Capstone Project

Final Report

2015

Project Title: Hybrid UAV Development for Emergency Response

Date: 27/08/2015

Project Team Information

Identifier:	**CP-CBU-155**
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Version:	1.2

Acknowledgements

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Contents

1 Introduction

Project title: *Hybrid UAV Development for Disaster Response*

This project aims to develop a prototype hybrid Vertical Takeoff and Landing (VTOL)/Fixed-wing aircraft, designed for assisting in disaster management and response. The aircraft will be capable of maneuvering and landing in cluttered environments without need for a runway, and traversing large distances (up to 60km), taking the advantages of both rotor-based and winged aircraft. The primary application of the project is in emergency transporting medical supplies across large distances. This is a sub-project of MASR (Melbourne Autonomous Search and Rescue), the official entrant into the UAV Outback Challenge 2016.

Since the release of the 2016 Outback Challenge rules **rules** in March, some elements of the projects scope have been updated, with approval, and are described in Table 1.

#	Change	Description	Date
1	Increased target range	Updated competition specifications require aircraft to travel a total of up to 60km, increased from the original 20km	21/3/15
2	Advanced detection algorithms	Outback Joe will only be identifiable by his blue jeans, requiring more advanced computer vision than first expected	21/3/15
3	Autonomous take-off and landing	Scope has been modified to include autonomous take-off, as well as landing, to meet the Outback Challenge specifications	21/3/15
4	Implementation of flight corridor management	The UAV must now remain inside pre-defined flight corridors (Geofences) in order to maximise safety during the competition	21/3/15
5	Develop Y3 prototype	Given the added difficulty of developing a 6 rotor (Y6) aircraft, the initial prototype will be a 3 rotor (Y3) craft, with Y6 being attempted if this is unsuccessful in meeting project objectives.	28/3/15
6	Development of test aircraft	A simple polystyrene prototype was created in order to test equipment, and avoid damaging the Skywalker platform	28/3/15

Table 1: Changes made to project scope since Scope of Works submission

2 Literature Review

The design of the Outback Challenge 2016 is such that a purely fixed-wing or rotor-based aircraft is unlikely to be successful; instead, teams will need to design aircraft that make use of both flight modes. As this project involves the development of a novel aircraft platform, there is scarce academic literature that is relevant to the problem at hand. This review will instead collate examples of commercial and hobby systems that were used to inspire and guide the development of the aircraft.

The requirement to land within a small obstructed area meant that last year's design, a fixed wing aircraft, would not be suitable for the 2016 competition (see scope of works). It was decided vertical take off and landing (VTOL) would be the best approach. Nothing existed off the shelf that could carry out the mission completely, however many designs existed to gather inspiration from.

2.1 Aircraft Design

2.1.1 Arcturus Jump

The Arcturus Jump **arcturus** (Appendix B, figure 8) is a quad-copter/fixed wing hybrid, with proopellers mounted across the wings for VTOL, and a propeller at the front for fixed wing flight. The problem this design is that modifying a fixed wing air frame to support the motors would add significant weight, decreasing thrust and maneuverability, and would also add significant drag.

2.1.2 X PlusOne

The X PlusOne **xplusone** (Appendix B, figure 9) is an incredibly fast and efficient hybrid with 4 front facing propellers. It is extremely small and light, and would be relatively cheap to build, but is too small for implementation onto existing airframes. Designing a new airframe would take a significant amount of time, and was outside the scope of the project.

2.1.3 TBS Caipirinha

A two propeller control, such as the TBS Caipirinha **caipirinha** (Appendix B, figure 10) was also a possibility. This would mean two front facing propellers with minimal modifications to existing airframes, but would require extremely advanced and less common control systems and significantly less hover maneuverability.

2.1.4 FireFly6

Finally, the FireFly6 **firefly** (Appendix B, figure 11) is a VTOL/Fixed-wing hybrid aircraft consisting of 6 propellers arranged in Y6 configuration, that can achieve 20-30 minutes of flight time, 7 minutes of hover, and a cruising speed of 54km/h. A modified design making use of the Skywalker X8 airframe would be the initial challenge specifications.

Due to the increase in range required by the competition rules **rules** over what was initially stated, it was uncertain whether the extra stability of a Y6 (as shown in **firefly**) was worth the extra weight and decrease in efficiency compared to a Y3. A Y3 has also been shown to be stable on the Skywalker X8 **y3** and that a range of over 140km can be achieved with less weight and drag when used as for fixed wing aircraft **range**

2.2 Flight Controller

The addition of a flight controller to the aircraft permits autonomous flight capabilities, including way point planning and motor control. The most viable (and well supported) options were the PixHawk **pixhawk** APM 2.6 **ardupilot** and PX4 **px4** In order to achieve reliable and safe autonomous flight the controller must be fast and have sufficient storage for additional firmware/software to extend its capabilities. A comparison of each option may be found in **controller˙comparison** showing that given its larger memory storage, faster processor, and additional capabilities such as in-build gyros and accelerometers, the PixHawk is the best choice for this project.

3 Progress to date

3.1 Updated timeline

Figure 1 shows an updated timeline for the project, specifically highlighting tasks that have been added since the scope of works, and tasks that were underestimated.

3.2 Prototype #1 - "Scorpion"

This section details the tasks that were completed on, or for, the first prototype aircraft. Development on the Skywalker X8 was postponed, and a replaceable foam model developed, so that problems (and damage) did not result in significant cost and delays to the project.

3.2.1 Parts selection

The specifications for parts to fit the design were modeled using eCalc **ecalc** as recommended by the drone building community. The site has a vast collection of empirical data for motors, propellers, batteries and configurations and boasts an accuracy of plus or minus 10% for all calculations. Details of the modeling can be found in appendix B.

Configuration: It was decided that a Y3 configuration would work best for the challenge. It is less intrusive, weighs significantly less than a quad or Y6, and is much less complex than forward facing VTOL. A Y3 configuration, however, requires a servo to actuate the back motor in order to counter the angular momentum produced by the excess torque from the odd number of motors.

