6702ENG UAV Design

Lab Report

UAV Design -

Propeller and Motor Performance Experiment

1. Title

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2. Introduction

In the worlds of manned aircraft and unmanned aerial vehicles (UAV), propellers produce the thrust required for the vehicle to take off and fly. The dimensions of propellers used in UAVs and manned aircraft vary depending on the application they are used for. The important factors affecting propeller performance are the number of blades, pitch, and diameter of the propeller. Two-blade propellers are more common than three-blade propellers, as more propellers generate more thrust, but they impact the efficiency negatively at the same time. The size of the propeller is 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 4.0" diameter and a pitch of 2.0" would be reported as 4020. Pitch is a measure of how far a propeller will move through the air in a single rotation. Increasing either diameter or pitch will lead to an increase in the thrust produced. To keep a good control authority of the drone, the maximum thrust achievable by the propeller should be about twice the hovering thrust. A propeller will have the same performance characteristics when paired with different motors. What may differ between setups is propeller efficiency with a given motor which is an important parameter in analyzing the performance of a remotely piloted aircraft system (RPAS). In this experiment, investigation on the efficiency of propellers will be carried out with thorough examination on propeller's parameters such as pitch and diameter. The propeller efficiency is defined as propeller power (thrust) produced divided by power applied (mechanical power).

$$Propeller\ efficiency\ \left(\frac{kgf}{W}\right) = \frac{Thrust\ (kgf)}{Mechanical\ power\ (W)} \tag{1}$$

Determining this efficiency will allow us to calculate the flight time of an RPAS built with a given motor-propeller setup. Overall, the flight time is dependent on the weight of the drone, the battery, and the efficiency of the propeller.

$$Flight\ time\ (h) = \frac{E_{battery}\ (Wh)}{Power\ (W)} \tag{2}$$

$$Power\ (W) = \frac{W_{drone}\ (g)}{Propeller\ efficiency\ \left(\frac{gf}{W}\right)} \tag{3}$$

The thrust produced by a propeller is only affected by the motor in terms of the rotations per minute (RPM) that it spins. Any motor spinning the propeller at a given RPM will produce the same thrust (this will be proven in the Results section of this report). However, the motor does affect the overall efficiency of an RPAS. The overall efficiency of an RPAS is an important parameter that we always want to optimize in most RPAS applications. Motors not working at their desired speed range or load level may introduce significant inefficiencies. Given that most RPAS are electrically powered, this means that the battery will be delivering more current than needed and endurance will be reduced. Therefore, the performance of motor, especially brushless motor, which is commonly used in RPAS, must be examined thoroughly. There are several key formulas for understanding brushless motors.

$$Motor\ efficiency = \frac{Mechanical\ power\ (W)}{Electrical\ power\ (W)} \tag{4}$$

$$Electrical\ power\ (W) = Voltage \times Current \tag{5}$$

$$Mechanical\ power\ (W) = Torque\ (Nm) \times Rotation\ speed\ (rad/s) \tag{6}$$

Additionally, brushless motor is characterized by K_v and K_t which are fundamental motor coefficient and motor torque coefficient. When the rotor turns, the voltage generated is proportional to the speed of the rotor. The higher the K_v, the faster the motor will spin for the same voltage input with no load. However, for a given size, a motor with a higher K_v will have lower torque, describe by K_t, as torque is proportional to current. Assuming SI units, K_v is inversely proportional to K_t.

$$Rotation\ speed\ (RPM) = K_v \times Back\ EMF \tag{7}$$

$$Torque = K_t \times Current \tag{8}$$

$$Back\ EMF\ \times Current = Rotation\ speed\ \times Torque \tag{9}$$

The overall performance of the system depends on a well-balanced combination of motor and propeller. The overall system efficiency is calculated as shown below. Changing the motor, propeller, or even the ESC will all contribute to varying the system efficiency. Moreover, the efficiency value will only be valid for a specific command input and mechanical load.

$$System\ efficiency\ \left(\frac{kgf}{W}\right) = Propeller\ efficiency\ \left(\frac{kgf}{W}\right) \times Motor\ efficiency \tag{10}$$

Propellers and motors significantly impact the overall performance of an RPAS. Having an optimized motor-propeller configuration not only allows the aircraft to fly for a longer duration, but to perform optimally. Therefore, testing motors and propellers throughout the UAV design process is of great importance, saving time and resources in the long run. There are several reasons for optimizing and testing motor and propellers including increasing flight time, payload, and range, reducing noise and vibration level, improving stability and reliability, … etc. Manufacturers' datasheets and recommendations may give an idea on suitable motor-propeller configuration for a particular design, yet the provided data is not standardized, so it is impossible to compare parts across different manufacturers. Due to the significance of motor and propellers on the performance of an RPAS, this experiment was conducted with the aim to gain an in-depth analysis on the efficiency of some motor-propellers configurations and from the experimented results, recommendations were given.

3. Materials and Methods

3.1 Apparatus

The following equipment, both hardware, and software, were used in the motor-propeller performance test:

- RCbenchmark GUI software
- Brushless motor and propeller test stand with enclosure
- RCbenchmark dynamometer
- Two 2207 brushless motors with different Kv: 1700Kv and 2400kV
- Four two-blade bullnose propellers with different dimensions: 5045, 5050, 6045, and 6050
- 30A power supply
- Safety glasses

3.2 Methods

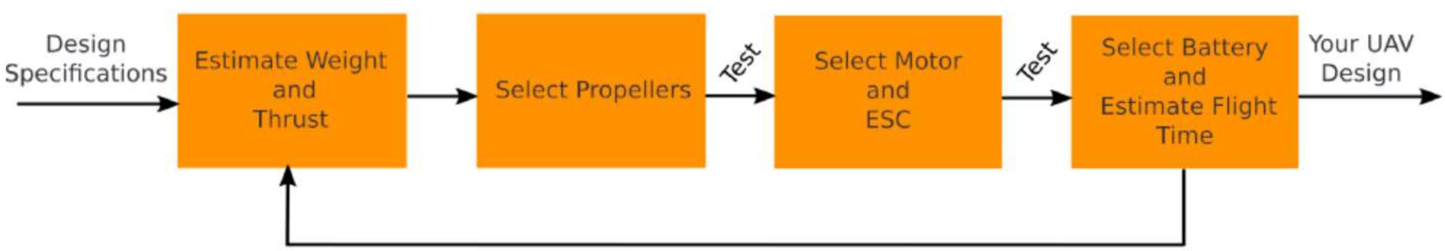

Figure 1:UAV optimization design loop [1].

Lab sheets on the procedure were provided by lab supervisors. Safety was ensured during the entire testing process. To optimize the motor-propeller configuration for an RPAS, a design loop should be followed.

