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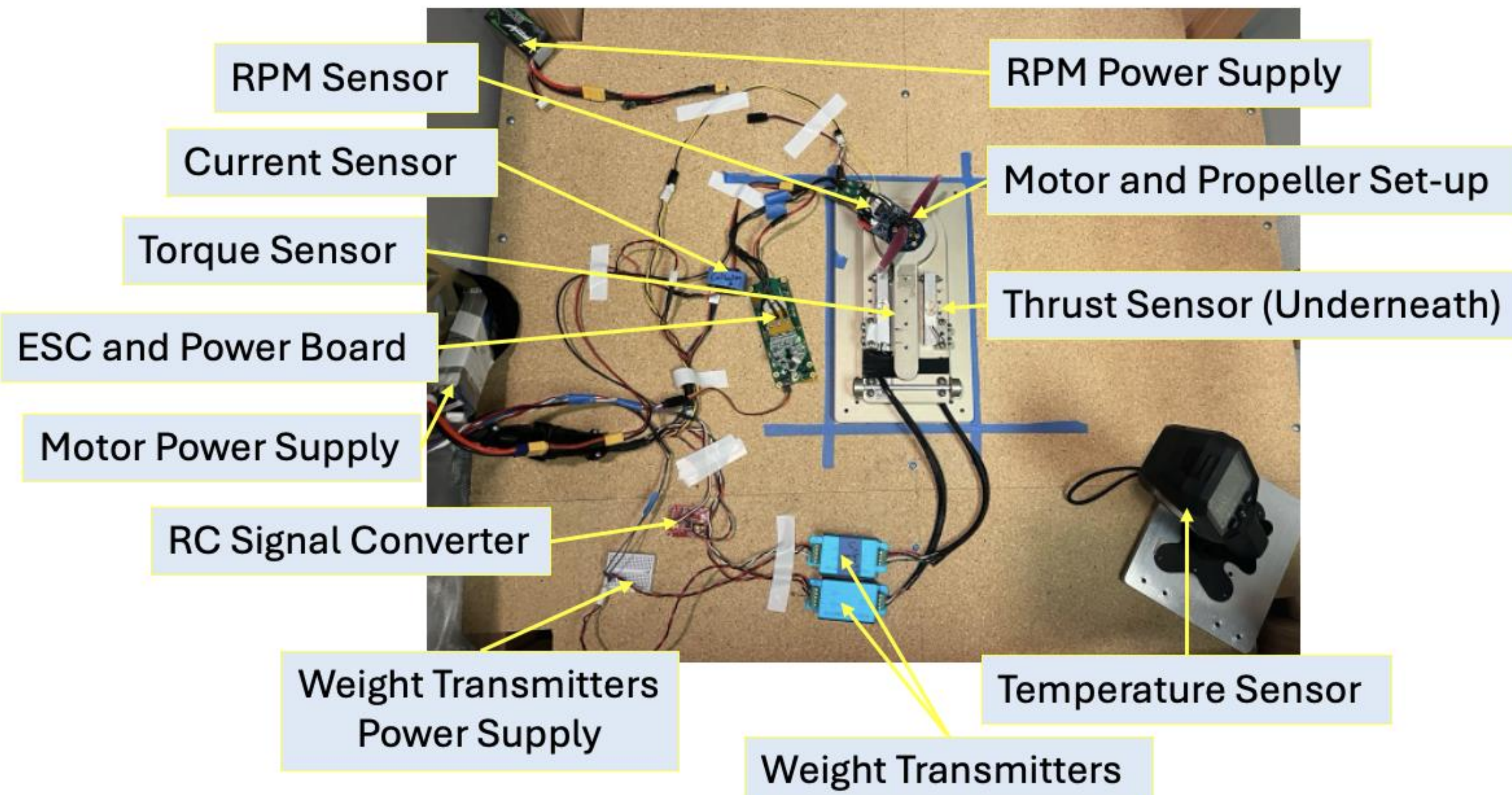
Small Form Factor Drivetrain Characterization

Introduction:

The small form factor drone uses small motors weighing less than 40g. To increase flight time various motors and propellers were paired together and compared. The goal of this work is to find the most efficient combinations for optimized flight time. To simplify this document, discussions will focus on motor and propeller combinations. Future studies will be conducted to understand effects batteries and ESC have on performance. Additional knowledge was also gained beyond knowing which motors and propellers should be used together. These findings will be outlined as is relevant. This document reports findings and suggest the use of the Xing Flight Pro 2207 1800KV motor paired with the Gemfan 3 blade 5.1*3.0 propeller. A suggestion for which propeller to be used with each motor is also made.



Testing Method:

Each motor was secured to the characterization stand. Sensors that were previously calibrated were fixed to the stand. The propeller would then be secured to the motor and alignment was then checked by powering on the motor and seeing which way it would spin, and what direction the thrust was going. The characterization stand collects 5 different data points from the motor. This data can then be used to find relevant information on the drivetrain performance. More information on the characterization stand is given in other documents.

For consistency, the same ESC and battery brand were used for each test. While one battery was charging another of the same brand and type was used. Testing showed that this did not affect the results in any major way. The battery and ESC used are listed in Table 1.

Table 1: Details on Batteries and ESC used.

Brand	Ratings	Notes
Gens Ace 14.8, 45C	3300mAh, 48.84Wh Capacity	4 S 1P
Kairos Autonomi	UxV/35 Wing Spar	Heat Sink is Equipped

The test set-up was also equipped with a thermal imaging camera that was used to measure temperature. It would give an audible alarm if temperatures in the motor or ESC rose to dangerous levels that would cause the motor or ESC to burn. In this experiment, this was its only role.

Information is given for each of the propellers and motors is given in table 2 and table 3.

Table 2: Details on each of the motors tested during the experiment. The color labeling system was used to differentiate between motors when comparing motor performance with a specific propeller.

Motor Brand Name	Size	KV Rating	Mass (g)	Label
Flight Xing Pro	2205	3200	24.5	Motor 1
Flight Xing Pro	2207	1800	34.2	Motor 2
Flight Xing Pro	2207	2750	32.7	Motor 3
Flight Xing Pro	2208	1800	37.2	Motor 4
T Motors	F1507	2700	15.1	Motor 5
Arthur Motors	1408	2800	17.1	Motor 6

Table 3: Details on each of the propellers used during the experiment. The color labeling system was used to differentiate between propellers when comparing performance with a specific motor.

Brand Name	# of Blades	Diameter	Pitch	Mass (g)	Label
Ethix	2	5.1	3.0	2.7	Propeller 1
Azure Power	3	4.8	3.8	4.1	Propeller 2
Gemfan	3	5.1	4.99	5.3	Propeller 3

Gemfan	3	4.0	3.2	3.2	Propeller 4

Preliminary Findings:

One thing that is noticed while preforming the experiment is the size of motors and their propellers had on performance. When the propeller was larger than the manufactures recommendation, the motor would heat up excessively. In some cases, the motor and propeller would be what the manufacture recommended but would still heat up excessively. What we found is that **motors generate heat because of power loss.** See figure 1 for a more detailed description.

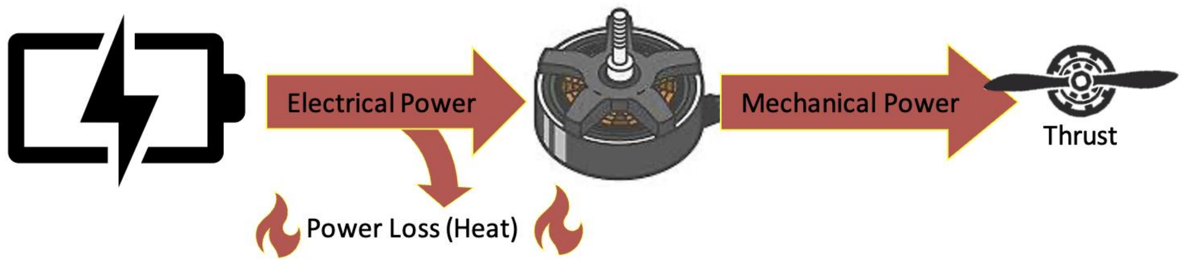


Figure 1: Electrical power comes from the battery. It is based on the battery voltage and current flowing from the battery. Resistance in the motor, ESC, and wiring cause the motor to lose power in the form of heat. The motor converts electrical power into mechanical power which provides the thrust. Excess electrical power that is not converted to mechanical power is lost and generates heat.

What we learned:

- When a motor is paired with a propeller that is larger than recommended, it requires more torque to spin the prop and increases power loss.
- Using the incorrect battery supply for a given combination increases power loss.
- The most efficient systems will require the motor, propeller, and battery to be combined in the most optimal way.
- High-efficiency systems experience less power loss and generate less heat
- Propeller Thrust is dependent on motor RPM. Any motor will cause the propeller to generate the same amount of thrust if ran at the same RPM.

Data Analysis:

Each motor and propeller combination tested was stored in a database and processed individually. From the five measurements taken we can find the electrical power, based on the current and voltage measurements, and mechanical power, based on RPM and torque measurements. Thrust is also considered. For simplicity this document takes the five measurements and finds three key efficacy metrics: motor efficiency, Mechanical efficiency, and electrical efficiency.

Motor Efficiency (%):

$$\boldsymbol{Equation\ 1}: Motor\ Efficiency\ (\%) = 100 * \frac{Mechanical\ Power(W)}{Electrical\ Power\ (W)}$$

Equation one shows how this metric is found. The larger this value is the more efficient a motor is at converting electrical power into mechanical power. It also translates into less power being lost due to heating from resistance.

Mechanical Efficiency (gf/W):

$$\boldsymbol{Equation\ 2}: Mechanical\ Efficiency\ (gf/W) = 1000 * \frac{Thrust\ (kgf)}{Mechanical\ Power(W)}$$

Equation two shows how this metric is found. The larger this value is the more efficient a motor is at generating thrust from the mechanical power created.

Electrical Efficiency (gf/W):

$$\boldsymbol{Equation\ 3}: Electrical\ Efficiency\ (gf/W) = 1000 * \frac{Thrust\ (kgf)}{Electrical\ Power(W)}$$

Equation three shows how this metric is found. The larger this value is the more efficient a motor is at generating thrust from the electrical power input. This is by far the most useful factor to investigate.

Interestingly efficiency in one area does not necessarily translate into the best overall efficiency. This is seen in figure 2.

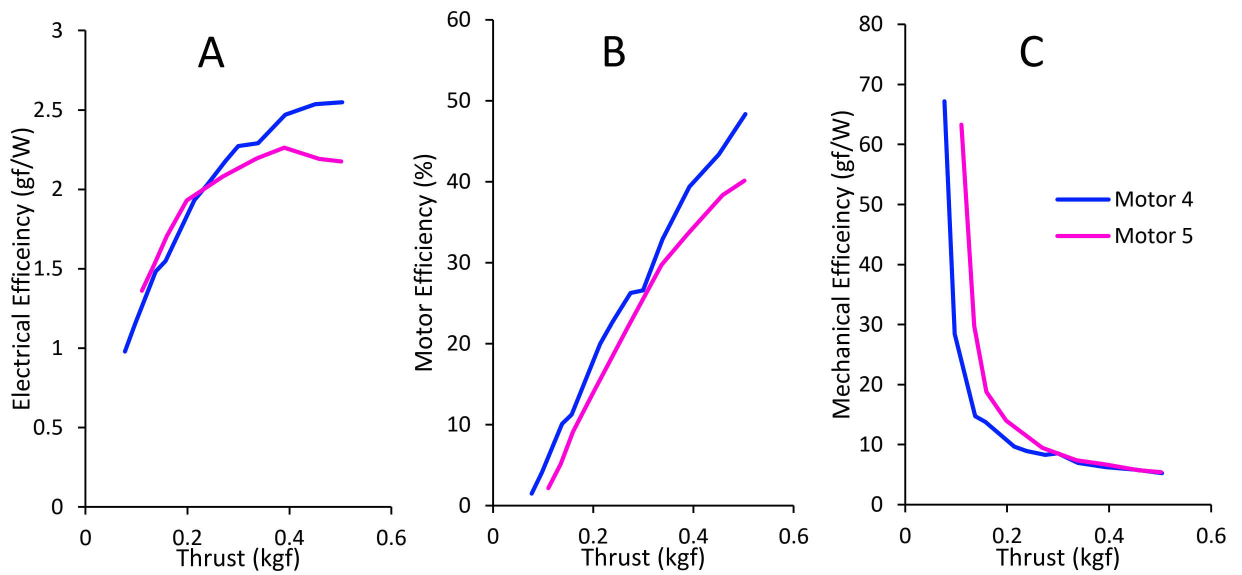


Figure 2: Above is a comparison of the three-efficiency metrics for Propeller 1 (Ethix 5.1*3.0 two blade propeller) with motors 4 and 5. We see in A that at lower thrust values motor 5 provides more thrust per electrical watt than motor 4. This is further illustrated in C were motor 5 provides more thrust per mechanical watt at first until they level out and become even with each other. Motor efficiency in B is greater overall for motor 4. These graphs indicate that motor 5, with this propeller, is more effective at converting the mechanical power into thrust than motor 4, but the conversion of electrical power into mechanical power is more efficient in motor 4 than in motor 5.

The Most Efficient Combination:

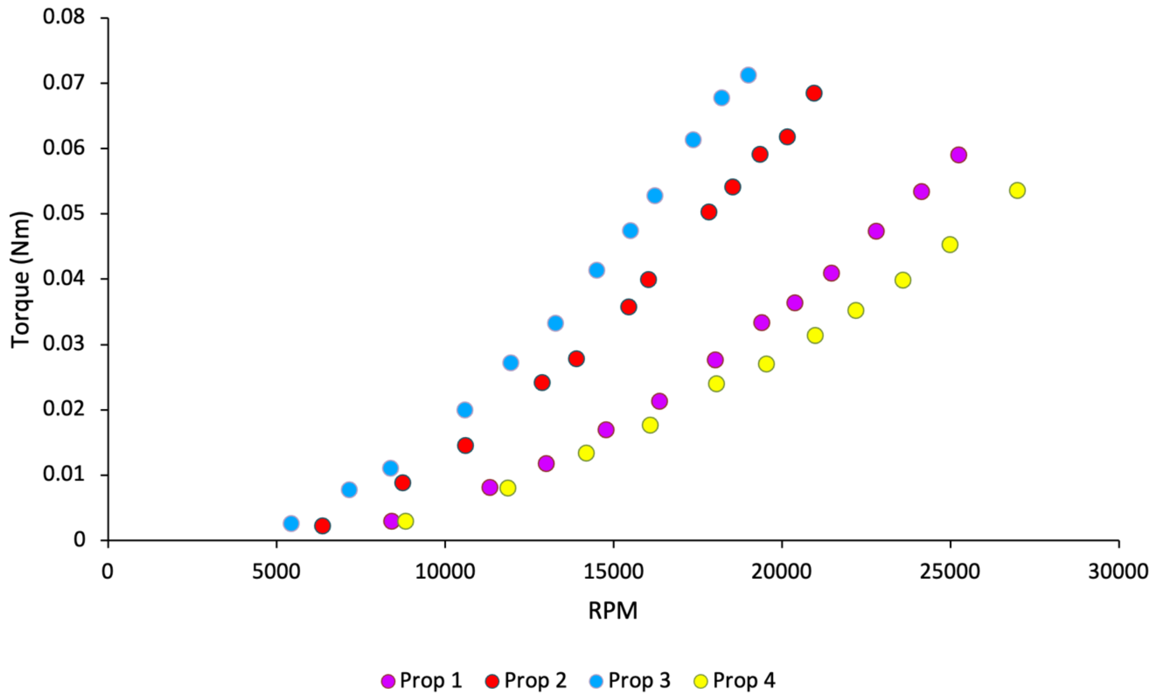
Figure 2 shows just how nuanced efficiency calculations can be. Where one propeller paired with one motor may increase the thrust per watt of electrical power used, the pair may cause overheating and prove very inefficient in the conversion of electrical power into mechanical power. Since the overall goal of this document is to find the most efficient combination of motor and propellers, so flight time can be maximized. Each motor will have its electrical efficiency metric compared with each propeller. We will compare this metric along the basic flight operation thrust. This range of thrust is calculated from the total mass of a flight basket. This flight basket included a battery, buckyball safety shell, and all other flight components. Since the motors, and propellers were different masses, an average was taken from their masses and added to the mass of the flight basket which came to 695g. Each motor provides for a 4th of the thrust needed to maintain a hover, the total mass was divided by 4 for the lower value in the investigation range, and this value was doubled for the upper value of our range. Since our mass is 695g the investigation range is set as 0.17-0.35kgf. The most effective propeller will have the highest electrical efficiency value in this range. If there is a tie further investigation will be done on that range with the tie breaker being whichever has a greater value of motor efficiency.