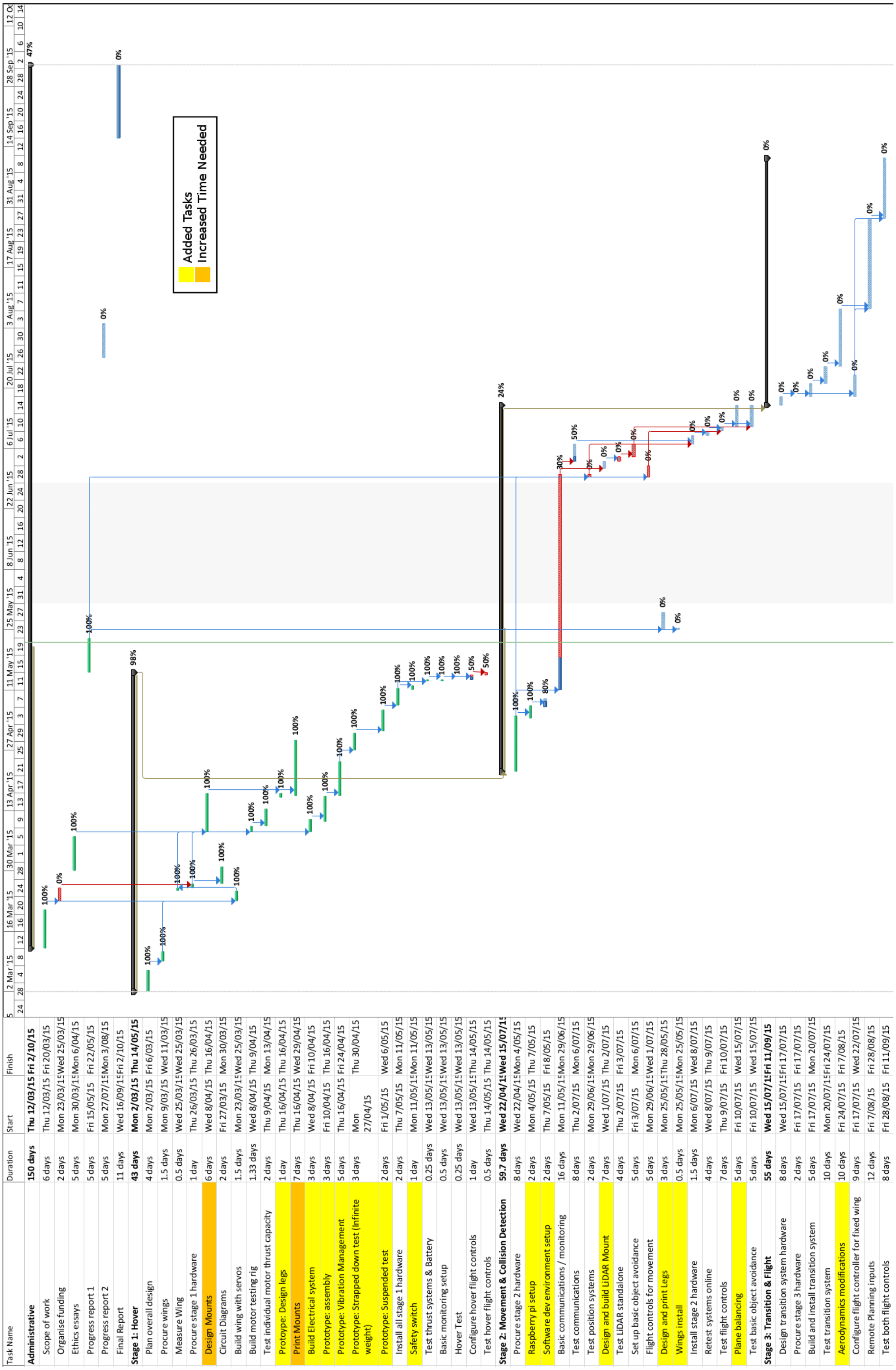


Figure 1: Updated Gantt chart, showing tasks that have been added or extended

Airframe: The Skywalker X8 was chosen as the airframe. It has a lot of space for components and the greatest wingspan to weight ratio of the airframes investigated. It was also well priced, well reviewed and available quickly from Australian suppliers.

Motor: The motors chosen needed to efficiently hover, but at the same time be able to cruise in fixed wing mode using minimal battery power. As such, the Turnigy SK3 3542 800kv motors were chosen. They are efficient, well priced, well reviewed and very effective at completing both objectives. They were also the motors used by **range** to achieve long range flight.

Propellers: Modelling using eCalc suggested that smaller propellers provide better performance in fixed wing flight (less drag, weight), but larger propellers are better suited for VTOL (more thrust), with modelling presented in Appendix B. As such, two sets of propellers were purchased (11×5.5 and 12×6) in both plastic and carbon fibre.

Battery: The primary concern for maximising flight time/range is by reducing weight. Multistar 8000 mAh batteries were selected as they allow for a much higher capacity at a lighter weight than conventional LiPo batteries.

Flight Controller: Following the discussion presented in **controller˙comparison** the PixHawk flight controller was found to be more powerful and faster, and more importantly, easier to reconfigure and add software to.

3.2.2 3D Modelling and Printing

In order to develop the Skywalker X8 into the custom hybrid that was envisioned, a number of components have require 3D modelling and printing. The parts need to not only be functional, but be light, and durable enough to last many flights and (hopefully few) crashes.

The direction in which a design is 3D printed plays a part in where its strength and weaknesses lie, and the most likely mode of failure. Each print was orientated in such a way to maximise the strength of the layers for the forces and moments being applied.

In order to achieve a "true" circle shape and thus lower friction for mated parts, critical ring shapes in designs were replaced by flatly printed ring inserts. These ring inserts were then either press fit into other printed components or "merged" onto other printed components using acetone. Tables 2, 3 and 4 show iterations of the motor mounts, front pole and servo mount, and back pole and servo mount respectively.

3.2.3 Propeller testing

In order to achieve the greatest lift for take-off, a number of tests were conducted on the rig shown in Figure **??** to measure the relative force of various propeller sizes and materials. Table 5 summarizes the results, which indicate that the 12×6 APC (Plastic) blades produce the greatest force, and are best suited for take-off. Further tests will be conducted to determine which type will permit the longest flight time.

3.2.4 Hardware Architecture

Figure 2 shows the hardware abstraction planned for both the current and future prototype, separated according the progress stages identified in the scope of works. Stages are implemented in sequence such that each stage builds on those prior.

3.2.5 Software Architecture

Development environment: Software development will be a large portion of the remaining part of the project and therefore it is important that this be setup in a way that enables parallel development of components, to ensure the project can be completed on time. This is somewhat more difficult in this project due to the software needing to interact with physical components, which we do not have spares for each member to test on. To facilitate parallel development two key items have been set up:

1. Remote wireless access has been setup to the plane's onboard computer (also available from home via VPN) to allow multiple users to access it for development.