First, we must understand the dynamics of a battery-powered RPAS. In other words, how a drone hovers and flies must be considered. In a quadcopter, the rotation of four propellers generates sufficient thrust that enables the drone to ascent and maintain a certain altitude. At hover, the combined thrust of the propellers is equal to the quadcopter's total weight. Therefore, with a given drone's weight, including the weight of the battery, we can deduce the required total thrust at hover and then divide that total thrust by the number of propellers to achieve minimum thrust on each propeller. Yet, this thrust is only for the drone to hover at a certain altitude. In other to keep a good control authority of the quadcopter, it is recommended that the maximum thrust achievable by the propeller should be twice the hovering thrust which means the thrust to weight ratio is 2:1. The requirements for the thrust generated by propellers may vary depending on applications of the RPAS as a racing drone will need to possess a higher thrust to weight ratio.

Secondly, the propeller with the highest efficiency must be chosen. To decide which propeller to be used in the final design, several propeller options were provided for the test using the thrust stand. Propeller data, including thrust, torque, and rotation speed, only depend on the propeller no matters the motor selection. Therefore, the data points on a thrust vs. rotation speed for a single propeller tested with multiple motors should all be very close to the same line as shown in Fig. 2. We achieved propeller data from propellers at 4 different sizes which can be plotted to be compared in terms of propeller efficiency as a function of thrust. From this, we decided on the propeller with the highest propeller efficiency at the required thrust.

Thirdly, the most efficient motor must be selected with the same process as the propeller for a well-balanced propeller-motor configuration that would optimize an RPAS. In this experiment, we only performed tests on two motors but there were various candidates to choose from. With the measurements, we obtained the data points for motor efficiency as a function of thrust. From the motor efficiency plot of a specific propeller, we can decide on the most efficient motor for that propeller at both hover thrust and peak thrust for sufficient control authority. The next step was to test and choose the most suitable electronic speed controller (ESC) for the motor. Yet, this test was out of scope for this experiment.

Finally, we calculated the optimized flight time of the quadcopter with the new propeller-motor configuration using the experimented results. For a battery-powered RPAS, the overall efficiency of the system must be calculated using Equation (10). The flight time was estimated using this overall efficiency, the total weight of the drone, and battery capacity. This was done using available flight time calculator spreadsheet which will be presented later in this report. In general, the flight time optimization process is a design loop so we will have to iterate on this process to find the optimal propulsion system as we might have to alter some initial specifications during the process.

It is important to note that the experimented results might be affected by several factors which present imperfection in the measurements. Errors can occur during the test due to the calibration process, the number of samples, the number of tests done for a specific propeller. Additionally, some of the measurements were not collected at maximum throttle due to safety reasons. Therefore, there will always be room for improvement in the test.

4. Results

In this section, some experimented results are presented. All data were acquired from the RCbenchmark software and the dynamometer which were then plotted on Microsoft Excel. Most of the graphs presented in this section are sufficient for analysis.

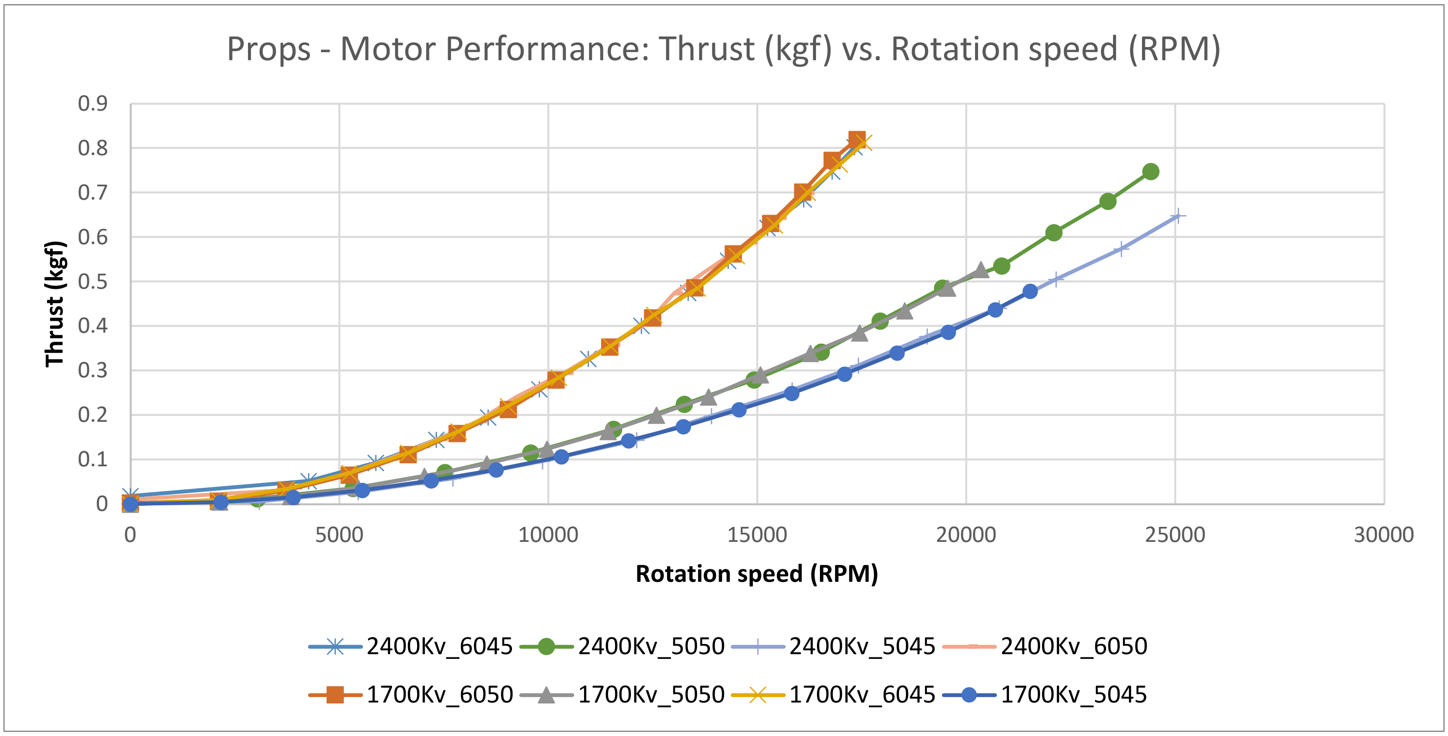

Figure 2: Thrust generated by different propellers.

