Drone Building and Optimization:
How to Increase Your Flight Time, Payload and Overall Efficiency

A free eBook by Tyto Robotics

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INTRODUCTION

There are many factors that affect a drone's flight time, payload and overall efficiency. Manipulating these factors can help you achieve top performance and gain a competitive advantage in the competitive drone industry. This eBook will guide you through the relevant equations and tests for ensuring your drone, RC plane or eVTOL aircraft is performing optimally.

SECTIONS

This guide follows the drone design and testing process from start to finish, but feel free to jump ahead to the section you need:

Part 1: Drone Building

Part 2: Drone Optimization

1. AERODYNAMICS AND HOW DRONES FLY

In order for a drone to take off and fly it must overcome its weight and drag. A drone's weight is the product of its mass times gravity. Drag is the force resisting the drone's motion through the air, dependent on reference area, air density and flow velocity. The thrust produced by the propellers is translated into lift and horizontal motion, which enable the aircraft to become airborne and fly (figure 1).

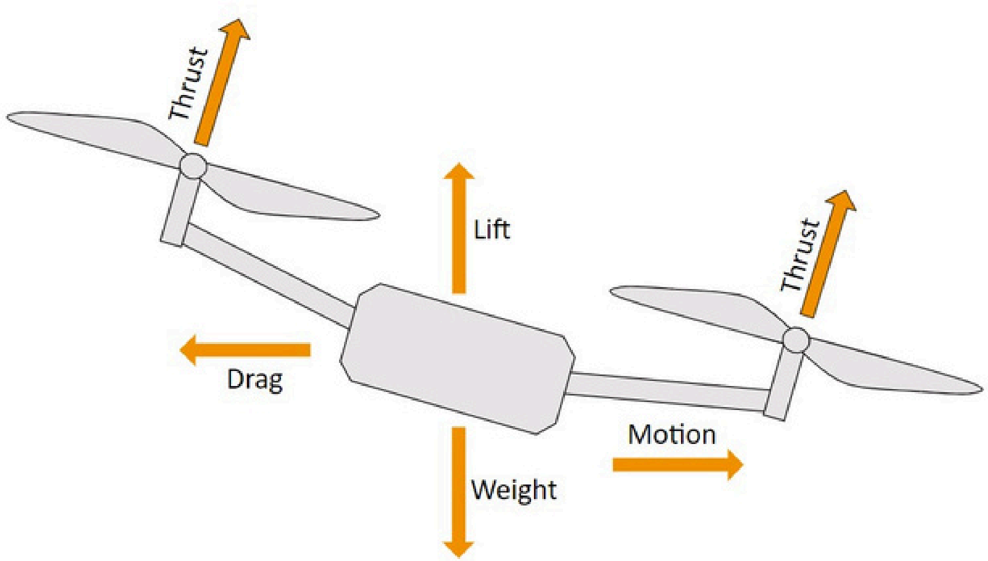

Figure 1: The forces controlling multicopter movement

These forces vary in different types of drones. For example, fixed-wing drones have aerodynamic surfaces that provide lift, so the propellers don't have to work as hard to keep the drone in the air. The thrust produced by fixed-wing drones also has a larger horizontal component as they do not have the capability for vertical take-off and landing (VTOL). In level flight, forward thrust opposes drag and lift opposes weight (figure 2).

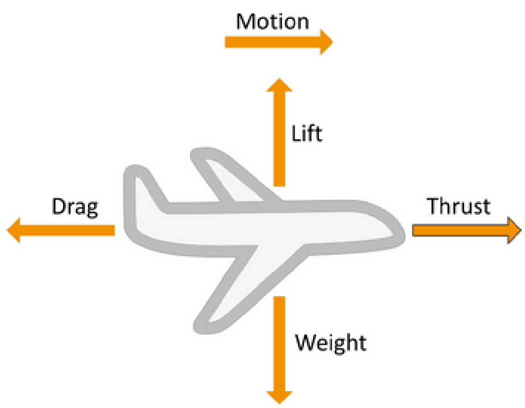

Figure 2: Fixed-wing drone forces

These features give fixed-wing aircraft the ability to fly long distances without refueling or recharging, but it also makes them unsuitable for applications that require hovering in place. More thrust and battery power is required to keep a VTOL drone in the air, but its design makes it better for changing direction and hovering in place.

The amount of thrust required for a drone to remain airborne is mainly dependent on its weight. For a multi-copter drone, hovering is possible when the weight of the drone is equal to the thrust produced by its propellers. For a fixed-wing drone, level flight at constant speed (cruise flight) occurs when forward thrust is equal to drag and lift is equal to weight. Steady flight is all about balancing these forces.

2. THE DRONE EQUATIONS

1. $\text{Hover thrust(N)} = M_{\text{drone}} \times 9.81(\text{m/s}^2)$
2. $\text{Mechanical power(W)} = \text{Torque(Nm)} \times \text{Rotation speed(rad/s)}$
3. $\text{Electrical power(W)} = \text{Current(A)} \times \text{Voltage(V)}$
4. $\text{Propeller efficiency(N/W)} = \frac{\text{Thrust(N)}}{\text{Mechanical power(W)}} = \frac{\text{Thrust(N)}}{\text{Torque(Nm)} \times \text{Rotation speed(rad/s)}}$
5. $\text{Motor efficiency} = \frac{\text{Mechanical power}}{\text{Electrical power}}$
6. $\text{Total electrical power(W)} = \frac{M_{\text{drone}}}{\text{prop}_{\text{efficiency}}(\text{g/W})}$
7. $\text{Battery capacity(Wh)} = \sigma_{\text{battery}}(\text{Wh/g}) \times M_{\text{battery}}$
8. $\text{Flight time(h)} = \frac{E_{\text{battery}}(\text{Wh})}{\text{Power(W)}} = \frac{\sigma_{\text{battery}} \times M_{\text{battery}}}{M_{\text{frame}} + M_{\text{battery}}} \times \text{prop}_{\text{efficiency}}\left(\frac{M_{\text{frame}} + M_{\text{battery}}}{\text{\# of propellers}}\right)$
9. $\text{Heat losses} = \text{Resistance}(\Omega) \times \text{Current}^2(\text{A})$

Where:
E = capacity
σ = energy density
M = mass in grams (g)

This eBook will show you how to use these equations for drone development.

3. INCREASE FLIGHT TIME, PAYLOAD AND EFFICIENCY

The drone equations hold the key to determining which variables should be altered to achieve maximum aircraft performance.

Equation 8 demonstrates that flight time is dependent on the battery capacity and the power consumed by the drone. By adding in the equations for battery capacity and total power, flight time becomes dependent on a number of factors including the weight of components, battery energy density, and propeller efficiency. Balancing these factors is essential to increase flight time. Increasing the battery's energy density alone will increase air time, but this requires changing the battery's chemistry, which can be complicated and costly.

One must also find a balance between the number of propellers and the propeller efficiency. We have a simple [flight time calculator]() that you can use to estimate your flight time using your drone's specifications and testing data. Follow the steps in the left side of the calculator document.

Ultimately, wind tunnel testing and real-world testing (described in section 8) are the best way to determine your true flight time.

Battery info	
Weight Battery (g)	
Capacity Battery (Wh)	
Energy density (Wh/g)	
# of props	
Weight without battery (g)	

Your Flight Time (min)	

Battery capacity (Wh)	Battery weight (g)	Total weight (g)	Control ratio (%)	Thrust / Prop @ Hover (g)
10		0		
20		0		
30		0		
40		0		
50		0		
60		0		
70		0		
80		0		
90		0		
100		0		
125		0		
150		0		
175		0		
200		0		

Figure 3: Flight time calculator

Increasing an aircraft's payload is also a matter of balancing variables. Keep in mind that to have a good control authority over a VTOL drone, it is recommended that the thrust produced by the drone be equal to twice its weight, so be sure to account for this in your payload calculations.

In terms of maximizing thrust, it is true that thrust increases linearly with rotation speed, but propeller efficiency also declines with a higher RPM. Adding more propellers can contribute thrust, but will also add weight and potentially change your design.

Achieving your drone's maximum flight time or payload comes down to choosing the most efficient combination of parts. Not all motors and propellers are created equal, nor do they work equally well together. Finding the most efficient combination of parts is a multi-step process involving the drone equations and real-life testing.

Our free database of electric motor and propeller performance can help to speed up this process by comparing results from other designers' public tests (figure 4). Use the "Add filters" tool to narrow results to the motors, propellers and ESCs you are interested in working with, or filter by powertrain data to narrow results with performance cut-offs.