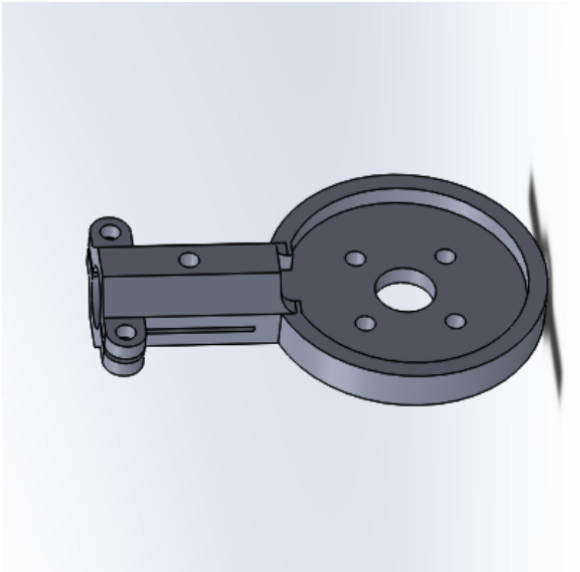
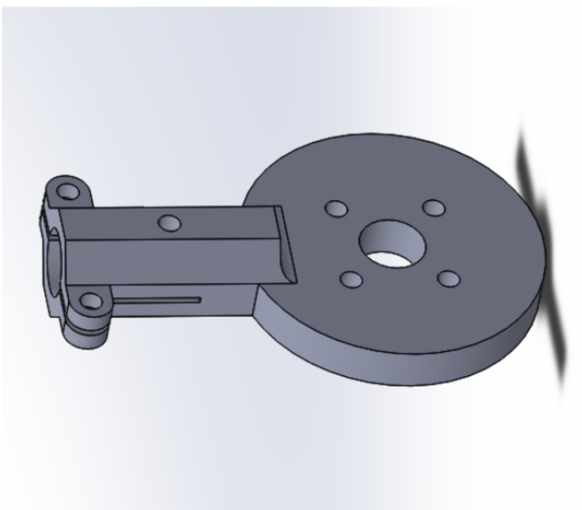
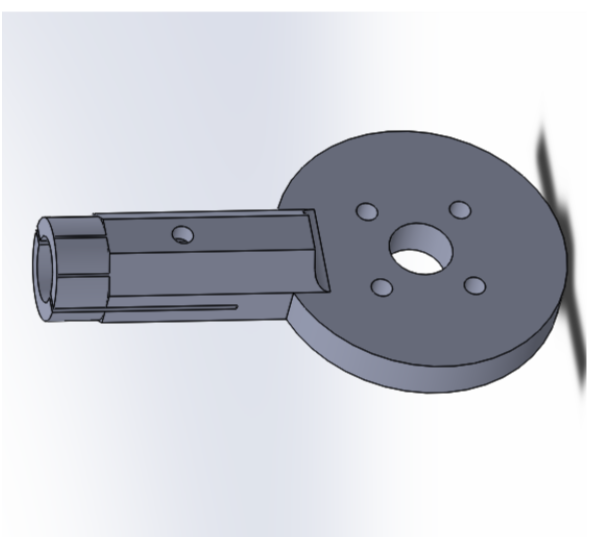
	Initial designs of the motor mounts cased the motor in a small indent and had a hole through the center of the mount to carry wires. It was printed to give best fit to the pole while also using as little material as possible. It failed during testing at both 30% and 100% fill just before the start of the fillet between the pole and the motor.
	The second design fixed the weak point by not only extending the pole support into the flat mounting section, but also by removing the indent on the flat section. Another boost of strength was given by printing the mount flat, rather than upright, resulting in grains that ran orthogonal to previous lines of weakness and not parallel with them. When side screws were then tightened to increase friction, they split the mount due to the new weakness in the orientation.
	The current design for the motor mounts removed the side tabs that were meant to provide increased friction onto the motor pole. These were replaced by a rounded section in which a hose clamp is used to grip the mount to the pole.

Table 2: Modelling iterations for motor mounts

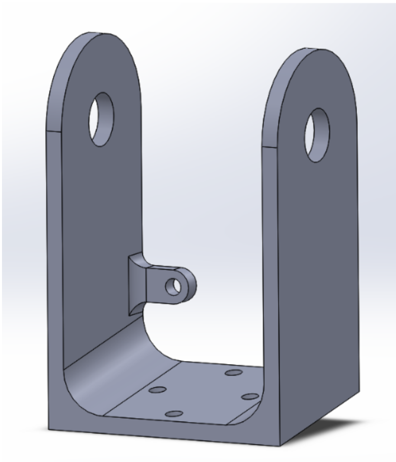
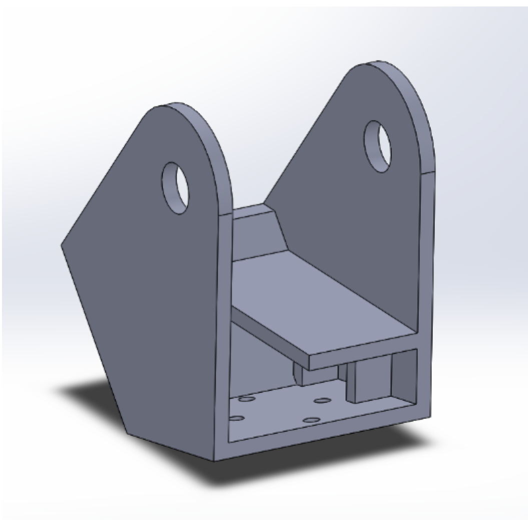
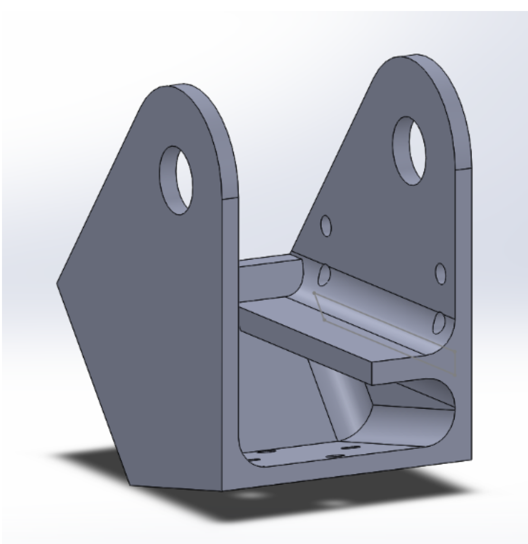
	Initial designs for the front pole mount were to support the pole holding the front two motors during flight. It was designed to attach to the bottom and back of the front recess in the Skywalker foam.
	The second iteration of the front motor mount included the front facing support surface and also a proposed location for servo mount. The front facing support surface was required when trying to include the servo onto the mount itself
	The current iteration of the front mount was altered to include fastening holes for the front servo. It also included larger holes for the front motors pole to allow for lower friction rings to be inserted.

