mechanical side, it ensures that a motor that is rated for the required power is picked to ensure appropriate responsiveness and avoid overheating and failure during flight. The electrical reasoning is to be able to calculate and make choices towards the battery to ensure that a needed flight time can be achieved while providing the motors with the power they require.

The Power that is needed to create this given thrust can be derived as follows (Hill & Peterson, 2010):

$$\frac{dm}{dt} = \rho A v$$

$$T = \frac{dm}{dt}v, \qquad P = \frac{1}{2}\frac{dm}{dt}v^2$$

$$T = \rho A v^2, \qquad P = \frac{1}{2}\rho A v^3$$

$$P^2 = \frac{T^3}{4\rho A}$$

$$\boldsymbol{P = \sqrt{\frac{T^3}{4\rho A}}}$$

Using the power equation above, the watts needed for each motor as well as the whole system is determined based on the propeller thrust. The best and worst case values of the power for the coper is determined in Table 1 as well. This will be important for the motor selection process as well as for determining the flight time as will be explained later.

2.1.3 OTHER DESIGN CONSIDERATIONS

These are conceptual design considerations that guided the initial decisions for the propeller choices. The first was to make sure that the propeller was made of carbon fiber to avoid any losses due to the blade deformation and vibration that occurs in plastic blades.

The most efficient propeller for slow flight and hovering is one that has a very long diameter with a low pitch value. The low pitch value reduces the stronger induced drag on the propeller and maintains the weaker skin friction drag as the dominant drag force of the propeller. As the propeller becomes longer, it can create the same amount of lift from a slower spin speed, which is more efficient from a power consumption perspective as well (Hill & Peterson, 2010).

2.2 MOTOR

The flight characteristic of this quadcopter is to be a craft that is optimized for a long flight time with a very stable platform. For this purpose, long propellers that can be spun slower to create the same amount of thrust is used as explained in the previous section 2.1.3. This also means that a slower spinning motor with higher torque can be used to reduce the amount of power required to create the same amount of thrust as a smaller propeller spinning at higher speeds.

The speed of the motor is determined by something known as motor velocity constant K_v. This constant has the unit of RPMs per volt. So by knowing the voltage that will be provided to the motor, the spin velocity of the propeller can be determined. This can be then chosen while looking at the RPMs needed to create the lift that the propellers need to create the appropriate amount of lift. Knowing the maximum voltage of the battery and RPM needed, the lowest K_v motor that can be used is determined.

$$K_v = \frac{RPM}{V}$$

Once the K_v needed is known, a motor can be found with a value for it that is close enough and available. The value for the power determined as shown in section 2.1.2 must now be used to choose a motor that is rated at a higher power value. The factor of safety here will vary based on the needs of the individual copter. A higher factor of safety here will decrease the likelihood that the motor will heat up during use and damage itself. A copter that will need to stay airborne longer will need to have a higher factor of safety compared to one that won't need to do so. This is because it isn't able to cool itself down as often if it stays airborne for a long period.

2.3 BATTERY AND FLIGHT TIME

The flight time a battery can provide is determined by only three factors for the scope of this project. Two of which are the intrinsic properties of the battery, the capacitance and voltage. The external aspect is the current that is drawn by the motors and other electronics on the quadcopter.

The current draw is a directly related to the power used by the system that the battery is powering by the equation $P = IV$. Here P is the power, I is the current and V is the voltage. Having determined the power needed for the rotors from section 2.1.2 and with the voltage rating of the battery known, the current draw is found using the relationship shown.

Once the current draw of the system and the capacitance of the battery is known, the drain time of the battery can be determined as shown below. Here C is the capacity, I is the current draw and Drain time is in minutes.

$$Drain\ time = \frac{C}{I} * 60$$

A given copter will always require the same amount of power to maintain flight in a controlled environment. This means that if the voltage of a battery is increased, the same amount of power can be provided with a lower current draw. Since the battery run-time is determined by the rate at which the current is drawn, it can be increased by increasing the voltage and thus reducing the current needed for the same amount of power. For this reason, the battery that was chosen has the highest voltage that the electronics on the copter are rated for. The voltage specification of the battery was thus 22.2V.

All the calculations mentioned in the Propulsion Design section is shown below in Table 1 for the specifications of this quadcopter model. The hover scenario is the best case scenario for flight time since the thrust needed is the lowest at that point. The worst case scenario is when the propellers are spun at the maximum RPMs that the motor can reach using the 22.2V battery that is on board.

Table 1: Calculating flight time based on propeller, motor and battery specifications

Category	*Variables*	*Hover*	*Max Power*
Free Stream Properties	Temperature (K)	288	288
	Pressure (N/m^2)	101325	101325
	Gas Cont. (R) (J/Kg*K)	287	287
	Air Density (kg/m^3)	1.226	1.226
	Free Stream Velocity (mph)	0	0
	Free Stream Velocity (m/s)	0.00	0.00
Propeller Specs	Diameter, d (in):	12	12
	Pitch (in):	4	4
Motor and Battery Specs	Motor Kv (revs/volt)	470	470
	Battery Voltage	22.2	22.2
	Battery Capacitance (Ah)	10	10
	Voltage (sets RPM)	13	22.2
	RPM	6110	10434
Thrust and Power	Static Thrust (N)	8.316	24.252
	Static Thrust (kg)	0.849	2.475
	Power (W)	40.10	199.67
	No. of Props	4	4
	Power (Total Thrust) (W)	160.38	798.70
	Efficiency Loss (%)	25	25
	Power (Total Thrust w/ loss) (W)	200.48	998.37
Current Drain and Flight Time	Current Draw (Motors) (A)	9.03	44.97
	Current Draw (Other) (A)	3	3
	Current (Total) (A)	12.03	47.97
	Flight Time (100% Drain) (min)	49.87	12.51
	Flight Time (80% Drain) (min)	39.90	10.01

3 STRUCTURAL DESIGN

The structural design at the most basic level was constrained by trying to make the design as simple, disposable and adaptable to payload types as possible.

3.1 MATERIAL AND GEOMETRY CHOICES

In this section, very little of the technical analysis will be covered and discussion will be kept mostly at the conceptual level. The Analysis section that follows will cover the technical side of the structural design.

3.1.1 ARM AND PLATE CHOICE

It is common knowledge in mechanical engineering as well as in the hobbyist community that a thin-walled circular tube has the highest strength to weight ratio for constructing any type of framework. Carbon fiber composite is the material of choice for these tubes as well due to its high strength to weight ratio as well (Megson, 2013).

All things that are mounted on the copter are done on top of flat plates. The plates then needs to have the stiffness and strength to maintain its shape and support the payloads under normal use while being as light as possible. Carbon fiber was again the obvious choice since it has the highest strength to weight ratio of any material that is available and is also known to be very stiff (Megson, 2013).

3.1.2 FASTENERS AND JOINTS

The disadvantage to round tube structures is that they are difficult to machine for the purpose of mounting things to them. The best way to overcome this issue is to use circular clamps that can tighten around the tube while providing a flat mounting surface above it. The original plan was that they would have to be custom designed but something similar was found with a vendor as seen in Figure 1 which is used for mounting motors above the circular tubes of 16mm diameter.

Figure 1: Motor Mount

The motor mount and clamps alone only solved the issue of mounting things onto the tube but not the issue of attaching one tube to another as needed for the design. So a perpendicular tube connector between two tubes were created by combining 4 of the separate clamps from Figure 1 into an assembly as shown in Figure 2**.**

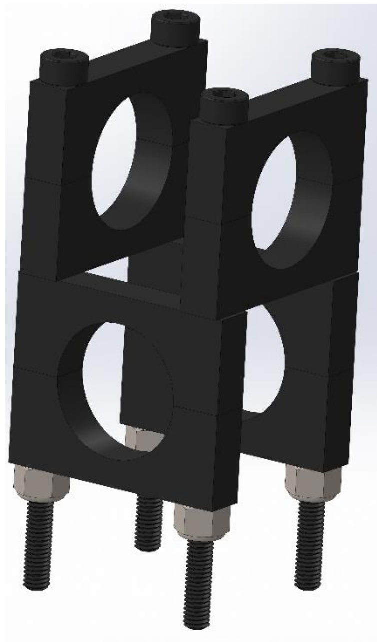

Figure 2: Perpendicular Tube Connector

Since the same clamps attach every part of the design together, the diameter of the bolt used for it is the only screw diameter that was used for the model. The 3mm screws that are required for the clamps are used for fastening everything to each other in the model. Their lengths only vary between the two sizes of 60mm and 30mm. There is also two pairs of 30mm screws with a low profile head to allow for mounting the battery over it without any resistance.

One of the issues that DIY (do it yourself) multicopter frame assemblies have in flight is their nuts coming loose during flight, from the vibration that the copter feels. This is a problem that can be solved easily by using nylock nuts which have a nylon ring on the nut that can grip very tightly onto the bolts and prevent loosening due to vibrations. As an additional layer of safety for these nuts, a thread locker solution will also be used on the nut and bolt threads to provide a light amount of adhesion between the threads as well.

3.1.3 WEIGHT DISTRIBUTION AND CENTER OF GRAVITY

Unlike traditional aircrafts, multirotors have the advantage of being able to fly with an unsymetric weight distribution without much change in its flight characteristics. This is because of the ability of the individual rotors to compensate for the uneven loads that each of them see, independently. Although this is convenient in short term use, it can cause motors on the heavier sections constantly overwork and have a shorter lifetime. It will also lead to an inefficient power budget. So maintaining the CG (center of gravity) at a point that is equidistant to all four motors was attempted.

From the information in Figure 3, the distances to the motor axis from the CG have a worst case percent difference of 0.619, which is negligible. The model does neglect the weight distribution of the wiring, connectors and velcro straps. They will be distributed evenly for the most part and the ones that won't be, will be of negligible weight in terms of changing the CG notably.

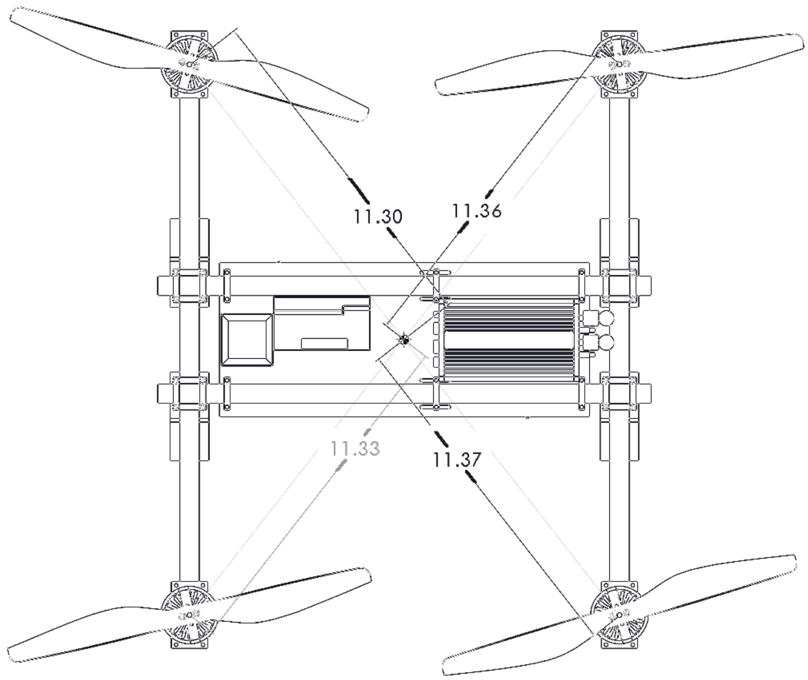

Figure 3: Distance from CG to each motor axis

The stability of the aircraft increases as the vertical distance from the CG to the propellers increases, with the CG being below the propellers. This is acheved by mounting the heaviest conmponents in the copter, such as the the battery, on the lower face of the baseplate. The other coponents are all mounted in level with or below the propellers as well to make sure the CG stays as low as possible for this frame configuration.