Showing 1 to 5 of 22 entries (filtered from 384 total entries)

	Title	Author	Device	Date	Motor	Propeller	ESC
☐	U15XXL with 62" prop	Dominic Robillard	Series 1780	2020-02-03	T-Motor U15XXL Kv29	T-Motor 62"x24" CF	T Motor FLAME 280A HV
☐	U15XXL and 62"Prop from T-motor	Baiyun Tang	Series 1780	2019-12-06	T-Motor U15XXL Kv29	T-Motor 62"x24" CF	T Motor FLAME 280A HV
☐	RCbenchmark 2407 1500kv 9x4 propeller v2	Audrey Schwartzenberger	Series 1580	2019-11-18	RCbenchmark x Xoar 2407 1500kv	RCbenchmark x Xoar 9x4	RCbenchmark x Xoar F50
☐	RCbenchmark 2407 2300kv 9x4 propeller	Audrey Schwartzenberger	Series 1580	2019-11-18	RCbenchmark x Xoar 2407 2300kv	RCbenchmark x Xoar 9x4	RCbenchmark x Xoar F50
☐	TA130-25 Kv80 with Xoar 40x10	Erwan Labadie	Series 1780	2019-04-16	Xoar TA130-25 KV80	Xoar PJP-T-L 40"x10"	Xoar titan esc

Figure 4: Database of motor, propeller and ESC performance

4. CHOOSING THE RIGHT MOTOR AND PROPELLER

The process of choosing the right motor and propeller for a drone begins with certain assumptions. We assume the final design will be airworthy and that the application has been determined. These assumptions help determine the quantity of thrust we need to aim for. For the purpose of this eBook, we will use a simple example to demonstrate the optimization process and the testing required.

Assumptions

Let’s say we are optimizing a quadcopter for inspection flights - checking power lines, wind turbines, etc. We can assume the drone will mainly hover and doesn’t need to reach high speeds or carry extra payload. The drone and all of its components, including a built-in camera and thermal sensor, will weigh <20 kg. The exact mass may change as we experiment with parts, but it won't exceed 20kg.

We use equation 1 to determine that we need a total of 196 N of thrust to keep the drone at hover where it will conduct most of its operations, (20)*(9.81) = 196 N. Since the drone is a quadcopter, each propeller will need to generate about 50 N of thrust for the drone to hover, equivalent to about 20 kgf (196 N/ 4 = ~49 N). For simplicity and a safety margin, we will round 49 N to 50 N.

Figure 5: Brushless motors and drone propellers

Choosing the propeller

When choosing a propeller, there are several variables to consider including the diameter, pitch, weight, and material. The diameter of the propeller refers to the diameter of the circle created by the blade tips during rotation, usually reported in inches. The pitch refers to the distance the propeller will travel in one full rotation through a fluid. The size of the propeller is often reported as a four-digit number, with the first two numbers referring to the diameter and the second two referring to the pitch. For example, a propeller with a 6.0" diameter and a pitch of 4.0" would be reported as: 6040 (figure 6).

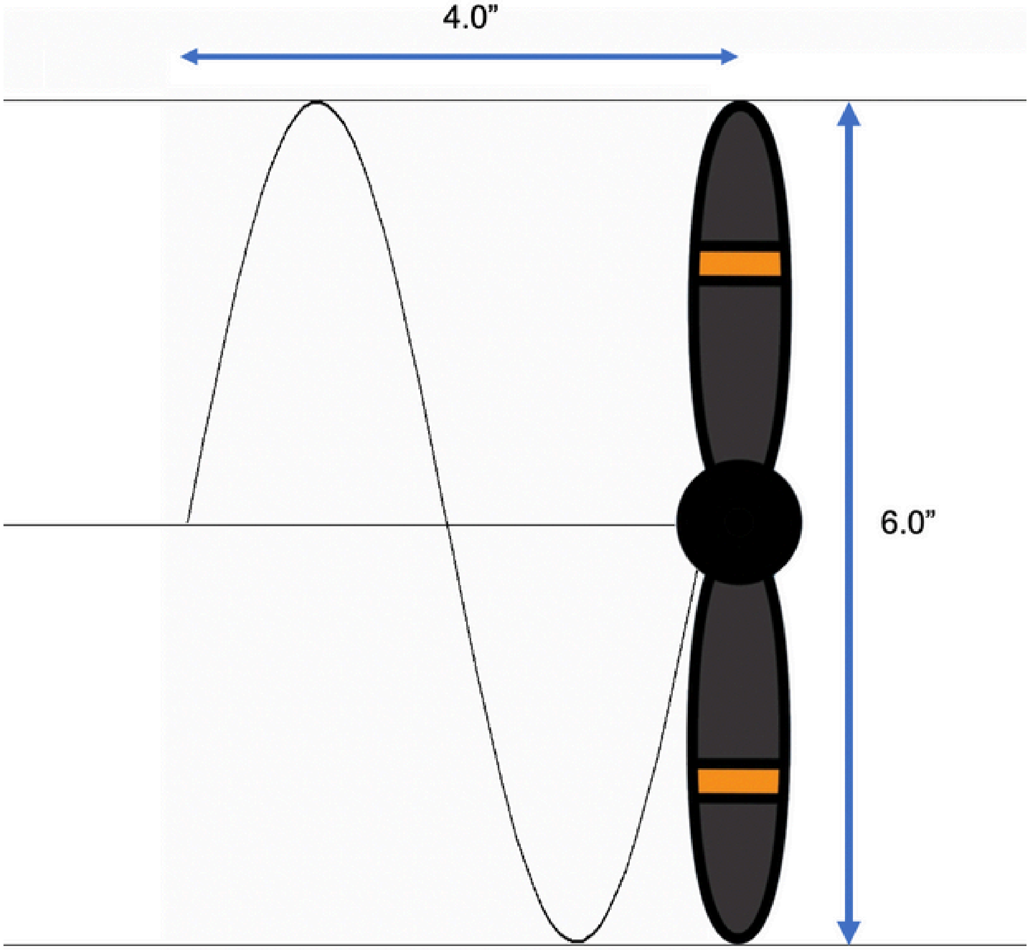

Figure 6: Diagram of propeller with a 6.0" diameter and 4.0" pitch

The weight of the propeller is dependent on its size and also on the material it is made of. Most drone propellers are made of polymeric composites that have a good balance of strength and weight, such as carbon fibre, nylon, fibreglass and stainless titanium.

The propeller diameter is limited by the size of the frame in many designs, but there is some room to play within that limit. The thrust of a specific propeller depends only on the propeller speed and the incoming air speed, so it is a matter of determining which propeller operates most efficiently. Longer propellers can generate higher thrust at a set speed, but it takes more torque and power from the motor to get them spinning. The same goes for the number of blades: more propeller blades produce more thrust, but they also have higher heat loss and lower efficiency.

Finding the ideal pitch for the propeller is also a balancing act as a higher pitch leads to an increase in thrust, but also increased heat losses. Lift and drag both increase with pitch, so the most efficient operating point exists where the lift: drag ratio is highest. Propulsion testing can help to determine which propeller has the ideal pitch and diameter for the desired operating range.

Another rule of thumb: less mass = more flight time, so if you can select a lighter propeller without losing thrust or strength, this can increase your air time.

Equation 4 tells us that to select the most efficient propeller we need to know the thrust, torque and rotation speed of the candidates. Achieving the highest output (thrust) to input (mechanical power) ratio gives us the highest efficiency.

Thrust, torque and rotation speed can be acquired with a test stand such as the Flight Stand 15. This stand can measure up to 15 kgf of thrust. We will compare three propellers with a diameter of 40" or less in this test:

	A	B	C
Diameter	40”	39”	39.5”
Pitch	9”	9”	10”
Mass	380g	375g	385g

Table 1: Propeller characteristics

A propeller’s thrust depends on the propeller speed and the incoming air speed, not on the motor powering it. Regardless of the motor you choose, the thrust generated will be the same at a given RPM. This is demonstrated in Figure 7.

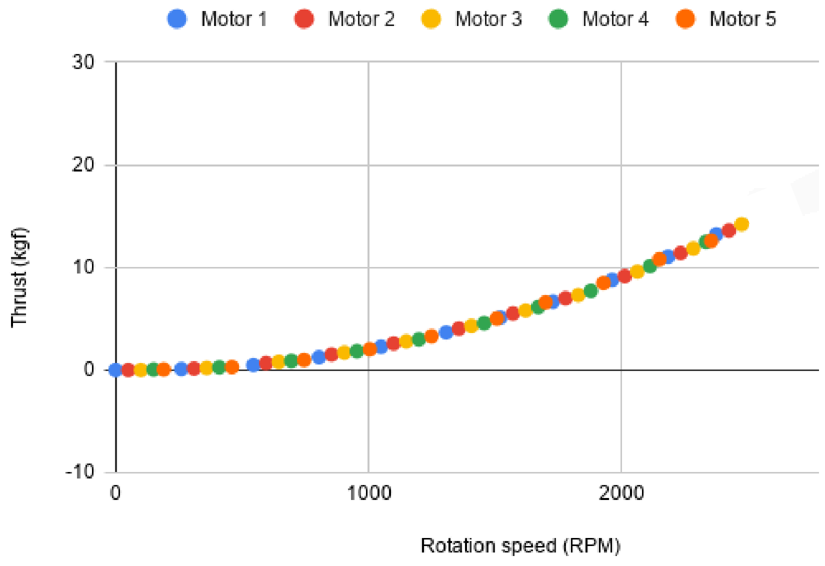

Figure 7: Thrust of Propeller A with five different motors

We will run a performance test with each of the propellers to determine their thrust, torque and RPM, which are automatically used to calculate efficiency values. The tests can be run manually or with a script. We need to find the propeller that most efficiently produces 50 N of thrust and can also produce a peak thrust of 100 N. As can be seen in figure 8, all three propellers can produce the peak thrust, but propeller A is the most efficient at 50 N with 16 N/W. Therefore, we will choose to use propeller A in our design.