Table 3: Modelling iterations for front pole and servo mount

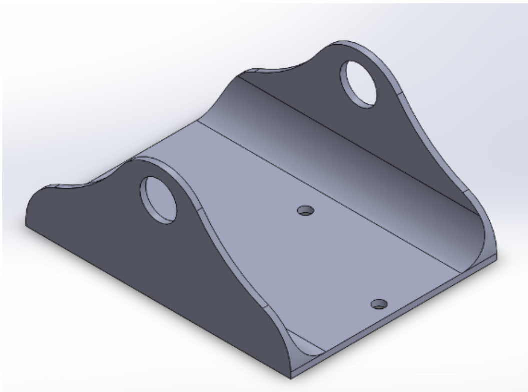
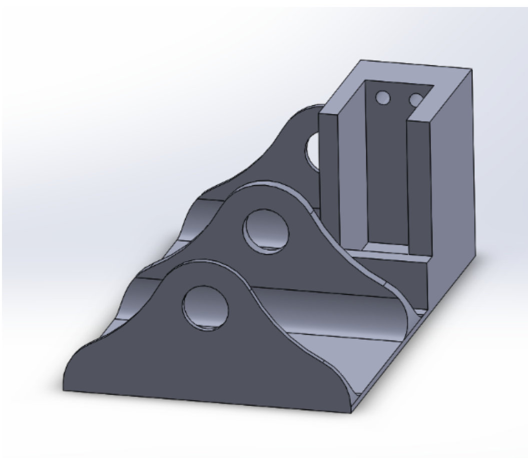
	Initial designs for the back mount were to support the rear motor pole and to allow for fastening to the flat bottom surface in the back section of the Skywalker.
	The current iteration was updated to include another web for additional motor pole support, and housing for the servo as well as larger holes for the front pole to allow for lower friction rings to be inserted.

Table 4: Modelling iterations for back pole and servo mount

Material	Dimensions	Measurements	Average Force (kg)
Carbon fibre	12×6	[1.685, 1.695, 1.692, 1.690. 1.700]	1.692
Carbon fibre	11×5.5	[0.635, 0.635, 0.635, 0.635, 0.635]	0.635
APC (Plastic)	12×6	[1.965, 2.030, 2.030, 2.020, 2.045]	2.02
APC (Plastic)	11×5.5	[1.645, 1.630, 1.625, 1.620 1.620]	1.628

Table 5: Measurements of propeller performance

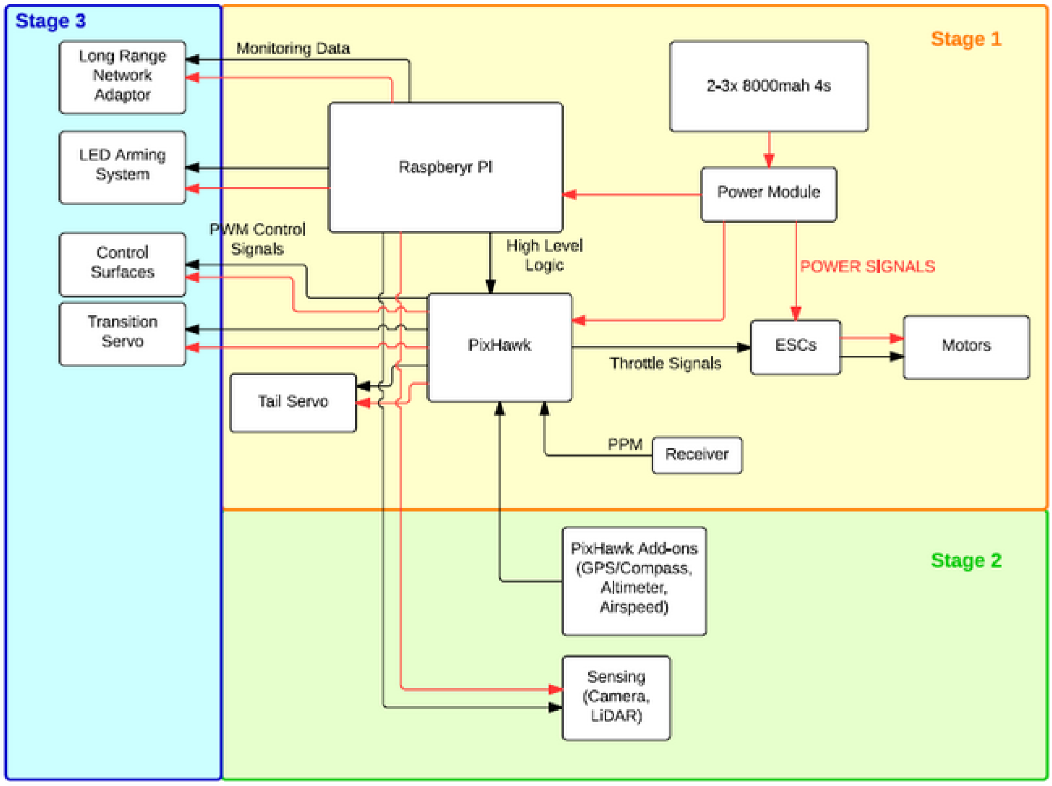


Figure 2: Architecture diagram for aircraft hardware

2. Each user has had a separate programming environment setup such that parallel development is possible without interfering with each other. In addition each team member can track (and rollback) their own software changes separately before choosing to push changes to the main branch for integration into other members work and the final software platform.

Software Framework: Figure 3 shows the software framework developed for this project. The framework consists of a series of modules (running on the Raspberry Pi) which communicate with the flight controller via an adapter module using the MAVLink protocol **mavlink** a protocol specifically designed for high speed, low latency communications with micro aerial vehicles. Using an adapter module permits swapping of the flight controller without the need for changing the code, which may occur as the plane is further enhanced for the competition.

All the internal modules for the project communicate via an observer / subscriber pattern (**gang of four ref**), further facilitating parallel development as each module doesnt need to know the details of how to communicate with other modules. It also easily allows the addition of other components to the plane (such as computer vision) at a later date without altering the current modules.

Lastly, all communication with physical components of the plane (such as the LiDAR or the transceiver) will be done through interface modules. This hides the communication details of the hardware from the software system which will allow swapping the hardware components for better or different versions in the future without changing the internal modules.