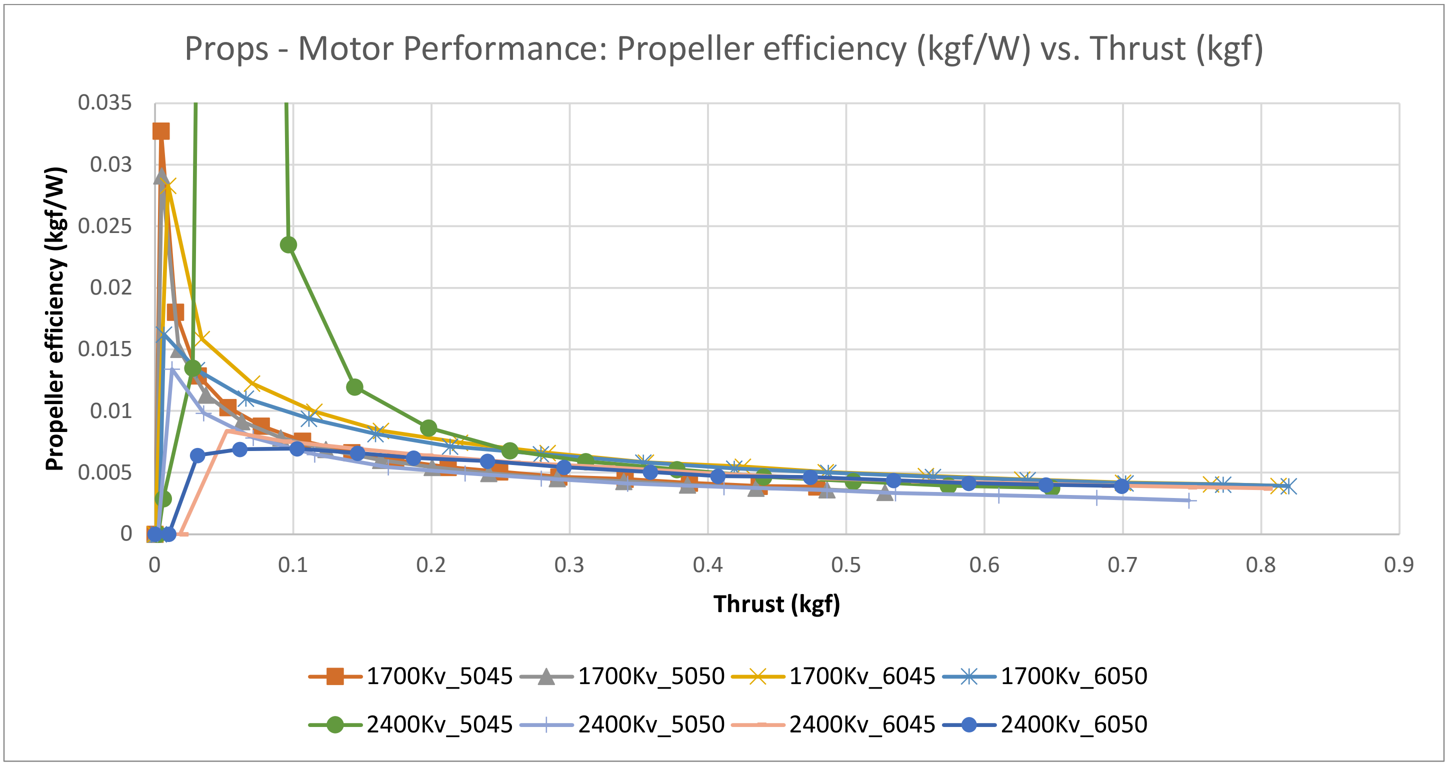

Figure 3: Propeller efficiencies of different propellers.

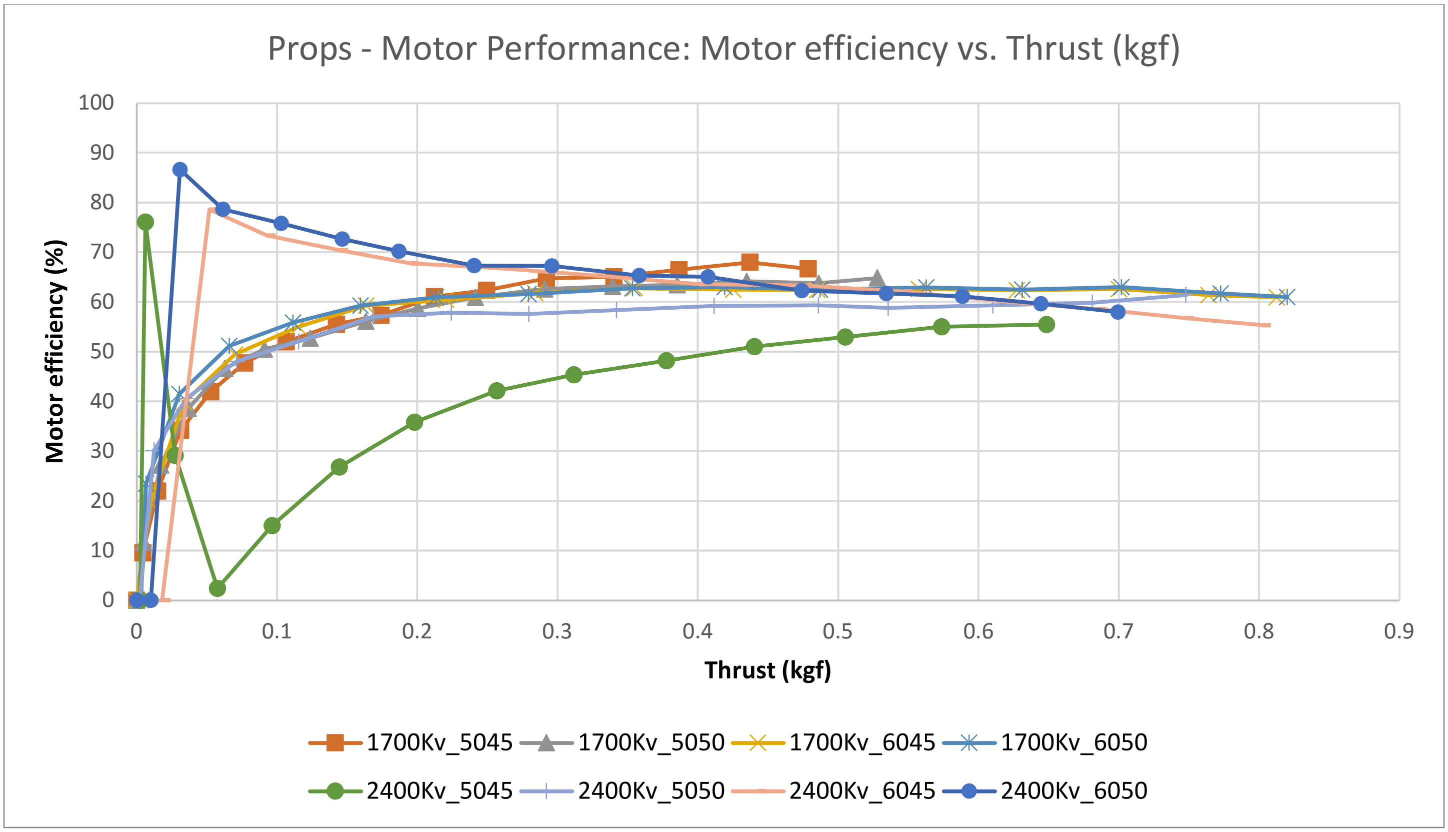

Figure 4: Motor efficiencies of 1700Kv and 2400Kv motors.

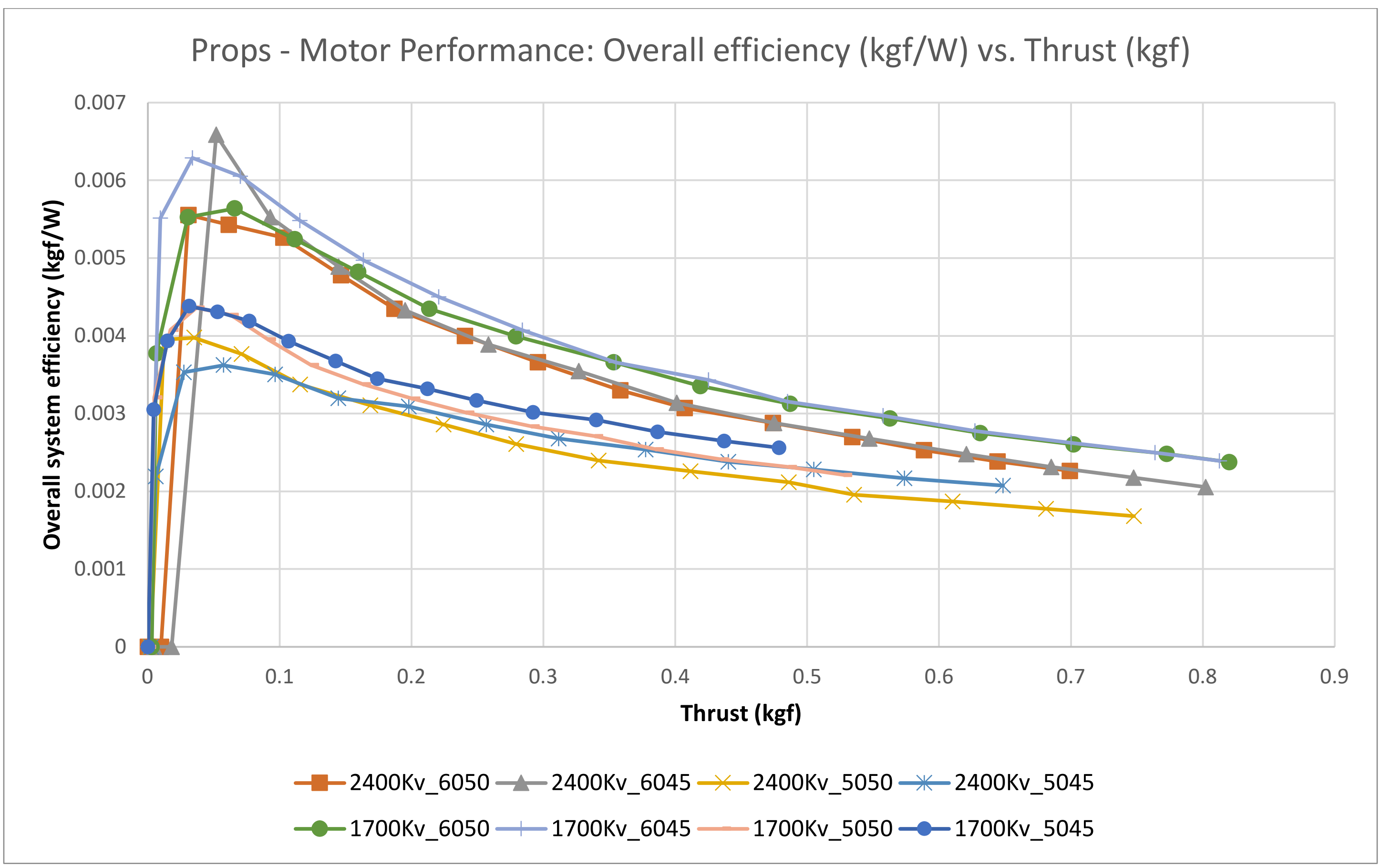

Figure 5: Overall system efficiency of different motor-propeller combinations.

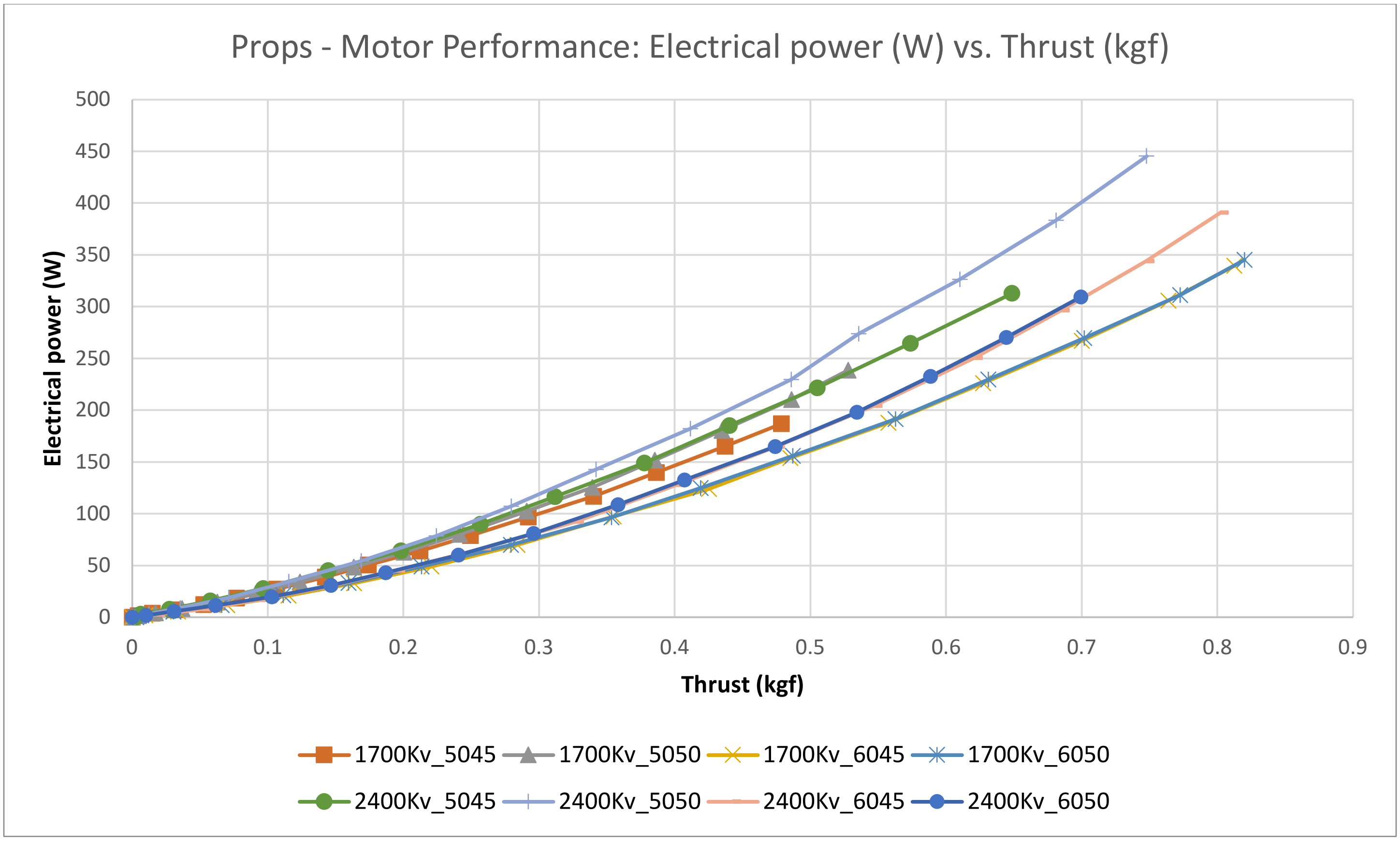

Figure 6: Electrical power consumptions of different motor-propeller combinations.

Fig. 2 shows the thrust generated by each propeller when paired with 2 motors at 2 different fundamental motor coefficients that are 1700Kv and 2400Kv, respectively. The thrust was different in propellers with different dimensions (except for 6045 and 6050 which had almost identical thrust generation). This is because propellers with higher diameter and pitch produced higher thrust. The thrust at a given rotation speed of a specific propeller is not affected by motor selection. Propellers with smaller diameters or pitches can spin faster, or having higher RPM, due to less load being applied to the motor. Thus, they tend to run smoother and are more responsive to control commands. This improves the general control stability of an RPAS.

The propeller efficiency at a given thrust is shown in Fig. 3. From our theory on propeller efficiency, we know that propeller efficiency is the function of the propeller itself. Regardless of the motor chosen to drive a particular propeller, the thrust generated will be the same and the same applies to propeller efficiency at a given rotation speed. However, Fig. 3. does not seem to reflect the theory of propellers. This was because of the imperfection presented in the measurements which led to few odd points in the figure. Also, the propeller efficiencies at slow rotation speed were not captured entirely as there was only one test carried out on all propeller-motor pairs. Additionally, the dynamometer took measurements at the microsecond settings of the electronic speed controller (ESC), and thus, for each propeller-motor configuration, there will be a different thrust as a function of rotation speed. The same issues also appeared in Fig. 4. Yet, the data is good enough for the analysis as we will not focus on the low thrust area in the figure.

Overall system efficiency is calculated using Equation (10) and is plotted as a function of thrust in Fig. 5. This figure is important in our analysis and calculation of the flight time of the optimized RPAS. Fig. 6. shows the relationship between electrical power drawn by the motor to generate the thrust. This figure has a correlation with Fig. 5 as higher electrical power at a given thrust corresponds to lower overall system efficiency at that thrust.

5. Discussion

From the figures presented in section 4 and relevant measurements, we can start optimizing the RPAS based on its required thrust to hover and maintain good control authority. We use a 1.1kg quadcopter, including battery and payload, as an example, so the total thrusts required for hovering and for good control authority are 10.791N and 21.582N, respectively (for g = 9.81m/s^2). This means that each propeller must produce at least 2.698N. We must keep in mind that, to maintain adequate control of the drone during its flight, the maximum thrust achievable by the propeller should be twice the hovering thrust, so 5.396N or 0.55kgf of thrust per propeller will also be considered.

After identifying the sufficient hovering thrust for each propeller for the design, we then select propeller for the quadcopter based on propeller efficiency in Fig. 3 where there are 4 propellers to choose from regardless of the motor powering the propeller. As shown in Fig. 3, at 2.698N or 0.275kgf, the best propeller is the 6045. This remains true for the thrust at 0.55kgf as propeller 6045 shows the highest efficiency among others. Thus, we can conclude that the 6045 propeller, in this case, is the most efficient propeller at 0.275kgf and 0.55kgf with the torque of 0.040Nm and 0.077Nm, respectively. The rotation speeds at 0.275kgf and 0.55kgf for the 6045 propeller are 10247RPM and 14505RPM, respectively. The 6050 propeller shows good propeller efficiency that is almost identical to the 6045 propellers. This can be useful in our design loop and it offers more propeller selection. Table 1 summarizes the propeller efficiencies at two considered thrusts for all the propellers used in the test.

Propeller size	Propeller efficiency at hovering	Propeller efficiency at good control
1700Kv_5045	4.663gf/W at 0.292kgf	x
1700Kv_5050	4.533gf/W at 0.291kgf	x
1700Kv_6045	6.600gf/W at 0.284kgf	4.750gf/W at 0.558kgf
1700Kv_6050	6.493gf/W at 0.279kgf	4.670gf/W at 0.563kgf
2400Kv_5045	5.914gf/W at 0.312kgf	3.944gf/W at 0.574kgf
2400Kv_5050	4.530gf/W at 0.279kgf	3.156gf/W at 0.610kgf
2400Kv_6045	5.431gf/W at 0.327kgf	4.130gf/W at 0.547kgf
2400Kv_6050	5.442gf/W at 0.296kgf	4.140gf/W at 0.589kgf

Table 1: Propeller efficiencies at hovering thrust and at 2:1 thrust to weight ratio of different motor-propeller combinations. Note: due to the steps in collecting sampled data, the compared thrusts are not the same among propellers.

It is important to note that errors in data collection were unavoidable in the test due to several factors such as testing equipment, setup process, electrical noise, sampling rate, and the number of steps in measuring efficiencies. Switching to different motors for testing also introduced some calibrating errors in the measurements. Therefore, there are some differences in the propeller efficiencies between the same propellers operated on 2 different motors, noticeably the 5045 propellers on 1700Kv and 2400Kv motors. Errors are more apparent at low thrust or low rotation speed. Yet, the errors should not severely affect the overall trend of the graph and the data is sufficient and good enough for the scope of this report.

The next step is to find the most efficient motor to pair with the propeller. The required operating points for the motor are 0.275kgf and 0.55kgf of thrust, the same as the operating points for the propeller. As shown in Fig. 3, at operating points, the most efficient motor at hover thrust is 2400Kv while 1700Kv motor seems to operate more efficiently at 0.55kgf thrust. However, the motor selection is affected by the errors presented in the data. Because of this, we will need to look at the overall system efficiency and power consumption figures in Fig. 5 and Fig. 6 before coming to the final conclusion. Table 2 summarizes the motor efficiencies at two considered thrusts for all the propellers used in the test. It is important to note that we only consider the motors paired with the 6045 propeller, yet the table shows all propeller-motor configurations for illustration purposes.

Motor	Motor efficiency at hovering	Motor efficiency at good control
1700Kv_5045	64.70% at 0.292kgf	x
1700Kv_5050	62.60% at 0.291kgf	x
1700Kv_6045	61.74% at 0.284kgf	62.58% at 0.558kgf
1700Kv_6050	61.55% at 0.279kgf	62.91% at 0.563kgf
2400Kv_5045	45.33% at 0.312kgf	54.98% at 0.574kgf
2400Kv_5050	57.61% at 0.279kgf	59.29% at 0.610kgf
2400Kv_6045	65.30% at 0.327kgf	62.09% at 0.547kgf
2400Kv_6050	67.26% at 0.296kgf	61.14% at 0.589kgf

Table 2:Motor efficiencies at hovering thrust and at 2:1 thrust to weight ratio of different motor-propeller combinations.

From Fig. 5 and Fig. 6, we can clearly see that the overall system efficiency and the electrical power consumption of the 1700Kv_6045 configuration are better than that of the 2400Kv_6045 configuration. Therefore, we can conclude that the 1700Kv-6045 motor-propeller combination is the most efficient among other configurations tested. Table 3 provides the overall system efficiency at hovering and good control thrusts for all motor-propeller combinations tested in this experiment.

Motor-propeller	Overall efficiency at hovering	Overall efficiency at good control
1700Kv_5045	3.017gf/W at 0.292kgf	x
1700Kv_5050	4.533gf/W at 0.291kgf	x
1700Kv_6045	4.074gf/W at 0.284kgf	2.972gf/W at 0.558kgf
1700Kv_6050	3.000gf/W at 0.279kgf	2.939gf/W at 0.563kgf
2400Kv_5045	2.680gf/W at 0.312kgf	2.168gf/W at 0.574kgf
2400Kv_5050	4.530gf/W at 0.279kgf	1.871gf/W at 0.610kgf
2400Kv_6045	3.547gf/W at 0.327kgf	2.678gf/W at 0.547kgf
2400Kv_6050	3.660gf/W at 0.296kgf	2.531gf/W at 0.589kgf

Table 3:Overall system efficiencies at hovering thrust and at 2:1 thrust to weight ratio of different motor-propeller combinations.

After having the most efficient motor-propeller combination, we then select an ESC to run the motor. Because this topic is out of scope in this experiment, we will assume that ESC used to operate the motor and propeller can deliver enough power and efficiently operate the motor.

The last step in the design is to choose a battery and estimate the flight time of the quadcopter. The flight time can be calculated using available spreadsheet to save time and burden in estimating flight time. It is important to keep in mind that when choosing a battery, we must not exceed the total weight of the drone proposed at the beginning of this section that is 1.1kg including battery and payload weight. Table 4 provides a number of 4S battery examples with different specifications to estimate the flight time of the quadcopter. The actual flight time is 1 or 2 minutes less than the value calculated in the table due to the safety discharge limit and battery voltage being lower at high load.

Batteries	Battery energy (Wh)	Battery weight (g)	Energy density (Wh/g)	Drone weight without battery (g)	Estimated fight time (minutes)
Ovonic 1300mAh 4S 100C Lipo Battery [2]	19.24	160	0.12025	940	6.107
Ovonic 1550mAh 4S 100C Lipo Battery [3]	22.94	190	0.12074	910	6.386
Ovonic 1800mAh 4S 100C Lipo Battery [4]	26.64	218	0.12220	882	6.683
Turnity 8000mAh 4S 12C Lipo Pack [5]	118.4	752	0.15745	348	18.23
Gens ace 5000mAh 4S 50C Lipo [6]	74	609	0.12151	491	11.467
NXE Power 5400mAh 4S 60C Lipo [7]	79.92	554	0.14426	546	12.148
Rhino 1500mAh 4S 50C Lipo [8]	22.2	193	0.11503	907	6.268
Turnigy 12000mAh 4S 12C Lipo [9]	177.6	1080	0.16444	20	36.134
ZOP Power 5000mAh 4S 60C Lipo [10]	74	535	0.13832	565	11.414

Table 4: Estimated hovering flight time for 1700Kv-6045 motor-propeller configurations with a number of batteries.

Assume all the batteries above are capable of safely delivering the maximum current that the ESCs need to drive the selected motors. As we can see in Table 4, we can estimate the flight time and maximum drone weight without battery for a 1.1kg quadcopter design. We can clearly see the effect of battery capacity and battery weight on the flight time of our 1.1kg quadcopter. We can model the drone's estimated flight time as a function of battery capacity for different batteries listed in Table 4 (refer to the Appendix for the figure). It is apparent if we increased the battery energy, we could also increase the flight time, but the trade-off would be the increase in total weight. This is where our quadcopter design loop begins to further optimize our RPAS depending on specific applications and requirements on flight time and total weight. Therefore, we can choose a new battery for our design to maximize flight time if the total weight is not a significant constraint.

From the figure in the Appendix, there is a steep growth curve in the flight time with increased battery energy from 0Wh up to 100Wh. Therefore, we can use a battery with around 100Wh of stored energy to maximize our flight time. The battery energy can be increased by choosing a higher number of cells in series in a battery which increases the nominal voltage of a battery, or by choosing a higher battery capacity which increases the mAh of a battery, or both. Yet, the number of cells in a battery must match with the maximum operating voltage of ESCs. Turnity 8000mAh 4S 12C Lipo Battery with a total flight time of around 18 minutes seems to be a good choice in our design, yet the maximum drone's weight without battery we can have for our optimized hovering thrust is around 350g. This number might be too low for some applications that required high payload weight. Let assume the maximum weight for our payload is around 800g, then the total weight is of our drone including Turnity 8000mAh 4S 12C Lipo battery is 1552g. This weight exceeds our initial design weight of 1.1kg. Thus, we must start our design process again to find the new optimization for our new design.

The total quadcopter's weight of 1552g means that 0.388kgf thrust per propeller is required for the quadcopter to hover and 0.776kgf of thrust per propeller is needed to maintain a 2:1 thrust to weight ratio. From Fig. 2, only 6045 and 6050 propellers are capable of delivering the peak thrust of 0.776kgf; thus, we can reduce our motor-propeller combinations to four options as thrust generated is independent of motor selection. Using the same method as we used initially to determine the most efficient motor-propeller configuration, we pair 1700Kv motor with 6045 propeller which gives the overall system efficiency of 2.484 gf/W at approximately 0.773kgf. At this point, it is important to note that due to sample rate and errors in measurements, the data may not be perfectly accurate; yet the data collected are sufficient for our design purposes. With the information relating to motor and propeller, we can use the flight time calculator spreadsheet [11] to estimate the new flight time for the 1552g quadcopter with 1700Kv 6045 motor-propeller configuration. This gives us approximately 11 minutes of total flight time. Hence, by increasing our payload from 348g to 800g, we have reduced our flight time from around 18 minutes to around 11 minutes.

To see the effect of optimizing the quadcopter with the most efficient motor and propeller, we compare the estimated flight time of 1700Kv 6045 motor-propeller versus two other combinations in Table 5.

Motor-propeller	**Overall efficiency (kgf/W)**	**Hovering thrust (kgf)**	**Battery model**	**Drone weight without battery (g)**	**Estimated flight time (minutes)**
1700Kv-6045	0.004074	0.284111	Turnity 8000mAh 4S 12C Lipo Pack	348	18.23
1700Kv-5050	0.002838	0.29096	Turnity 8000mAh 4S 12C Lipo Pack	348	14.14
2400Kv-5050	0.002609	0.279517	Turnity 8000mAh 4S 12C Lipo Pack	348	12.06

Table 5: Flight time comparison of several motor-propeller configurations using the same battery.

6. Conclusion

It is obvious from our analysis and discussion that optimizing motor and propeller means of testing to select the most efficient motor and propeller provides us greater estimated fight time for hovering quadcopter. Our test limited the number of motors and propellers used for testing, but tests can be performed on a larger motor and propeller to further optimize the RPAS. Even though the experiments gave an overall design procedure and the importance of optimizing a quadcopter, there were noticeable errors in the measurements. These errors were not severely impacting our results and analysis, but they can be reduced by increasing the sample rate, increasing the number of measure steps per motor-propeller combination and properly calibrating the dynamometer before performing the data collection, etc...

References

[1] L. Nagel, "The Drone Design Loop for Brushless Motors and Propellers", *Tyto Robotics Inc*, 2021. [Online]. Available: https://www.tytorobotics.com/blogs/articles/the-drone-design-loop-for-brushless-motors-and-propellers?_pos=3&_sid=85480a184&_ss=r. [Accessed: 17- Aug- 2021].

[2] "OVONIC 1300mAh 4S 14.8V 100C LiPo Battery with XT60 for 5'' 6''FPV drone Cinewhoop Global Warehouse / 1pack", *Ovonicshop*, 2021. [Online]. Available: https://www.ovonicshop.com/products/ovonic-1300mah-4s-14-8v-100c-lipo-battery-with-xt60-for-fpv?variant=39280865214533&currency=AUD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&gclid=CjwKCAjw092IBhAwEiwAxR1lRmC1oklrDRvg7DZVpwfFjCncc9HKKwQd-wjyd-qdatL2iKSDo1MeGhoCY_wQAvD_BwE. [Accessed: 17- Aug- 2021].

[3] "OVONIC 1550mAh 4S 14.8V 100C LiPo Battery with XT60 Plug for 5'' 6''FPV drone AU-G Warehouse / 1pack", *Ovonicshop*, 2021. [Online]. Available: https://www.ovonicshop.com/products/ovonic-1550mah-4s-14-8v-100c-lipo-battery-xt60-plug-for-fpv?variant=39418670940229&currency=AUD&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic. [Accessed: 17- Aug- 2021].

[4] "Ovonic 1800mah 4S 14.8V 100C Lipo Battery Pack with XT60 Plug for quad FPV", *Ovonicshop*, 2021. [Online]. Available: https://www.ovonicshop.com/products/ovonic-1800mah-4s-14-8v-100c-lipo-battery-pack-with-xt60-plug. [Accessed: 17- Aug- 2021].

[5] "Turnigy High Capacity 8000mAh 4S 12C Lipo Pack w/XT90", *Hobbyking*, 2021. [Online]. Available: https://hobbyking.com/en_us/turnigy-high-capacity-battery-8000mah-4s-12c-drone-lipo-pack-xt90.html?wrh_pdp=6&utm_source=google&utm_medium=cpc&utm_campaign=google_au_shopping&countrycode=AU&gclid=CjwKCAjw092IBhAwEiwAxR1lRvK6r0VhRAc4GNCyTxPKbLsyHSjddv1ibjthhih-uuNVVPGqDHmbWRoCxvAQAvD_BwE. [Accessed: 17- Aug- 2021].
[6] "Lipo Battery 14.8V 5000mAh Lipo 4S 50C RC Battery Pack Deans Plug", *Folk Battery*, 2021. [Online]. Available: https://www.folkbattery.com/lipo-battery-14-8v-5000mah-lipo-4s-50c-rc-battery-pack-deans-plug.html?fee=1&fep=30&gclid=CjwKCAjw092IBhAwEiwAxR1lRgvlZh2U78ucw8K3JlPU9SVGB7jJfbY24QNDV3-0de9BkdteSgmHjxoCmssQAvD_BwE. [Accessed: 17- Aug- 2021].

[7] "14.8V 5400mAh LiPo 4S Battery Pack with Deans Connector", *Aus Electronics Direct*, 2021. [Online]. Available: https://www.auselectronicsdirect.com.au/14.8v-5400mah-lipo-4s-battery-pack-with-deans-conn?gclid=CjwKCAjw092IBhAwEiwAxR1lRtDEPW0plZcJaZcw6hrcAVWKEHJHPpACRvh212zg3N970CXsmuJG-xoCNz4QAvD_BwE. [Accessed: 17- Aug- 2021].

[8] "Rhino 1500mAh 4S 50C Lipo Battery Pack w/XT60", *Hobbyking*, 2021. [Online]. Available: https://hobbyking.com/en_us/rhino-1500mah-4s-50c-lipo-battery-pack-w-xt60.html?wrh_pdp=6&utm_source=google&utm_medium=cpc&utm_campaign=google_au_shopping&countrycode=AU&gclid=CjwKCAjw092IBhAwEiwAxR1lRhvLbx_3Z8LEOQNrZs9bGK-uHPlNRAFBPCgaFN3vwAXp7i0OrcbcvxoCE-sQAvD_BwE&___store=en_us. [Accessed: 17- Aug- 2021].

[9] "Turnigy High Capacity 12000mAh 4S 12C Multi Rotor Lipo Pack XT90", *Hobbyking*, 2021. [Online]. Available: https://hobbyking.com/en_us/turnigy-high-capacity-12000mah-4s-12c-multi-rotor-lipo-pack-xt90.html?wrh_pdp=6&utm_source=google&utm_medium=cpc&utm_campaign=google_au_shopping&countrycode=AU&gclid=CjwKCAjw092IBhAwEiwAxR1lRjMZq6XQN_Xhkyf1oUyehXQU-zOF4fOyicxxZO8fjn_NH6xzte_Z0RoCD8IQAvD_BwE. [Accessed: 17- Aug- 2021].

[10] "ZOP Power 14.8V 5000mAh 60C 4S Lipo Battery XT60 Plug for RC Racing Drone", *www.banggood.com*, 2021. [Online]. Available: https://au.banggood.com/ZOP-Power-14_8V-5000mAh-60C-4S-Lipo-Battery-XT60-Plug-for-RC-Racing-Drone-p-

1170983.html?utm_source=googleshopping&utm_medium=cpc_organic&gmcCountry=AU&utm_content=minha&utm_campaign=minha-au-en-pc&currency=AUD&cur_warehouse=CN&createTmp=1&utm_source=googleshopping&utm_medium=cpc_bgcs&utm_content=tanya&utm_campaign=tanya-pla-aug-all-0207&ad_id=497075483882&gclid=CjwKCAjw092IBhAwEiwAxR1lRvc9Y4dwKvk8tUK0FZN7Rzkp7X3X97tZvPtpjfWlMFpxm7GmE6tFpBoC_4sQAvD_BwE. [Accessed: 17- Aug- 2021].

[11] "Flight Time calculator", *Google Docs*, 2021. [Online]. Available: https://docs.google.com/spreadsheets/d/1G9zeRnEKNyZKFfD0QQFb3an53sGvwxXs6VtPaq8duSM/edit#gid=0. [Accessed: 17- Aug- 2021].

Appendix: Flight time estimations

The figure in this Appendix are only true for 1.1kg quadcopter, including the weights of battery and payload.

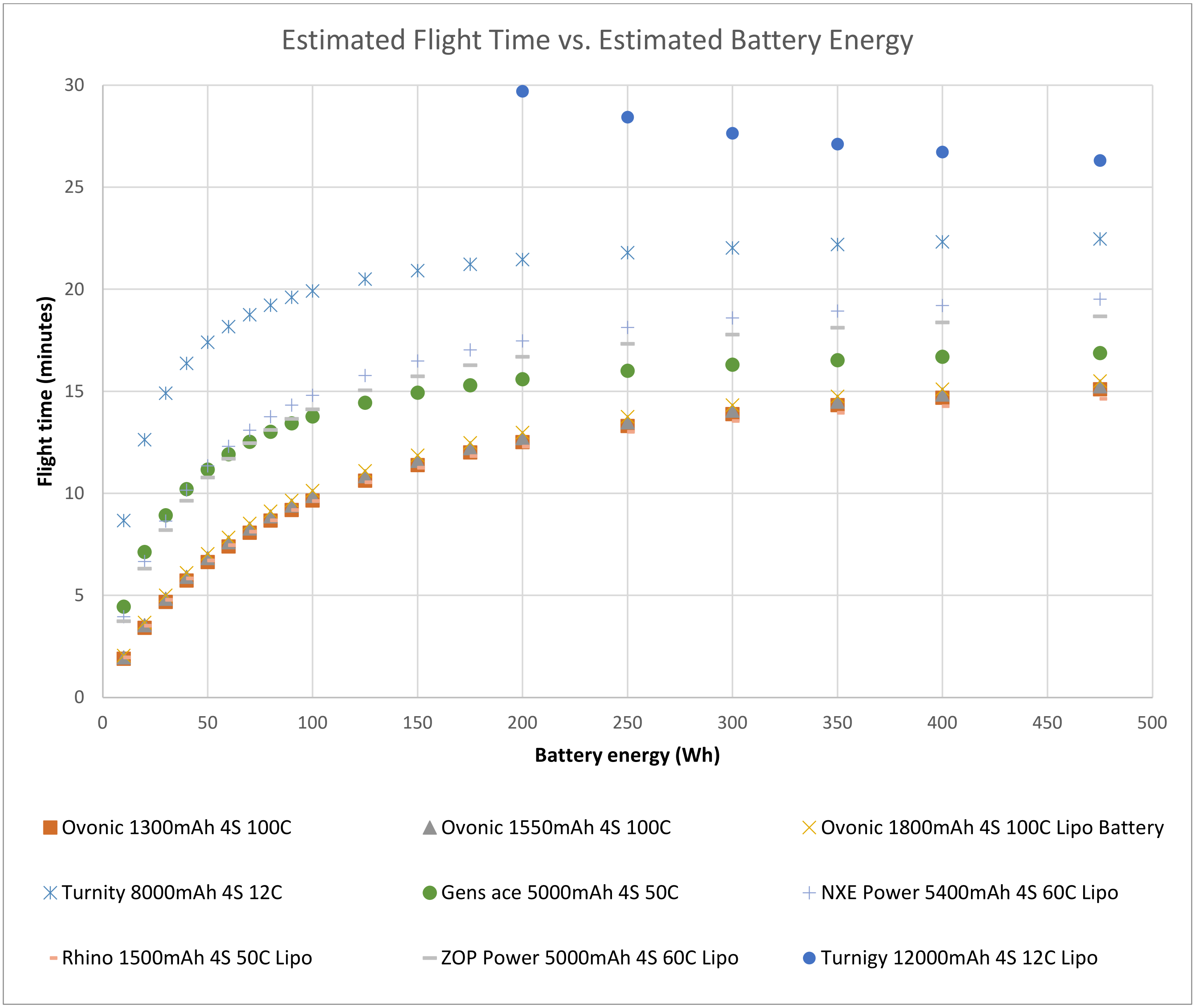

Figure 7: Estimated flight time as a function of estimated battery energy for different battery models.