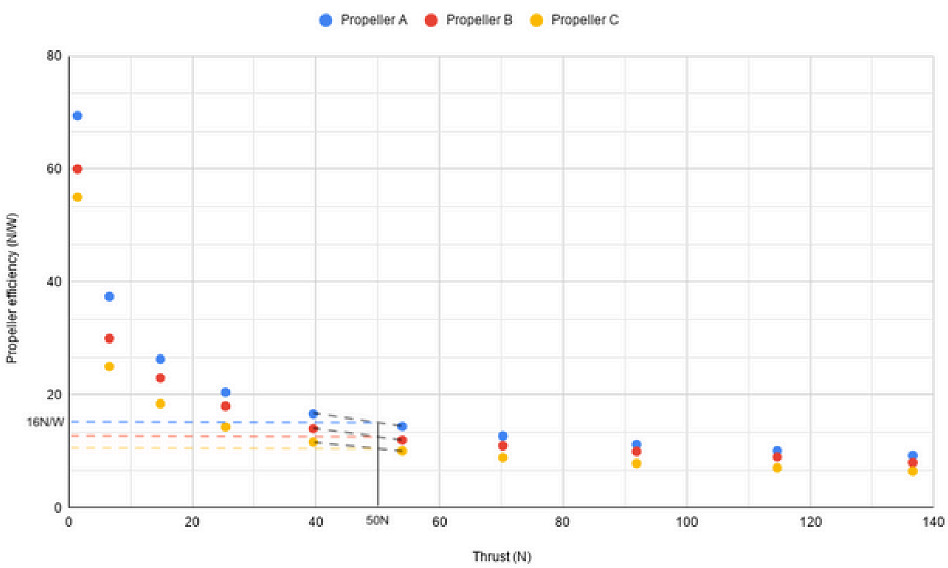

Figure 8: Propeller efficiency vs. thrust

At 50 N propeller A generates 2.2 Nm of torque at 1415 RPM (figure 9). At our peak thrust of 100 N, it generates 4.5 Nm of torque at 2050RPM. This information will help us to choose the correct motor to go with this propeller.

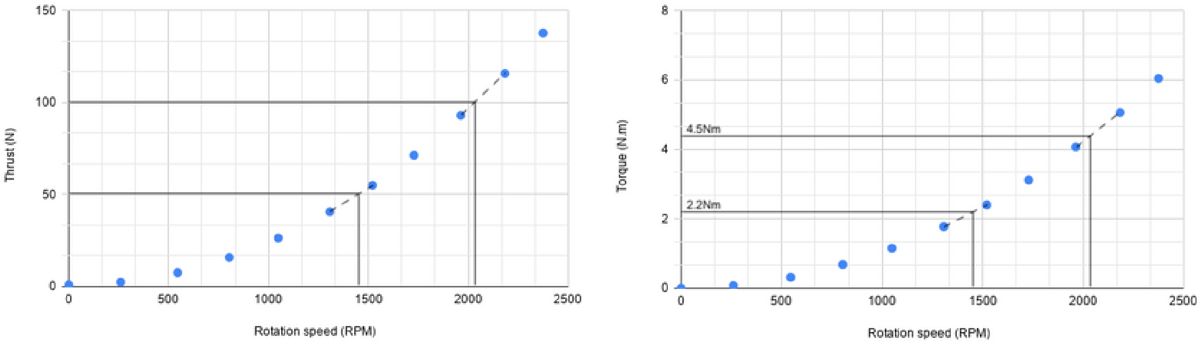

Figure 9: Rotation speed vs. thrust (left) and torque (right)

Choosing the motor

The first step in finding the most efficient motor is creating a shortlist of candidates based on our needs and limitations. Some manufacturers provide motor specifications on their websites, though information may be missing or incomplete. For larger projects, consult our detailed list of brushless motor manufacturers for large drones and eVTOL applications.

When comparing motors, several properties can vary such as weight, stator-rotor layout, and Kv. The weight of the motor is important for the same reasons as the weight of a propeller. While a larger, heavier motor may produce more thrust and torque, it can also weigh down the drone and reduce flight time.

The stator-rotor layout can come in the form of an inrunner, where the rotor is within the stator, or an outrunner, where the rotor is outside the stator (figure 10).

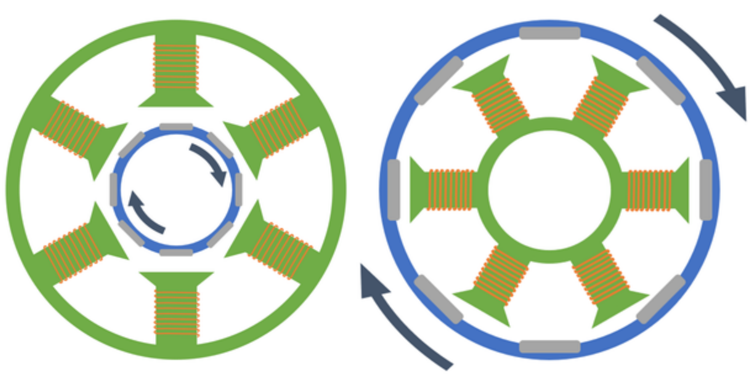

Figure 10: Inrunner (left) and outrunner (right) motors

Outrunners have a larger rotor diameter, which means they produce high torque and run better at lower RPMs. Inrunners have a smaller diameter and can efficiently run at higher RPMs, though they produce less torque. Inrunners are often coupled with a gearbox to help generate more torque, though this increases the number of components that can fail.

The Kv rating refers to the number of revolutions per minute a motor with no load will turn when 1 volt is applied to it. The value is often reported in terms of Kv, i.e. 100 RPM/V = 100 Kv. Therefore, if a 100 Kv motor was connected to a 20 V battery, it would spin at 2000 RPM. Low Kv motors operate at lower RPMs and produce more torque, ideal for larger propellers. High Kv motors operate at higher RPMs and are ideal for low torque, small, and fast spinning propellers.

A few helpful rules:

1. Go with the smallest motor that will meet your performance needs. There is little benefit in having more thrust capacity than required, but the extra weight will negatively impact your flight time.
2. While smaller drones tend to have inrunner motors due to their high RPM and efficiency, larger drones may benefit from the high torque of outrunner motors.
3. Lighter, fast moving drones such as racing quads are best served by high Kv motors that offer high RPM. Heavier, slower moving drones are better served by low Kv motors that offer high torque to turn a large propeller.

From our propeller data, we know that our motor must generate at least 100 N of thrust, 4.5 Nm of torque and rotate at 2050 RPM. We will narrow it down to three motors that are capable of operating at our hover and peak thrust performances, found using our database of electric motor data:

	A	B	C
Mass	2070g	1950g	2000g
Style	Outrunner	Outrunner	Outrunner
Kv rating	80Kv	100Kv	80Kv

Table 2: Motor characteristics

Since we have determined that we will use propeller A, we are now looking for the most efficient motor at the operating point of 50 N, 2.2 Nm and 1415 RPM.

Figure 11 shows the mechanical efficiency of the motors when run with propeller A. At 50 N of thrust, the most efficient motor is motor B with about 64% efficiency. We did not determine that this is a better motor in general, only that it performs best with this specific propeller. We can also see in figure 11 that motor B is capable of reaching our peak thrust of 100 N.