3.2.6 Vibration Elimination

A major problem encountered throughout testing was vibrations; each time our prototype began to hover, parts would come loose (sometimes breaking), putting our tests to a halt. The best way to fix this was to eliminate vibrations as much as possible by utilizing vibration resistant fasteners, and damping as much of the vibrations that were running through the pole as possible.

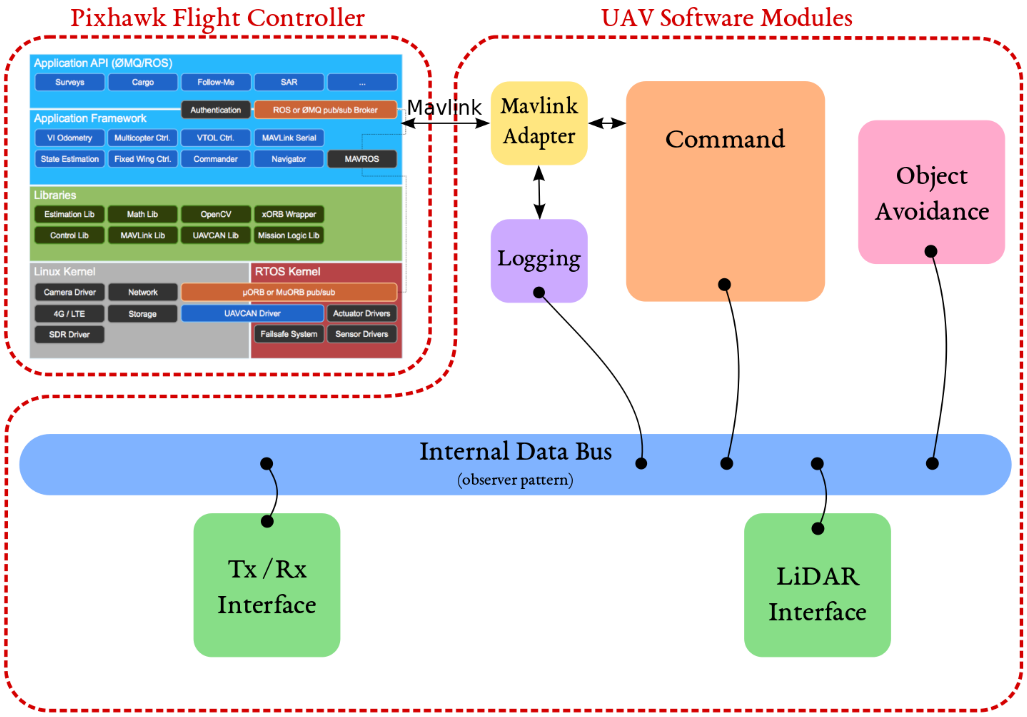


Figure 3: Architecture diagram for aircraft software

In order to eliminate vibrations generated from propellers they must be balanced, which is accomplished by either adding (using tape, or similar) or removing (shaving off material) mass from either side of a propeller. A non-destructive method was preferred, so small pieces of tape were added to the propellers using the balancing apparatus shown in figure 4 to ensure the mass distribution was equal. Seismograph testing (using a free app) of the propellers before and after balancing showed a very obvious decrease in vibrations.

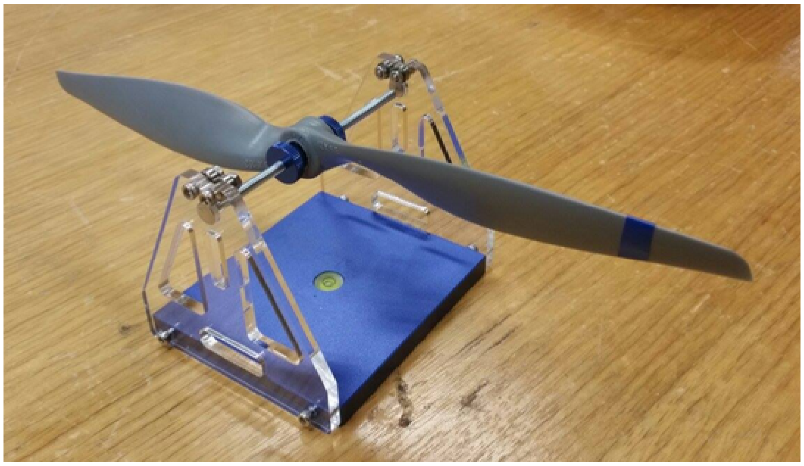


Figure 4: Propeller balancing apparatus, with propeller taped to improve balance

To improve the vibration of fasteners, each bolt in critical areas of vibration, such as poles and mounts, was secured with a nyloc nut. Spring washers were also added to each screw to prevent them coming loose. A final change was the addition of rubber "feet" to the base of each motor to damp any vibratory response down the shaft. Overall this was extremely effective in increasing stability, as vibrations appeared to mitigated in follow-up tests.

3.3 Prototype #2 - ”Dragonfly”

Figures 5 and 6 show the current prototype (nicknamed “Dragonfly”), prepared for the most recent test flights.

