

High Altitude Autonomous Weather Balloon Quadcopter

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by
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Abstract

Weather prediction uses a number of tools to make accurate predictions. One of these tools is the regular launching of weather balloons. These balloons are filled with gas and when released travel up to the edge of the atmosphere before bursting and falling back to earth, transmitting data back to ground stations via radio band. Only twenty percent of these weather balloons are ever recovered and returned. A single weather balloon assembly can cost over a hundred dollars, totaling in substantial losses over time. These lost weather balloons also contribute to pollution when not recovered. Modern day multirotor technology is rapidly increasing and would make a valuable substitute for many of these weather balloon launches, reducing waste by creating a reusable apparatus.

Introduction

Weather balloons are launched from many locations around the world. They are the cornerstone of modern weather prediction and measurement. Of the hundreds of weather balloons launched daily, only a small number are recovered and fewer are in condition to be reused. This is damaging to the environment and costly for the companies that launch them.

The proposal is the design of a reusable weather measuring apparatus. This apparatus would be capable of flying up to nearly 20,000ft, take various measurements, then return to the set off location to be used again.

Research

Background

It is nearly impossible to predict the weather without knowing the conditions of the upper atmosphere. It may be sunny and quiet at sea level, but at 18,000 feet (5,486 meters), a weak storm system could soon turn into something more dangerous. By sending up regular squadrons of balloons to measure the conditions of the upper atmosphere, meteorologists can keep tabs on brewing storms.

A century ago, scientists could only predict the weather from measurements taken on the ground. With such a limited data set, the best meteorologists can do is predict the weather a few hours into the future. With weather balloons, though, scientists can plot out weather conditions for days in advance.

This information doesn't just keep joggers out of the rain -- it saves lives. High-altitude weather data is critical for predicting oncoming natural disasters like tornadoes, thunderstorms or flash floods. Thanks to weather balloons, officials can scramble supplies and emergency personnel to an affected area before a weather disaster strikes.

The core component of a weather balloon assembly is the radiosonde which consists of three basic atmospheric instruments: Thermistor, Hygistor, Aneroid barometer. Modern versions of these components can weigh less than a few grams.

Of the 75,000 weather balloons that are released each year, only 20 percent are returned. A complete weather balloon assembly costs approximately 150 dollars. Annually the means the loss of nine million dollars. Even if the assembly is successfully returned the balloon has popped and must be replaced.

Current State

Quadcopters are becoming increasingly more common and standardized, with power to battery capacity and weight improving constantly. Years ago drones were lucky to reach ten minutes of flight time, but today some drone configurations are capable of hovering for hours [1]. This burgeoning technology has only started to be used in modern applications, leaving many institutions (FAA) unable to keep pace with this rapidly changing technology. The reason I mention the FAA is due to the most recent ruling from the Federal Aviation Administration that

states no drone is to fly above 400ft. This is due to the rule that aircraft are not to fly lower than 500ft, leaving a 100ft buffer zone. Due to this ruling for this experiment we will only be testing to 400ft, however, the drone will be built to fly to 20,000ft.

Needs

The apparatus is to include a thermometer, humidity sensor, aneroid barometer, GPS, data logger. These instruments in addition to the motors, flight controller, ESCs, battery, and frame will make up the entire build.

The frame construction must be as sturdy enough to withstand 10mph winds and the prop force, while being as light as possible to maximize flight time.

Altitude is the number one priority of this project, therefore the best use of battery consumption must be calculated. It will take more power to increase altitude than it will to return to the ground, so this value will need to be calculated. The props will only be able to withstand so much force, so the fastest possible safe descent must be calculated to ensure the props are not destroyed and landing failed.

Because the apparatus must return to the exact set off point, the motors will have to account for wind speed. Depending on this value the flight controller can also be used to calculate wind speed.

The most lightweight frame must be decided upon either carbon fiber or aluminum, whichever provides the best strength without trading off much weight. The props will be standard plastic props for easy replacement, unless aluminum or metallic props are found to be more efficient.

Future State

The purpose of this project is to prove drones can replace wasteful weather balloons. While current limitations to motor power and battery capacity and weight must be considered, it is not unreasonable to say in the near future batteries will double in capacity while dropping in weight, making drones increasingly more efficient.

Survey

The survey was sent out to several local weather stations and contained very few but concise questions:

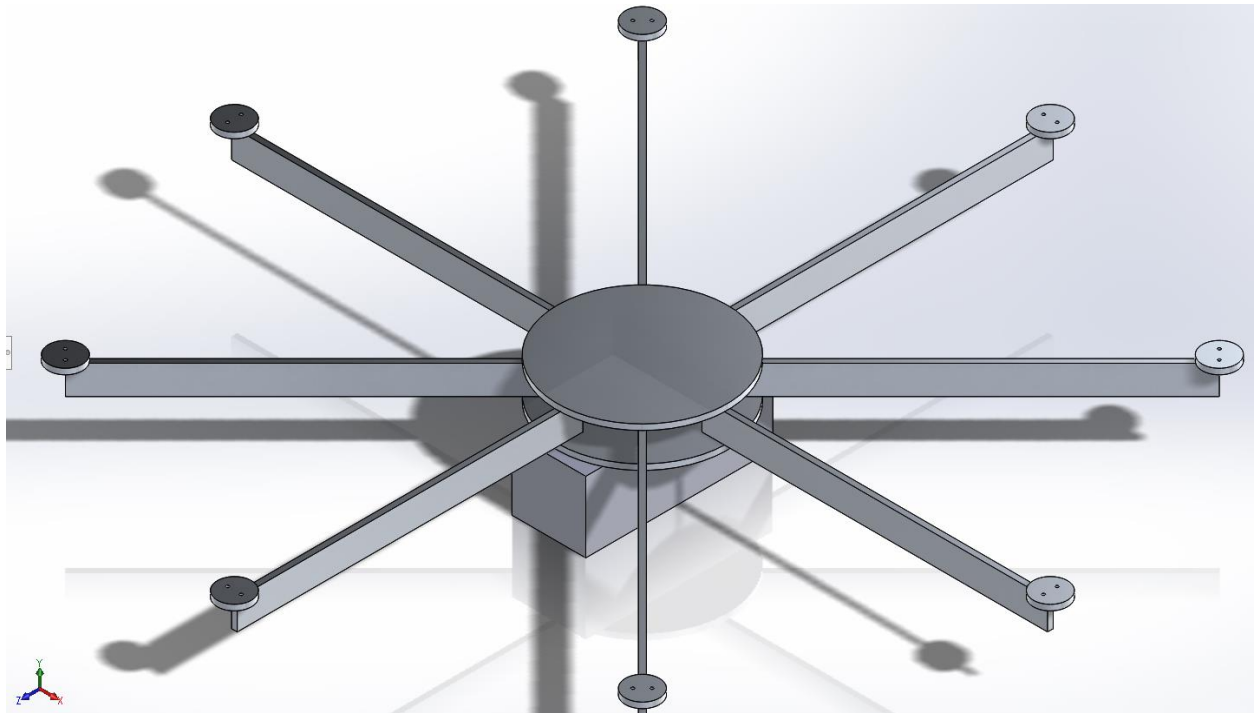
1. What is the cost to your institution to launch a single weather balloon?
2. Would you have any use for low altitude weather data?