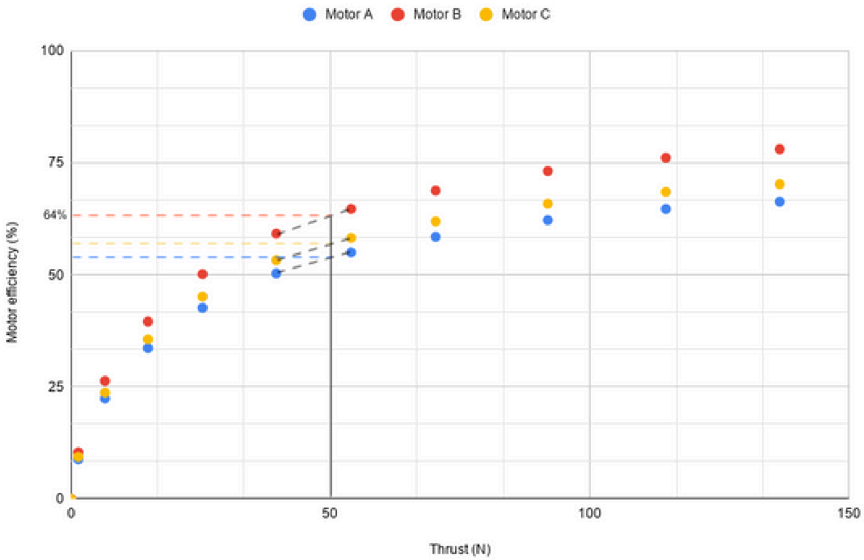

Figure 11: Motor efficiency vs. thrust

Finally, we must confirm that motor B is capable of generating 4.2 Nm of torque and rotating at 2050 RPM. Tests performed with motor B and propeller A confirm that it can achieve this performance (figure 12):

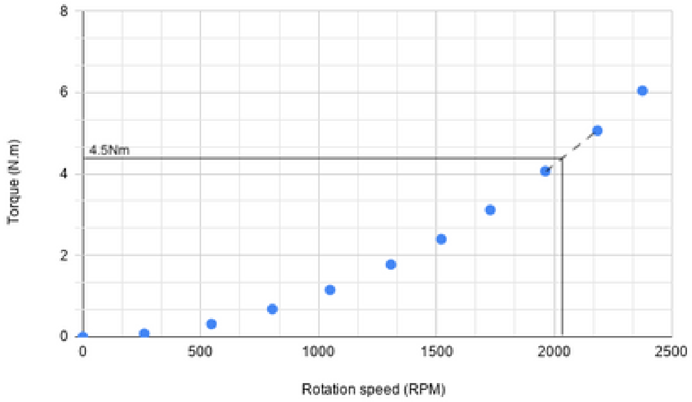

Figure 12: Thrust, torque and RPM of motor B with propeller A

5. CHOOSING THE RIGHT BATTERY

Choosing the right battery and ESC will not only help improve performance, but also increase the lifetime of your drone. Just like the motor and propeller, your battery will eventually fail, but this can be postponed by choosing the right one.

Drone batteries

The most common batteries in drones are lithium-based due to their high energy density compared to nickel cadmium or nickel metal hydride batteries. Lithium-polymer (LiPo) batteries differ from other Li-Ion batteries because they are made of a porous/ gel-like compound instead of a liquid. LiPo batteries rival Li-Ion batteries in terms of energy density, but are especially popular because they are less likely to leak or combust.

The energy density of LiPo batteries ranges from 140 - 265 Wh/kg in terms of weight and 250 - 730 Wh/L for volume. Volume energy density is important to consider when building a drone so the battery fits on the frame, but for performance calculations, the energy density by weight is more relevant. With higher density comes higher cost, so budgets may be a limiting factor.

For common LiPo batteries, the nominal or average voltage is 3.7 V/cell with a maximum voltage of 4.2 V/cell. After the cell is fully charged, it will briefly provide 4.2 V before dropping to 3.7 V for most of the battery life. It becomes dangerous to discharge the battery after the cell voltage has dropped below 3.2 V because the resistance in the battery increases, causing it to heat up and swell, resulting in damage.

To avoid this, many motor manufacturers have added a low voltage cutoff (LVC) to their controls, which stops them from drawing charge after a certain threshold, usually in the range of 3.2 - 3.4 V. Overcharging a LiPo battery is equally dangerous and can result in overheating and even an explosion.

For more LiPo battery safety tips, check out The Drone Girl's article on "15 things every LiPo battery user should know".

LiPo batteries are labelled with a few important pieces of information, including: battery capacity, voltage, cell configuration and discharge rate (figure 13):

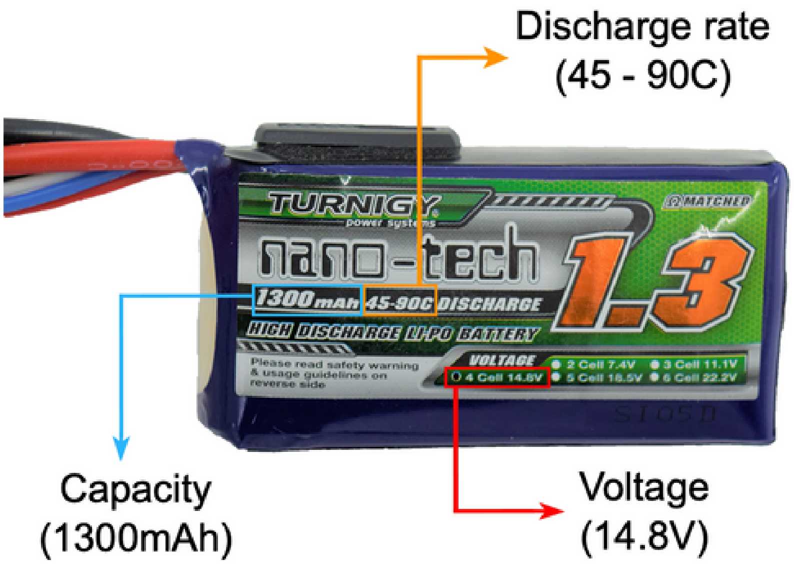

Figure 13: LiPo battery labels

- Battery capacity is given in mAh or Ah and can be used to estimate your flight time using equation 8. Battery capacity is more specifically defined as the number of hours of current or power the battery can provide. Common units are the ampere-hour (Ah) and the watt-hour (Wh). If a battery has a capacity of 1 Ah, you can draw 1 A of current for one hour. If the capacity is 1 Wh, the battery would provide 1 W of power for one hour.

- The voltage rating of the battery will allow you to determine your motor speed and amperage. Since motors are rated in Kv with the unit RPM/Volt, the number of volts your battery can supply will determine how fast your motor will spin. You can cause damage to your circuit or even cause a fire if your voltage rating is too low or your current drawn is too high, so it is important to choose your battery voltage carefully.
    - To determine the maximum current that your drone will draw, set up your motor and propeller with a propulsion test stand and run them at maximum throttle. The current recorded at 100% throttle tells you the maximum amperage your motor will draw, so multiply this by the number of motors to get the total current draw for your drone. The battery should be able to provide at least this amount of current to avoid overheating.

    - Another way to determine the maximum amperage you can draw from the battery is by multiplying the capacity in Ah by the C rating. For a battery rated for 5800 mAh/5.8 Ah and 25C continuous, the maximum current you can safely draw is 145 A (5.8 x 25 = 145).

- The cell configuration is sometimes present on the label and describes the number and layout of LiPo cells in the battery. Recall that one LiPo cell has a nominal voltage of 3.7 V and several LiPo cells can be connected in series. A 4S battery would have four LiPo cells in series (S), giving a 14.8 V battery (4 x 3.7 V = 14.8 V). A battery might also have a code like 4S2P, which tells us that there are four cells connected in series and two cell sets connected in parallel (P), for a total of eight LiPo cells.

- The discharge rate or the C rating is a measure of how quickly the battery can safely discharge. If a battery has a C rating of 25 and a capacity of 5800 mAh/ 5.8 Ah, you could safely discharge it at 25 times the capacity of the battery, 25 x 5.8 = 145 Ah. With continuous power at that rate, the 5.8 Ah battery could be discharged in 2.4 minutes ((5.8 / 145) x 60 = 2.4). Batteries may also have a range or 'peak' discharge rate, where the battery may exceed its constant power output for a short period of time without overheating, such as during a sudden climb or correction. A higher C rating is great for applications like drone racing that require bursts of speed, since the battery can deliver the charge needed very quickly.

Choosing the battery

The best battery for your drone is the one that best suits your application. If flight time is your main concern, you will want to reduce your mass and maximize battery capacity (equation 8), which is dependent on energy density and mass (equation 7). If power and speed are your top priorities, you will want a battery that can deliver high amounts of charge quickly and without overheating, so you're looking for a high voltage and C rating.