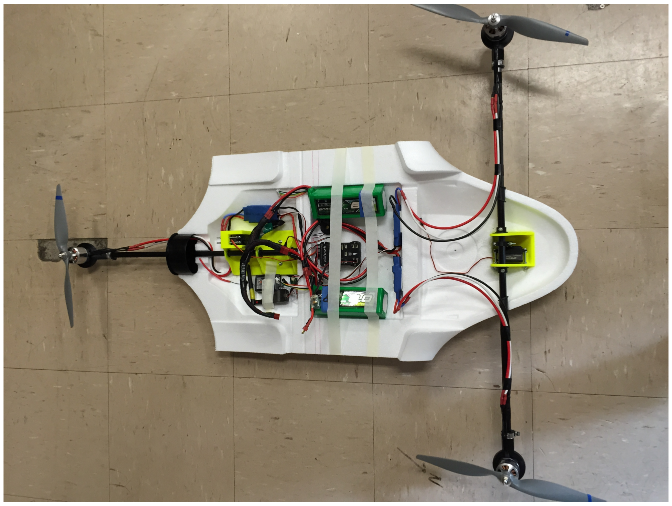


Figure 5: Internal view of “Dragonfly” prototype

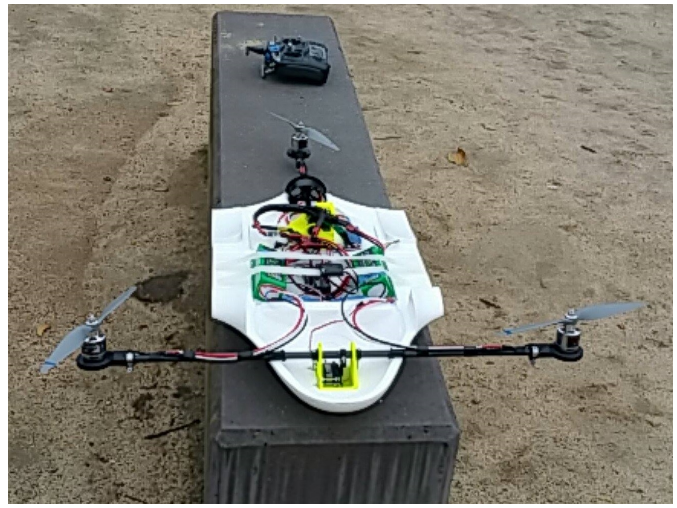


Figure 6: “Dragonfly” assembled without wings prior to test flight

3.3.1 Mass Balancing

The center of gravity of the new aircraft may be changed by repositioning the batteries (the heaviest items to be carried). The CoG needed to meet two specifications:

1. The center of mass had to be at the center of thrust of the VTOL. As there are two propellers in the front and one in the back this would be one third of the distance from the front propellers to the back propeller (approximately 30cm from the front motors), resulting in an equal moment about the center of gravity. This would allow all motors to produce the same amount of thrust without causing the aircraft to tilt.

2. The centre of mass also had to be at the centre of lift, which for Skywalker X-8 is given as 44cm from the nose of the aircraft. The distance of the front motors from the nose of the aircraft is approximately 14cm. With the center of mass positioned 30cm from the front motors, the center mass and center of lift are coincident.

4 Discussion

Delays in work were expected due to the late release of the competition specifications, and a complete set of project tasks not being fully realised. While some attempt was made to leave contingency time available to deal with this, some issues, in particular the vibrational disturbances (discussed above), were unexpected and took much longer than anticipated to resolve. With a majority of the physical building complete and ample contingency time allocated for the remainder of the project, it is envisioned that the project will proceed undisturbed and on time. The setup of the software architecture to allow for parallel development will allow future tasks to be completed at a much quicker rate.

5 Environmental Health & Safety

See attached task safety assessment form.

Appendix A

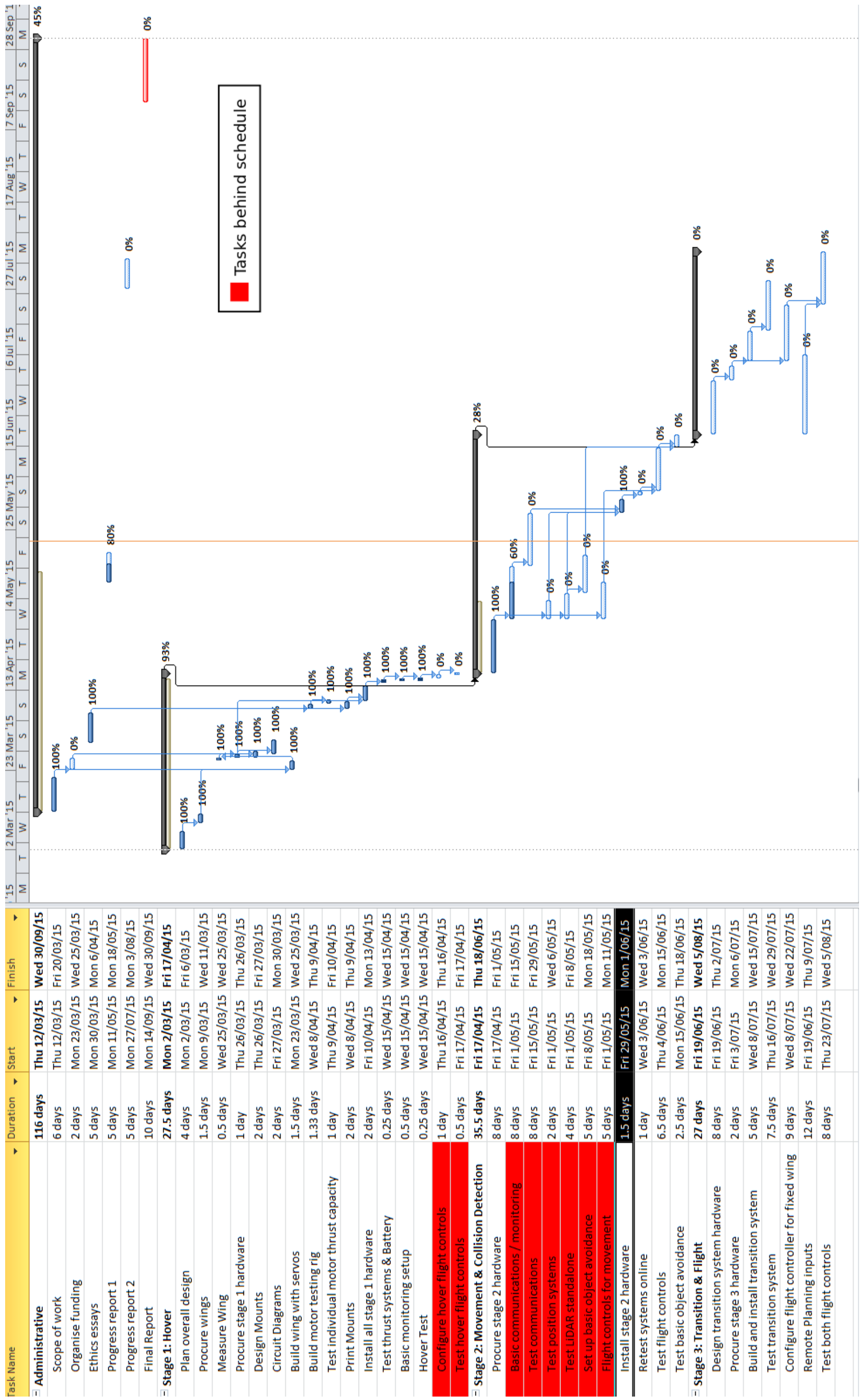


Figure 7: Updated Gantt chart, identifying tasks that are behind schedule

Appendix B

Existing Aircraft

Figure 8: Arcturus Jump, taken from http://www.arcturus-uav.com/aircraft_jump.html

Figure 9: X PlusOne, taken from
https://www.kickstarter.com/projects/137596013/x-plusone-your-ultimate-hover-speed-aerial-camera