3.1.4 LANDING GEAR

There are currently no exact specifications on what needs to be done for a quadcopter landing gear. To base the design on some level of design convention, it is assumed that it can be modeled after airplane landing gear design. Figure 4 shows the minimum lateral tip-over criteria of a typical airplane (Roskam, 1985**)**. This is the angle between the landing gear contact point to the ground and the CG of the aircraft. This has to be a value that is less than 55 degrees.

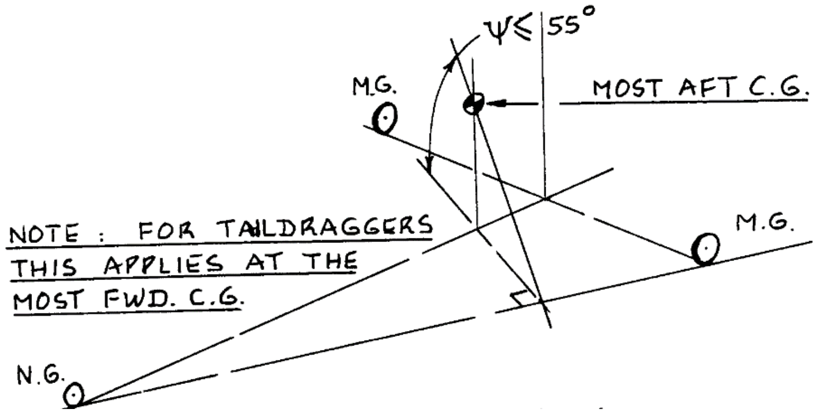

Figure 4: Lateral tip-over criterion

Assuming that this is a valid rule to base the landing gear design of the quadcopter, the current design will be unlikly to flip over during its landings. Figure 5 shows the the two possible points of the landing gear that can be considered to be the best and worst case for a balanced landing laterally. Both of these angles are well below the 55 degress that are required for an airplane . This makes the inherent tendency of the copter to be of one to come down on all of the landing gear, as opposed to tip over on its side and have the propellers hit the ground.

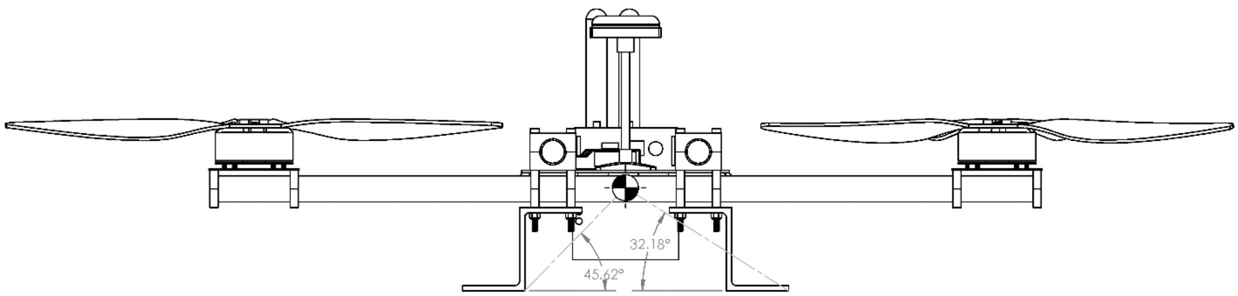

Figure 5: Lateral tip-over criterion for the copter

Figure 6 shows the same angular relationship to the landing gear from the CG but in the forward and aft direction. The angles for each of the cases along this axis is well below half of the required 55, creating an extremely stable landing scenario.

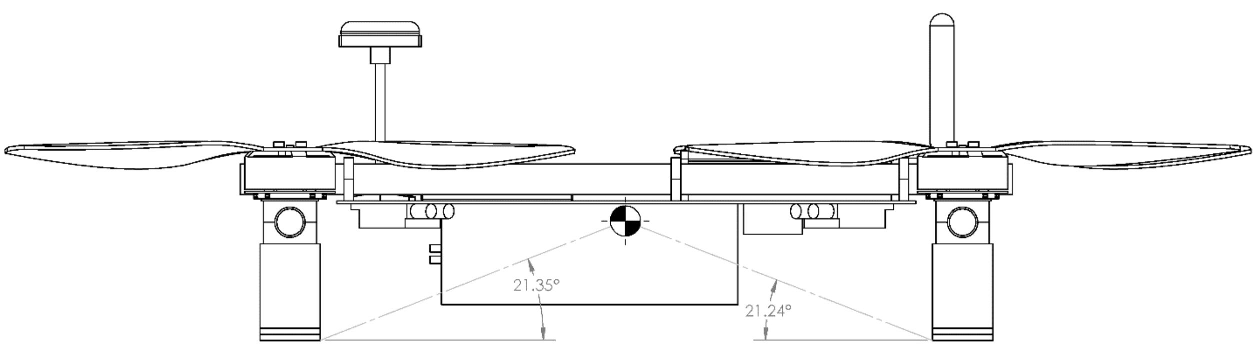

Figure 6: Forward and aft tip-over criteria for the copter

3.1.5 COMPONENT WEIGHT

This section is dedicated to account for every single component that will be on the aircraft and show the total weight based on that. This will also have an error margin that is within ±100 grams due to the reliability of certain weight estimates and minor changes that could occur during the final build. However this level of an error is accounted for in the design and is thus negligible.