Here is a summary of how each battery variable affects your performance:

Battery capacity

- Higher capacity = higher mass = longer flight time (in general)
- Increasing battery capacity will give you more flight time, but with diminishing returns as the mass of the battery increases (figure 14)
- Testing several batteries can help you find the maximum useful capacity

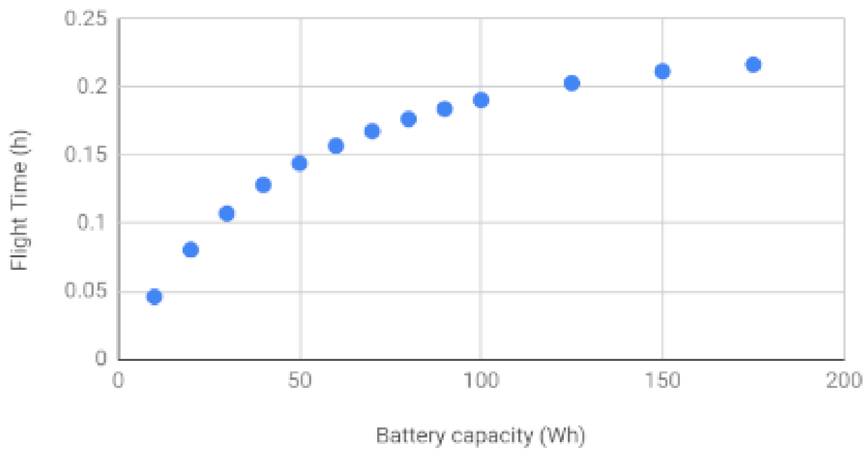

Figure 14: Flight time vs. battery capacity

Voltage

- Higher voltage batteries will spin the motor at a higher RPM, so find a voltage that matches your desired rotation speed range
- Higher voltage batteries tend to be more efficient but also heavier - consult efficiency values from thrust tests to find a balance

Discharge/ C rating

- Choose a rating based on your application - high speeds and quick delivery vs. constant low power
- If the discharge rate is too low, your drone will lack power and underperform
- If the discharge rate is too high, you may be carrying unnecessary weight

Current draw

- Use the techniques mentioned to determine the current drawn by your motors
- The battery should be able to provide at least as much current as the drone will draw to avoid overheating

For our inspection quadcopter, we want a battery that will give us a long flight time, but we don't need fast power bursts. We will choose a battery with the highest possible capacity that still keeps our drone's total weight at less than 20 kg. Our drone's mass so far is approximately 12.5 kg so we have about 7.5 kg of weight available for our battery (4 propellers x 0.38 kg + 4 motors x 1.95 + 2.5 kg frame and cameras + 0.7 kg ESC and wires = 12.5 kg).

Our motor manufacturer tells us that our motor's maximum continuous current is 100 A. Multiplied by 4 motors, our battery would need to be able to provide at least 400 A of continuous current if operated at maximum capacity. However, we can look at our motor's thrust tests to see that at double our hover thrust (100 N), each motor only draws about 27 A (figure 15). Multiplied by 4 motors, our drone will be drawing no more than 108 A total for the majority of its mission.

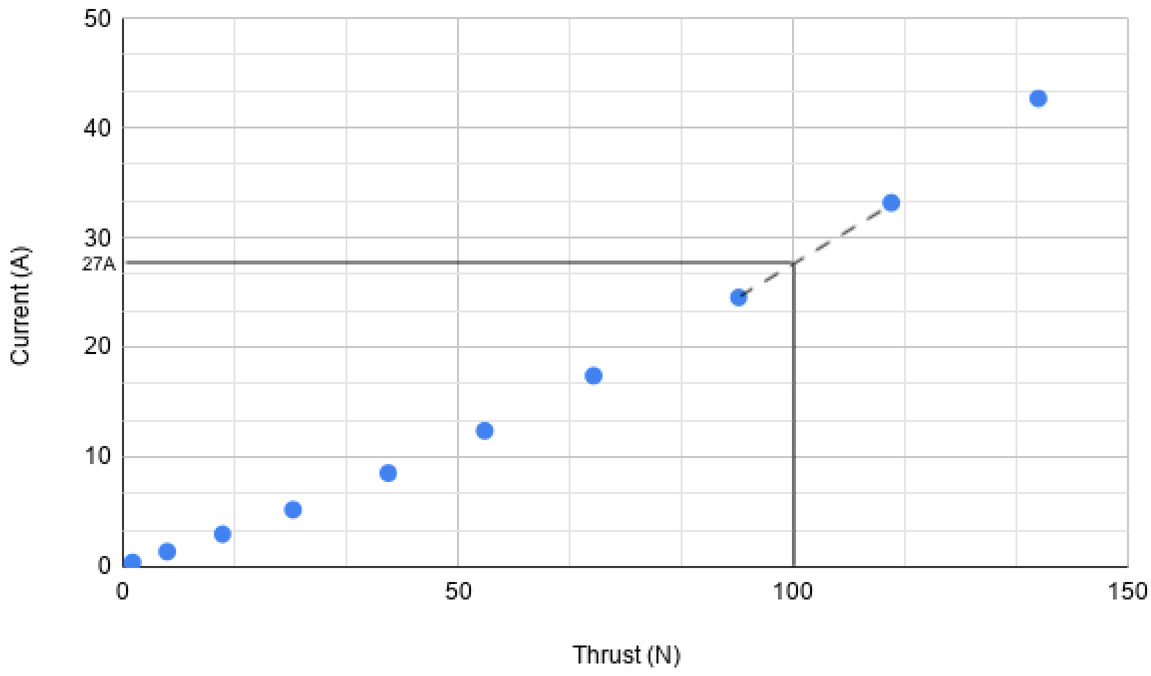

Figure 15: Motor thrust and current draw

In terms of voltage, the motor manufacturer did not provide any data, but we can return to our propulsion test results to see that the motor drew between 45 - 49 V in our operating range (figure 16).

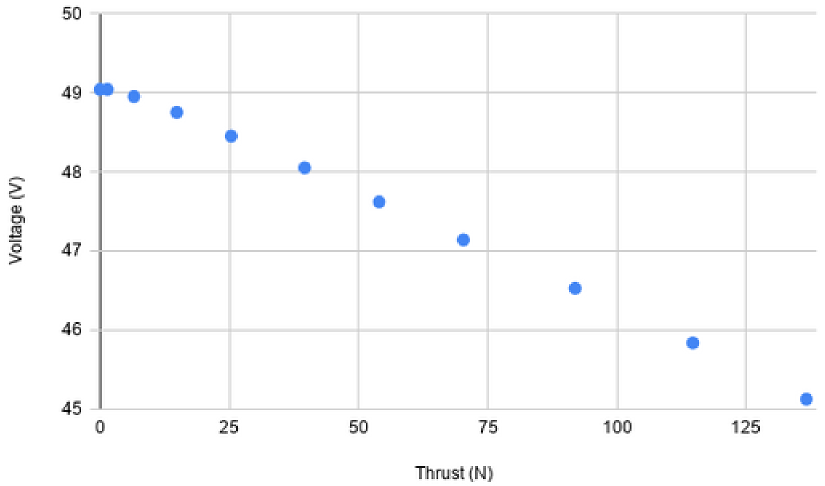

Figure 16: Voltage drawn by the motor

We don't need explosive speed for our drone, so we will look for a 14S / 51.8 V battery with a minimum discharge rating of 25C, weighing less than 7.5 kg.
Here are our candidates:

	A	B	C
Mass	6900g	7100g	6450g
Capacity	22,000mAh	20,000mAh	22,000mAh
C Rating	25C	65C	25C
Flight time	32 mins	29 mins	33 mins
Price	$450	$290	$350

Table 3: Battery characteristics

To calculate the estimated flight time we used a revised version of equation 8. We converted Ah to Wh by multiplying the Ah value by 47 V and we used a fixed value of 10 g/W for propeller efficiency:

$$Flight\ time(h) = \frac{E_{battery}(Wh)}{M_{drone}/(10g/W)}$$

Based on these results, battery C will give us the longest flight time (33 mins), and won't exceed our weight limit. The maximum current we can draw from this battery is 550 A (22 Ah x 25C = 550), which exceeds the max. draw of our motor.

6. CHOOSING THE RIGHT ESC AND CONNECTORS

The final step is to find an ESC that will receive data from our controller and act as the brain of our drone. Once we hook it up with the correct wires and connectors, we will be ready to start testing our design.

Electronic speed controller (ESC)

The role of the ESC is to deliver power from the battery to the motor in a controlled manner. If you input 50% throttle on the controller, the ESC will deliver 50% power to the motor. One one end, the ESC has two wires to connect the battery, a red (positive) wire and a black (negative) wire (figure 17).

On the other end are three wires that connect the ESC to the coils of the brushless motor. If the motor spins in the wrong direction after connecting it to the ESC, switching any two of the wires will make it spin in the right direction.

The final extension connects to the throttle receiver, which is powered by the battery eliminator circuit, discussed later.

Figure 17: External view of ESC wiring

Within the ESC there are a number of important components, including the microcontroller, gate driver and MOSFETs (figure 18).

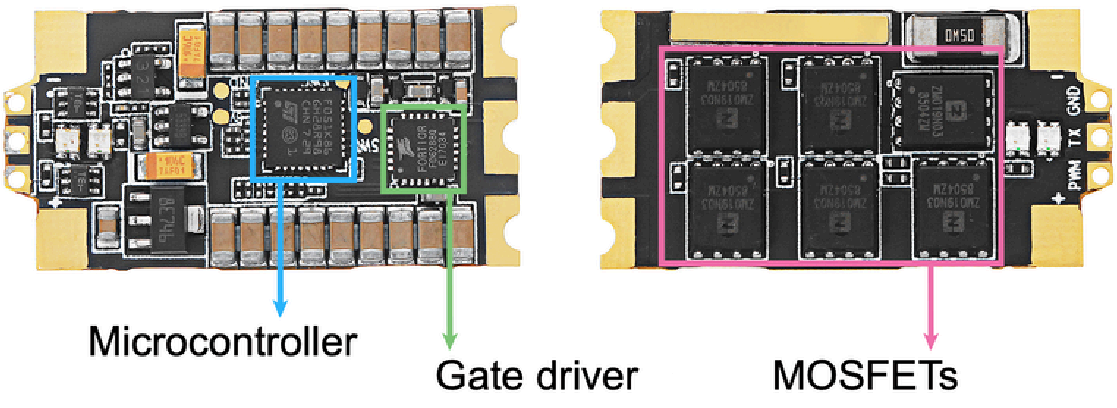

Figure 18: The microcontroller, gate driver and MOSFETs in an ESC

Microcontroller

The microcontroller plays two key roles in the ESC's operation: 1) housing the firmware that interprets signals from the controller, 2) keeping track of the motor's position in order to ensure smooth acceleration.

- The firmware used in ESCs is often pre-installed by the manufacturer, but open source versions can also be obtained from 3rd party sources. In hobby drones, the pre-installed firmware is generally a variation of BLHeli, either BLHeli_S or BLHeli_32, though other softwares like SimonK and KISS are also available. The chosen firmware must be compatible with the hardware as it will determine the ESCs performance and what protocols can be used.

- The microcontroller also determines the motor's position through a sensored or sensorless system. Sensored systems use electronic sensors in the motor to track the rotor's position, great for low speed, high torque applications such as ground vehicles. The more popular sensorless systems use back EMF to determine the location of the rotor relative to the stator. This works great at high speeds, though when the motor is turning at lower speeds with less back EMF, the sensorless system does not work as well. This is generally not an issue when driving a propeller. Overall, for high speed applications, the sensorless system is more efficient, cheaper and more reliable.

Gate driver

The gate driver's job is to act as the middleman between the controller and the gate of the MOSFETs. Upon receiving a low-voltage signal from the micro-controller, the gate driver amplifies the signal and delivers a high-voltage signal to the MOSFETs. The driver has lower resistance than the microcontroller so can deliver higher current, which also amplifies the speed of the signal. This allows for faster switching and lower heat production. Some ESCs have insulation optical chips between the low voltage microcontroller and the high voltage transistors. Manufacturers sometimes call those ESCs Opto-ESC.

MOSFET

The Metal Oxide Semiconductor Field Effect Transistors or MOSFETs are switches that strategically deliver power to the motor. The ESC has six of these transistors and each wire from the motor is connected to two of them. The MOSFETs receive signals from the microcontroller then deliver power to the motor so that each of its coils is in one of three phases: high voltage, low voltage, or off/ grounded.

As the motor rotates, the signals from the MOSFETs switch the phases of the coils so the push-pull of the permanent and electromagnets keeps the rotor spinning. The ESC uses direct current coupled with the switch system to achieve an alternate three-phase current (figure 19). The higher the throttle input, the faster the switching frequency, leading to a higher RPM in the motor. There are several signal delivery protocols that control this process, each with a different performance and signal frequency.

For a more detailed explanation of a motor's inner workings, check out our article on [How brushless motors work](#).

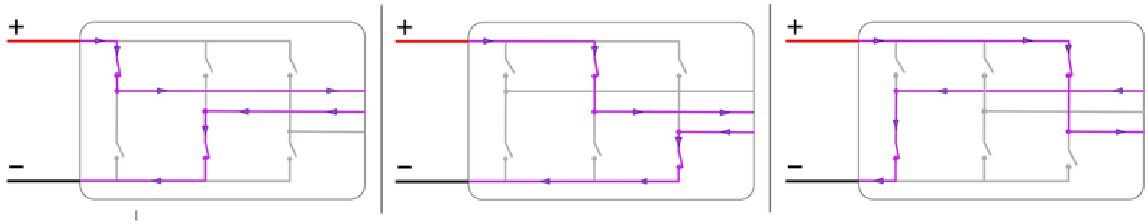

Figure 19: Electronic speed control in three steps

Signal delivery protocols

There are a number of protocols the flight controller can use to communicate with the ESC. These work like unique signal languages with different ways of conveying throttle information. Prior to 2015 there was just one ESC protocol commercially used by small UAVs, called pulse width modulation (PWM). Since then, several new protocols have been created and it is common for hardware developed after 2017 to support all or most of them.

The most commonly used protocols include Oneshot125, Oneshot42, Multishot, and Dshot300, Dshot600 and Dshot1200. The Oneshot and Multishot protocols use analog signals like PWM, whereas Dshot uses a digital signal. Analog protocols require calibration to ensure that the oscillators in the flight controller and ESC are synced, while digital protocols do not require this step. Newer protocols synchronize the control loop with the ESC update signal to minimize latency.

Dshot1200 is the fastest protocol, delivering 1,200,000 bits of data per second. Dshot1200 has a fixed signal length of just 13 us, which is almost twice as fast as Multishot, which is the next fastest with a 25 us signal length (figure 20). While Dshot1200 is impressively fast, some say the difference between Dshot600 and Dshot1200 is negligible in practice. Following Multishot is Dshot600 and Oneshot42 with higher signal durations.

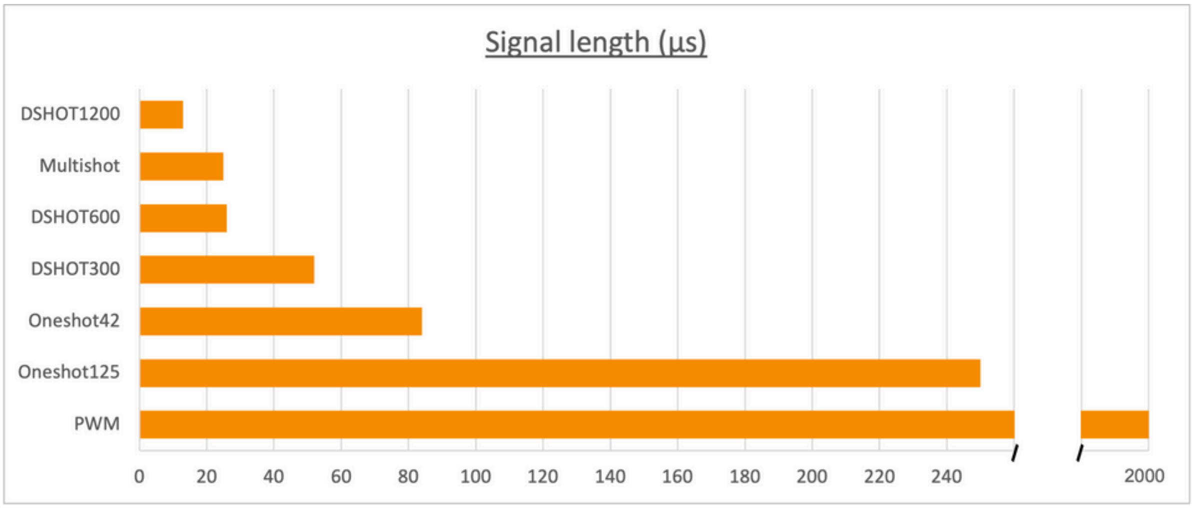

Figure 20: Signal length for common protocols in microseconds

ESC voltage and current

ESCs have a maximum voltage limit that may be given as a voltage range or a cell range: an ESC rated for 3S - 8S cells will support a voltage of 11.1 - 33.6 V. Some ESCs offer the option of changing the chemistry type and number of cells for automatic low voltage protection based on the battery's chemistry. The ESC may also let you set a switch-off voltage that will alert you when the battery voltage becomes too low (3.0 - 3.4 V). A low voltage cut-off (LVC) circuit senses the voltage drop as the battery discharges and sends a warning signal or commences an automatic shut down procedure in response

The ESC's current rating should be 10 - 20% higher than the motor's. This will prevent it from overheating and provide a bit of wiggle room when operating at max throttle. You do not want to go much higher than this range because if the ESC delivers a much higher current it could damage the motor. The ESC has two current ratings: continuous and burst. The continuous current is sustainable for prolonged periods of time and the burst current for short periods only.

When wiring ESCs into a quadcopter you can have one ESC for each motor or use a 4-in1 ESC with a single board and four motor connectors. Having four ECSs can help spread the load if the motors have a high power draw while a 4-in-1 ESC is a great option for saving space and limiting weight from hardware.

ESCs often have a built-in battery eliminator circuit (BEC), which doesn't eliminate the need for a battery but acts as a voltage regulator to eliminate the need for a separate battery for on-board electronics. The power going through the BEC is dropped to a lower voltage, usually 5 V, which safely powers the receiver and any other devices on board (figure 21).

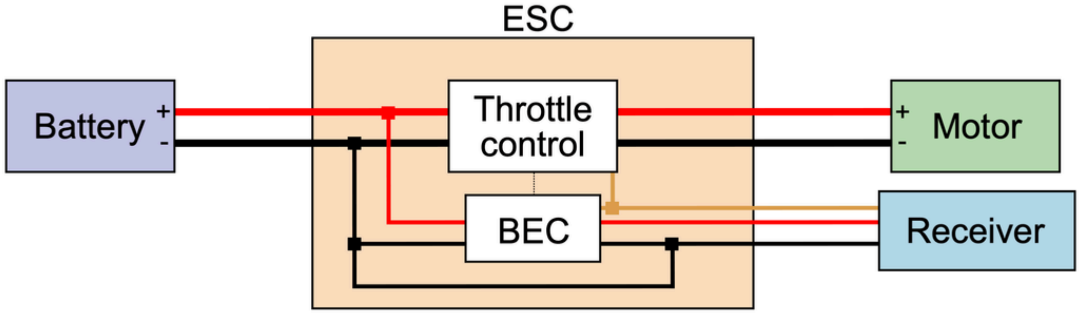

Figure 21: Drone power circuit including an ESC and a BEC

Wires and connectors

Let’s also look at the factors involved in selecting the right wires, connectors and circuit protectors. When choosing wiring you must be sure that it can handle the current that will be flowing through it. Multi-strand silicone wires are commonly used to connect drone batteries due to their flexibility and heat resistance. It is important to check current ratings with wire manufacturers, but for a rough estimation you can use this formula to approximate the current capacity of a silicone wire, current rating (A) = cross sectional area (mm2) x 25. For long wires used in large drones, it is also wise to calculate the voltage drop per meter.

There are several types of connectors that can be used to connect the battery to the ESC. A few of the most common connectors are Deans, EC3, EC5, XT60, and XT90 (figure 22). Most LiPo battery connectors are polarity protected so it is impossible to plug them in backwards. It is important to ensure that the connector is rated for the current coming from the battery because if it is not, overheating or a voltage drop can occur. Connectors follow the same principle as the wiring in that the larger the connector, the more current they can handle.

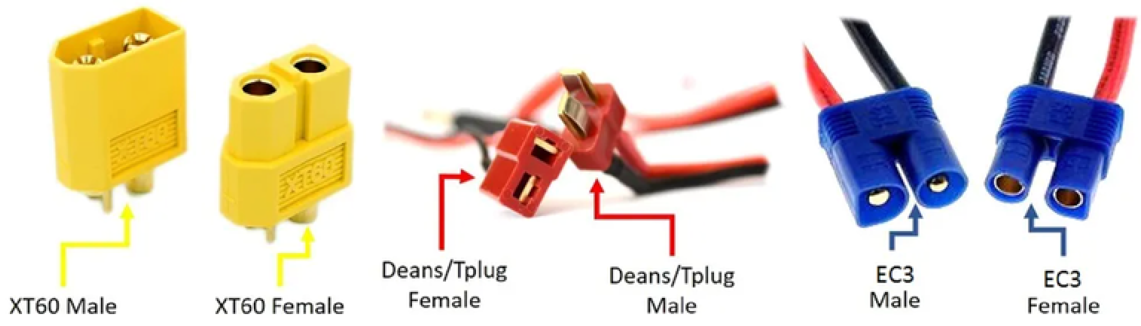

Figure 22: Common battery connectors, image from modelflight.com

Connectors can vary in terms of life span, how easy they are to solder or replace, how easy they are to plug and unplug, and cost. Cost differences are easy to observe, but preferences for the other variables can develop with experience over time. Many drone batteries will come with a connector already fitted so if you aren't picky, you can use the ones that come with the battery. For larger batteries (>150 A) there is less selection for off-the-shelf connectors, so this may be the simplest option.

Choosing the ESC and connectors

We have determined that the maximum current drawn by our motors is 400 A, so we will choose an ESC setup that can handle a 10 - 20% higher current, in the range of 440 - 480 A. We could go with four ESCs that operate in the range of 110 - 120 A or a 4-in-1 ESC with a 440 - 480 A range. The 4-in-1 ESCs on the market don't meet our current needs so we will use four separate ESCs.

The ESC we will select is rated for 120 A, 5-14S batteries, and weighs 140 g. Multiplied by four ESCs this is equal to 560 g, which will keep us within our weight limits even after wiring is considered.

Our batteries are pre-fitted with XT-90 connectors, which we will keep in our design. The ESC also has BLHeli_32 firmware pre-installed, so we know it will be compatible with almost any control protocol we want to use.

7. PROPULSION TESTING

Now that we have completed a first draft of our design, complete with a 40" propeller, 100 kV motor, 22,000 mAh battery and a properly rated ESC, we are ready to start testing our drone with a propulsion thrust stand.

There are a number of key tests that can be conducted using a propulsion thrust stand (figure 23), including:

1. Endurance tests
2. Efficiency analysis
3. Flight replay testing
4. Propeller balancing
5. Coaxial motor testing
6. Reliability
7. Diagnostics
8. Throttle response
9. Motor thermal testing
10. Gas engine testing

Figure 23: The Flight Stand 50 thrust stand

1.Endurance Tests

A few examples of endurance tests are constant thrust tests, which use a PID script to study performance at steady thrust, and mechanical endurance tests, where continuous operation is simulated to identify when components may fail. Fatigue tests demonstrate the system's ability to handle cyclic loads, and environmental endurance tests assess performance in both warm and cold environments.

These tests help determine the useful life of components, improve safety and reliability, and provide data for creating accurate technical documents. They also support drone certification by ensuring systems meet performance standards.

2. Efficiency Analysis

A thrust stand can be used to measure the efficiency of motors and propellers by analyzing their performance under different operating conditions. By varying the throttle input and recording the corresponding thrust, power, and RPM, you can determine how effectively the motor and propeller convert electrical energy into mechanical output. This data helps assess the system's efficiency at various stages of flight, including takeoff, cruising, and landing.

The key metrics collected during these tests—such as thrust, torque, and power consumption—are automatically converted to efficiency values for the motor-propeller combination in the Flight Stand software. By comparing these results to theoretical models or benchmarks, you can identify potential improvements in motor or propeller selection to maximize efficiency and flight time. Thrust stand testing also helps in fine-tuning the propulsion system to ensure optimal performance under different load conditions.

3. Flight Replay Testing

A flight replay test recreates a past flight in the lab using throttle data stored on the onboard flight computer. This test helps analyze your propulsion system's performance at different flight stages, identifying power usage and efficiency. It's a highly accurate method for simulating flight, especially when combined with wind tunnel testing, and is useful for estimating battery life.

To run the test, export the throttle data, import it into Flight Stand software, and create a custom script. Then, connect the propulsion system to the thrust stand and observe real-time changes in thrust, torque, RPM, and power.

4. Propeller Balancing

Balanced propellers are vital for maintaining UAV performance, efficiency, and longevity. Even minor imbalances can lead to a chain reaction of issues, such as increased vibration, mechanical stress, higher power consumption, and accelerated wear. Proactively addressing imbalances prevents costly repairs, extends component lifespan, and ensures stable flight performance.

Below are some key reasons why propeller balancing is essential:

- **Noise Levels**

One of the biggest concerns for applications such as videography, surveillance and wildlife monitoring is how much noise the drone will make. Motors and propellers produce the majority of the noise in a drone, so testing and comparing motors and props is our best bet for creating the quietest version of our design. We may be willing to sacrifice a few seconds of flight time if a less efficient motor cuts our noise level in half.

- **Vibration**

All powertrains generate some degree of vibration, but excessive reverberation can cause damage to our components and is generally indicative of a lack of efficiency. Running a vibration test is a great way to balance the propeller, detect inefficiencies and streamline the design. In doing so, we will likely notice that parts last longer and we get more performance out of a single battery charge.

How to Balance Propellers and Motors

Propeller balance quality is commonly compared to ISO standard 21940-12:2016. The standard uses a balance quality grade known as G-value, a numerical measure of balance precision. For UAV propellers, G 6.3 is the commonly accepted value, though users can select a custom G value.

With the G-value in mind, the Flight Stand propeller balancing software balances motors or propellers in just three spins:

- Spin 1: Capture a base reading.
- Spin 2: Add a trial weight and spin again to calibrate the algorithm.
- Spin 3: Add a final correction weight and spin to confirm optimal balance.

To learn more, download our white paper on Static and Dynamic Propeller Balancing Techniques.

5. Coaxial motor testing

For certain drones, the best set-up is having two rotors in a coaxial setup (figure 24). In these designs, twice the thrust is generated in the same area, but interference between rotors must be considered. Propulsion testing is a great way to determine your most efficient coaxial set up, testing back-to-back, face-to-face, and offset rotor configurations.

Figure 24: Flight Stand 150 thrust stand in a coaxial set-up

6. Reliability

There is great incentive to increase reliability in the drone industry as the drone failure rate is about two orders of magnitude higher than in manned commercial aviation. Performing a Reliability, Availability, Maintainability and Safety (RAMS) assessment is a great way to prove the reliability of our drone as it is an industry-recognized test that consumers trust. Once a system has been optimized, data from reliability tests can be a useful resource to reference or even publish as part of a marketing strategy.

7. Diagnostics

In addition to the design phase, recording diagnostics at scheduled intervals, every 50 flight hours, for example, can help monitor a drone’s performance over time. Such tests are useful for detecting wear and tear as well as lost efficiencies. Diagnostic testing of the propulsion system can detect weaknesses before a failure occurs, preventing uncomfortable or potentially dangerous situations.

8. Throttle response

Learning how quickly a propulsion system reacts to a change in control input is useful for testing ESCs and characterizing the drone. A typical way to physically test the reactivity of a propulsion system is to subject it to one of three reactivity tests: a frequency sweep control signal test, a proportional integral derivative (PID) test, or subjecting the powertrain to a step input. These tests can be performed using a test stand with sufficient scripting capabilities, allowing for a complete understanding of a UAV's throttle response.

9. Motor thermal testing

One of the most common causes of drone failure is engine overheating leading to engine failure. Maximum temperature and voltage ratings are often provided with electric motors, but it can be unclear when the motor is approaching these limits.

Additionally, despite the fact that engine cooling depends on current, current ratings are not standard in the industry. One way to test a motor's limits is to measure its temperature at various speed intervals using thermal probes, a useful strategy for circumventing failures.

Check out this article for more reasons why you should perform propulsion testing with your drone.

Figure 26: The Series 1585 Test Stand comes with 2 temperature probes

10. Gas engine testing

Characterizing a combustion engine enables the detection of inefficiencies and mechanical issues, in addition to the fine-tuning of performance. An engine test stand like the Flight Stand 60 (figure 32) allows you to collect this key engine data.

Below are some of the key data you can measure and how they contribute to engine evaluation:

- **Thrust and torque measurement**

Thrust and torque are key engine performance variables. A thrust stand helps compare the thrust produced by different propellers and identify torque peaks during key moments like engine start.

- **RPM measurement**

Comparing different propellers at the same RPM allows for the identification of the most efficient engine-propeller combination. The Flight Stand 60's fiber optic sensor provide high accuracy and faster response time, making it ideal for engine testing.

- **Fuel flow measurement**

Fuel flow sensors help measure fuel consumption rates, providing insights into engine efficiency and endurance. This data is critical for adjusting carburetor settings, refining air-to-fuel ratios, and identifying potential fuel leaks.

- **Exhaust temperature measurement**

Thermocouples monitor exhaust temperature, providing insights into combustion efficiency within cylinders. Temperature imbalances can signal cylinder performance issues, helping determine if one cylinder is working harder than the other or if both are performing equally.

- **Airspeed measurement**

Airspeed sensors measure airflow using differential pressure. This data is particularly useful in variable-pitch propeller tests, helping understand the impact of pitch adjustments on performance.

Figure 27: The [Flight Stand 60 Engine Test Stand] measures up to 60 kgf of thrust

8. WIND TUNNEL TESTING

The real test of a drone's performance is how well it succeeds in its work environment. One way to improve chances of success on launch day is by testing the aircraft in similar conditions in the lab. While propulsion testing is a great way to optimize a design, motors and propellers tend to generate more thrust when tested statically compared to in-flight. This means that the current draw may be lower than predicted and flight time may be longer than expected.

Free flight testing with a wind tunnel can help to determine a drone's true performance in flight. Here are a few examples of information you can gain from free flight testing.

Flight time in realistic conditions

There are several ways to estimate how long a drone will stay airborne, but free flight testing is the only way to confirm the true flight time. When you take into account ground effect, ambient temperature, air resistance, etc., you may find yourself with more or less air time than expected. Wind gusts and obstacles also have an effect on flight time, so testing a drone in various wind profiles can give an estimate of the flight time we can expect in the field.

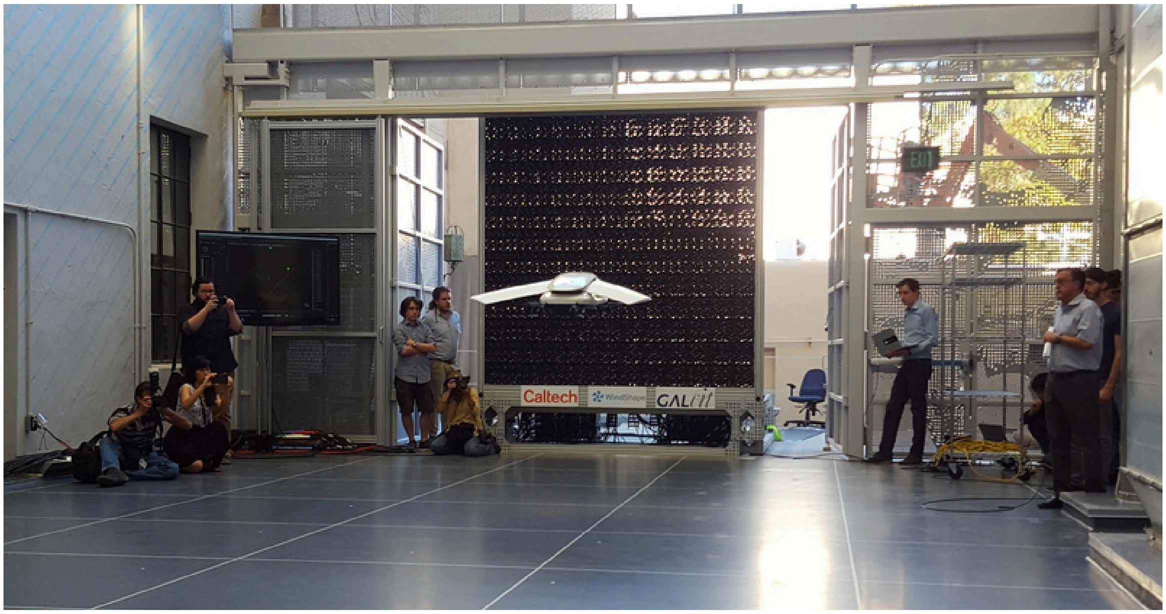

Figure 28: Free flight testing with a large wind generator ([click for video])

Turbulence tolerance

Determining a drone's turbulence tolerance is important as wind conditions can greatly influence aircraft performance and even a go/no-go decision. A wind tunnel allows for simulation of wind gusts and different turbulence profiles coming from all angles and directions. This is a great way to test how a drone recovers from a gust or disturbance and determine whether it has sufficient thrust to overcome it.

Landing phase optimization

Take-off and landing are often the most challenging parts of a flight. This is especially true for tilt-rotor drones that undergo a rotor transition in flight. Testing with a wind tunnel can help develop strategies and techniques for landing softly and safely to protect the drone. Taking the time to optimize the landing phase can help protect valuable aircraft and set expectations for the operator.

Environmental testing

If a drone is meant to work in any weather, a great way to find out how it will hold up is to test it in rain, fog, snow or icing conditions. Moisture and icing can have a big impact on drone performance, reducing flight time and system longevity. Pairing wind testing with climatic effects like precipitation or icing can help to predict their effects and prepare our drone for all conditions.

Click here for more information on drone testing with a Windshaper.

Figure 29: Testing a drone in rain and fog (click for video)

9. CONCLUSION

Building and optimizing a drone is a complex and exciting process that requires a lot of time and testing. We hope this eBook has been helpful in teaching you about the different motor, propeller, battery and ESC factors to consider, while demonstrating the importance of different types of testing.

There is always more to learn so look out for new versions of this eBook as well as more informative articles on our website. We discuss everything from the types of drones available, to how brushless motors work, to motor manufacturers to look out for.

For more information on any of the products mentioned in this eBook, check out these links:

Propeller Balancing - Propellers of all sizes

Series 1585 Test Stand - Measure up to 5 kgf

Flight Stand 15 Thrust Stand - Measures up to 15 kgf

Flight Stand 50 Thrust Stand - Measures up to 50 kgf

Flight Stand 150 Thrust Stand - Measure up to 150 kgf

Flight Stand 500 Thrust Stand - Measure up to 500 kgf

Flight Stand 60 Engine Test Stand - Measure up to 60 kgf of thrust

Windshapers for Drone Testing - Custom and ready-made wind tunnels

If you have any comments or questions, feel free to contact us via our website: https://www.tytorobotics.com/

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