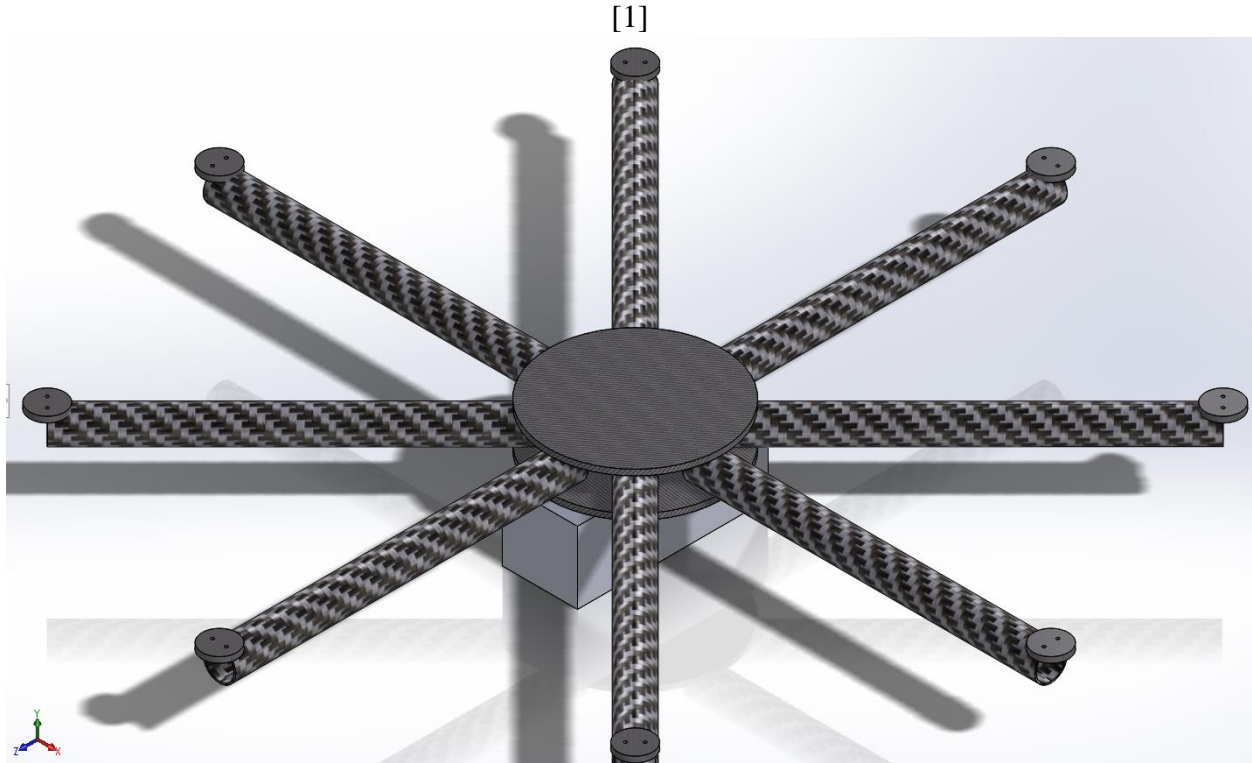
Only one response was received for this survey.

1. Our station in Virginia and also now here in Minnesota does not launch weather balloons. That is up to the national weather service.
2. Low altitude data is good, but 10,000 ft isn't enough to map the atmosphere profile.

Concept Generalization and Selection

The purpose of this project is to build a high altitude drone. This means that the primary objective is to maximize flight time. The trouble with multirotor is to increase flight time we need to increase battery capacity, which means increasing battery weight. When we increase the weight we have to lift, we require larger motors. Larger motors require more power and thus, larger batteries. Adding more motors seems to be one of the best possible solutions. More motors mean more batteries and longer flight time. Initial research indicated that eight low RPM motors in combination with large props would lead to the most efficient setup. The following are designs for a 10,000mAh battery with an aluminum frame and a carbon fiber frame.

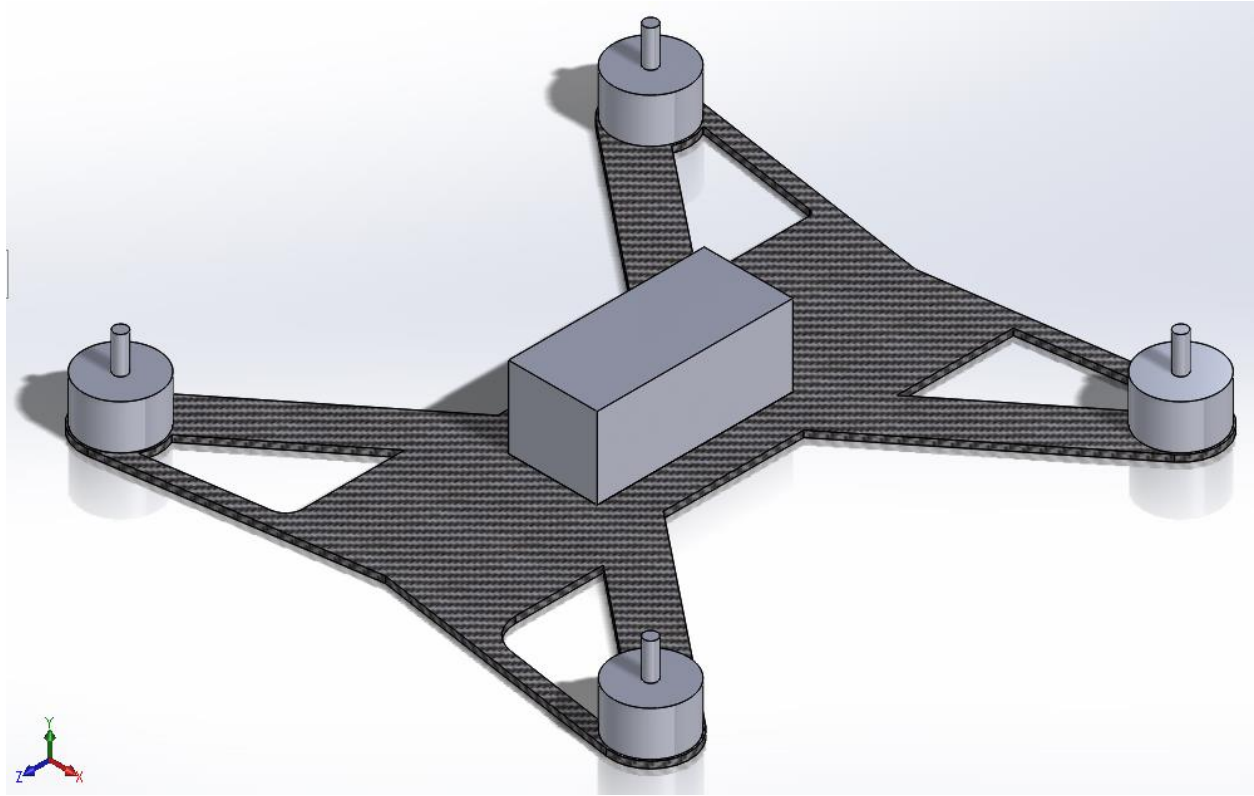




[2]

These designs weigh 2830.5g for aluminum and 2424.7g for carbon fiber including the battery. The remaining components are expected to weight under 500g. For these models each motor would need to output 700g and 600g of thrust, respectively, simply to hover. In order to maintain stable flight the drone needs to be able to hover at 50% throttle, meaning motors delivering 1400g of thrust would be required for this layout. As one can imagine the price of this drone is rapidly increasing, with the battery nearly 200\$ and motors capable of delivering 1400g of thrust nearly 100\$ each. This will quickly set this project over budget.

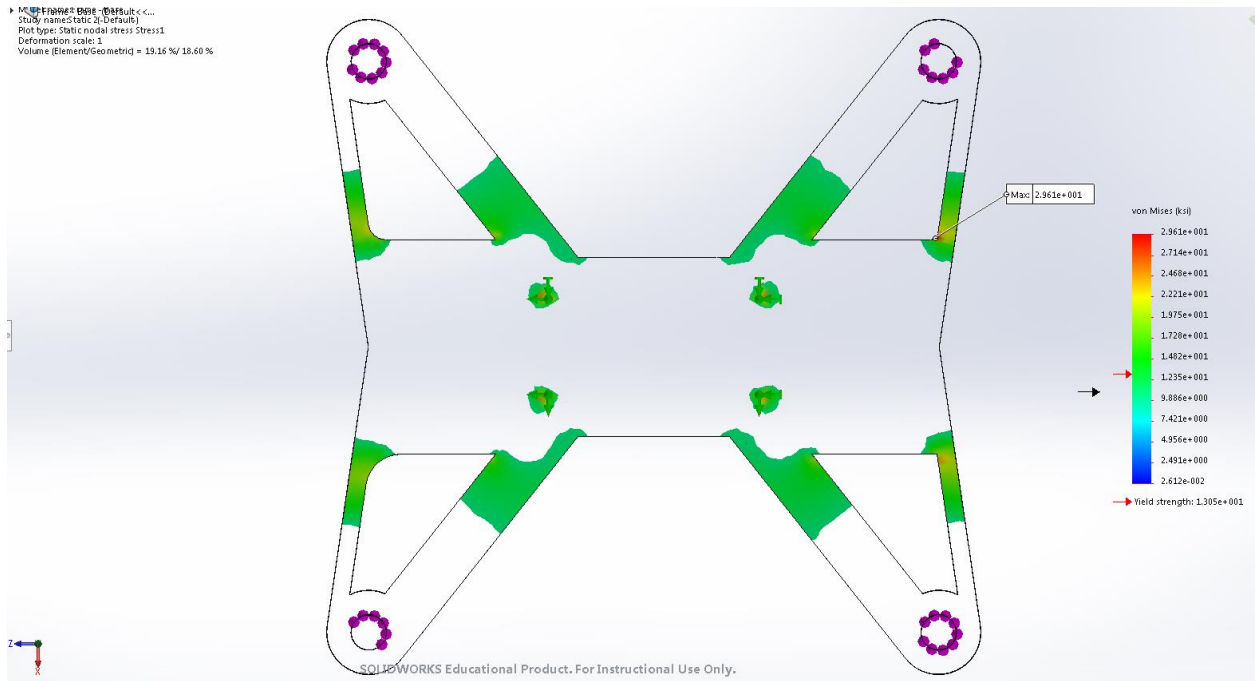
After reevaluting the purpose of this project, to take several lightweight components to high altitudes, a realization was made. These larger drones may be more efficient, but they are more efficient for dealing with larger payloads. Because this project does not mean a large payload a much smaller drone would be more ideal. Another reason for this design change is easy of use for the end user. Carrying around a large awkward drone would be much more difficult than carrying a smaller and easier to store drone, likely a less fragile one due to minimalistic designs. The following is the intial design for the minimal quadcopter drone.



[3]

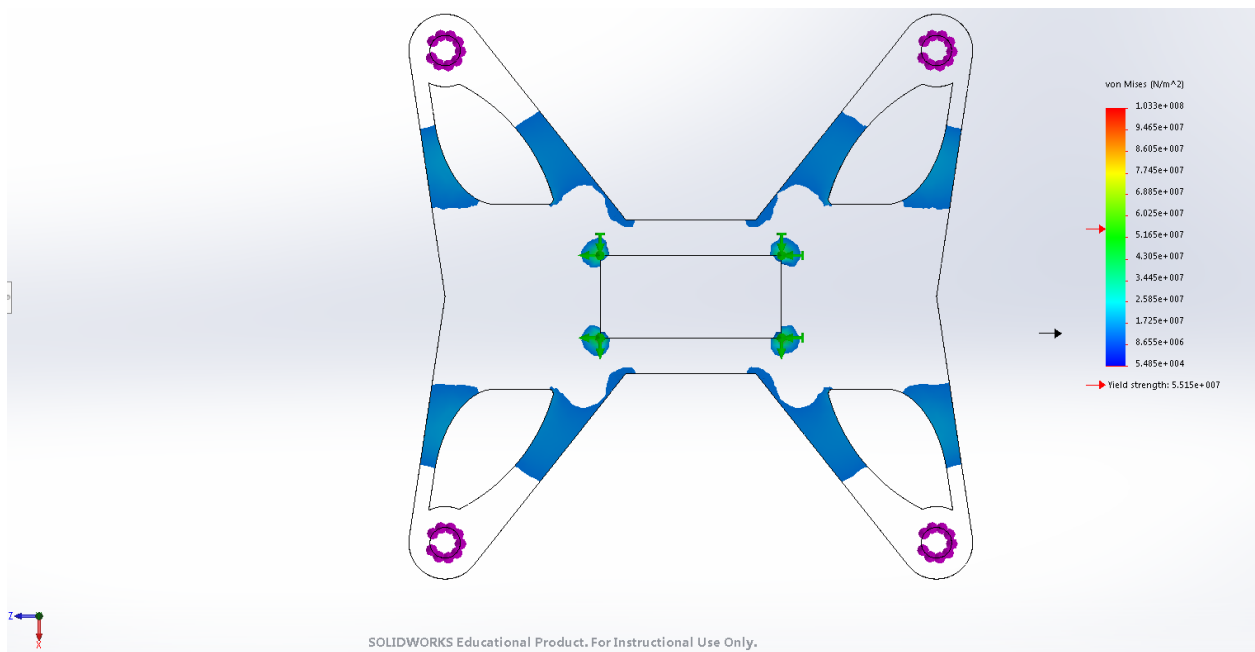
Design

The selected design is much smaller and still allows for the required instruments. To make this frame as efficient as possible, it needs to be as thin as possible. As we can see in the following image, with fillets at each corner, the 1mm fillet actually had worse stress than the edge without a fillet. This tool will be the primary tool in designing the prop arms.



[4]

As we can see in image 4 the bottom left fillet has the least concentrated stress. Using this method of test and check in solid works a model with very low stress can be found while still maintaining the gap for airflow. The inner arms in image 5 have a minimum distance of 12.3mm, which is slightly smaller than the ESC which will be mounted there, at 14.5mm.



[5]

As can be seen in image 5 above there is very little stress on the arms, with maximum stress concentrated at the fixtures which were necessary for calculation in the software, but will not exist in the actual model.

Calculations

Before this project progresses any further we must know if our design will be able to, theoretically, reach the target height. For this it is required to take into account a number of details. One of these is air density. As the drone climbs the air density will decrease. At ground level the density is 1.225 kg/m³, however, at our target of 20,000ft (6096m) the density drops to 0.660 kg/m³. This will greatly hinder the drones rate of climb. We can calculate the acceleration of the drone fairly easily using the thrust of the motors against the weight, however, eventually the drone will no longer be able to accelerate. We can find the maximum speed of the drone using the following equation.

$$F_{Thrust} - F_{Gravity} - F_{AirDrag} = ma$$

$$T - m * g - \frac{\rho}{2} * C_D * A * v^2 = ma$$

Assuming acceleration is zero and solving for v:

$$v = \sqrt{\frac{2 * (T - mg)}{\rho * C_D * A}}$$

Using this equation, we find our maximum velocity at ground level, 400ft, and 20,000ft.

Gravity	m/s ²	9.81
Drone Mass	kg	0.5
Drag Coeff. (Cd)		1.28
Motor Thrust 90%	kg	0.838
Effective Drag Area	m ²	0.0242

Altitude	Altitude (m)	Air Density (kg/m ³)	Maximum Velocity (m/s)	MPH
Ground	0	1.225	38.4	86.0
400ft	120	1.195	38.9	87.1
20000ft	6096	0.660	52.4	117.1

This is of course assuming that the thrust would remain constant while the effective air drag was decreasing, which is obviously untrue. As the altitude increases, the air density will decrease, and the motor thrust will also decrease. It would be fair to say that the thrust would be proportional to the air density. So if we have 838g of thrust at a density of 1.225kg/m³, then at an air density of 0.66kg/m³(53.8%) the thrust would be 449g. Adjusting the previous table for motor thrust:

Altitude	Altitude (m)	Air Density (kg/m ³)	Thrust 90% (g)	Maximum Velocity (m/s)	MPH
Ground	0	1.225	0.722	35.2	78.7
400ft	120	1.195	0.704	35.1	78.5
20000ft	6096	0.660	0.389	31.9	71.3

These numbers are still quite promising, however, as the drone reaches these higher altitudes and loses thrust, the RPM of the motor will increase and which will likely cause damage to the motor or the battery. We can, however, still calculate the time it would take for the drone to reach this altitude.

$$F_{Thrust} - F_{Gravity} = ma$$

$$a = (4 * 0.722kg * 9.81m/s^2 - 0.5kg * 9.81m/s^2)/(0.5kg)$$

$$a = 46.85m/s^2$$

$$v = at$$

$$35.2m/s = (46.85m/s^2) * t$$

$$t = 0.75s$$

$$d = at^2$$

$$d = (46.85m/s^2)(0.75s)^2$$

$$d = 35.2m (115ft)$$

$$d = vt$$

$$122m (400ft) - 35.2m = (35.2m/s)t$$

$$t = 2.47s$$

$$time\ to\ reach\ 400ft = 2.47s + 0.75s$$

$$t = 3.22s$$

$$d = vt$$

$$6092m (20,000ft) - 35.2m = (31.9m/s)t$$

$$t = 190.0s$$

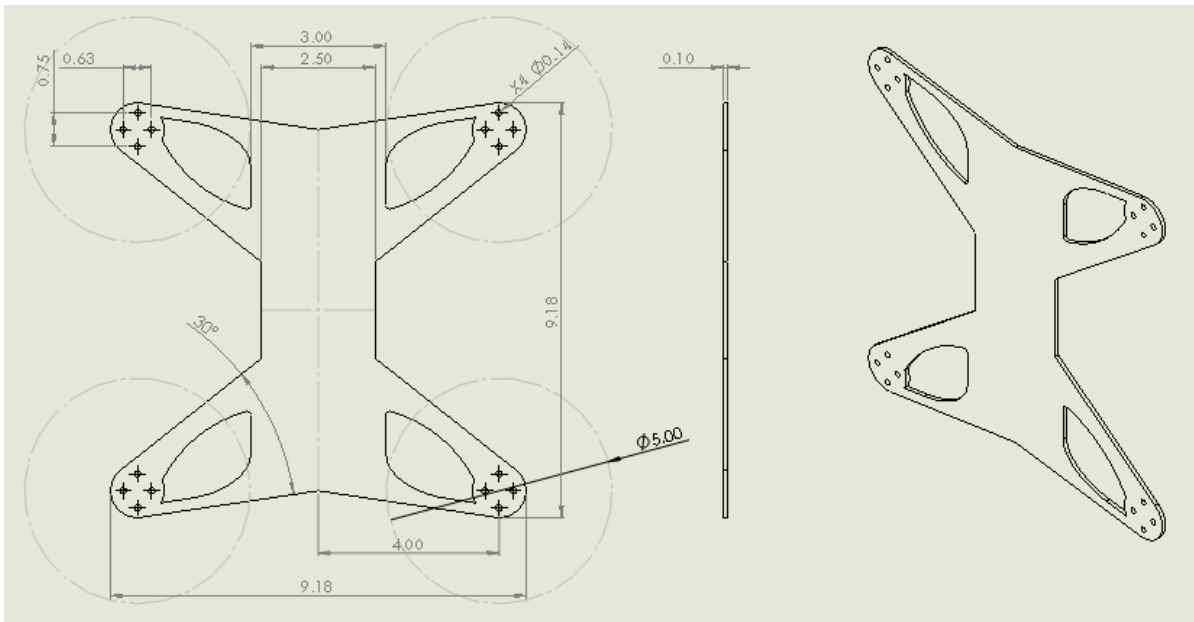
$$\text{total time} = 190.0s + 0.75s$$

$$t = 190.75s$$

So it will take this particular drone setup 3.22s to reach the 400ft ceiling, or a bit over 3 minutes to reach 20,000ft. This is good news for our battery life, as we will have plenty left over for descent.

Fabrication

The base originally was to be 3D printed on a Mark One Composite 3D Printer in Carbon Fiber Nylon mixture. However, the build envelope on this printer was not large enough for the current design. The frame material was changed to ABS plastic on a dimension printer. This change also included an increase of one millimeter in thickness to account for the decrease in material strength. ABS plastic is similarly flexible as the carbon fiber material and will allow bending caused by the motors and the cross winds at altitude. This material also gives the flexibility needed to maintain stable flight and precise motor calculations by the flight controller.

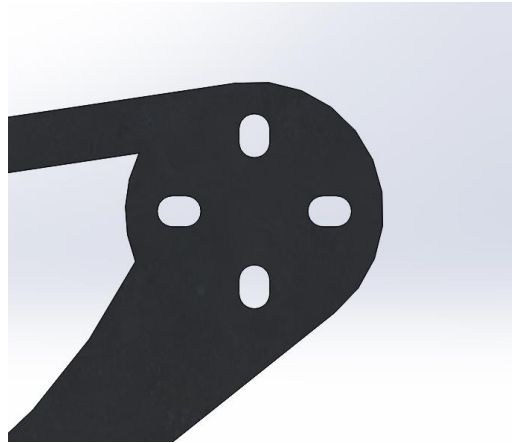


[6] All units in inches

The ESCs will be affixed to the thicker portion of the arm by zip ties. All sensors and batteries will have holes drilled and bolted to the frame for more flexible placement. Strength tests will be conducted once assembled and if drilling has compromised the strength the holes will be added to the model and reprinted. The ease and relative low cost of the 3D printed materials will enable multiple frames to be produced and improved during testing.

Originally the flight controller was to be the Arduino Mega Pro board and would be programmed in the Arduino IDE software. The power distribution board includes a positive 5v power source for this purpose.

The first problem that this project ran into was the holes for the motor mounts did not match up as originally planned. For this reason the motor holes have been changed to slots, and the holes on the printed frame will be drilled out to allow the motors to fit on the current frame.



The original Arduino Mega that was to be used was wired to the motors and in initial tests was able to make the motors spin and read some data from the sensors. However, as time progressed on this project the group started to come to the realization that writing an entire flight controller program in Arduino's native language was going to be beyond our capabilities. Due to this open source flight controller firmware had to be researched. A number of options for Arduino are available, however, for this project the best was decided to be Ardupilot's Arducopter software. This was written to work with an Arduino Mega and had the libraries necessary to interface seamlessly with the current sensors. Ardupilot also allows for very easy communication with a ground station via a telemetry radio unit.

Using the standard Arduino Mega the Arducopter flight controller software was uploaded to the board and all the required sensors were alligator clipped on for initial testing. Running the standard Arduino firmware on this board provided data from the sensors and all appeared to be working properly, however, when the Arducopter firmware was uploaded to the board, the board would appear to be working properly, but when attempting to connect to the ground station, the mav-link connection repeatedly timed out. The mav-link is the connection from the Arduino to the ground station. Considerate research into this error revealed that the problem was the firmware did not include libraries for the selected accelerometer sensor, the MPU-6050, and only included libraries for the old sensor, the MPU-6000. This sensor is no longer available for purchase because the new sensor has replaced it. This problem is the reason the flight controller needed to be changed from an unmodified Arduino Mega to the APM 2.6 flight controller. The APM 2.6 (ArduPilot Mega) controller included a build in accelerometer, the MPU-6000.

The new flight controller required different component than the ones intended for the stock Arduino Mega. Specifically the GPS and separate compass needed to be switched to the all in one Ublox NEO-6M GPS and compass.

Initially the motors were to be soldered directly to the ESCs, however, motor failure is the most likely possibility and it was decided that a more modular setup would be ideal. For this reason bullet connectors were to be used between the motors and the ESCs.



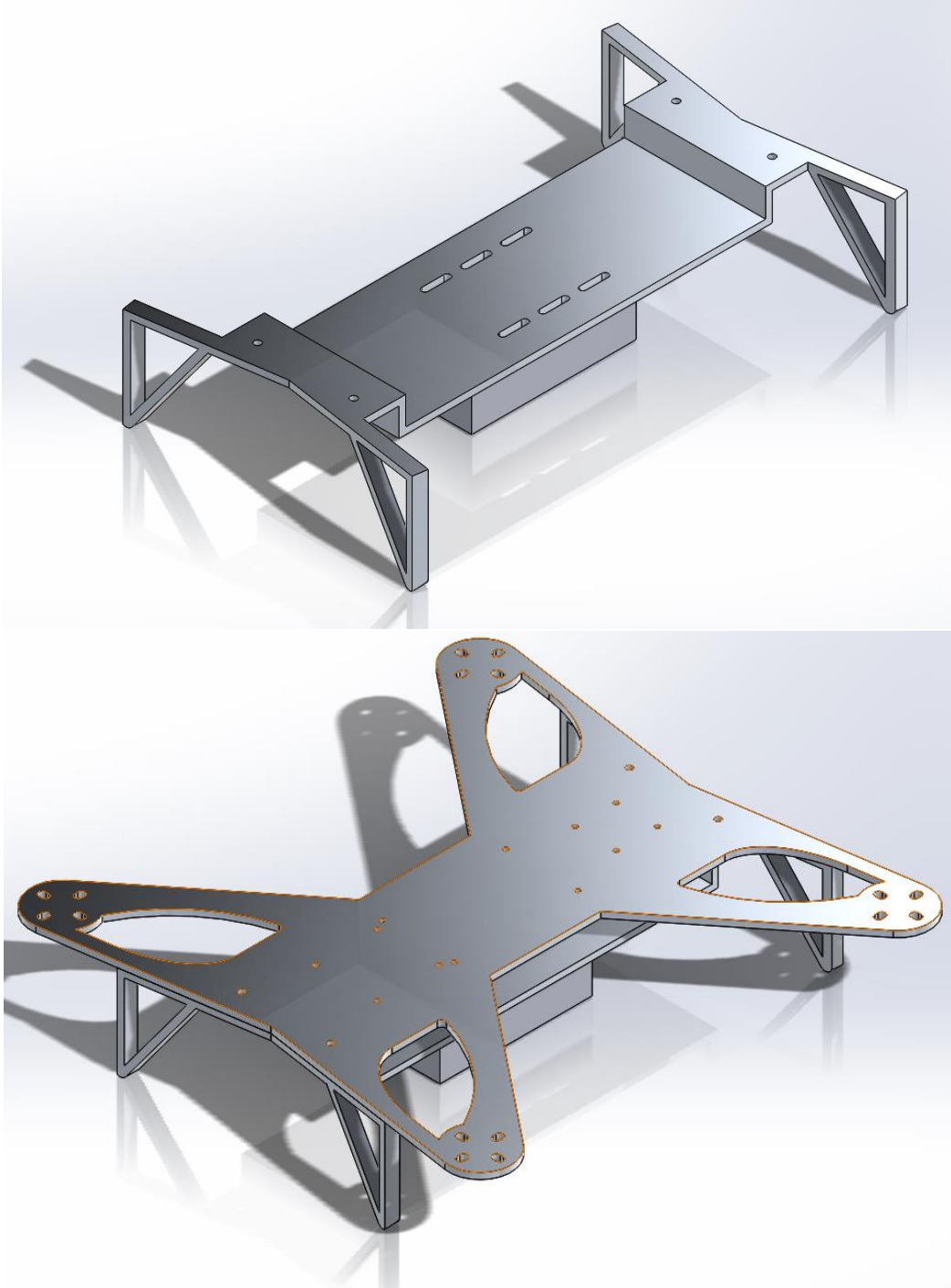
This solution proved excellent for switching out motors quickly in the case of a failure, however, the shrink wrap used did not cover all the exposed metal and cause a short on one motor. This short destroyed the motor and showed that in addition to shrink wrapping the connector's additional insulation was required where metal was exposed.



Originally the design called for the battery to be affixed to the top of the frame with no landing gear used. The flight controller was to be mounted upside down to the bottom of the frame. This caused problems in the flight controller software as can be seen in the following image.



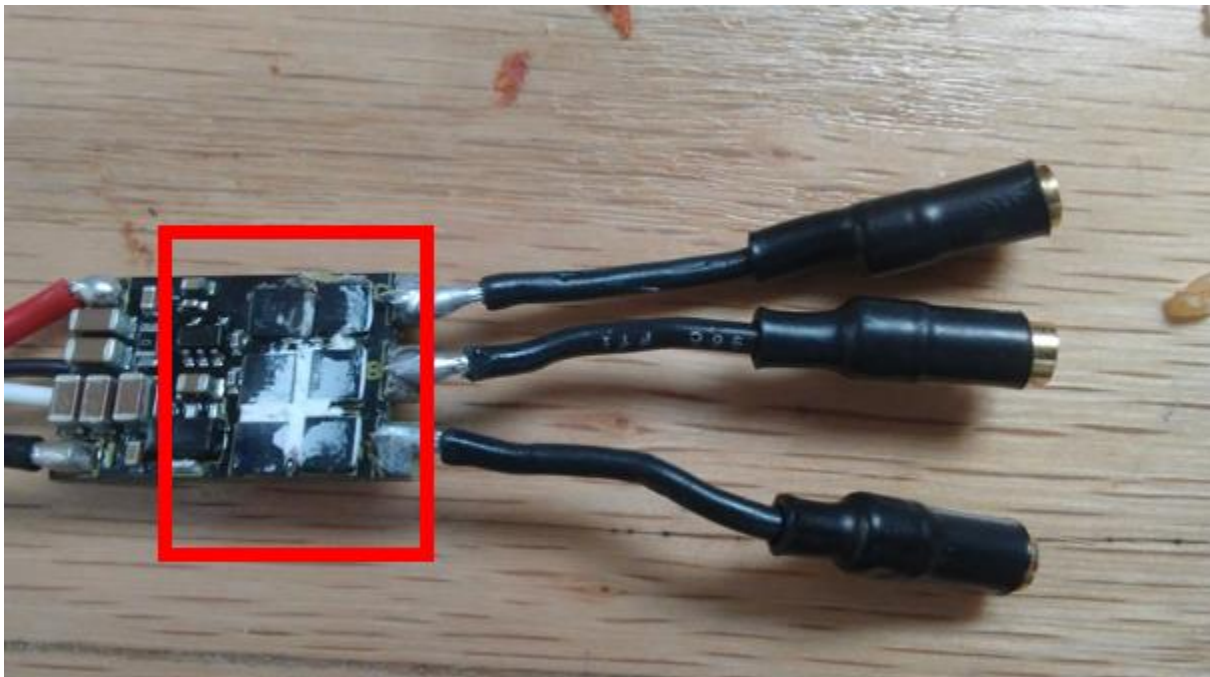
The solution to this problem was to move the flight controller to the top of the frame and move the battery to the bottom. Having the battery in this location would likely prove very difficult for safe landing, and for this reason landing gear with special battery mounting slots would be added to the drone.



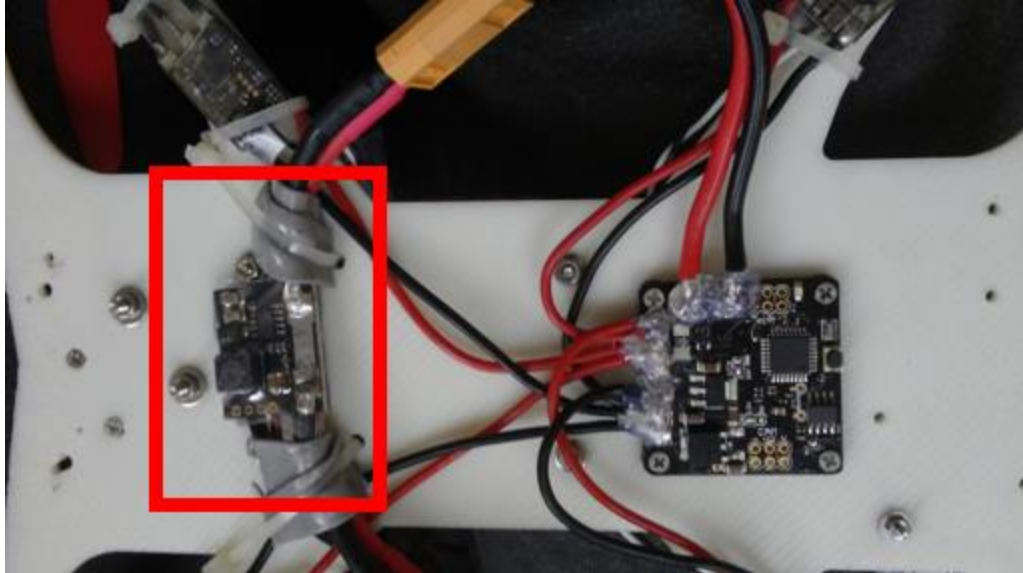
The landing gear would be printed on the Mark One in carbon fiber and would be designed to be the exact largest size possible on the printer. This extra strength would be helpful for holding the battery and giving the entire frame more stability. This will also lower the center of gravity and make flight more stable.

The next problem arose from powering the flight controller via onboard power. Up until this point testing had been performed with the flight controller powered via a USB connection. The

flight controller sent signals to the motors and the motors spin. The final design would need the drone flying entirely with its own power. Normally the flight controller is powered via voltage regulators in the ESCs, however, the selected ESC did not include this feature, so the flight controller was to be powered off the 5V+ on the PDB and grounded through the ESCs. Unfortunately the ground on the ESC was only meant for the small current used to send signals from the flight controller and not the 2 amps that the flight controller consumed. While attempting to run initial tests on the motors with the new flight controller via radio with the ground station, the ESCs temperature was high enough to liquefy the hot glue intended to provide insulation. Fortunately this mistake only resulted in the loss of one ESC as seen in the following image.



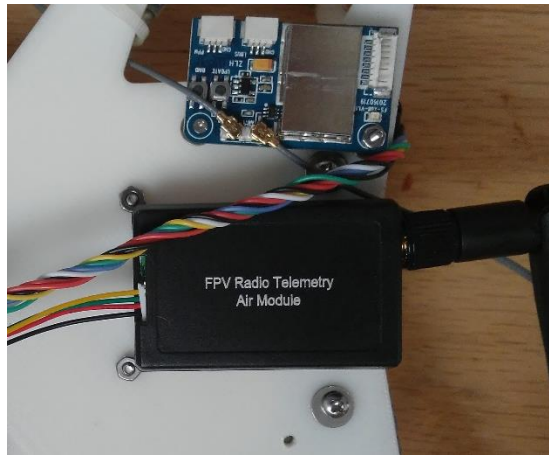
This problem was corrected by adding a power regulation module between the battery and the PDB. This module also allowed the flight controller to monitor the voltage and the current from the battery, which can be used to judge remaining flight time. The module is circled in the following image.



Before flying the flight software required a GPS lock. The GPS module used could not get a lock and the compass did not hold a continuous setting. Research suggested that this problem was caused due to interference from the electromagnetic field created by the battery and motors. The best solution to this was to move the GPS as far away from these components as possible, however the current frame design limits the amount of room possible for this. A lightweight stainless steel mount proved to be the best solution to this problem as can be seen in the following image.



Originally no direct control was going to be used for this project, however, a growing concern for safety eventually resulted in direct control addition. If the software were to send the drone in an undesired direction direct control could be taken to land the drone safely. Holes originally intended for the GPS were repurposed for mounting the RC receiver. The telemetry module was mounted using high strength outdoor double sided tape.



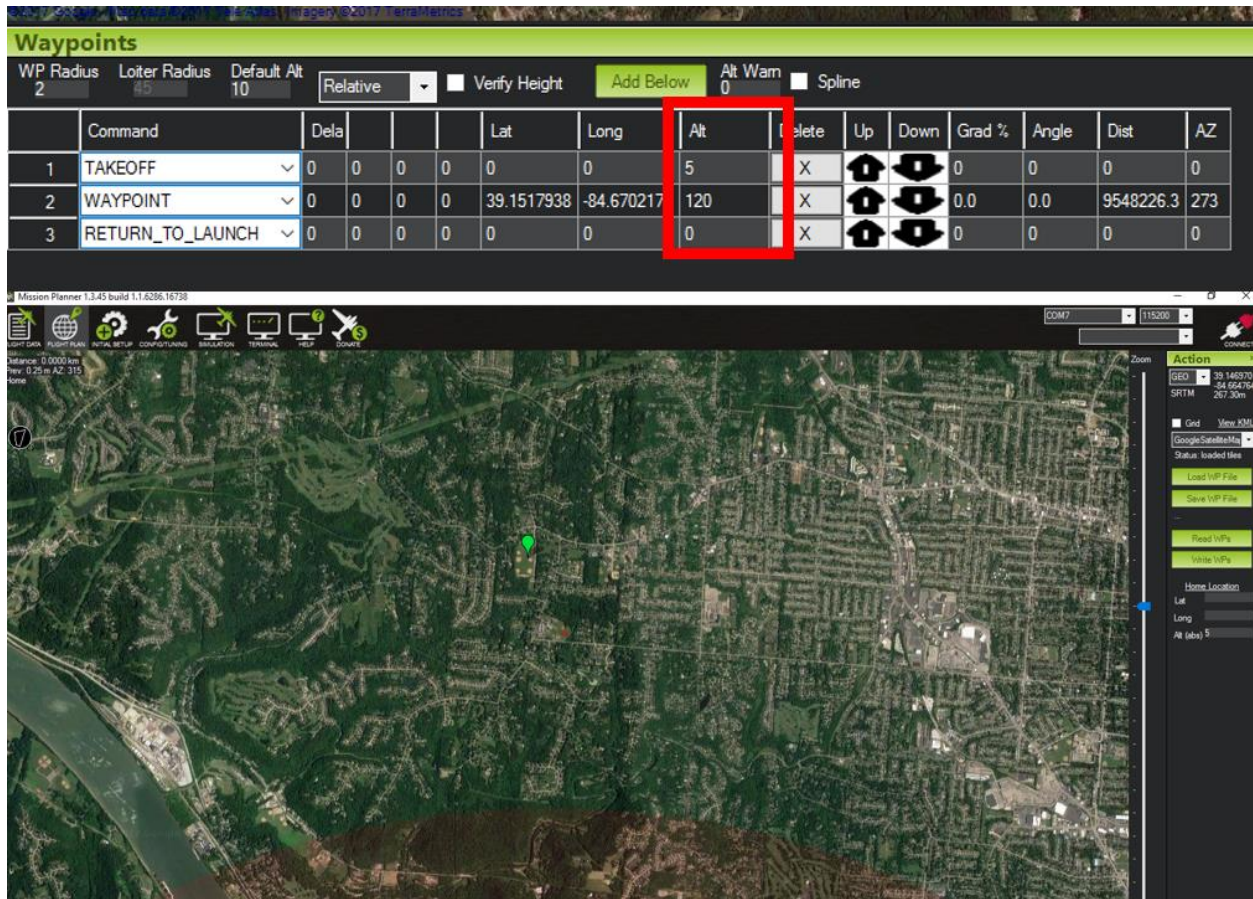
To ensure the longest flight time and the lightest possible assembly, these are the only components installed on the drone. The entire weight, less the battery is 471 grams with battery weights of 150-175 grams.



Testing

Due to unexpected delays in fabrication, assembly, and unfavorable weather very limited testing was done. Initial tests involved motors tests and direct flight control tests. Stabilize mode, where the drone works to remain level and Loiter mode, where the drone attempts to maintain

position, proved successful. Full auto mode was tested and an altitude of 400ft (120m) was achieved only once. The battery was drained from this trip and due to extended battery charging times and preliminary tests was the only test completed.



Recommendations

As stated before the goal of this project was to reach an altitude of 400ft. For the data obtained by the drone to be particularly useful for meteorology higher altitudes would need to be reached. This particular drone only used a small capacity battery and rotors to reach the intended altitude and return safely, however, larger batteries and props would increase the flight time and thrust of the drone, which would allow for higher altitudes. It is difficult to estimate the exact altitude attainable, however the motor amperage consumption and battery capacity will allow us to estimate within reason the flight times and comparing them to the flight time of this drone it is reasonable to say much high altitude would be attainable.

		Prop													
Bare Weight (g):	471	5x4					Max A:	102.05	6x4					Max A:	148.45
Throttle		IDLE	25%	50%	75%	100%		IDLE	25%	50%	75%	100%			
Current (A)		1.74	2.76	6.13	13.43	24.95		1.80	3.27	8.61	19.81	36.55			
Current (A) x4		6.96	11.04	24.52	53.72	99.80		7.20	13.08	34.44	79.24	146.20			
Thrust (g)		36	133	375	732	1119		52	198	565	1042	1472			
Thrust x4 (g)		144	532	1500	2928	4476		208	792	2260	4168	5888			
		Hover													
		5x4 Flight Time (min)					6x4 Flight Time (min)					Throttle / Flight Time			
Battery / Weight (g)	mAh	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%	5x4	6x4		
Tatu 75C 3S	1300	11.2	7.1	3.2	1.5	0.8	10.8	6.0	2.3	1.0	0.5	30%	24%		
	125 ΔT	-452	-64	904	2332	3880	-388	196	1664	3572	5292	5.8	6.8		
Tatu 75C 4S	1350	11.6	7.3	3.3	1.5	0.8	11.3	6.2	2.4	1.0	0.6	30%	24%		
	152 ΔT	-479	-91	877	2305	3853	-415	169	1637	3545	5265	6.0	7.0		
Turnigy 60C 3S	2200	19.0	12.0	5.4	2.5	1.3	18.3	10.1	3.8	1.7	0.9	31%	25%		
	193 ΔT	-520	-132	836	2264	3812	-456	128	1596	3504	5224	9.7	11.4		
Turnigy 40C 3S	3000	25.9	16.3	7.3	3.4	1.8	25.0	13.8	5.2	2.3	1.2	32%	26%		
	278 ΔT	-605	-217	751	2179	3727	-541	43	1511	3419	5139	12.9	15.2		
Turnigy 25C 3S	5000	43.1	27.2	12.2	5.6	3.0	41.7	22.9	8.7	3.8	2.1	35%	28%		
	412 ΔT	-739	-351	617	2045	3593	-675	-91	1377	3285	5005	20.7	18.8		
Multistar 10C 4S	10000	86.2	54.3	24.5	11.2	6.0	83.3	45.9	17.4	7.6	4.1	42%	33%		
	804 ΔT	-1131	-743	225	1653	3201	-1067	-483	985	2893	4613	36.8	34.4		
Multistar 10C 4S	20000	172.4	108.7	48.9	22.3	12.0	166.7	91.7	34.8	15.1	8.2	57%	45%		
	1610 ΔT	-1937	-1549	-581	847	2395	-1873	-1289	179	2087	3807	40.8	56.2		

As we can see in these charts the flight time of this drone are quite small, however, as battery capacity increases the flight time would increase. The last battery is the largest battery currently available on the market, however, one could use multiple batteries from there to increase capacity. The flaw in the charts logic is that the same frame would be used with these heavier and higher capacity batteries. This would not be possible as the frame was clearly flexing under the current minimal load. Improvements to the frame would need to accompany larger batteries and larger props.

Schedule and Budget

Schedule

	Proposed		Actual		Delay (days)
	Start	Complete	Start	Complete	
Research	9/1/2016	9/30/2016	9/1/2016	10/30/2016	30
Design	10/1/2016	10/31/2016	10/30/2016	11/30/2016	30
3D Model and Calculations	11/1/2016	11/30/2016	11/30/2016	12/31/2016	31
Procure Materials	12/1/2016	12/31/2016	12/31/2016	1/15/2017	15
Fabrication and Assembly	1/1/2017	1/14/2017	1/15/2017	3/24/2017	69
Programming and Testing	1/15/2017	3/20/2017	3/24/2017	4/4/2017	15
Final Modifications and Testing	3/21/2017	4/11/2017	4/4/2017	4/12/2017	1

As stated before fabrication too much longer than originally planned and programming time was not needed as originally intended. Only a few weeks were allowed for testing.

Budget

As stated before originally the project was to use parts already on hand. This did not end up working out and new parts were required to be added. Also not originally accounted for was extra motors and ESCs, which is accounted for in the actual budget. While this is double the initial budget, it is not unreasonable for what was accomplished.

Proposed:

	Name	Cost	Number	Weight (g)	Total
ESC	Hobbywing XRotor Micro Beheli_S 30A	\$ 13.79	4	6.8	\$ 55.16
PBD	RR OSD PRO MINI PDB	\$ 35.00	1	7	\$ 35.00
Battery	VcanZ 4S 1350mAh 75C 14.8V LiPo (SM)	\$ 23.90	2	155	\$ 47.80
Props	HQ5045	\$ 5.02	2	3.2	\$ 10.04
Motor	T-Motor 2305 2400kv	\$ 24.98	4	28	\$ 99.90
Frame	Custom 3D printed	\$ 50.00	1	150	\$ 50.00
				612.6	\$ 247.90

Actual:

	Name	Cost	Number	Weight (g)	Total
ESC	Hobbywing XRotor Micro Beheli_S 30A	\$ 13.79	6	6.8	\$ 82.74
PBD	RR OSD PRO MINI PDB	\$ 35.00	1	7	\$ 35.00
Battery	VcanZ 4S 1350mAh 75C 14.8V LiPo (SM)	\$ 23.90	2	155	\$ 47.80
Props	HQ5045	\$ 5.02	4	3.2	\$ 20.08
Motor	T-Motor 2305 2400kv	\$ 24.98	6	28	\$ 149.85
Frame	Custom 3D printed	\$ 50.00	1	150	\$ 50.00
FC	APM 2.6	\$ 28.98	1	10	\$ 28.98
RC	Fly Sky	\$ 54.99	1	15	\$ 54.99
Radio	Temetry Module	\$ 19.59	1	20	\$ 19.59
GPS	Ublox NEO-6M GPS Module Compass	\$ 17.36	1	50	\$ 17.36
				783.6	\$ 506.39

References

- [1] <https://www.rcgroups.com/forums/showthread.php?1880665-129min-15s-flighttime-with-quad>
- [2] <http://klsin.bpmsg.com/how-fast-can-a-quadcopter-fly/>
- [3] <https://iacra.faa.gov/IACRA/Default.aspx>
- [4] <http://www.ecalc.ch/xcoptercalc.php>