Table 2: Accounting for all components by weight

Part #	Component Name	# Per Copter	Weight	T Weight (g)
1	APM	1	26	26
2	GPS	1	16.8	16.8
3	RC Receiver	1	12.4	12.4
4	Servo jumper cables	1	13	13
5	USRP	1	375	375
6	USRP Antenna	2	10	20
7	3DR Radio	2	11.5	23
8	ESC	4	33	132
9	Motor	4	98	392
10	Battery (6S) 10Ah	1	1189	1189
11	Battery (USRP) (3S) 610mAh	1	50.9	50.9
12	Power Module	1	17	17
13	XT90 male to XT60 female (2 pack)	2	12	24
14	Power Splitter Cable	1	29	29
15	USRP Power Adapter	1	8	8
16	16 AWG Wires	1	25	25
17	Propellers	4	10	40
18	Motor Arm Tubes	1	122.5	122.5
19	Connector Arm Tubes			
20	Base Plate	1	84.9	84.9
21	Motor Mounts	4	9.2	36.8
22	Tube Clamps	22	4.7	103.4
23	GPS Tower	1	17	17
24	Z-bar landing gear	4	36	144
25	Crash Dampners	8	5	40
26	M3 60mm Bolt	16	3.3	52.8
27	M3 30mm low-profile Bolt	28	1.7	47.6
28	M3 Nylock Nut	44	0.4	17.6
29	Zip ties	4	1	4
30	Velcro Straps	6	8	48
31	Velcro Tape	1	3	3
32	Clear Tape	1	10	10
	Total			**3124.67**

The total weight can be seen as 3.125kgs from Table 2 above. This is very close to the initial weight estimate that was made prior to all design. Since all prior calculations accounted for this level of variation in weight, no work will have to be redone at this point.

3.2 ANALYSIS

The goal of the frame design is to be able to carry the necessary payloads safely while airborne and be structurally sound enough to repeatedly land on surfaces of any level of rigidity. The design also needs to take measures to ensure that if there is a high speed impact of the copter, the frame will fail in a way to ensure the impact energy is not seen by the important electronics on board. All components of the copter are designed to be disposable and easily replaced in case of damage, so that no notable setbacks will be caused by any major structural components failing. Due to this reason and due to the fact that there is incomplete information about some of the structural properties, a reliable study of a catastrophic crash cannot be completed meaningfully.

Two different scenarios will be modeled and analyzed to ensure airworthiness. The first model will look at how the structure reacts to the highest g-loading that can be produced by the propulsion of the copter. The second will look at the shock loading of the system from the normal landing speed of the copter controlled by the autopilot (it is configured to be at the lowest speed of 30cm/sec). The factor of safety plots in both these cases will provide a look into the margin of safety the copter has during regular use.

3.2.1 PROPERTIES AND WEIGHT DISTRIBUTION

Table 3: Materials and Yield strength used for analysis (Hills, 2004)

Component	Material	Yield Strength (MPa)
Landing Gear	6061 Aluminum	55
Clamps	6061 Aluminum	55
Tubes	Std. Carbon Fiber	200
Plate	Std. Carbon Fiber	200
Bolts	Alloy Steel	301
Nuts	Alloy Steel	301

Table 3 has the material properties that are essential to the analysis completed. There were other material properties that were built into the analysis software for determining non failure related information. They are omitted here for the sake of simplicity.

Table 4: Simplified weight distribution for analysis model

Loading Locations	Weight (kg)	% of Total Load
Full Copter	3.125	100
Motor Mounts (all)	0.4	12.8
Payload Mount Plate (Distributed on plate)	1	32
Payload support tubes (Applied on clamps)	1.5	48
Unaccounted (Applied on Landing gear)	0.225	7.2

Table 4 shows the simplified loading distribution of the actual weight of the copter for the purposes of the 3D analysis. The weight distribution ratio used here will be used to distribute the new inertial loads felt in the following analysis models.

3.2.2 AIRBORNE LOADING

Knowing the weight of the copter and the maximum thrust possible from the rotors, the maximum load factor of copter can be determined. This will provide the maximum g-force that the copter will see in flight.

$$n = \frac{L}{W}$$

Here n is the load factor, L is the lift or maximum thrust and W is the copter weight (Megson, 2013).

The maximum value of thrust per motor determined in section 2.1.1 is 2.4kgs. Since there are 4 propellers for this copter, that gives a total of 9.6kgs of thrust. The weight of the copter is determined to be 3.125kgs from section 3.1.5 on component weights. Knowing the maximum thrust and weight, the load factor can be determined below.

$$n = \frac{9.6}{3.125} = 3.072$$

Now that the load factor is known, the weight distribution on the 3D model of the copter can be redone to account for the increased values. The new load values are distributed to the sections of the copter following the same ratio described in Table 4 in Table 5. The difference will be that the weight of the motors will be set to zero and they will become the fixed constraint locations for the frame. When the rotors are accelerating the copter, it can be assumed that weight of the motors do not account for the stresses in the frame since they hang directly under the propellers and practically become weightless to the frame while still affecting the load factor.

Table 5: Loading during maximum acceleration

Loading Locations	**% of Total Load**	**Load (N)**
Full Copter	100	94.08
Motor Mounts (all)	12.8	~~12.04~~
Payload Mount Plate (Distributed on plate)	32	30.11
Payload support tubes (Applied on clamps)	48	45.16
Unaccounted (Applied on Landing gear)	7.2	6.77

The model has "fixed geometry" constraints on the motor mount plates as shown in Figure 7 to simulate the rest of the frame hanging from the motors. Rest of the loading locations listed in Table 5 are also shown as small arrows in Figure 7 as well.

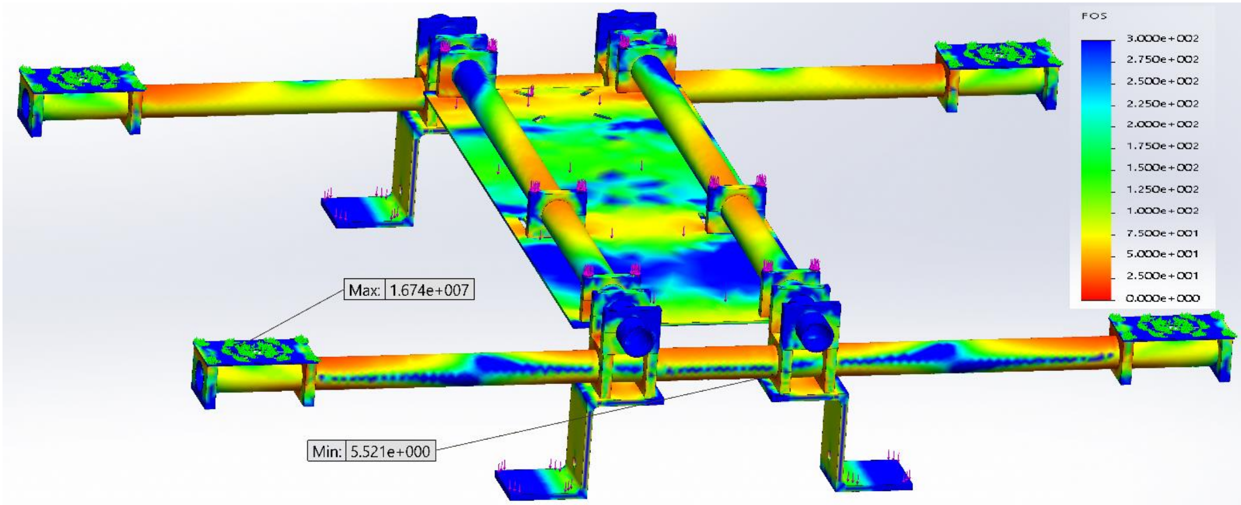

Figure 7: Factor of safety plot of frame in flight

The locations of the maximum and minimum factor of safety for this frame for the given loading due to acceleration is labeled in Figure 7. The minimum value shown is the only one that is meaningful for the purposes of this analysis since it will be assumed that yield failure at any location is a failure for the entire copter. The location of this value is at the point where the motor support tube is attached to the inner clamp of the perpendicular tube attachment assembly. The factor of safety here has a value of 5.5, which means that the copter will have to accelerate at a rate that is 5 times what it is currently capable of doing, for structural failure. This is definitely not possible with the power system design of this copter.

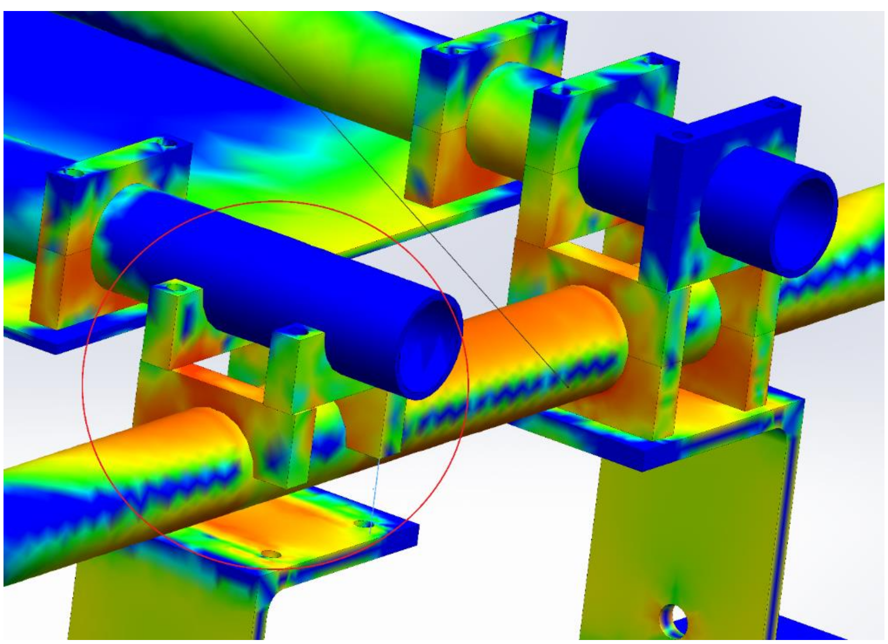

Figure 8: Visual on why the bolts are not loaded by the copter weight

Figure 8 shows the benefit of the way in which the clamps are used to connect the motor arms to the payload bearing arms. This method ensures that the load bearing beam essentially "sits" above the motor tube as opposed to hanging from the motor tube by the bolts. This provides a huge advantage in that the strength of the nuts and bolts now become irrelevant in terms of predicting failure. All load transfer between the perpendicular tubes are passed through the clamps and the bolts only serve to maintain the clamps in their respective locations.

However, the strength of the bolts and nuts do matter at the motor mount locations. There are four motors on the quadcopter and each motor is attached to the carbon fiber tubes with four 3mm bolts and nuts each. This means that a total of 16 bolts and nuts carry the entire load of the copter during flight. It can be assumed that the weight is evenly distributed between them. The weight of the motors can be ignored as it was for the Finite Element Analysis since the weight of the rest of the copter is hanging from the motors. The individual loads, stresses and factor of safety for the bolts can then be determined as follows using the numbers from Table 5 (Megson, 2013).

$$Load_{total} = 94.08 - 12.04 = 82.04N$$

$$Load_{per\ bolt} = \frac{Load_{total}}{\#\ bolts} = \frac{82.04}{16} = 5.13N$$

$$\sigma = \frac{F}{A} = \frac{Load_{per\ bolt}}{\frac{\pi\ d^2}{4}} = \frac{5.13}{\frac{\pi.003^{\ 2}}{4}} = 726000Pa$$

The minimum tensile strength of the bolt is given as 170,000 psi or 1.2GPa (Black-Oxide Class 12.9 Socket Head Cap Screw, 2015). Which gives the factor of safety as the following:

$$FS = \frac{Material\ Strength}{Design\ Load} = \frac{1200000000}{726000} = 1652$$

The factor of safety on the bolts for carrying the maximum load seen by the copter is larger than what is needed by about a factor of 1000. The only way the bolts here can fail is if the nuts on them come lose during flight. To avoid this, vibration resistant nylock nuts are used along with a thread locker solution.

3.2.3 CONTROLLED LANDING ANALYSIS

In the case of a controlled landing, the copter maintains a constant velocity during the descent. This allows for the use of the kinetic energy equation to determine the energy it will have on impact during any given landing.

$$KE = \frac{1}{2}mv^2$$

Here m is the mass and v is the vertical descent velocity of the copter.

The work that needs to be done to stop an object in motion is described as follows:

$$W = F * d$$

Here F is the force and d is the distance in which the object is brought to a stop. The work needed to stop an object in motion is equal to its kinetic energy. So the work equation can also be written as follows:

$$W = KE$$

$$F * d = \frac{1}{2}mv^2 \quad \rightarrow \quad F = \frac{mv^2}{2d}$$

The above equation now relates the mass of the object m, its descent velocity v and the amount the frame and or landing surface is able to deform d (without structural damage), to find its stopping force F. Since it is also in vertical descent, the force from its weight will also have to be added in to determine the accurate loading that the frame sees at the moment of touching down.

$$\boldsymbol{F = \frac{mv^2}{2d} + mg}$$

Table 6: Solving for the shock load

Mass (m) (kg)	3.125
Descent Velocity (v) (m/s)	0.3
Deformation(d) (m)	0.01
Accel. due to gravity (g) (m/s^2)	9.8
Shock Load (F) (N)	**44.69**

The value for the shock load found above in Table 6 will be the weight that the copter feels at the moment of impact on every controlled landing situation. This value can then be distributed to the sections of the copter in the 3D model according to the same ratios described in Table 4 as shown in Table 7.

Table 7: Landing load distribution on copter

Loading Locations	% of Total Load	Load (N)
Full Copter	100	44.69
Motor Mounts (all)	12.8	5.72
Payload Mount Plate (Distributed on plate)	32	14.3
Payload support tubes (Applied on clamps)	48	21.45
Unaccounted (Applied on Landing gear)	7.2	3.22

The model has "fixed geometry" constraints on the end face of all landing gear as shown in Figure 9 to provide the worst case stresses on the landing gear. The loading locations listed in Table 7 are also shown as small arrows in the image as well.

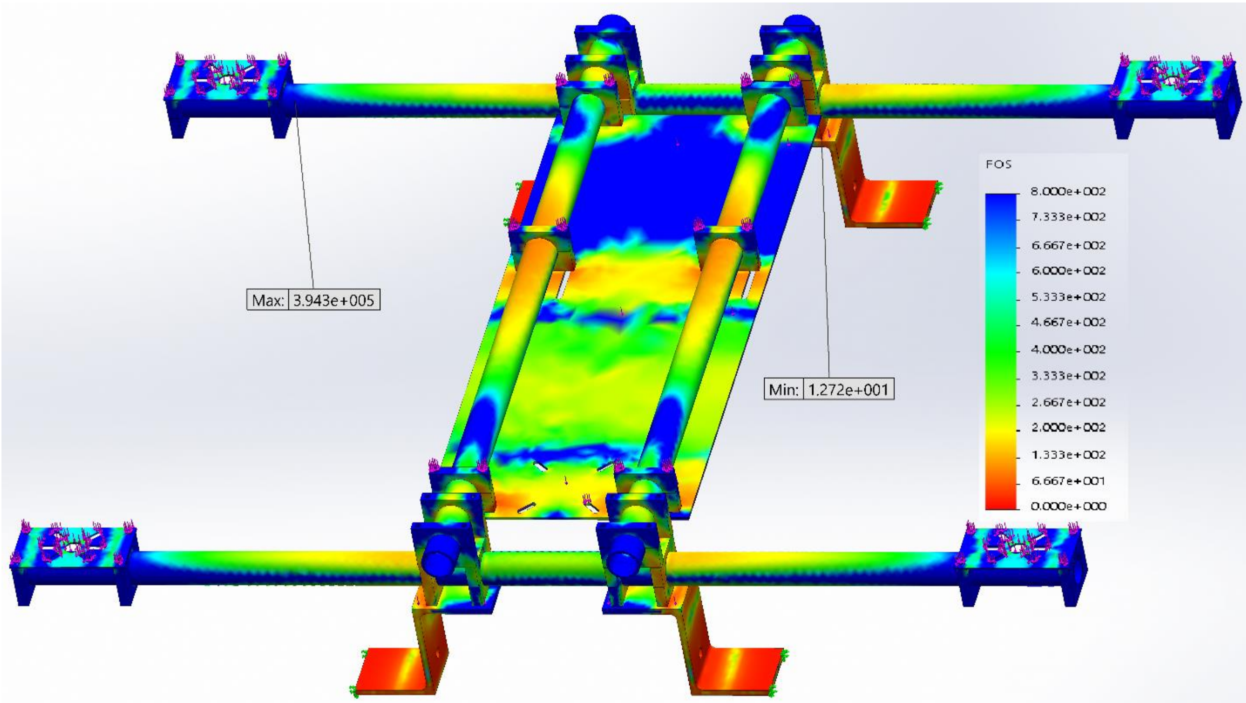

Figure 9: Factor of safety plot for landing load

The locations of the maximum and minimum factor of safety for this copter is labeled in Figure 9. The minimum value shown is the only one that is meaningful for the purposes of this analysis since it will be assumed that yield failure at any location is a failure for the entire copter. The location of this value is one of the points where the landing gear connects to the clamps that attach it to the rest of the frame with a value of 12.7. This means that the landing gear will be able to handle a load that is 12.7 times greater than the one seen by the frame due to the controlled descent velocity value that is used for the analysis.

The force equation that is determined in this section can then be back-solved to find the fastest rate at which the copter can descent without structural failure.

$$v = \sqrt{\frac{((12.7 * F) - mg)2d}{m}} = 1.85\ m/s$$

Since this value is 6.2 times greater than the intended value, there is a comfortable safety margin for any errors in the flight controller that may drop the copter at a faster rate.

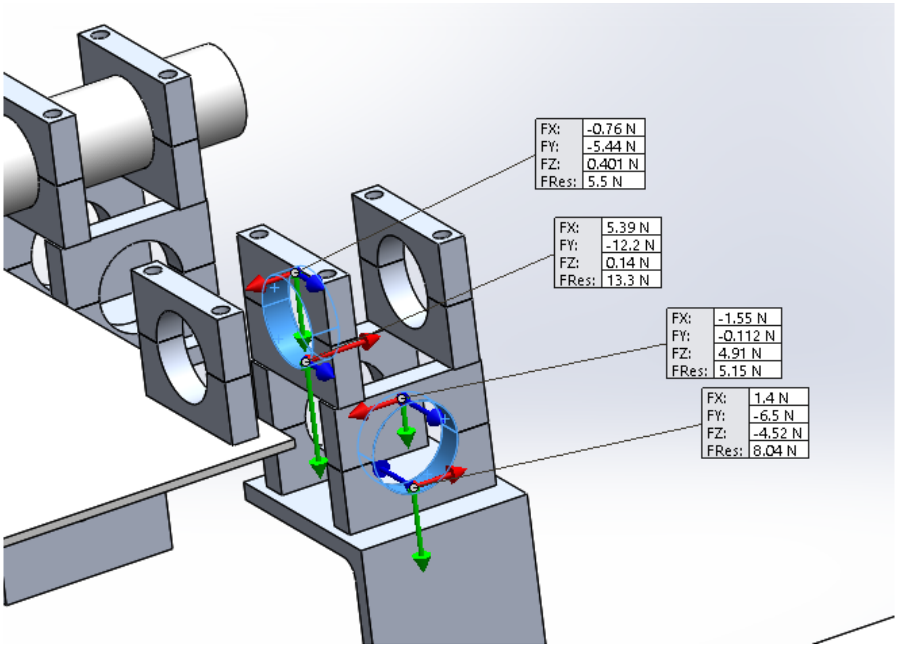

Figure 10: Largest forces seen by the perpendicular tube connector clamps

Table 8: Summed clamp loads

Free Body Force (N)		
Component	Selection	Entire Model
Sum X:	4.4814	-0.037684
Sum Y:	-24.22	-0.15362
Sum Z:	0.932	-0.072561
Resultant:	24.649	0.17403

The maximum reaction values on the perpendicular connector clamp assembly will be on the clamp pairs that first grip the payload mounted tube as well as the ones that grip the motor carrying tube first. Figure 10 shows which sets those are. The tubes are hidden but the reaction forces from them are still accounted for. Once all the loads from them are accounted for and summed as shown in Table 8**,** the maximum possible loads that the bolts will see in all direction can be seen. The y-axis which is along the direction of the bolt axis has a value of 24.2N. The axial stress on the bolt can then be determined as follows:

$$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi\, d^2}{4}} = \frac{24.2}{\frac{\pi .003^{\,2}}{4}} = 3.42MPa$$

The yield strength of the steel bolts are 301MPa from Table 3**.** So the highest loaded bolt has a factor of safety of 88.01. This is much higher than what was seen for the landing gear. This means that the landing gear will fail before any other copter component, including the bolts, in the case of a harsh landing.

Additional note: The landing gear and other areas of the copter that are likely to impact the ground will be padded to reduce the value of shock loads in any unexpected fast impacts. This will significantly reduce the stress values predicted by all computer models, which are intended to provide pessimistic results with respect to reality.

3.3 PROTOTYPING AND ASSEMBLY

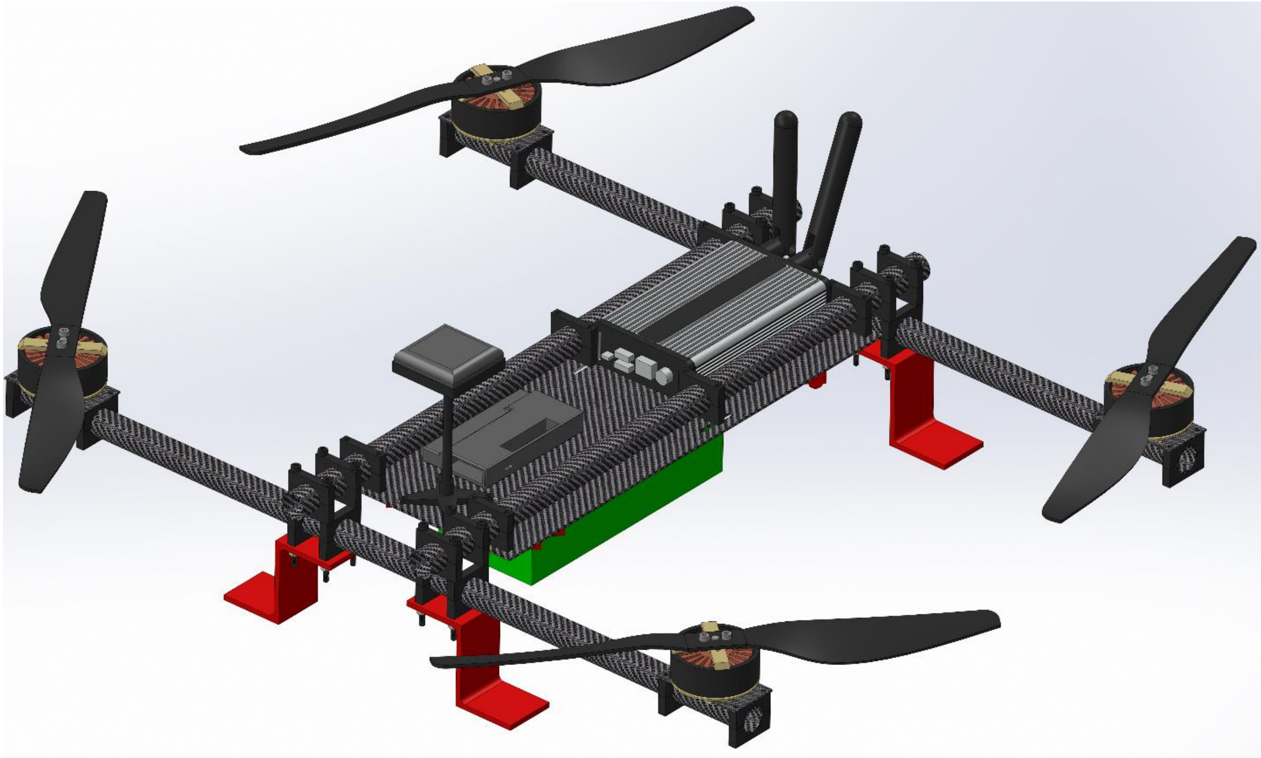

Figure 11: 3D model of fully assembled copter

See "Assembly and Handling Documentation" for this info

4 FLIGHT CONTROL SPECIFICATIONS

The flight controller in this copter is an award winning open source ardupilot named APM 2.6. This allows the user to control the copter manually or through preprogrammed commands from the computer or a mix of both. It has failsafes and control restrictions that can be configured for safe operation. Its relevant capabilities will be discussed below.

4.1 FLIGHT CONTROLLER (APM)

The APM has built in gyroscopes and magnetometers for determining its orientation in flight, a barometer to determine its altitude and accelerometers for determining unexpected behaviors. For manual control of the copter, all that is needed are these sensors and a RC receiver. It has a confirmed altitude ceiling of 60ft as well.

4.2 FRSKY D8R-II

This is the 2.4 GHz RC receiver that is used in this copter for manual control and override. It has a range between 1.5 and 2.5km and has 8 channels for communication (FrSky D8R-II PLUS 2.4Ghz 8CH Receiver with Telemetery). Commands received through the Receiver will also be able to override the autonomous modes of the copter if need be.

4.3 3DR UBLOX GPS

A GPS is necessary for the flight controller before it is able to do any form of autonomous directional flight. Without it, the APM will not be able to locate its position and find where to go to next. The mentioned GPS has provided accurate positioning of the copter once it has been able to lock onto more than 6 satellites in a given location (3DR uBlox GPS with Compass Kit).

4.4 3DR RADIO PACKAGE

This is another set of receiver and transmitter package that is needed besides the FrSky D8R-II if the copter is to have autonomous control. The transmitter radio will connect to a computer via USB and will communicate to its counterpart that connects to the APM. This allows direct access to the settings and data logs of the flight controller while in flight through the computer. This allows for gaining complete control of the copter using only the computer software and full missions can be done without any direct user control through a traditional remote (3DR Radio 915 MHz).

4.5 FAILSAFES

Since the copter can cause safety concerns in non-ideal scenarios, there are three different failsafes that are built into the flight controller to ensure safety in those situations.

4.5.1 RADIO FAILSAFE

This ensures that if the radio ever lost contact with the copter, the flight controller will first attempt to go into the RTF (Return to Home) mode. In this mode, the copter will orient itself and fly back to the GPS coordinates where it began its flight and land. However, if the copter is unable to find GPS signal where, it will then decide to just go into land mode where it will come down at the preset landing rate (Radio Failsafe, 2015).

4.5.2 BATTERY FAILSAFE

This failsafe prevents the copter from staying in the air until the battery is completely emptied and fall without any control. Based on the battery that is being used for any given flight, the lowest value for the voltage and mAh can be set so there is enough power leftover to bring the copter down safely. Also in this scenario, the first choice for the APM is to attempt RTF mode if there is GPS connectivity. Otherwise it goes directly into land mode and comes down directly below wherever it is currently flying (Battery Failsafe, 2015).

4.5.3 GPS FAILSAFE

In the case of the GPS losing connectivity during a self-navigated mission by the copter, the failsafe no longer has the option for RTF. The options are then to either hold altitude where the pilot can manually take control or simply land where it is (GPS and GCS Failsafes, 2015).

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