Thoughts will also be taken on motor heating. This document does not discuss details of motor heating, but some test for inefficient combinations were abrupted early due to overheating. A second place propeller for each motor will be listed, for future documentation on motor heating.

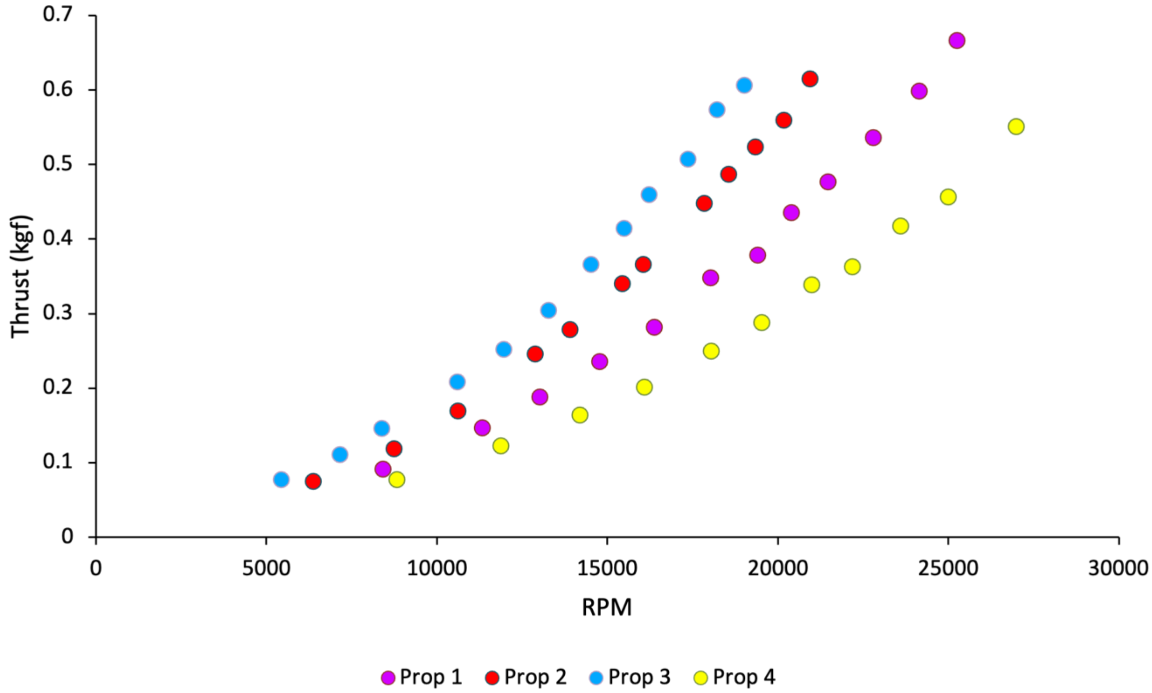
Each motor in this document will have data comparing propellers paired with it. The comparison includes 5 different graphs. After which there is a short explanation as to which propellers were selected as the most efficient. The 5 graphs are:

1. RPM vs. Torque (Nm)
2. RPM vs. Thrust (kgf)
3. Thrust vs. Motor Efficiency (%)
4. Thrust vs. Mechanical Efficiency (gf/W)
5. Thrust vs. Electrical Efficiency (gf/W)

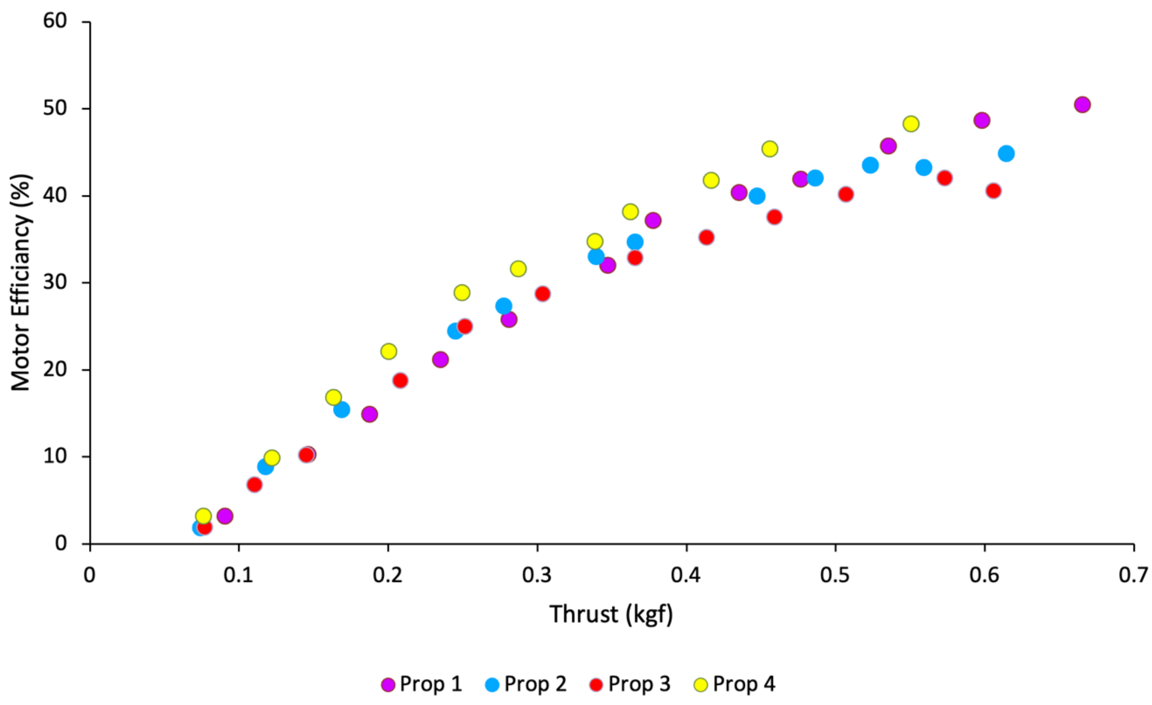
Motor 1, Xing Flight Pro 2205 3200KV:



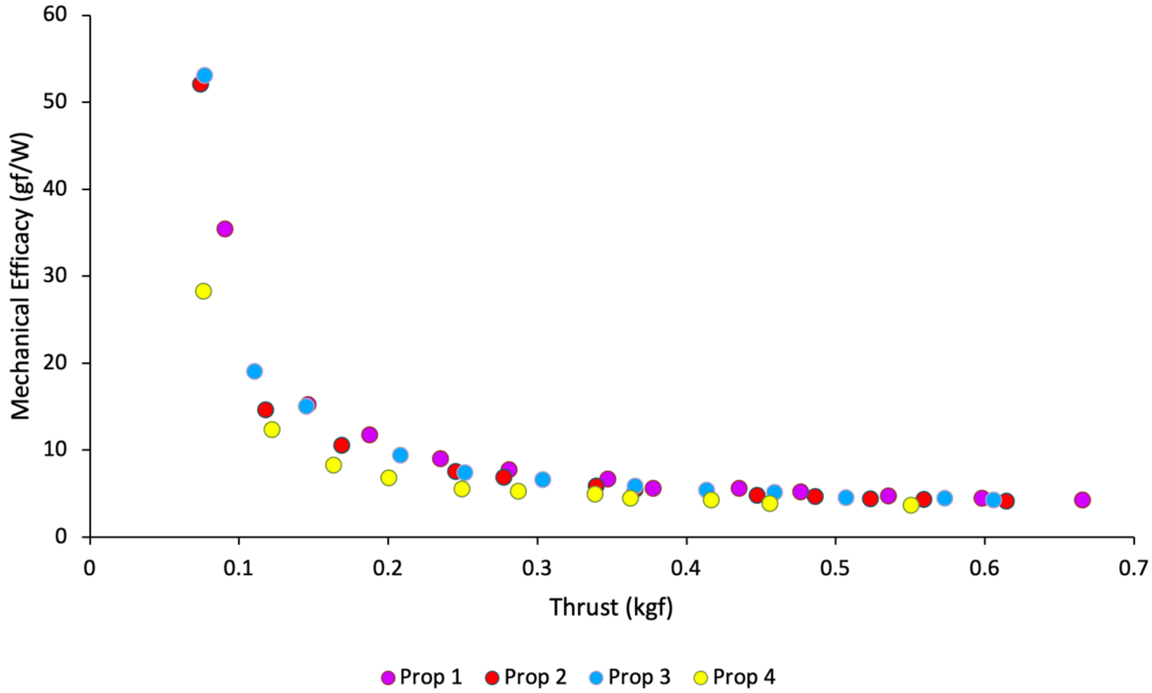
RPM vs. Torque



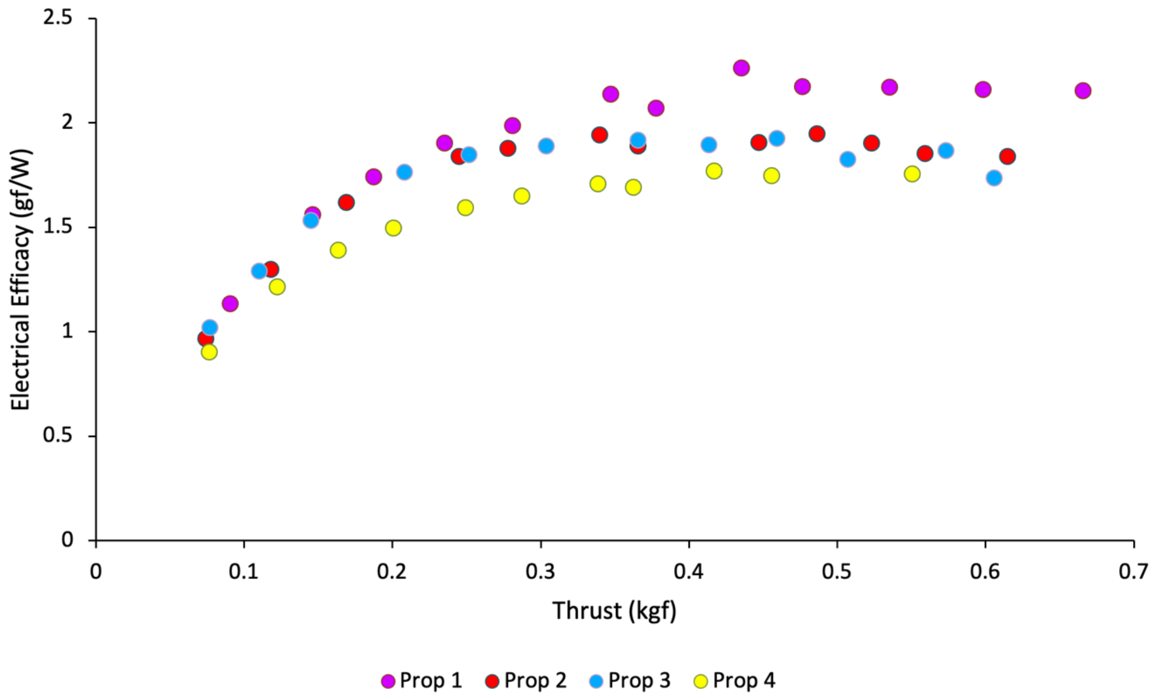
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

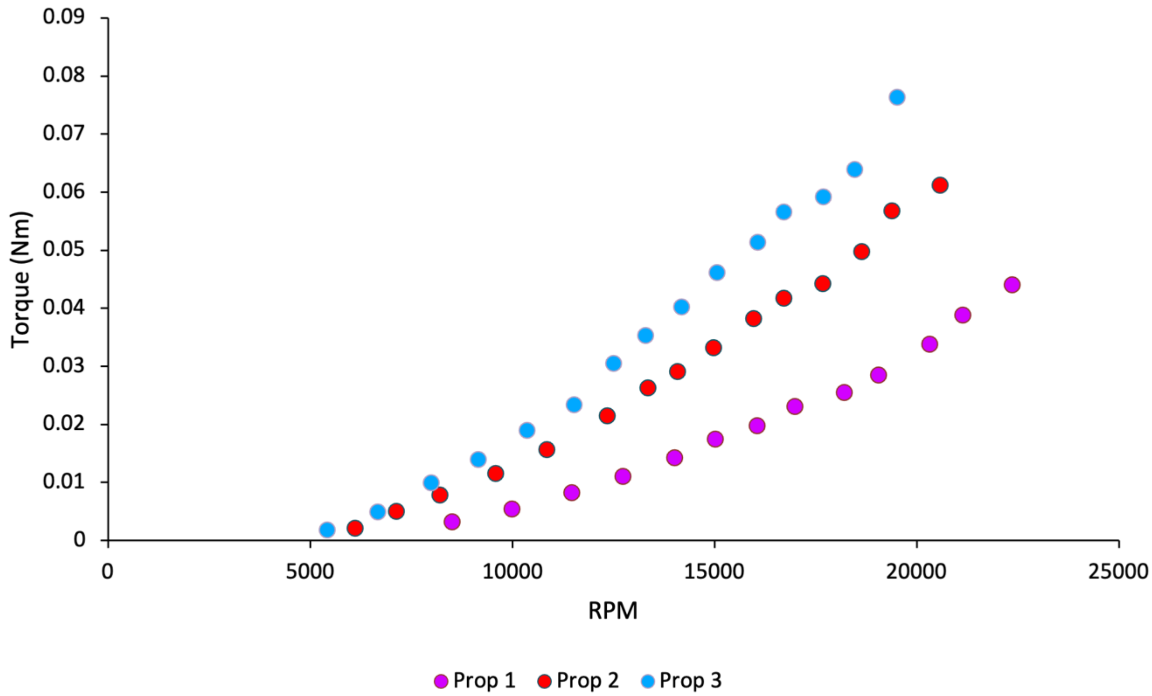


Thrust vs. Electrical Efficiency

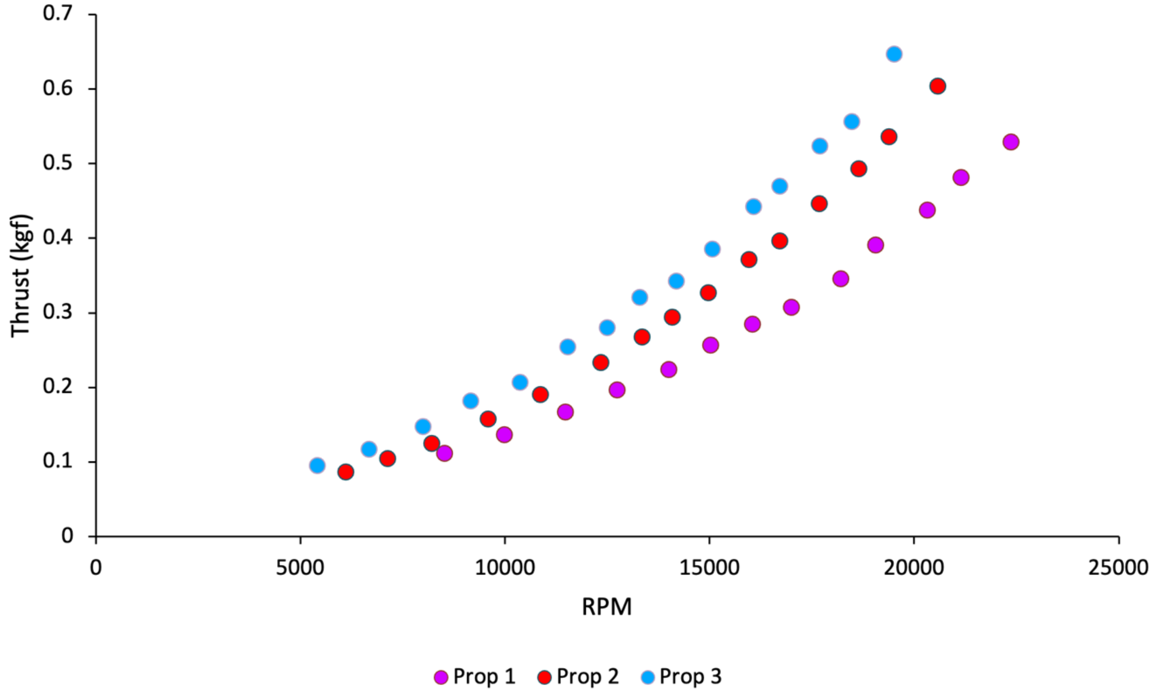
Propeller of Choice:

Propeller 1 (Ethix 5.1*3.0 two blade propeller) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be propeller 2.

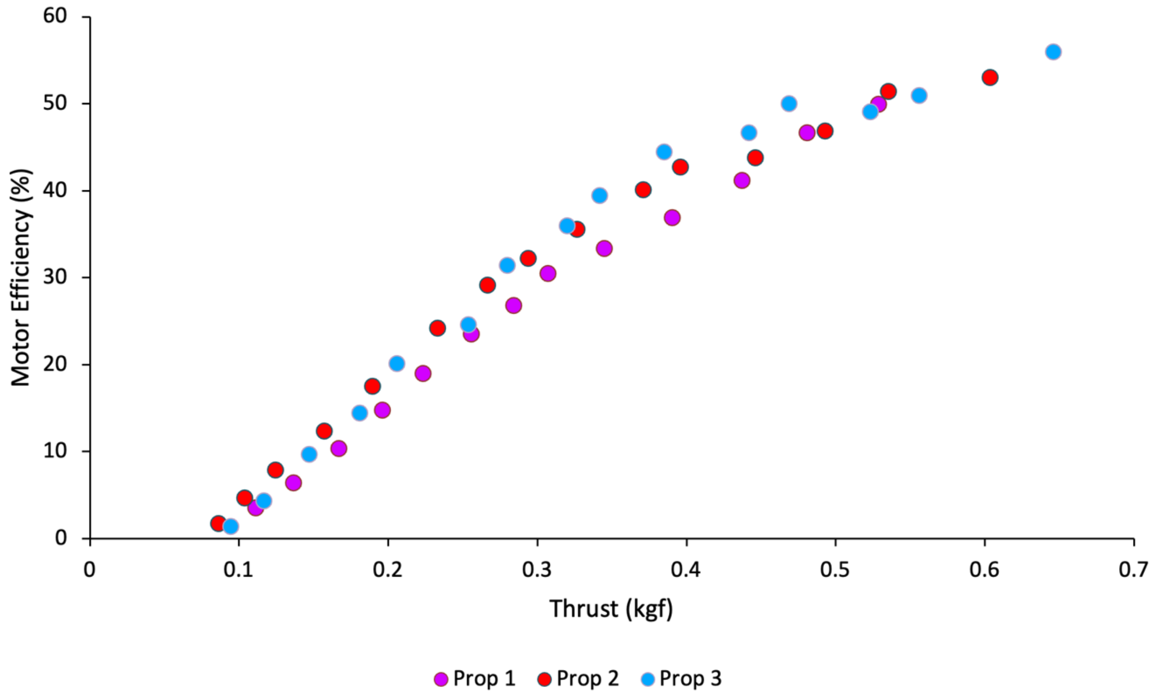
Motor 2, Xing Flight Pro 2207 1800KV:



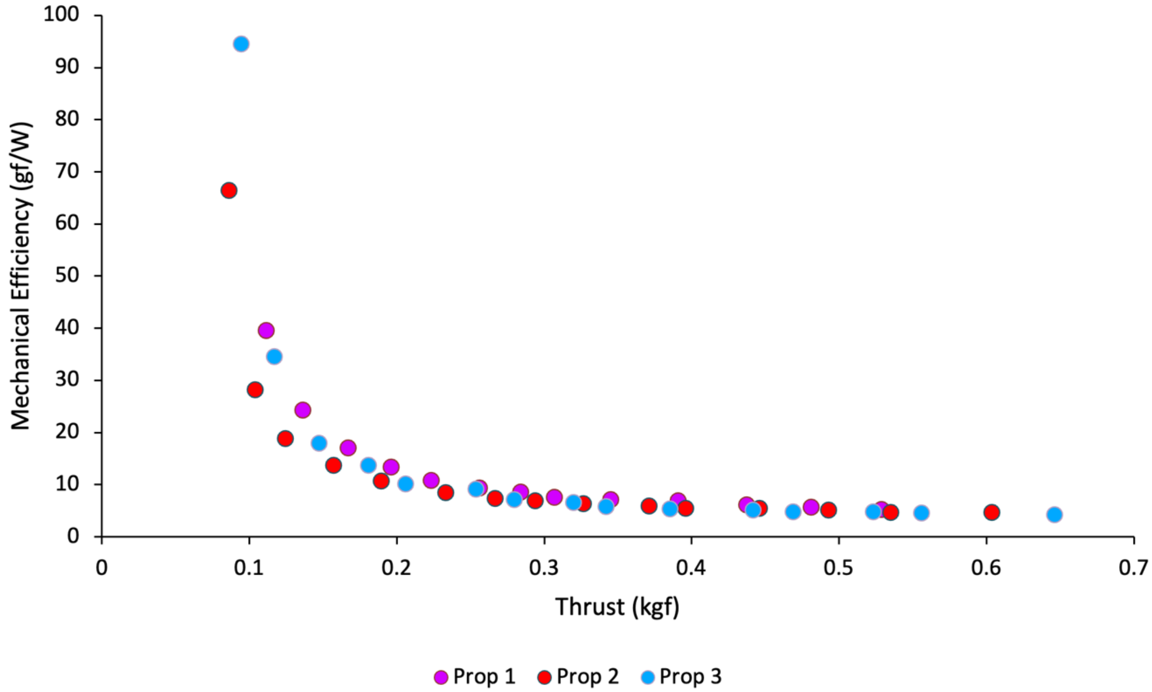
RPM vs. Torque



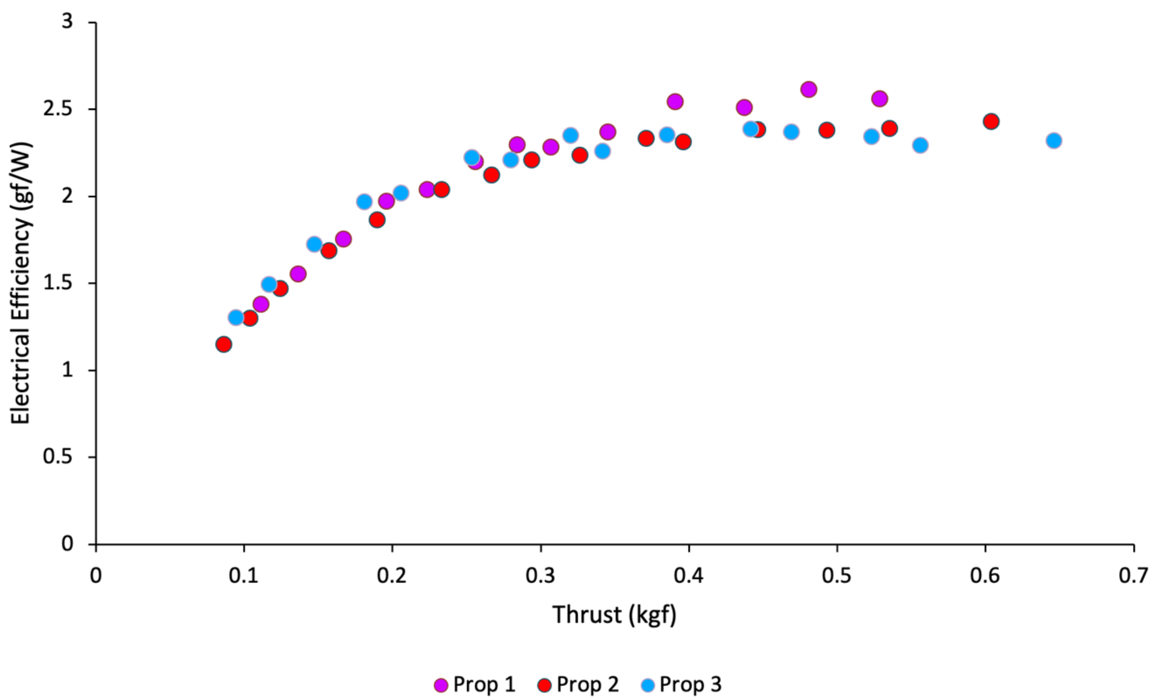
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

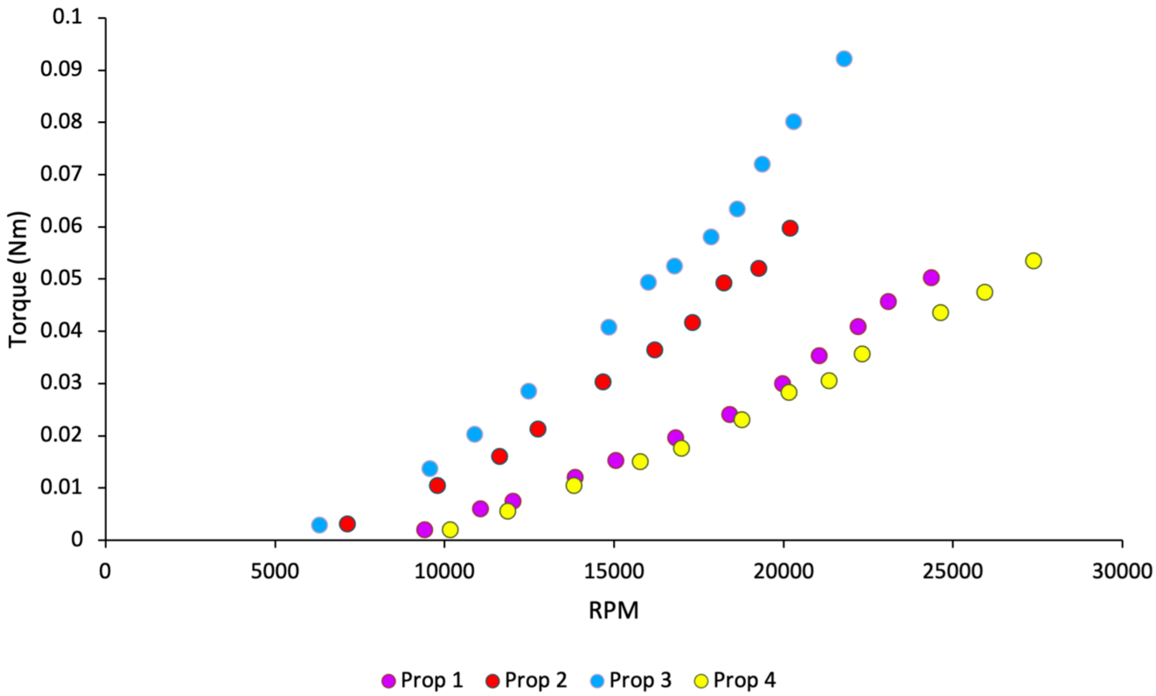


Thrust vs. Electrical Efficiency

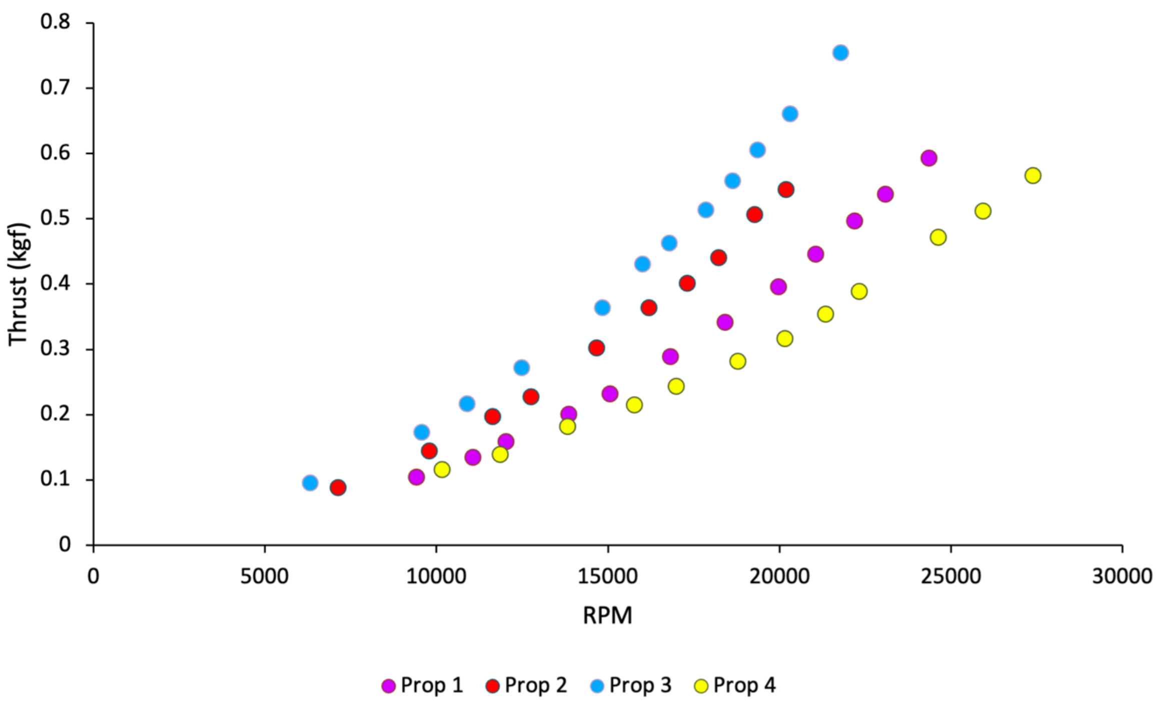
Propeller of Choice:

Propeller 3 (Gemfan 3 Blade 5.1*4.99) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be Propeller 1 (Ethix 5.1*3.0 two blade propeller). It is noted that these propeller blades all seem to have a very similar efficiency with this motor.

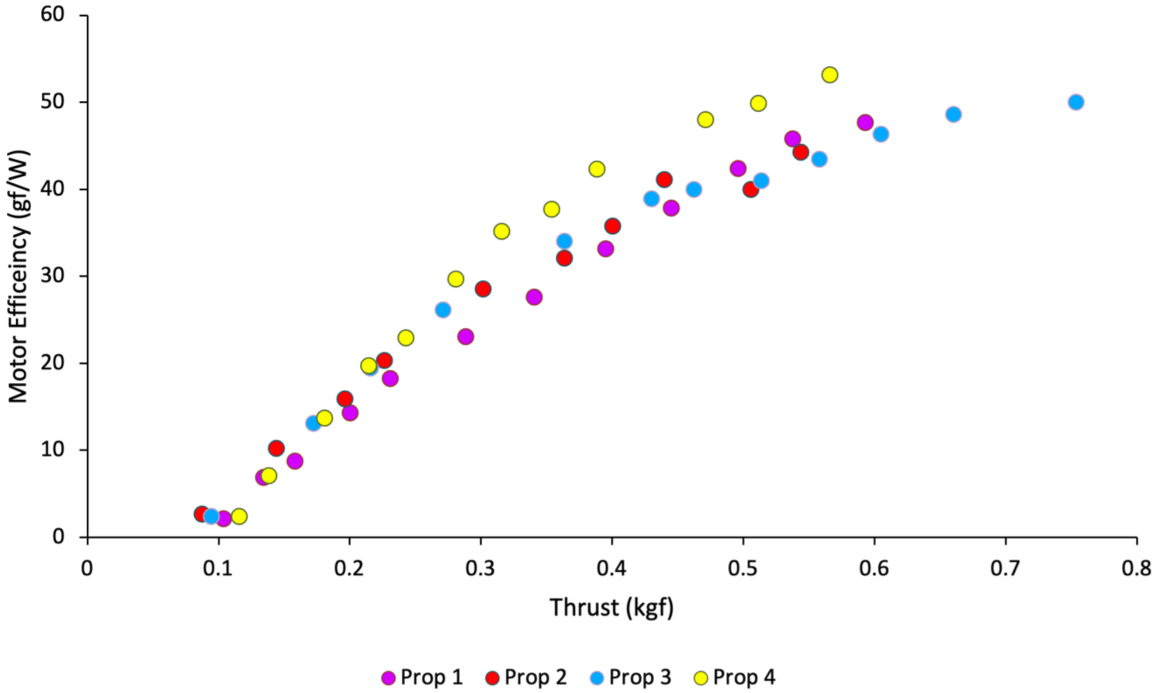
Motor 3, Xing Flight Pro 2207 2750KV:



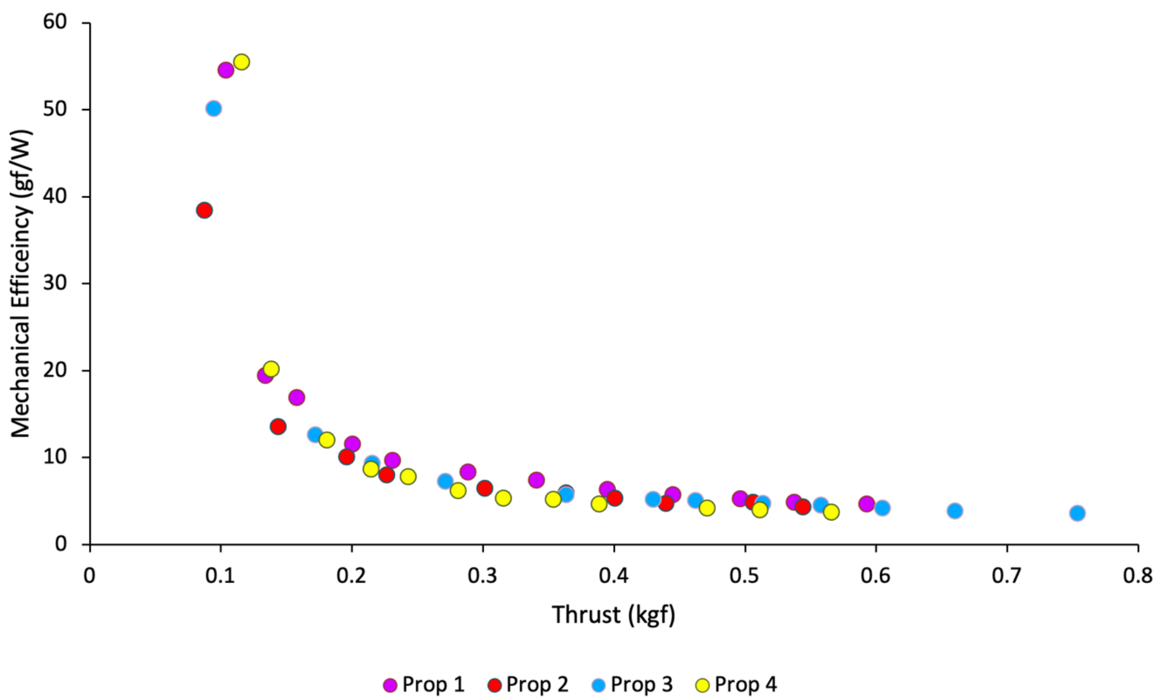
RPM vs. Torque



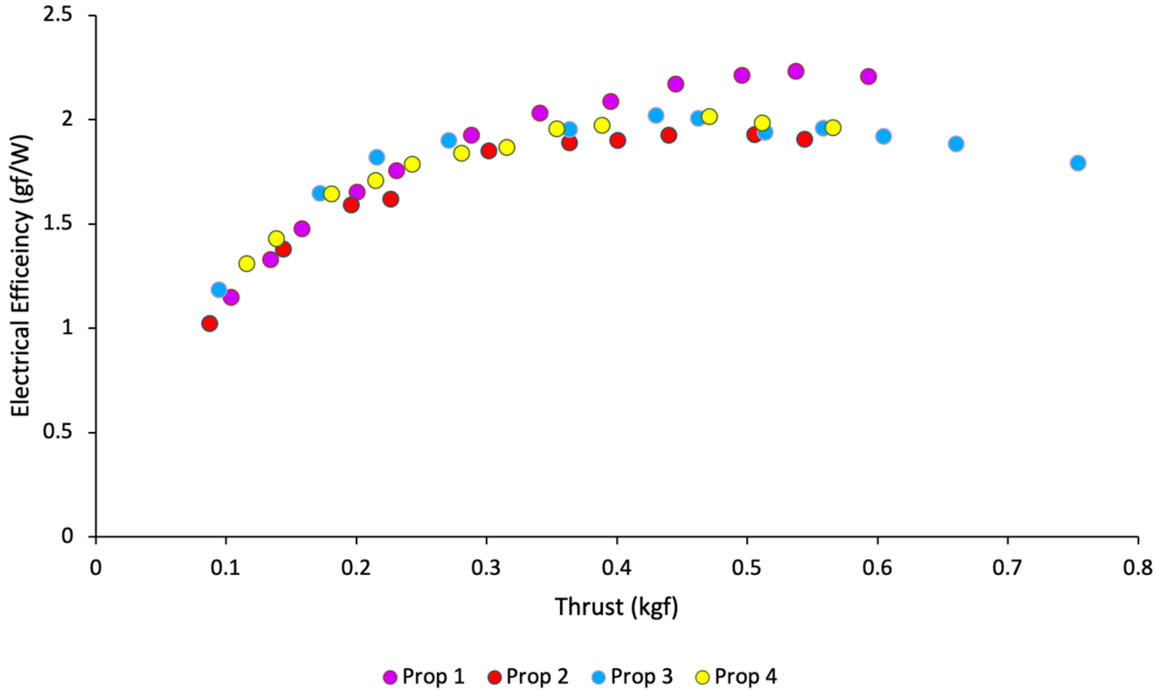
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

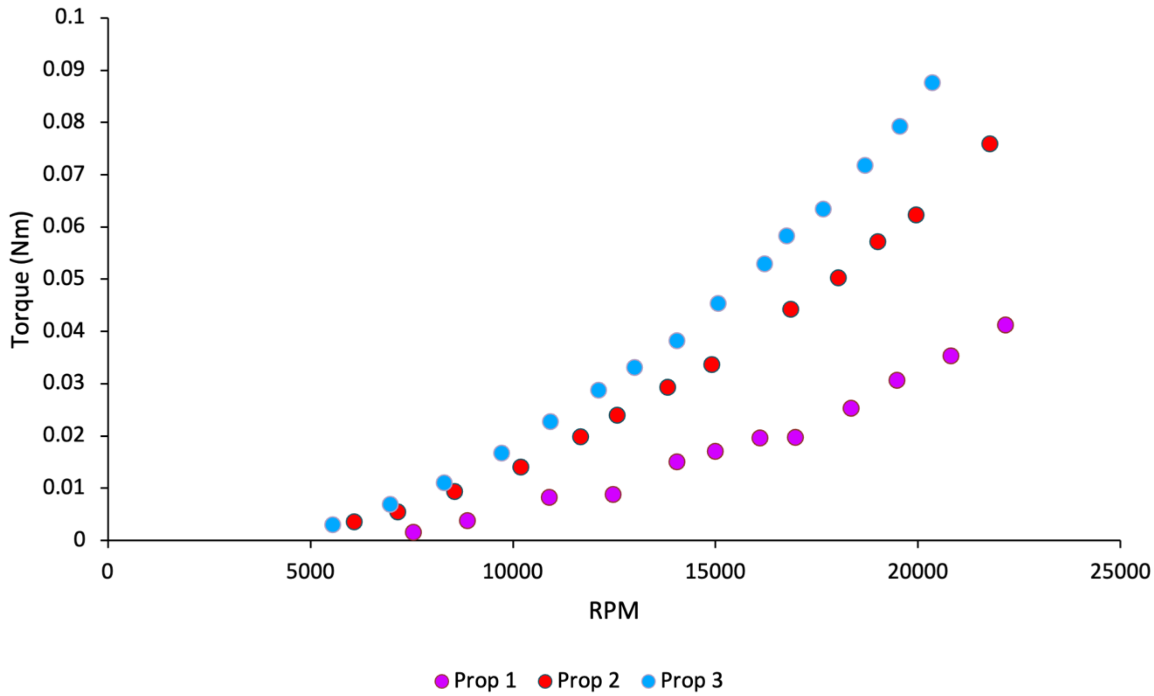


Thrust vs. Electrical Efficiency

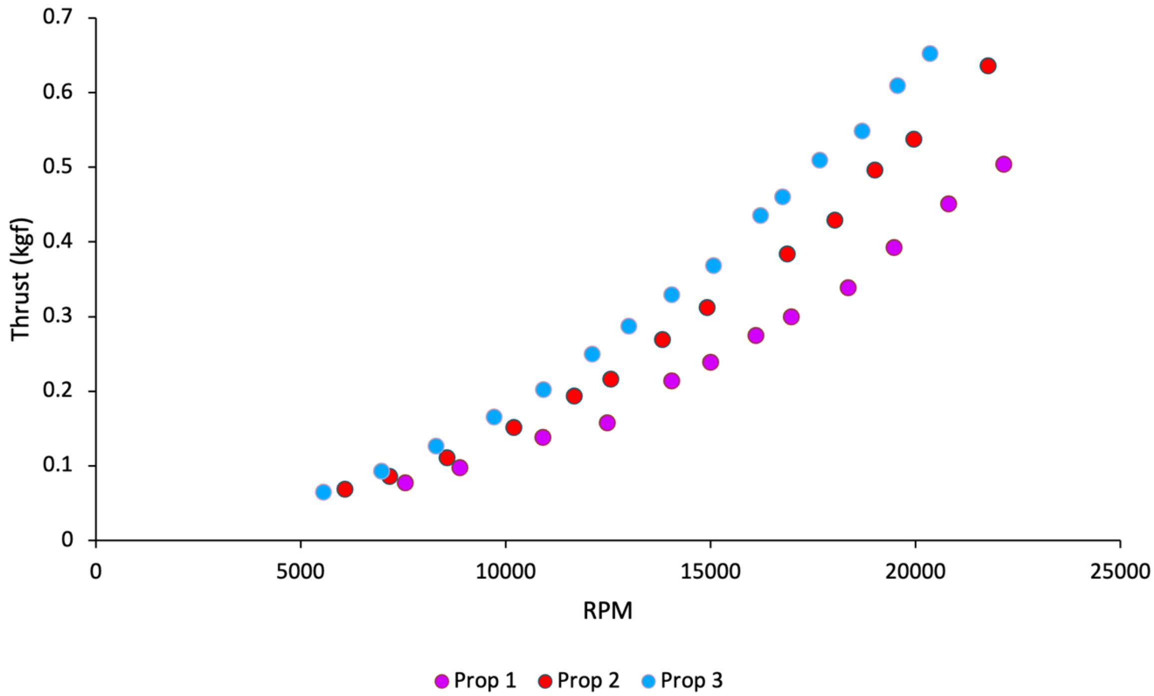
Propeller of Choice:

Propeller 3 (Gemfan 3 Blade 5.1*4.99) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be Propeller 1 (Ethix 5.1*3.0 two blade propeller).

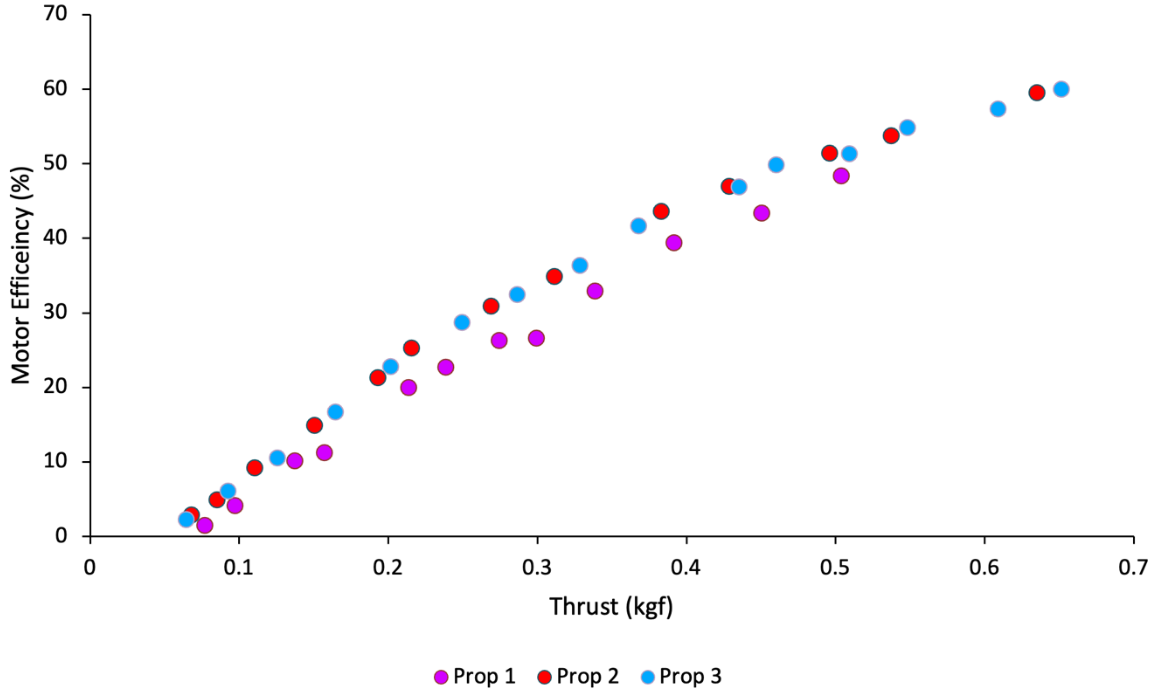
Motor 4, Xing Flight Pro 2208 1800KV:



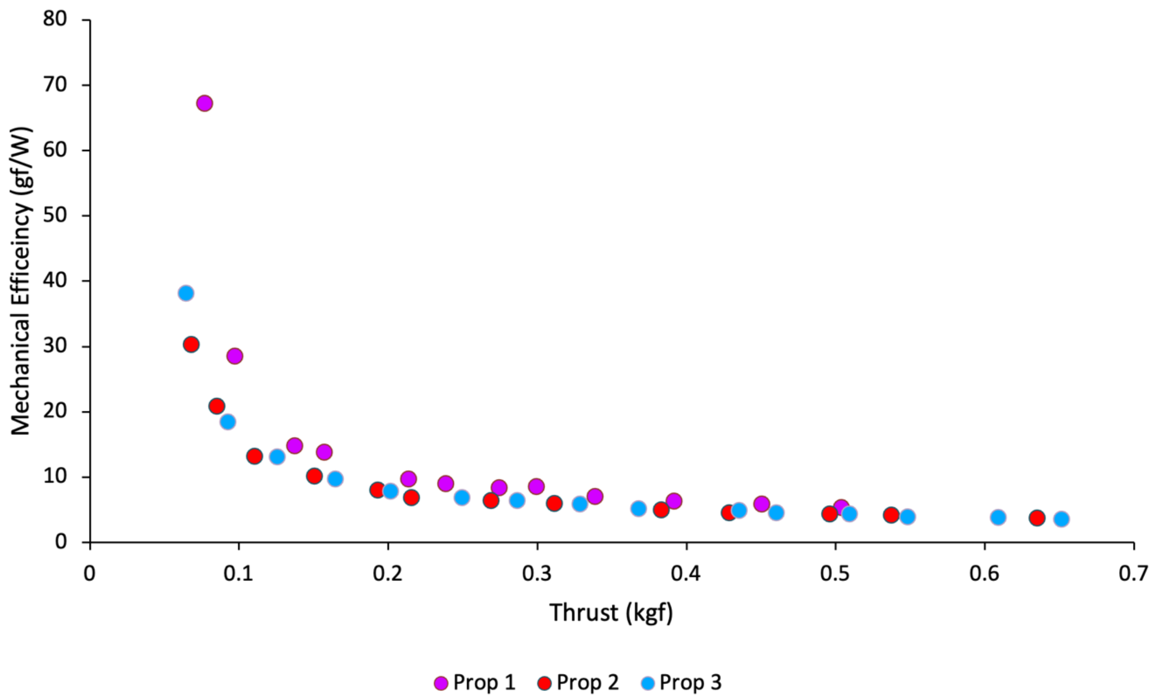
RPM vs. Torque



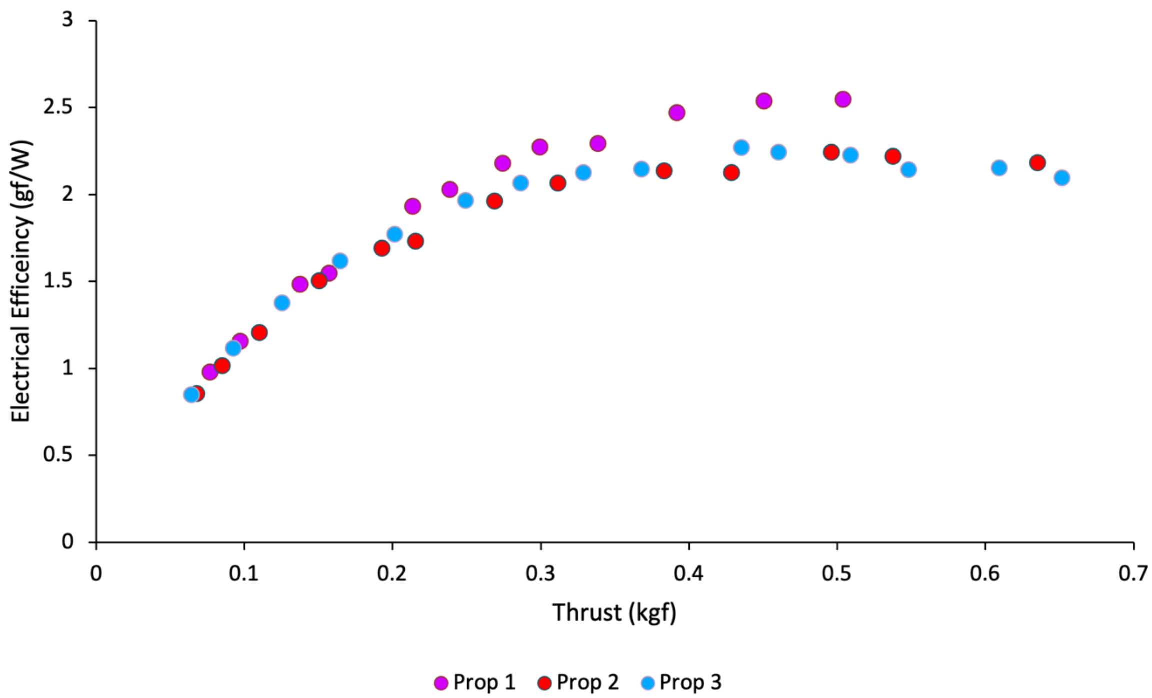
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

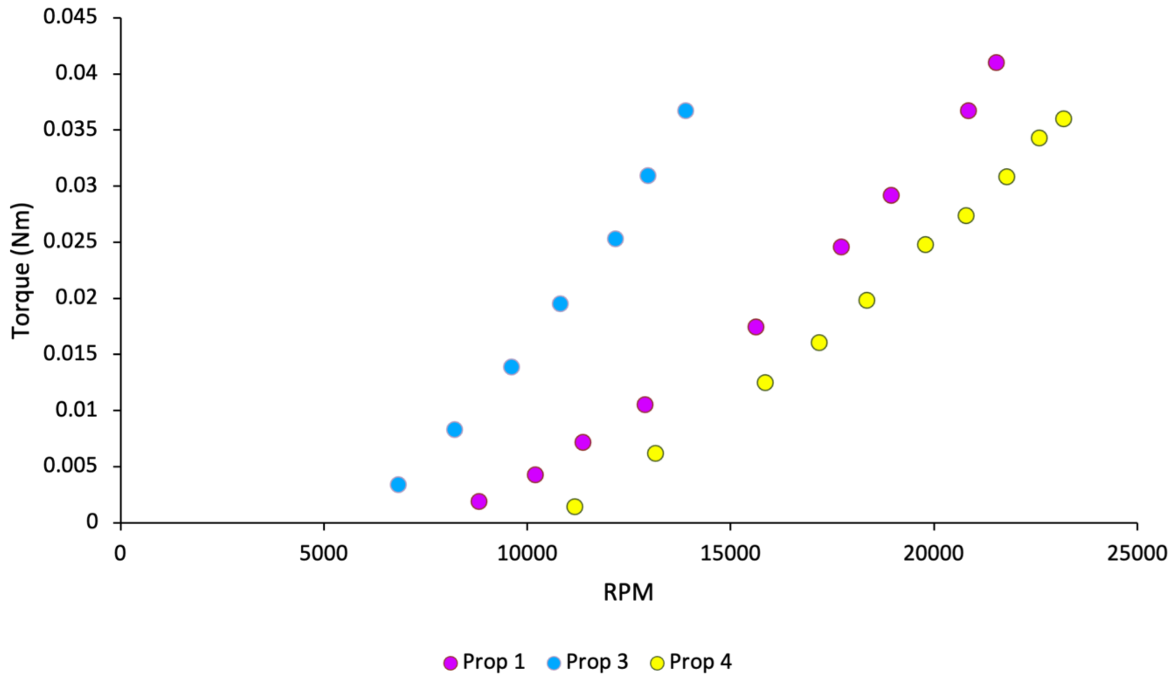


Thrust vs. Electrical Efficiency

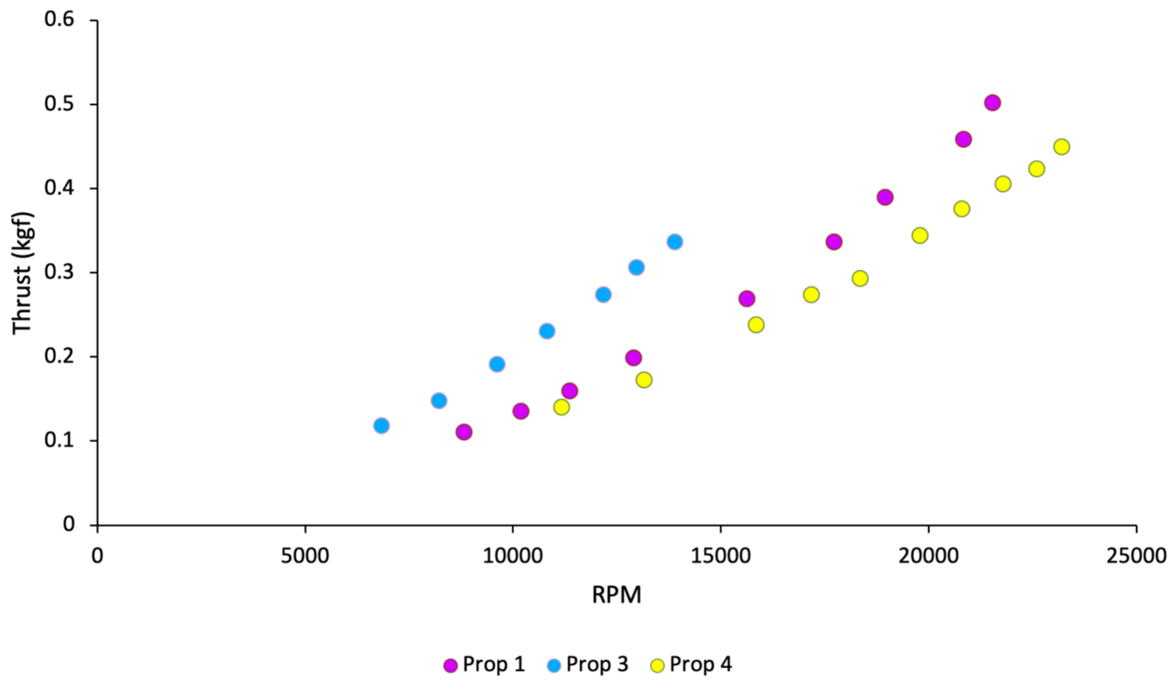
Propeller of Choice:

Propeller 1 (Ethix 5.1*3.0 two blade propeller) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be Propeller 3 (Gemfan 3 Blade 5.1*4.99). It is noted that Propeller 2 (Azure Power 3 Blade) and three have very similar performance.

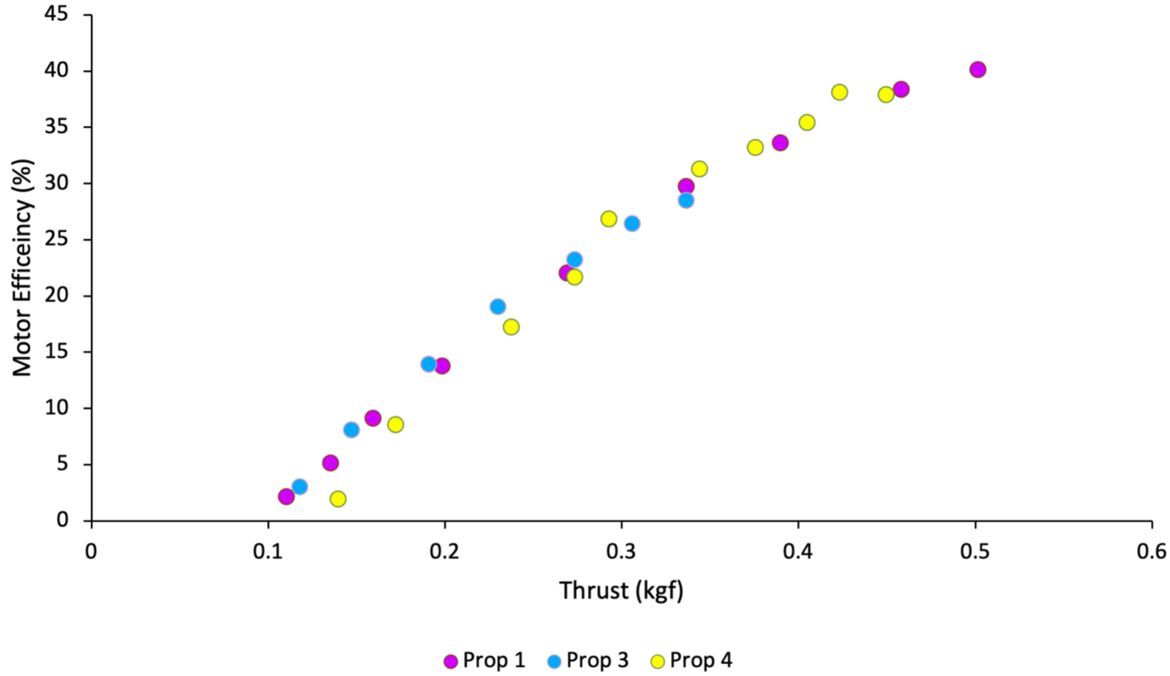
Motor 5, T Motors F1507 2700KV:



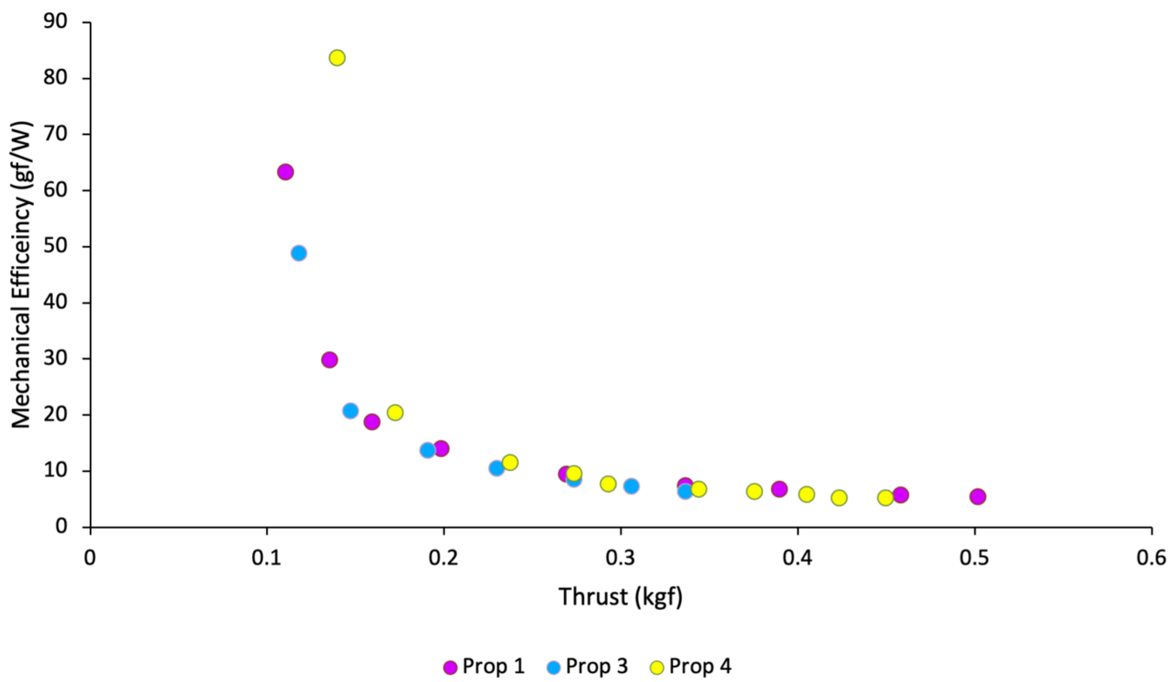
RPM vs. Torque



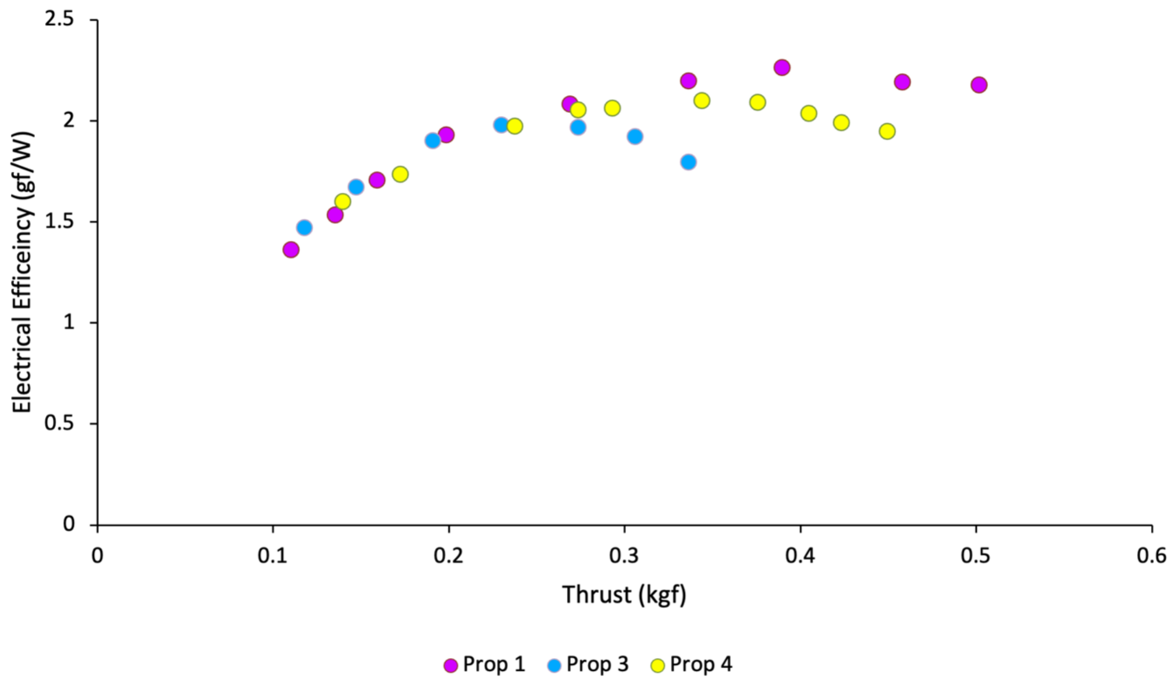
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

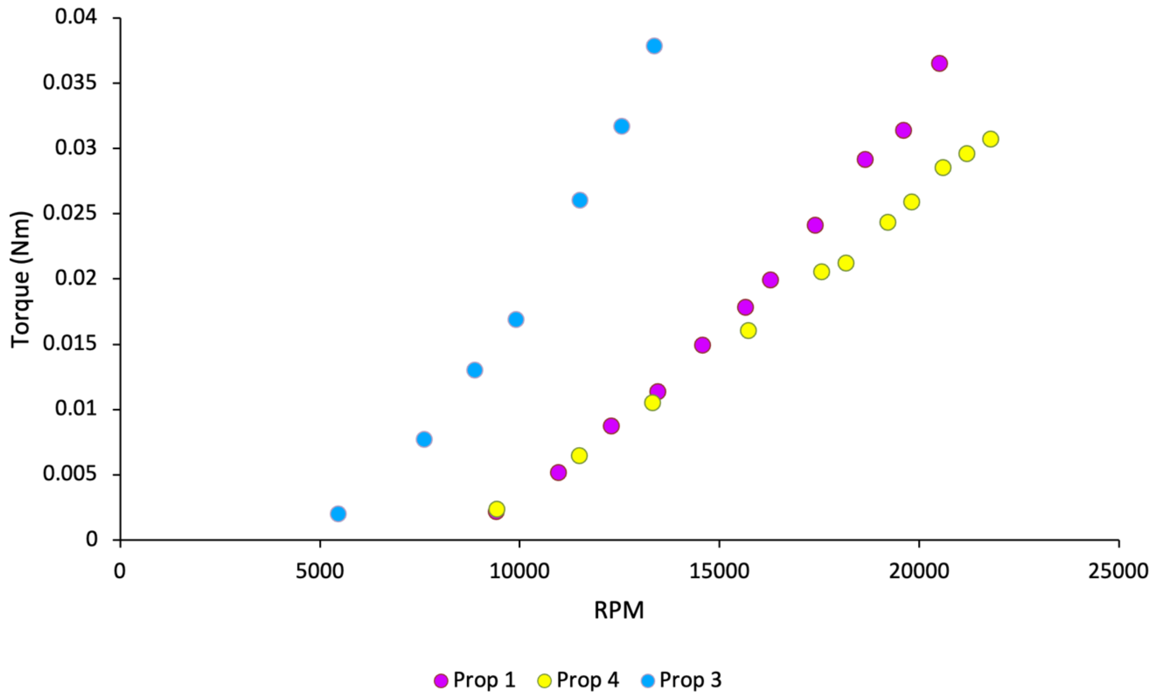


Thrust vs. Electrical Efficiency

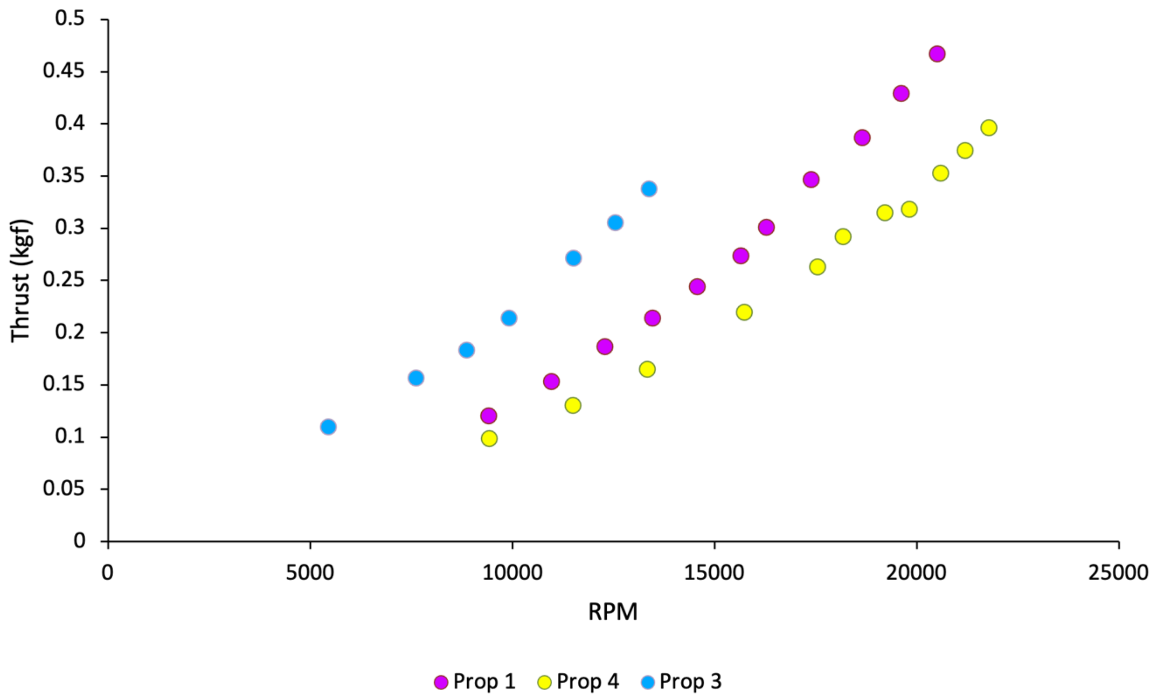
Propeller of Choice:

Propeller 1 (Ethix 5.1*3.0 two blade propeller) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be Propeller 4 (Gemfan 3 Blade 4.0*3.2).

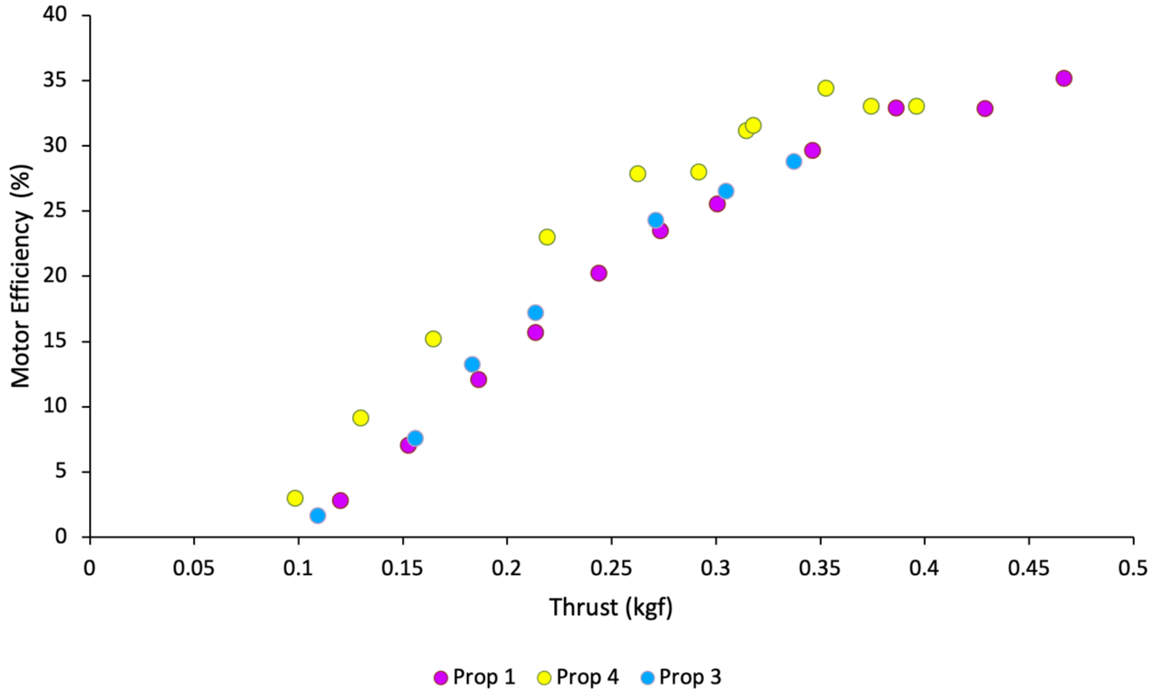
Motor 6, Arthur Motors 1408 2800KV:



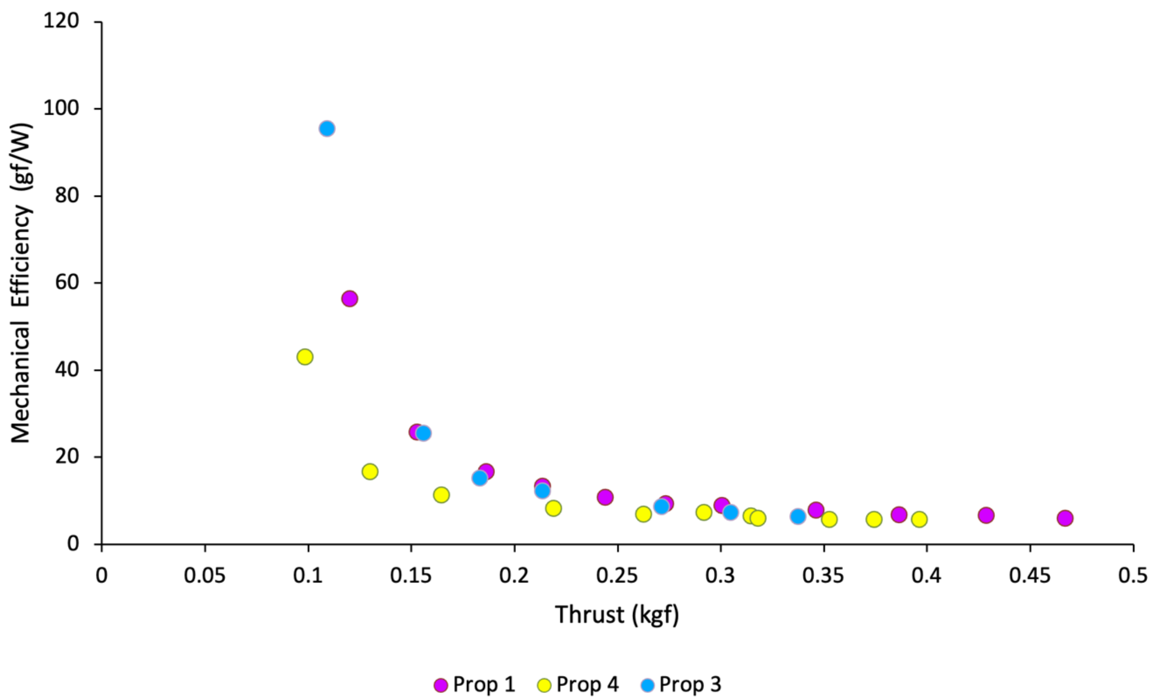
RPM vs. Torque



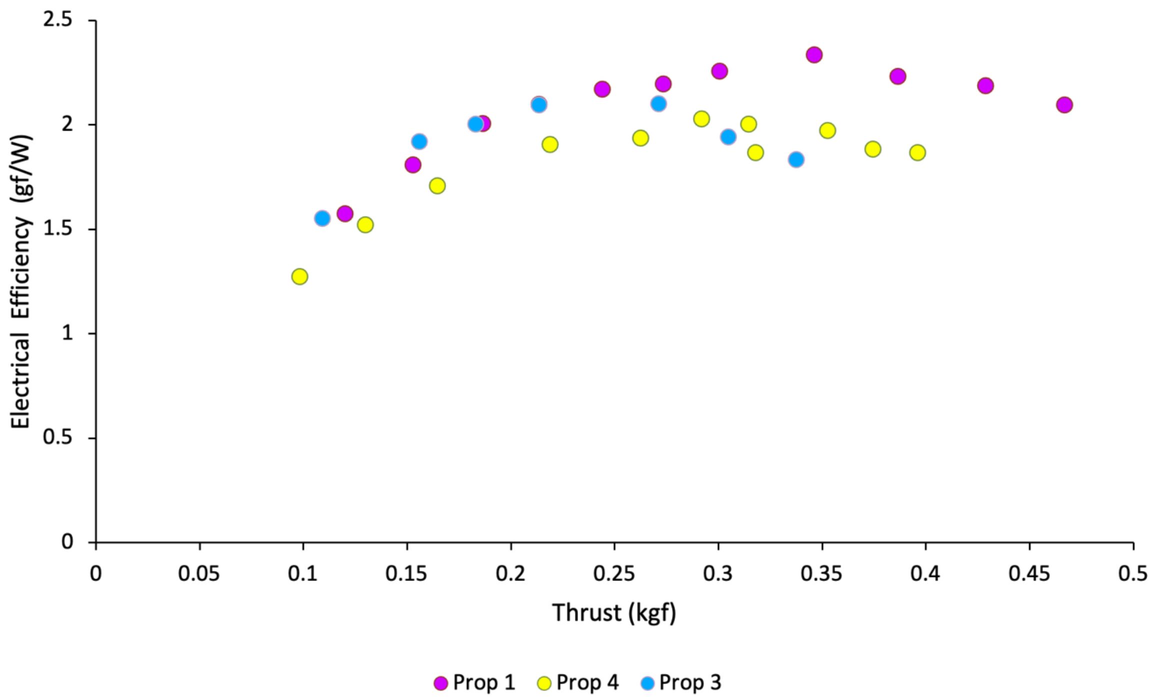
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency



Thrust vs. Electrical Efficiency

Propeller of Choice:

Propeller 1 (Ethix 5.1*3.0 two blade propeller) is the most efficient propeller to operate with this motor. It gives the greatest electrical efficiency at the operation thrust. The second-best propeller would be Propeller 3 (Gemfan 3 Blade 5.1*4.99).

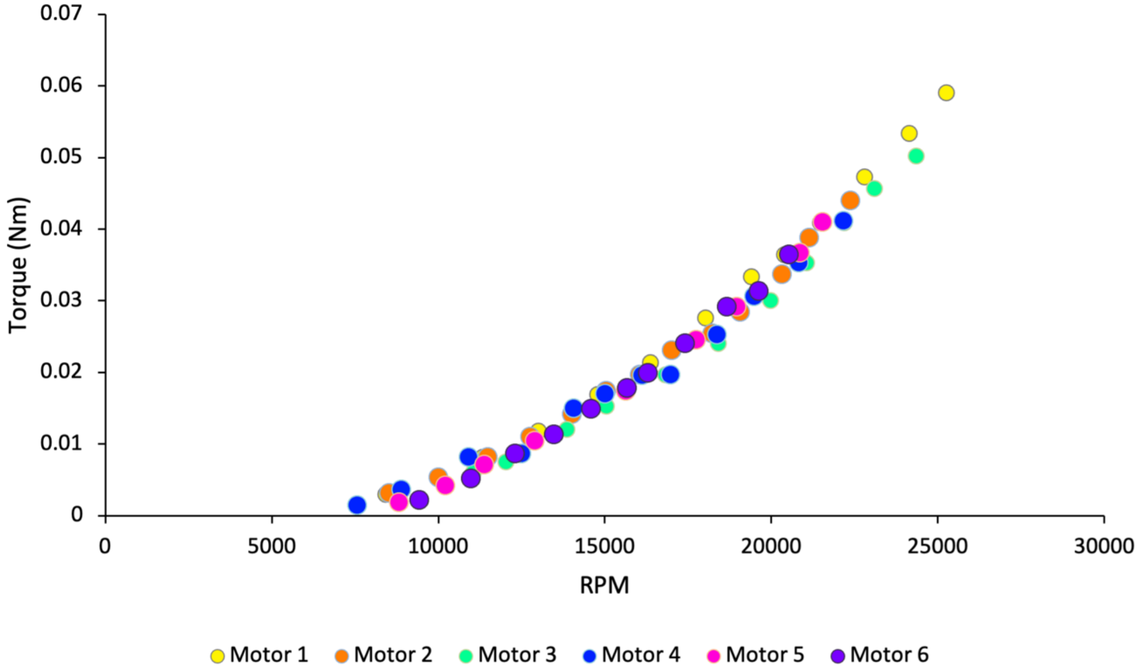
The Most Efficient Combination:

Table 4: A summary of the most efficient propellers with each of the motors. Refer to Table 2 and 3 for details on each propeller. Propeller one seems to have the greatest overall efficiency, and Propeller 3 (Gemfan 3 Blade 5.1*4.99) the second-best overall efficiency.

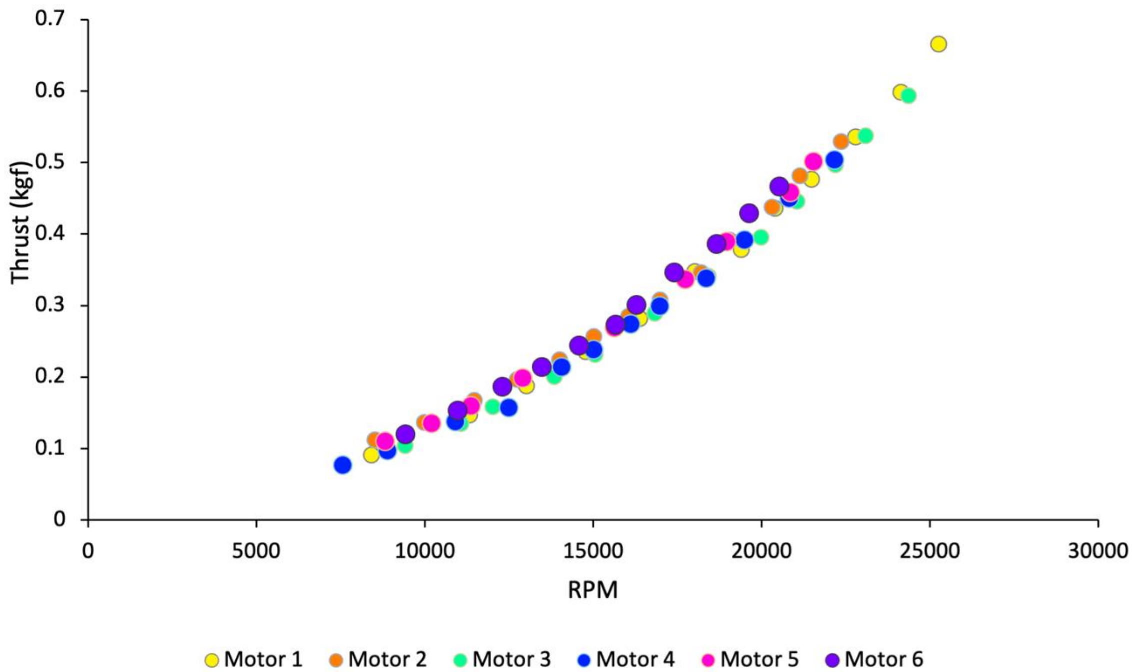
Motor	1st Choice Propeller	2nd Choice Propeller
Motor 1	**Propeller 1**	**Propeller 2**
Motor 2	**Propeller 3**	**Propeller 1**
Motor 3	**Propeller 3**	**Propeller 1**
Motor 4	**Propeller 1**	**Propeller 3**
Motor 5	**Propeller 1**	**Propeller 4**
Motor 6	**Propeller 1**	**Propeller 3**

Now that we have an idea of how each motor handles each propeller, and from the results we can see that Propeller 1 (Ethix 5.1*3.0 two blade propeller) has the greatest efficiency overall we will compare the efficiency metrics of all the motors with Propeller 1 (Ethix 5.1*3.0 two blade propeller) and Propeller 3 (Gemfan 3 Blade 5.1*4.99). From this selection we will have the most efficient combination of motor and propeller.

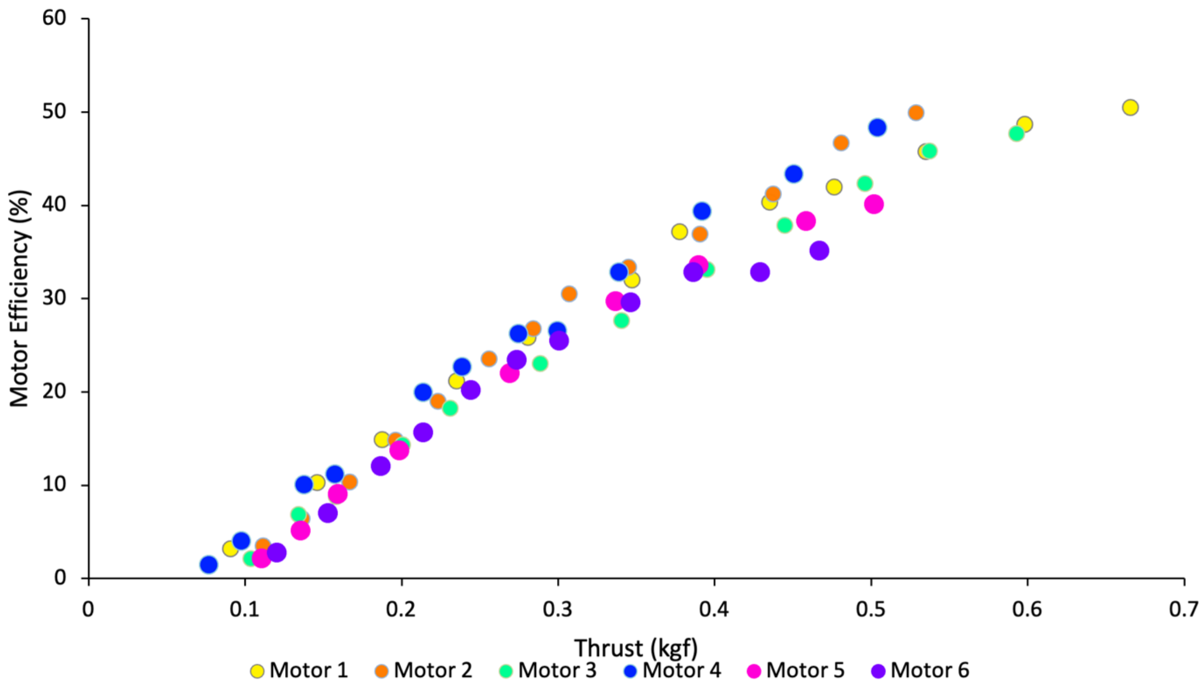
Propeller 1, Ethix 2 blade Propeller 5.1*3.0:



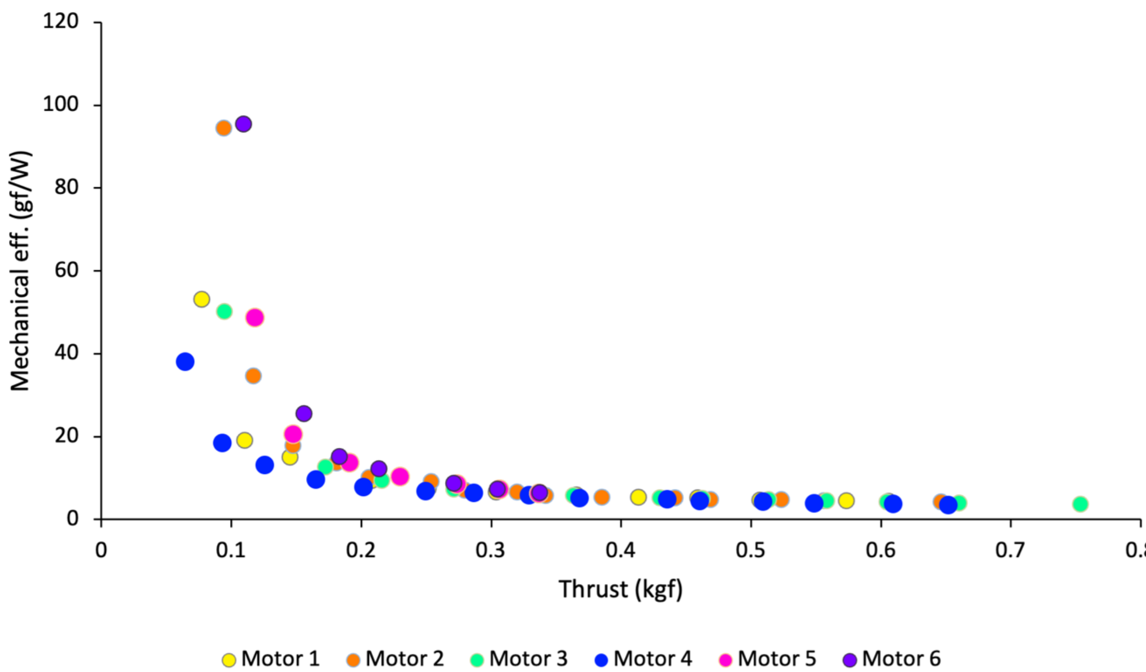
RPM vs. Torque



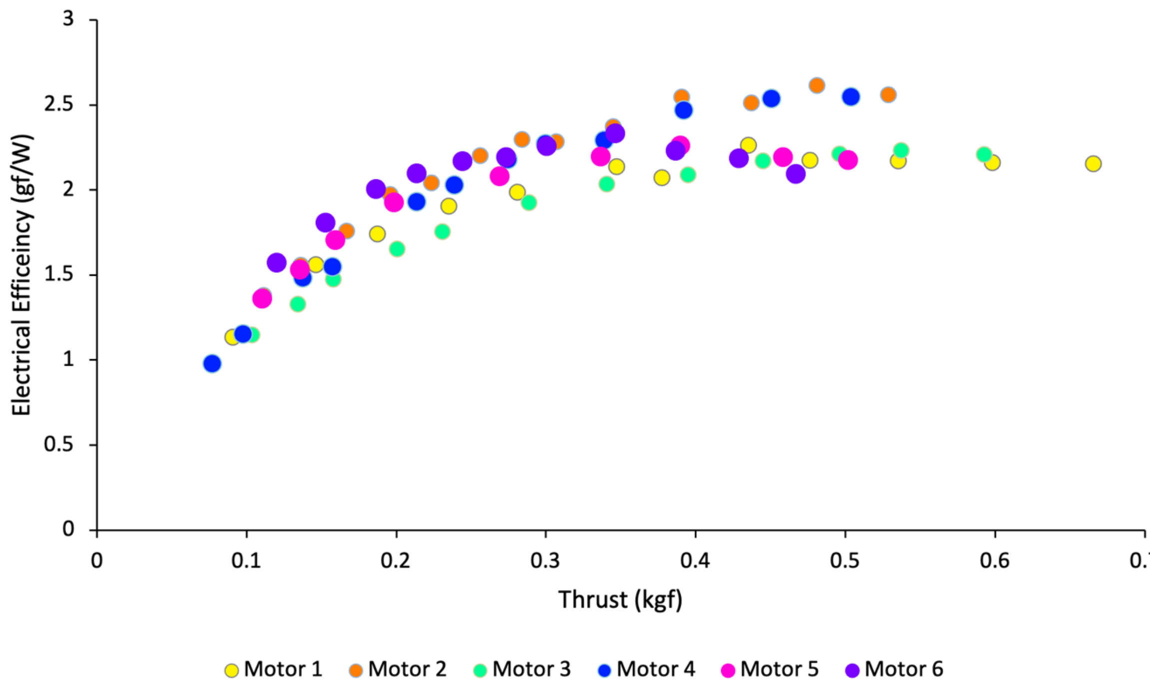
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency

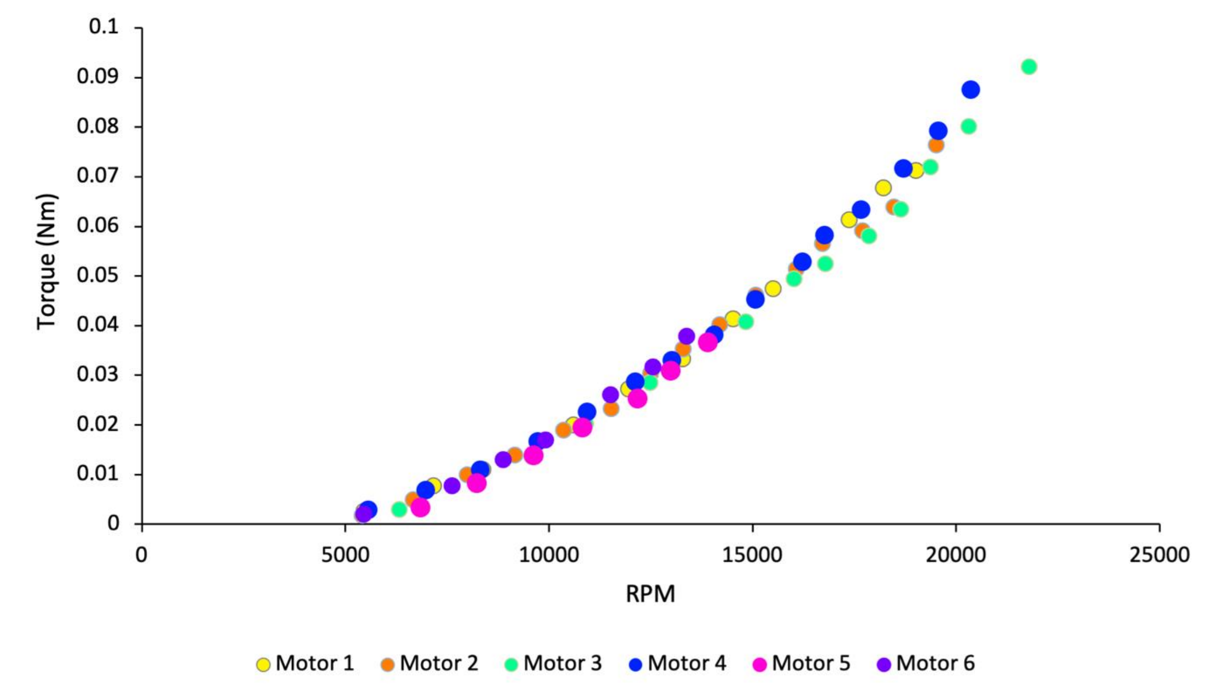


Thrust vs. Electrical Efficiency

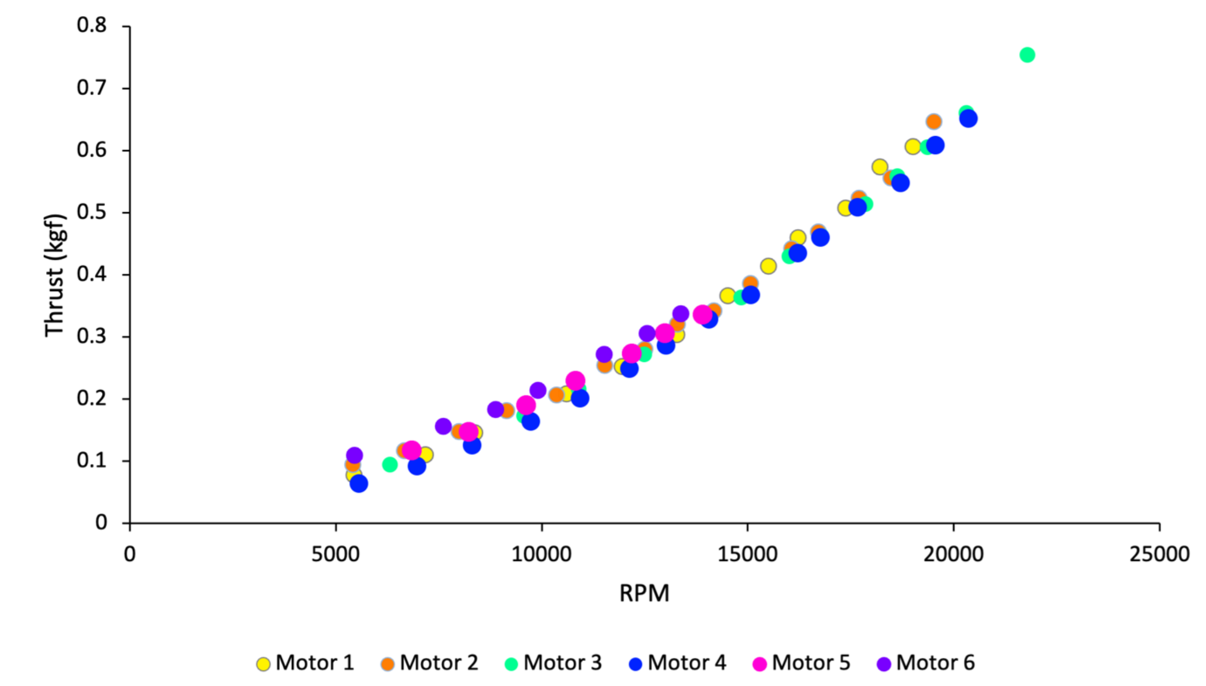
Motor of Choice:

Motor 6 (Arthur Motor 1408 2800KV) is the most efficient motor to operate with this propeller blade. With second-best motor being Xing Flight Pro 2207, 1800KV.

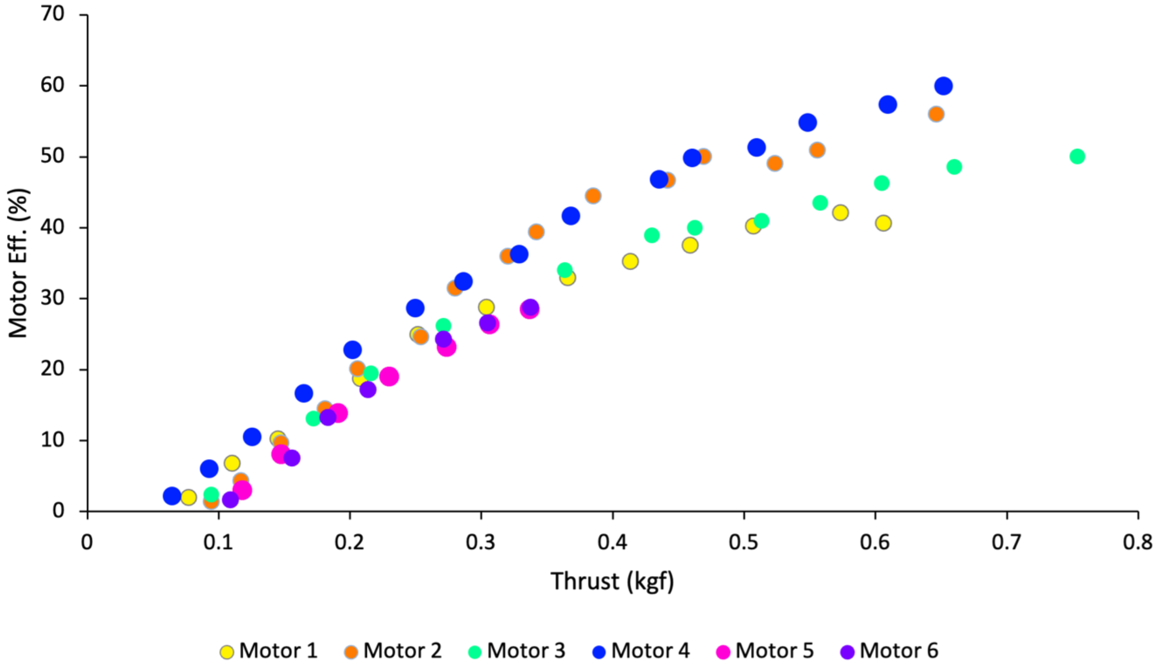
Propeller 3, Gemfan 3 blade Propeller 5.1*4.99:



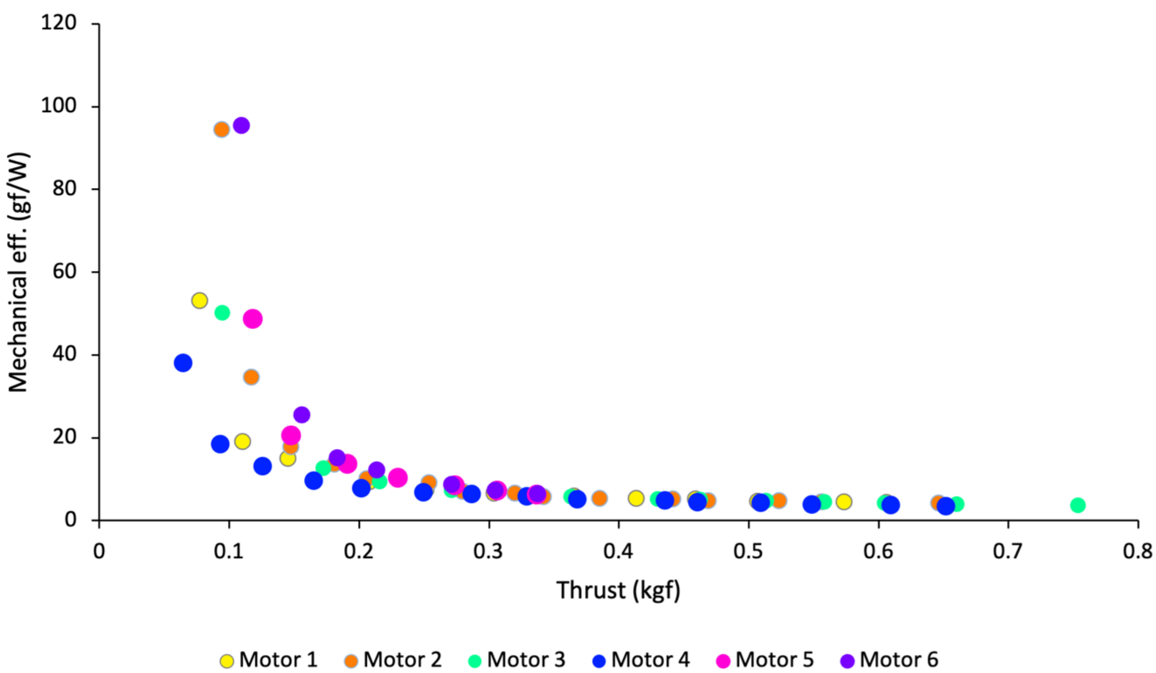
RPM vs. Torque



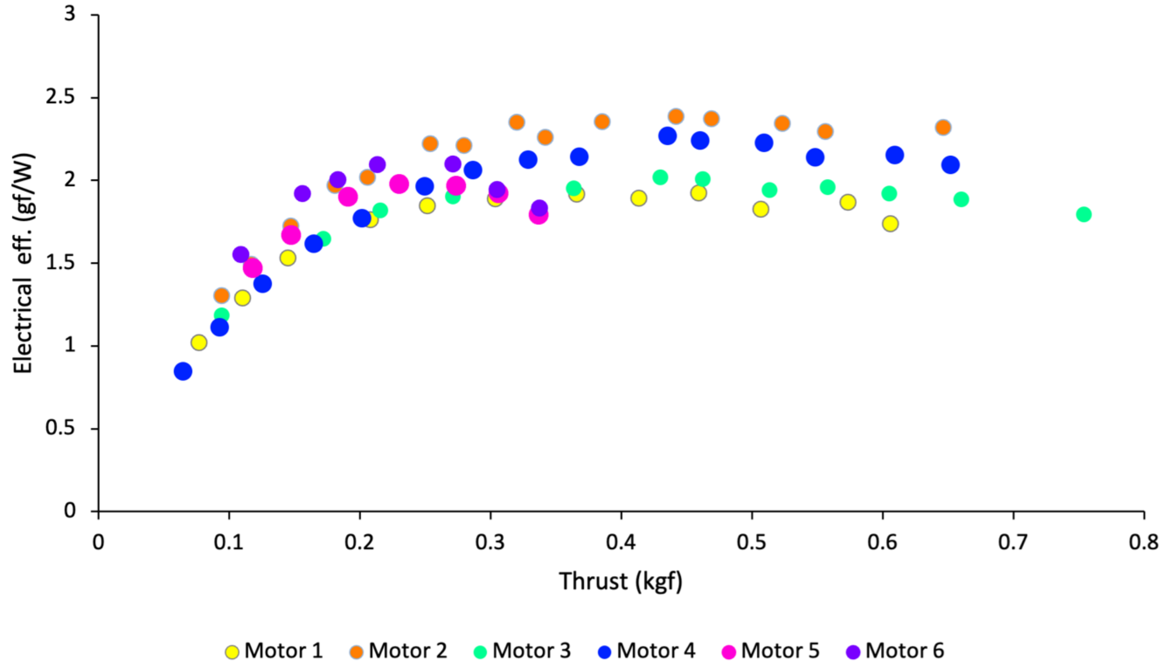
RPM vs. Thrust



Thrust vs. Motor Efficiency



Thrust vs. Mechanical Efficiency



Thrust vs. Electrical Efficiency

Motor of Choice:

Xing Flight Pro 2207, 1800KV is the most efficient motor to operate with this propeller blade. With second-best motor being Motor 6 (Arthur Motor 1408 2800KV). It should be noted that Motor 6 (Arthur Motor 1408 2800KV) begins to under preform at the top end of operational thrust.

Conclusion:

Motor 2 (Xing Flight Prop 2207 1800KV) paired with propeller 3 (Gemfan 3 Blade 5.1*4.99) seems to be the most efficient combination of motor and propeller. Using this combination will provide the longest flight time. We also learn that a motor can have a poor efficiency in conversion of electrical power to mechanical power but make up for the loss in efficiency with a higher conversion of mechanical power to thrust. Further studies are to be conducted on motor heating and ESC performance.

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Revisions

Name/Signature	Date	Description
Cameron H Miller	6/17/2024	First Draft