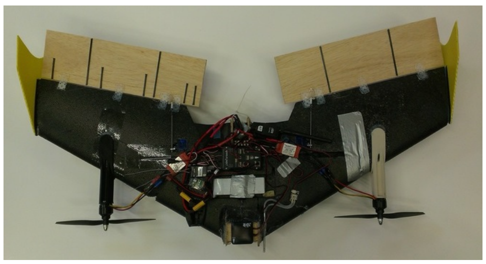


Figure 10: TBS Caipirinha, taken from https://pixhawk.org/platforms/vtol/tbs_caipirinha_vtol

Figure 11: FireFly6, taken from http://www.robotshop.com/ca/en/firefly6-vtol-y6-multirotor-drone-frame.html

eCalc Modelling

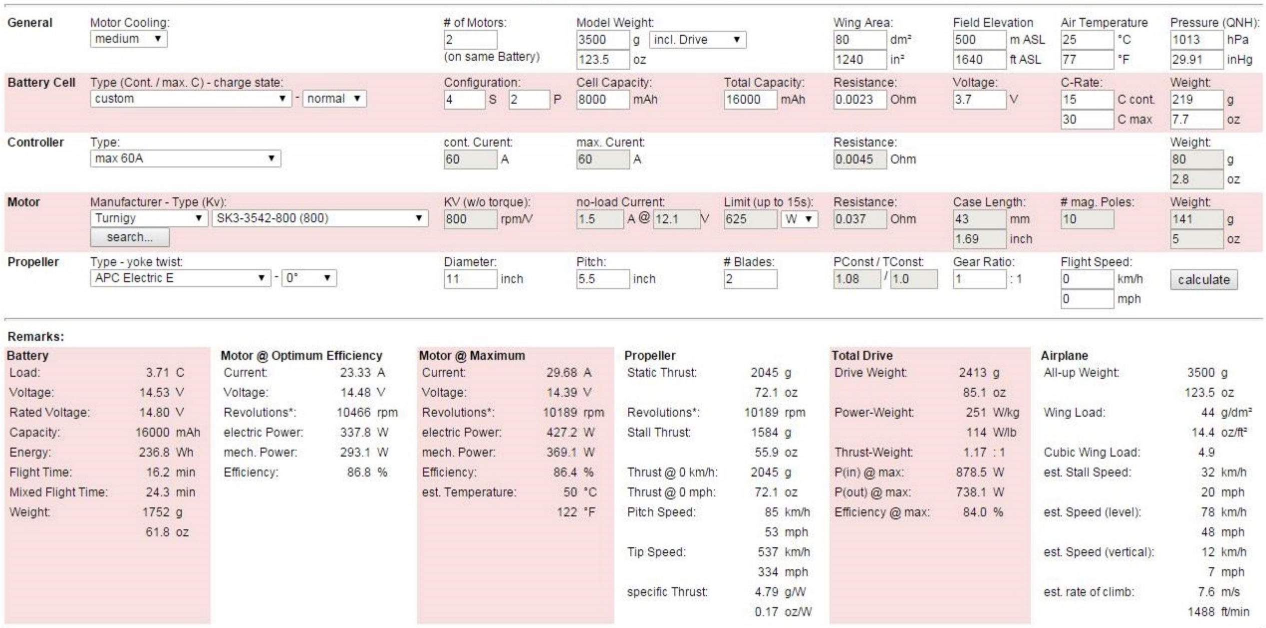


Figure 12:

Figure 13:

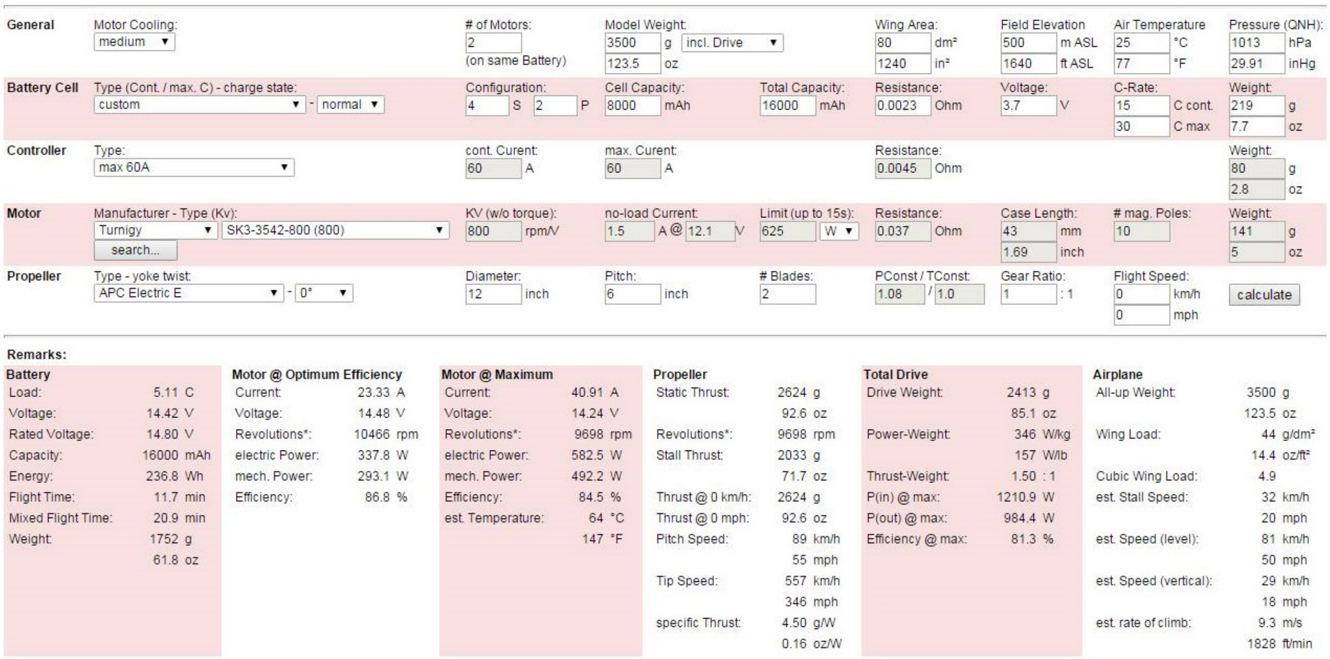


Figure 14:

Figure 15:

General	Motor Cooling: medium	# of Motors: 2 (on same Battery)	Model Weight: 4000 g / 141.1 oz, incl. Drive		Wing Area: 80 dm² / 1240 in²	Field Elevation: 500 m ASL / 1640 ft ASL	Air Temperature: 25 °C / 77 °F	Pressure (QNH): 1013 hPa / 29.91 inHg
Battery Cell	Type (Cont. / max. C) - charge state: custom - normal	Configuration: 4 S 3 P	Cell Capacity: 8000 mAh	Total Capacity: 24000 mAh	Resistance: 0.0023 Ohm	Voltage: 3.7 V	C-Rate: 15 C cont. / 30 C max	Weight: 219 g / 7.7 oz
Controller	Type: max 60A	cont. Curent: 60 A	max. Curent: 60 A		Resistance: 0.0045 Ohm			Weight: 80 g / 2.8 oz
Motor	Manufacturer - Type (Kv): Turnigy - SK3-3542-800 (800) search...	KV (w/o torque): 800 rpm/V	no-load Current: 1.5 A @ 12.1 V	Limit (up to 15s): 625 W	Resistance: 0.037 Ohm	Case Length: 43 mm / 1.69 inch	# mag. Poles: 10	Weight: 141 g / 5 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 11 inch	Pitch: 5.5 inch	# Blades: 2	PConst / TConst: 1.08 / 1.0	Gear Ratio: 1 : 1	Flight Speed: 0 km/h / 0 mph	calculate

Remarks:

Battery		Motor @ Optimum Efficiency		Motor @ Maximum		Propeller		Total Drive		Airplane	
Load:	2.50 C	Current:	23.42 A	Current:	30.00 A	Static Thrust:	2068 g	Drive Weight:	3377 g	All-up Weight:	4000 g
Voltage:	14.62 V	Voltage:	14.55 V	Voltage:	14.48 V		72.9 oz		119.1 oz		141.1 oz
Rated Voltage:	14.80 V	Revolutions*:	10518 rpm	Revolutions*:	10246 rpm	Revolutions*:	10246 rpm	Power-Weight:	222 W/kg	Wing Load:	50 g/dm²
Capacity:	24000 mAh	electric Power:	340.8 W	electric Power:	434.5 W	Stall Thrust:	1602 g		101 W/lb		16.4 oz/ft²
Energy:	355.2 Wh	mech. Power:	295.7 W	mech. Power:	375.3 W		56.5 oz	Thrust-Weight:	1.03 : 1	Cubic Wing Load:	5.6
Flight Time:	24.0 min	Efficiency:	86.8 %	Efficiency:	86.4 %	Thrust @ 0 km/h:	2068 g	P(in) @ max:	888.0 W	est. Stall Speed:	34 km/h
Mixed Flight Time:	33.3 min			est. Temperature:	50 °C	Thrust @ 0 mph:	72.9 oz	P(out) @ max:	750.6 W		21 mph
Weight:	2628 g				122 °F	Pitch Speed:	86 km/h	Efficiency @ max:	84.5 %	est. Speed (level):	78 km/h
	92.7 oz						53 mph				48 mph
						Tip Speed:	540 km/h			est. Speed (vertical):	3 km/h
							335 mph				2 mph
						specific Thrust:	4.76 g/W			est. rate of climb:	7.1 m/s
							0.17 oz/W				1396 ft/min

Figure 16:

General	Motor Cooling: medium	# of Rotors: 3 flat	Frame Size: 800 mm / 31.5 inch	Model Weight: 4000 g / 141.1 oz	incl. Drive	Field Elevation: 500 m ASL / 1640 ft ASL	Air Temperature: 25 °C / 77 °F	Pressure (QNH): 1013 hPa / 29.91 inHg
Battery Cell	Type (Cont. / max. C) - charge state: custom - normal	Configuration: 4 S 3 P	Cell Capacity: 8000 mAh	Total Capacity: 24000 mAh	Resistance: 0.0023 Ohm	Voltage: 3.7 V	C-Rate: 15 C cont. / 30 C max	Weight: 219 g / 7.7 oz
Controller	Type: max 60A	cont. Curent: 60 A	max. Curent: 60 A		Resistance: 0.0045 Ohm			Weight: 80 g / 2.8 oz
Motor	Manufacturer - Type (Kv): Turnigy - SK3-3542-800 (800) search... Prop-Kv-Wizard	KV (w/o torque): 800 rpm/V	no-load Current: 1.5 A @ 12.1 V	Limit (up to 15s): 625 W	Resistance: 0.037 Ohm	Case Length: 43 mm / 1.69 inch	# mag. Poles: 10	Weight: 141 g / 5 oz
Propeller	Type - yoke twist: APC Electric E - 0°	Diameter: 11 inch	Pitch: 5.5 inch	# Blades: 2	PConst / TConst: 1.08 / 1.0	Gear Ratio: 1 : 1		calculate

Remarks:

Battery		Motor @ Optimum Efficiency		Motor @ Maximum		Motor @ Hover		Total Drive		Multicopter	
Load:	3.71 C	Current:	23.33 A	Current:	29.68 A	Current:	20.26 A	Drive Weight:	3620 g	All-up Weight:	4000 g
Voltage:	14.53 V	Voltage:	14.48 V	Voltage:	14.39 V	Voltage:	14.52 V		127.7 oz		141.1 oz
Rated Voltage:	14.80 V	Revolutions*:	10790 rpm	Revolutions*:	10504 rpm	Revolutions*:	8237 rpm	Current @ Hover:	60.79 A	add. Payload:	369 g
Capacity:	24000 mAh	electric Power:	337.8 W	electric Power:	427.2 W	Throttle (linear):	78 %	P(in) @ Hover:	899.7 W		13 oz
Energy:	355.2 Wh	mech. Power:	293.1 W	mech. Power:	369.1 W	electric Power:	294.3 W	P(out) @ Hover:	754.4 W	max Tilt:	24 °
Flight Time:	16.2 min	Efficiency:	86.8 %	Efficiency:	86.4 %	mech. Power:	251.5 W	Efficiency @ Hover:	83.8 %	max. Speed:	35 km/h
Mixed Flight Time:	18.5 min			est. Temperature:	50 °C	Efficiency:	85.4 %	Current @ max:	89.04 A		21.7 mph
Hover Flight Time:	20.1 min				122 °F	est. Temperature:	43 °C	P(in) @ max:	1317.8 W	est. rate of climb:	3.1 m/s
Weight:	2628 g						109 °F	P(out) @ max:	1107.2 W		610 ft/min
	92.7 oz					specific Thrust:	4.53 g/W	Efficiency @ max:	84.0 %	with Rotor fail:	
							0.16 oz/W				

Figure 17:

Figure 18:

Figure 19: