Motor, Propeller, ESC, and Battery Sizing Introduction

for MAE 162D/E

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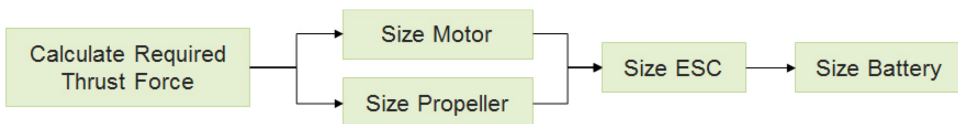
The following is an introduction to sizing motors, propellers, ESCs, and batteries for the purposes of 162D/E. The order of the process is as follows:



Note: The motor and propeller must be sized *together* as it is the combination of the two that produces the thrust force (more on this below). The motor/propeller is the challenging part—once selected, the ESC and battery are simple to choose.

Thrust vs. Mass

A thrust is a *force* and therefore should have units of Newtons [N]. This is in contrast to a *mass* which should have units of kilograms [kg] (or grams [g]). However, it is common for vendors to report motor thrust "forces" in units of grams [g]. Understand that—technically speaking—this is incorrect. The following is something you never want to say in a job interview:

"I measured the propeller thrust as 150 grams."

Also, your calculations will be incorrect if you mistakenly substitute a mass for a force or the other way around. Conversion between the two is simple:

$$F = mg$$

where g = 9.81 [m/s^2] (an acceleration). As an example, say we find a motor/propeller combination with a reported "thrust" of 50 g. The actual force is:

$$F = \frac{50}{1000} \cdot 9.81 \approx 0.49 \text{ N}$$

Always keep this in mind when reported values, talking about your work, and performing calculations!

Thrust Force and Kv Value

A “Kv” value (sometimes incorrectly written as “KV”), is the no-load rotational velocity of a motor per 1 V of input. Kv values are reported in units of [RPM/V]. For example, an unloaded motor with a Kv value of 2300 would spin at 11500 RPM if we applied 5 V to it.

On one hand, this gives us an idea of how “powerful” a motor is and how fast it can spin: A “large” Kv value (such as, say, 4000) will spin *really* fast (4000 RPM for every 1 V you give it) but will do so without much power (torque) behind it. On the other hand, a “small” Kv value (such as, say, 340) will spin pretty slow (only 340 RPM for every 1 V you give it), but will do so with a lot of torque.

On the other hand, the Kv value by itself tells us little about the actual thrust force produced. A motor by itself (unloaded, like that reported by a Kv value) doesn’t *do* anything: it requires a propeller to produce thrust. Likewise, a propeller by itself will just sit around all day: it requires a motor to spin it. Therefore, the motor/propeller *combination* is what you want to consider—not just the motor!

For this reason, it is insufficient to simply look at the Kv value of a motor. Instead, it is strongly recommended to only consider buying motors that that have manufacturer- or vendor-reported experimental thrust data. Below is an example:

Specs:
Rpm/V: **4000KV**
Dimensions(Dia.xL): **14*16.5mm**
Weight: **5.5g**
Shaft: **1.5mm**
Voltage: **2S~4S (7.4v to 14.8v)**
Watts: **81.4W**
Max Current: **5.5A**
Suggested Prop: **3020 (3S 11.1v~4S 14.8v)**
Motor Mount Holes: **M2 x 9mm**
Propeller Mount Holes: **M2 x 5mm**
Includes:
1 x BE1104-4000KV Motor
4 x M2x4mm Screws
4 x M2x6mm Screws
Required:
Multirotor Carbon Fiber T-Style Propeller 3028 (CW/CCW) (2pcs)
Thrust Data:

Prop	V	Amps	Watts	Thrust(g)
3020	11.1	1.1	12.2	50
3020	11.1	2.9	32.2	100
3020	11.1	4.3	47.7	144
3020	14.8	1.2	17.8	60
3020	14.8	2.8	41.4	120
3020	14.8	5.5	81.4	190

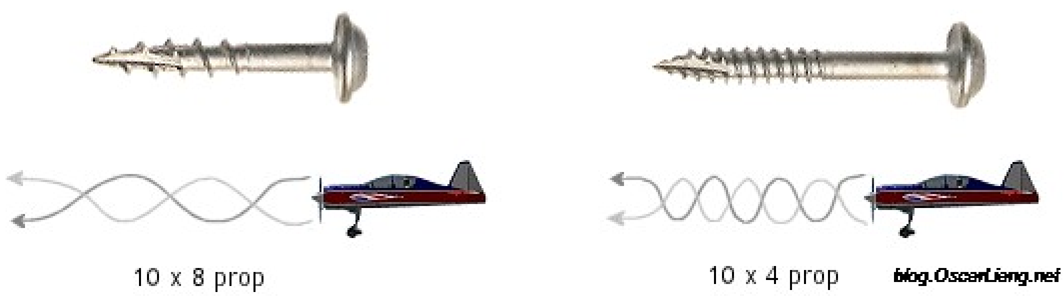
At the bottom is a very useful chart. This tells us that someone attached a “3020 propeller” (more on this next) to this specific motor and measured the output “thrust” (in [g]) for different applied voltages and currents. The maximum output “thrust” reported is 190 g, which gives us confidence in what this one specific motor/propeller combination is capable of. Without this data, we would only have the no-load Kv value without any information on what happens when we attach a propeller to the motor.

Propeller Sizing

A propeller “size” is reported as either a 4-digit number or as a diameter × pitch value. The 4-digit method is simply a shortened form of the second. For example:

6045 = 6.0 in. x 4.5 in.
3020 = 3.0 in. x 2.0 in.

Again, the first number is the diameter (measured from tip to tip) and the second is the pitch. Almost always, these numbers are in inches. The **pitch** is how much the propeller translates in one rotation. The following images illustrates this:



Both propellers shown have a diameter of 10 inches but different pitches (on the left: 8 inches; on the right: 4 inches). In general, the larger the pitch, the greater the thrust force: the propeller “pulls” or “cuts through” more air per single rotation. However, a larger pitch also requires more power and is less stable. A smaller pitch can spin faster and is generally more stable, but produces less thrust force. Larger diameters increase the thrust force but take more time to change speed.

Finally, the mounting hole size and configuration of a propeller is important but, unfortunately, are horribly un-standardized and oftentimes not clearly reported. First, read online reviews by customers to see if their motor/propeller combination worked for them. Second, you can always enlarge an under-sized hole in a propeller, but cannot shrink an over-sized hole—so, when in doubt, err on the side of smaller mounting hole.

CW vs. CCW (Clockwise vs. Counter-Clockwise)

Oftentimes, motors and propellers are designated as being CW or CCW. For multi-rotors this is an important distinction, but for the purposes of 162D/E, it is relatively unimportant. If, after construction, the thrust force is in the wrong direction, the force direction is changeable.

Sizing an ESC (Electronic Speed Controller)

The basic operation of a QC motor is as follows:

Microcontroller (MyRIO) → ESC → Motor

where the text represents electronic hardware, the first arrow is a PWM signal, and the second arrow is a 3-phase signal. An ESC "converts" the PWM output of a microcontroller into a signal that the motor can understand.

To size an ESC, the most important specification is the **maximum current capacity**. In short, you want the maximum current capacity of an ESC to be larger than the maximum current draw of the motor/propeller combination. For example, our motor spec sheet is:

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This motor is pretty small and only draws a maximum current of 5.5 A. We round this up to the next tens-place (in this case that would be 10 A). This number is the "size" of the ESC we will need to control this motor/propeller combination. In other words, the maximum amount of current that the motor/propeller can draw is 5.5 A, while the maximum amount of current the ESC is capable of providing is 10 A. Therefore, a 10 A ESC would be sufficient for this motor/propeller combination.

Nearly all ESCs are rated in denominations of 10 A: 10, 20, 30 and so on, upwards of 70 A or so. Note: the larger the value, the heavier the ESC.

The second most important specification of an ESC is the **S-rating**. LiPo batteries have an output voltage reported as an S-rating (more on this later). You want to ensure that the maximum ESC S-rating is greater than or equal to the S-rating of the battery you use.

"Throttle"

Because these types of motors and ESCs are commonly used in multi-rotor applications the word "throttle" oftentimes appears. This is simply a measure of how fast you're telling the motor to spin over a range of 0 to 100%; for example, "50% throttle" means half speed (thrust).

For our purposes, the PWM duty cycle is equivalent to “throttle” so a duty cycle of 0.5 would correspond to half speed (thrust).

LiPo Batteries

LiPo (lithium-ion) batteries are energy-dense, lightweight batteries. There are four values you want to be concerned with when sizing them:

1. Mass, in units of [g]
2. Capacity, in units of [mAh]
3. S value (or Voltage)
4. C-rating

Mass is self-explanatory. **Capacity**, usually reported in units of [mAh] (milliamp-hours), is a metric on how long the battery will last. The larger the value, the longer the battery will last. To calculate an approximate runtime, divide this number by the amount of continuous current you will be drawing from it. For example, if we push our motor/propeller combination continuously at full speed (full “throttle”), it will draw its maximum current of 5.5 A. If our battery is rated at 3000 mAh, then the runtime is calculated as:

$$\frac{3000}{1000} \cdot \frac{1}{5.5} \cdot \frac{60}{1} \approx 32.7 \text{ min}$$

Note: This is not a lot of time—therefore, we might want to consider the purchase of a second battery and a charger!

The **“S” Value** is another way to report the output voltage of the battery. LiPo batteries are composed of stacked “cells,” and each cell is standardized to output 3.7 V. The S-value tells you how many cells are in the battery and therefore tells you the output voltage. For example, a 3S LiPo battery outputs 11.1 V and a 4S LiPo battery outputs 14.8 V.

The **C-Rating** is a measure of how quickly energy (electricity) can be discharged from the battery. To determine the maximum continuous discharge the battery is capable of, this number is multipled by the capacity. For example, if a battery has a capacity of 2000 mAh and a discharge of 25C, then the maximum continuous discharge is:

$$\frac{2000}{1000} \cdot 25 = 50 \text{ A}$$

This means that our example battery can—at most—discharge 50 A without damaging itself. This number must be larger than the manufacturer-reported value of maximum current draw for the motor. Usually, it’s difficult to exceed this value, but it is important to check because for Lithium-ion batteries, “damaging itself” is usually equivalent to “catches on fire.”

Note: Sometimes a “burst” C-rating is also reported. Definitions between manufacturers differ on what exactly this means, but it’s basically a measure of how much current the battery can output for a few seconds at a time. Do not rely on this number for any sizing calculations.

Battery Concept Review: Below are the specifications of a LiPo battery:

Spec.
Capacity: **3000mAh**
Voltage: **4S1P / 4 Cell / 14.8V**
Discharge: **25C Constant / 50C Burst**
Weight: **299g (including wire, plug & case)**
Dimensions: **150x45x24mm**
Balance Plug: **JST-XH**
Discharge Plug: **4mm bullet-connector Connector**

This battery has a capacity of 3000 mAh, an output voltage of 14.8 V (4S), a discharge of 25C, and has a mass of 299 g (the "case" is the plastic cover of the battery). The maximum continuous discharge is calculated to be 75 A. Ensure this value is larger than the maximum current of your motor/propeller combination. Ensure the S-value is equal to or less than what your ESC is rated for. Calculate the runtime from the provided capacity and known continuous current draw.