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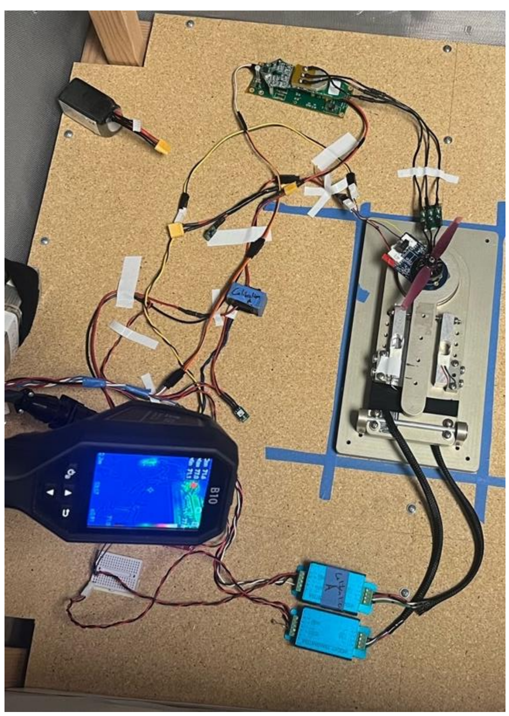
Kairos ESC Characterization

Summary:

The testing procedure and results from characterization of different ESC present here at Kairos Autonomi. Two approaches were used in accessing performance. While performance of the different ESCs is very similar, statistical analysis revealed significant differences worth mentioning. These differences allowed for the following conclusions to be outlined below.

1. Adding a heat sink to the Kairos ESC decreases the motor efficiency (Figure 20).
2. The newer battery base board seems to improve motor efficiency (Figure 21).
3. The 51 Amp BL-Heli 32-Bit Lumenier ESC seems to have the best motor efficiency out of all ESCs tested (Figure 25).
4. Each different model, and brand of ESC is going to behave differently based on interpretation of signals (Figure 28).
5. The Kairos ESC has a lower operating switching frequency than the BL-Heli and some Simon-K ESCs (Figure 27).

Further testing is required to solidify the first 2 claims and would assist in providing greater supporting evidence in all claims. Such testing is outlined in the document. The most significant finding in this testing is that t**he Kairos ESC has a motor efficiency on par with Simon K branded ESCs** (Figure 26) and **is only slightly less efficient than the BL-Heli ESCs** (Figure 25).



Introduction:

Electronic Speed Controllers (ESCs) are devices responsible for controlling the speed of motors. Although the designs of different ESCs may vary, they all have the same basic functions and components. Typically, ESCs have 6-8 cables: two leads for power from the battery, three wire leads connecting to the motor phases, and additional wires or a single cable connecting to the servo control or flight controller.

An ESC board consists of three main parts: the microcontroller, the gate driver, and the MOSFETs. The microcontroller stores the firmware, interprets signals, and tracks motor position to enable smooth acceleration. The gate driver receives signals from the microcontroller and amplifies them for the MOSFETs, which control the motor phases (high voltage, grounded, or low voltage). The higher the throttle, the more frequent the phase switching, resulting in greater RPM.

Since ESCs are electrical components through which all consumed electrical power passes, characterizing different ESCs is crucial for understanding their impact on flight time. This document outlines two testing methods and presents the results of characterizing several ESCs used at Kairos. The two tests help answer five main questions regarding ESC performance:

1. Does adding the heatsink significantly impact motor efficiency?
2. Does a different battery baseboard impact motor efficiency?
3. Is there a difference in performance between models of the same brand?
4. Does the Kairos Autonomi ESC have similar performance to other ESCs?
5. How does the Kairos phase switching frequency compare to other brands?

Statistical analysis comparing all the data sets from the first test is complex, but side-by-side comparisons of the data provided some insights into the main questions.

The second test aimed to reduce the complexity of comparing all the data sets by creating a series of data sets that could be analyzed using a single-factor ANOVA test. This would have answered questions about potential performance differences between all ESCs. However, this could not be accomplished due to ESC calibration issues in the mission planner. Future testing could be attempted which would provide greater evidence to the claims made. Notwithstanding, the data collected in this report is sufficient to the claims made.

Set-up:

Motor Combo:

For this series of tests, the same motor and propeller combination was used throughout. The motor selected was the Xing-Flight Pro 2207 1800KV motor, paired with a 2-blade Ethix 5.1*3.0 propeller. This combo was chosen for its excellent performance during the characterization of various motor and propeller combinations, making it one of the top choices.

Battery:

As in previous tests, the battery type remained consistent. Two separate batteries of the Gens Ace 3300 mAh 14.8 V model were used, ensuring the battery percentage was kept above 70% during testing.

Heat Monitoring:

For this round of testing, an IR heat camera was mounted and fixed in place. This setup allowed for continuous temperature monitoring of all components, primarily to maintain safe temperature levels. No temperature measurements were recorded.

ESCs:

All the ESCs used are listed in Table 1. Pictures of each ESC are included in Figures 1-12. Each ESC was assigned a number label and a color marker, as noted in Table 1. One observation was the presence of heatsinks on almost every model.

Table 1: The table includes the firmware, model name, and other important details for each ESC. Some ESCs were wired such that the servo controller required separate power.

Firm Ware	Model Name	Heat Sink	Rating	Label	Marker	Notes:
Kairos ESC	PCB 783B1a	Y		1a	●	Base Board A
Kairos ESC	PCB 783B1a	N		1b	●	Base Board A
Kairos ESC	PCB 783B1a	Y		1c	●	Base Board B
Kairos ESC	PCB 783B1b	N		2	●	Base Board B
Kairos ESC	PCB 783A1	N		3	●	Base Board B
BL Heli	32 Bit	Y	51 A	5	■	
BL Heli	32 bits	N	51 A	6	■	Same Model as Above
BL Heli s	F	Y	30A	7	■	
Simon K	Q win Out	Y	30 A	8	■	
Simon K	Unknown	Y		9	▲	
Simon K	Unknown	N		10	▲	Same Model as Above
BL Heli	Nidici	Y	35 A	11	▲	
Simon K	Hobby Power	Y	30 A	12	▲	Has a Stutter at High RPM
Simon K	Self-mounted	N		13	▲	

From the table it is implied that 1 A, B, and C, is the same circuit board. It is the same model that was used in testing motor and Propeller efficiencies. These were tested to serve as controls and to address some of the main questions.

The different Kaios Autonomi ESCs also required a battery base board. The scope of this testing was limited but extremely useful as another control test and in addressing the main questions. Images of the different battery base boards are included in figures 13 and 14.

Figure 1: ESC 1. This is paired with a battery base board.

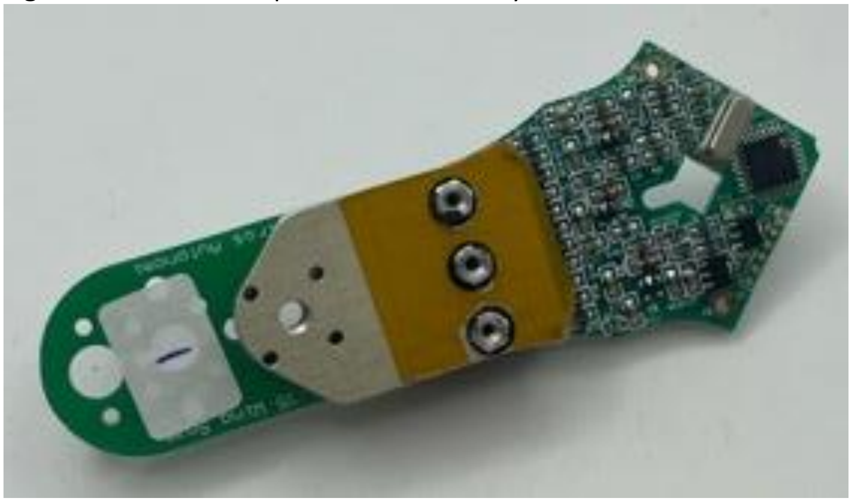


Figure 2: ESC 2. This is paired with a battery base board. Same model as ESC 1.

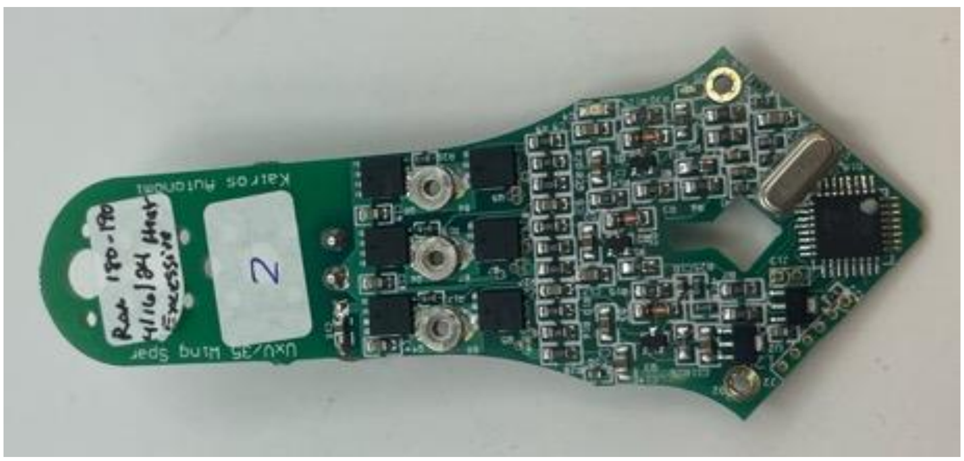


Figure 3: ESC 3. This is paired with a battery base board.

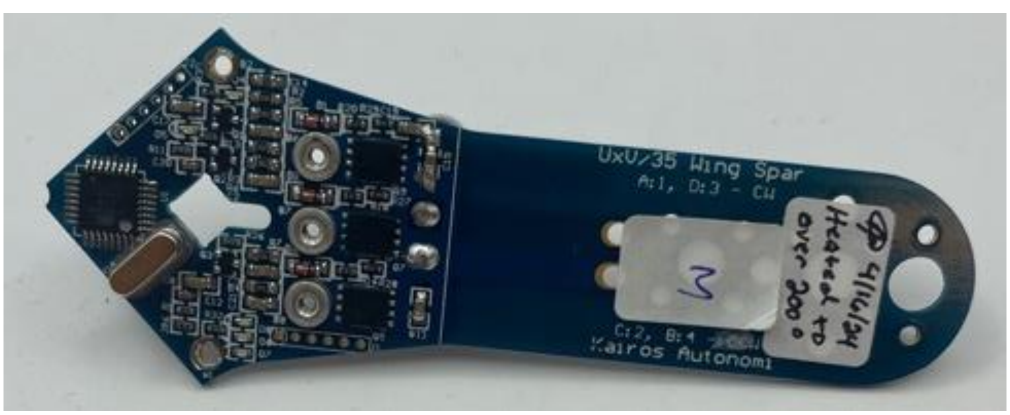


Figure 4: ESC 5.

Figure 5: ESC 6. Same Model as ESC 5, without a heat sink.

Figure 6: ESC 7.

Figure 7: ESC 8.

Figure 8: ESC 9.

Figure 9: ESC 10.

Figure 10: ESC 11.

Figure 11: ESC 12.

Figure 12: ESC 13. This ESC is mounted. The board that is mounted is shown here as well.

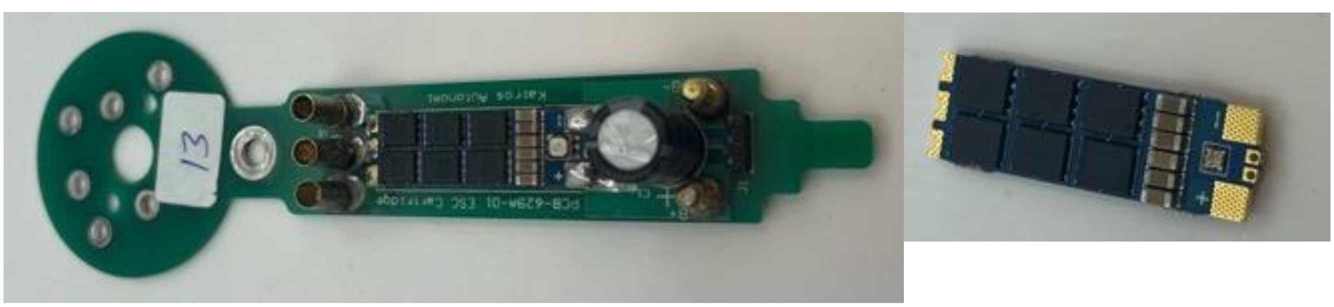
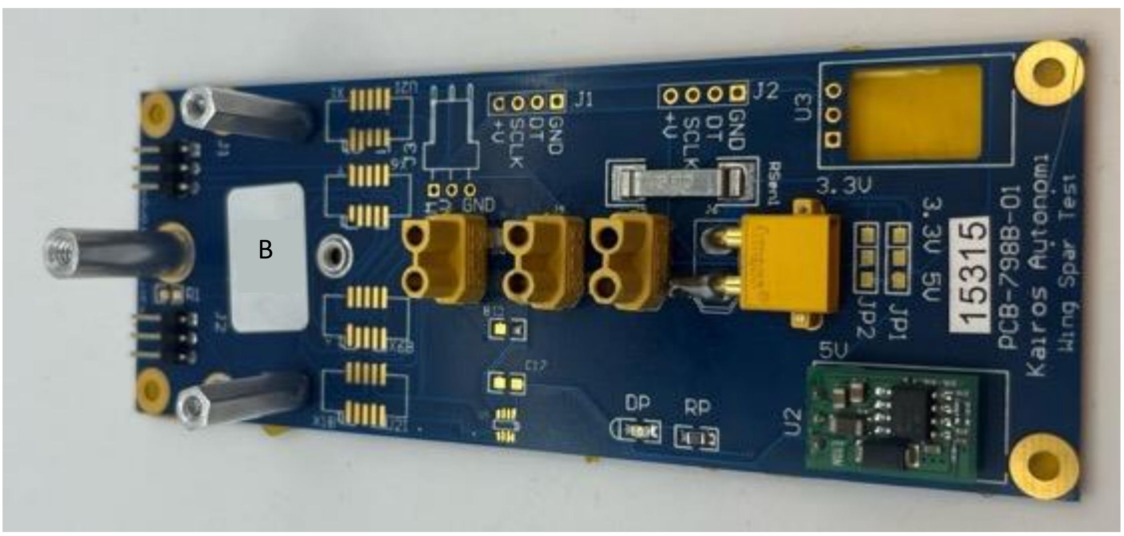


Figure 13: Battery base board A. This model is a little older and was the board used in the testing of different motor and propeller combinations.

Figure 14: Battery base board B. This model is newer.



Testing Methods:

First Test Method:

The first test of the different ESCs was conducted using the following method:

1. **Mount the ESC**: Secure the ESC and perform a torque and thrust check.
2. **Power On the Motor:** Verify the spin direction and ensure the RPM is recognized.
3. **Check Settings:** Check the voltage, RC, and current settings.
4. **Initiate Motor Start-Up:** Close the birdcage and start the motor.

5. **Data Collection Start:** Begin data collection when the analog voltage signal for torque reaches 0.03V.
6. **Step-Up Motor:** Increment the motor RC value with servo control at each test point.
7. **End Data Collection:** Stop the motor when the temperature alarm sounds, or the RC value is maxed out. End data collection and save the data onto a USB.
8. **Normalize Temperatures:** Cut power to the motor and allow temperatures to normalize.

This process was repeated three times for each motor. After completing the tests with one ESC, a new ESC was mounted, and the process was repeated.

Second Test Method:

A second test was also performed with some of the ESCs, comparing the motor output using a flight controller. The steps were as follows:

1. **Randomize Order:** Randomize the order of ESCs being tested.
2. **Mount the ESC:** Mount the ESC and perform basic checks on voltage, current, and spin direction.
3. **Torque and Thrust Check:** Verify the torque voltage and thrust voltage, like the first test.
4. **Connect Flight Controller:** Connect and test the flight controller. Using Mission Planner, set the motor at a specific throttle percentage to determine motor output.
5. **Confirm Connection:** Once the connection to Mission Planner is confirmed, start data collection.
6. **Set Output Levels:** Set the motor at four different output levels (25%, 50%, 75%, and 95%) for a period of 25 seconds each. Increase the throttle percentage after the allotted time.

Note that some motors failed to connect to the flight controller and Mission Planner. In these cases, these ESCs were omitted entirely.

Initial Results:

Four figures given below are of 4 key efficiency metrics with each of the ESC. These metrics are RPM vs. Thrust, RPM vs. Torque, thrust vs. Motor Efficiency, and Thrust vs. Electrical Power. Here lies the reasoning for choosing these specific metrics.

1. **Thrust, RPM, and Torque:** Observing these metrics helps identify any potential errors in obtaining the measurements.
2. **Electrical Power:** This allows us to see how current and voltage are changing and to understand their relationship.
3. **Thrust vs. Motor Efficiency**: Observing this metric (calculated as Mechanical Power/Electrical Power*100) provides the greatest insight into how all the measured parameters are interrelated.

Visual analysis indicates little difference between all the ESCs. Before drawing any conclusions from the visual analysis, statistical methods were employed to verify a statistical difference between the different curves. Once this difference is established, conclusions from visual analysis can then be drawn. With the initial visual analysis, we see that the curves have a very narrow band for both thrust and torque over the range of RPMs tested. The broadness increases with both the other metrics plotted. The extreme closeness of each curve highlights the need for additional statistical methods for analysis.

Figure 15: The plot of RPM vs. Torque (Nm) for each ESC.

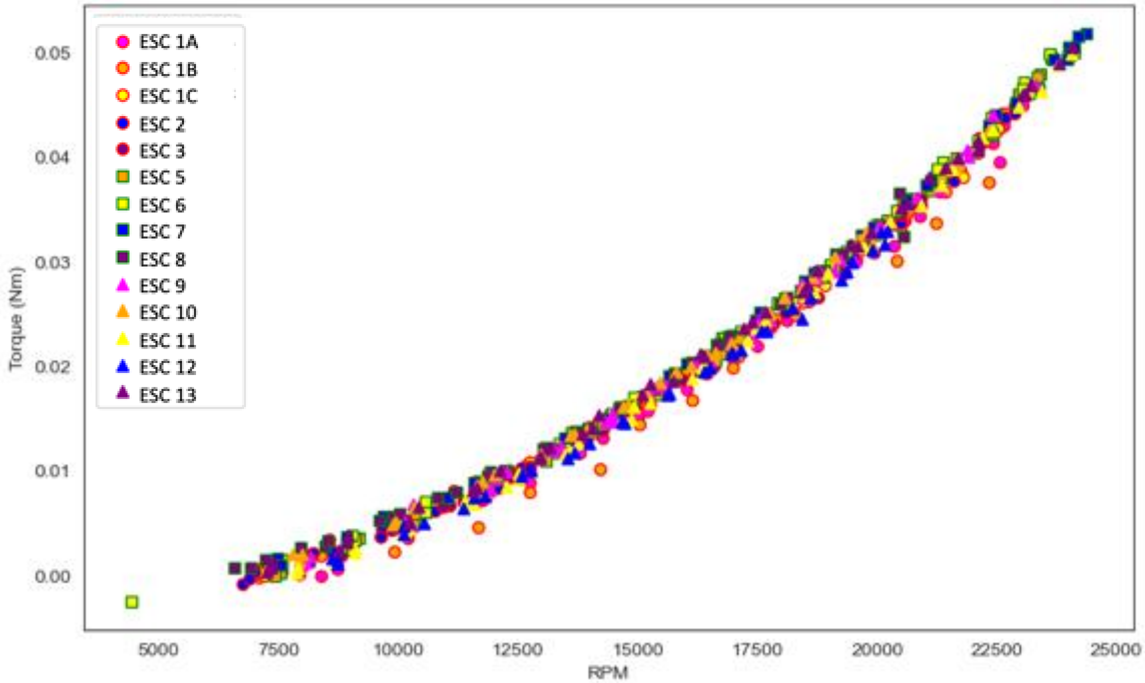


Figure 16: The plot of RPM vs. Thrust (kgf)for each ESC.

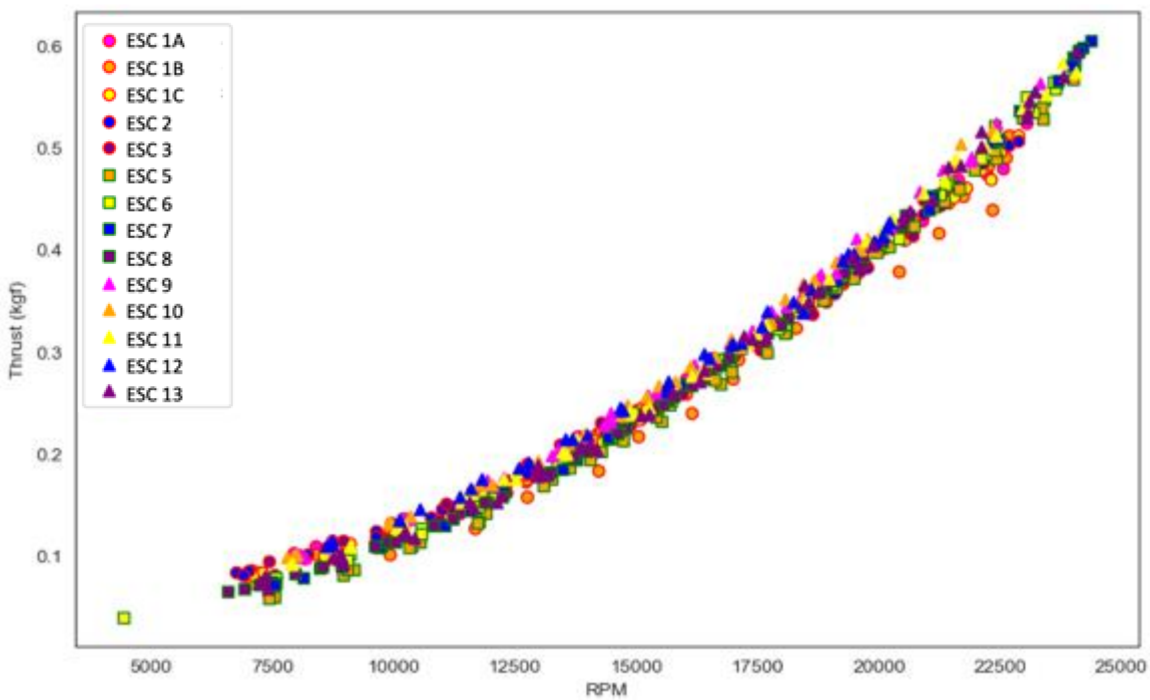


Figure 17: The plot of Thrust (kgf) vs. Motor Efficiency (%) for each ESC.

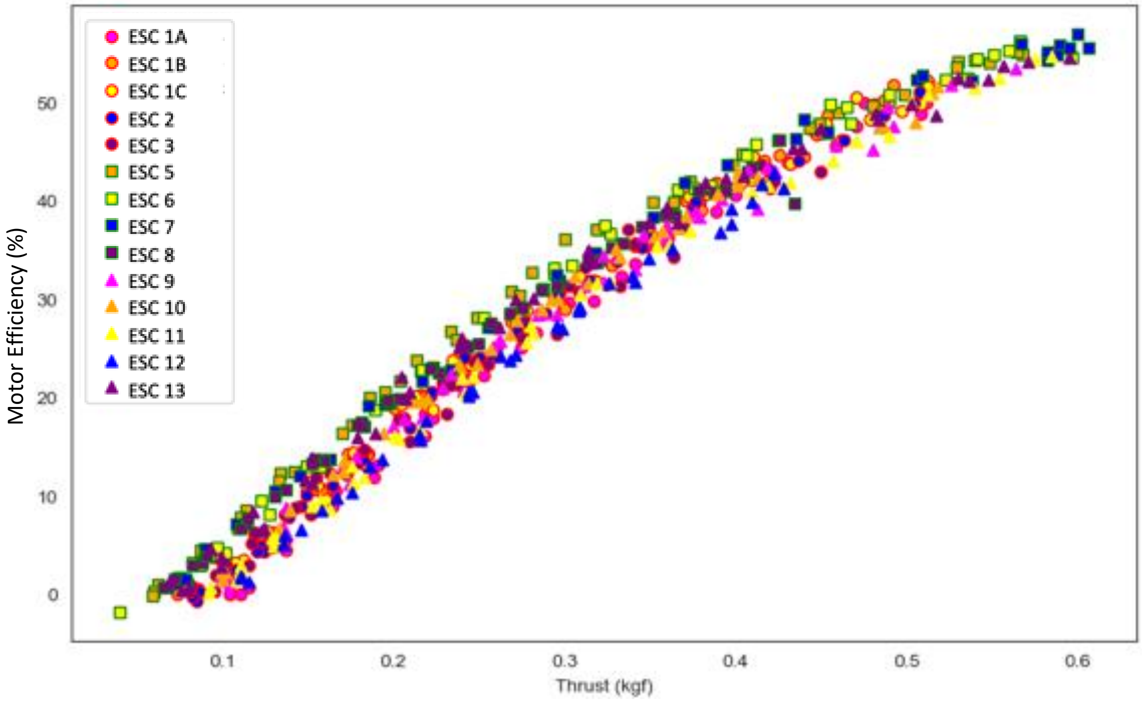
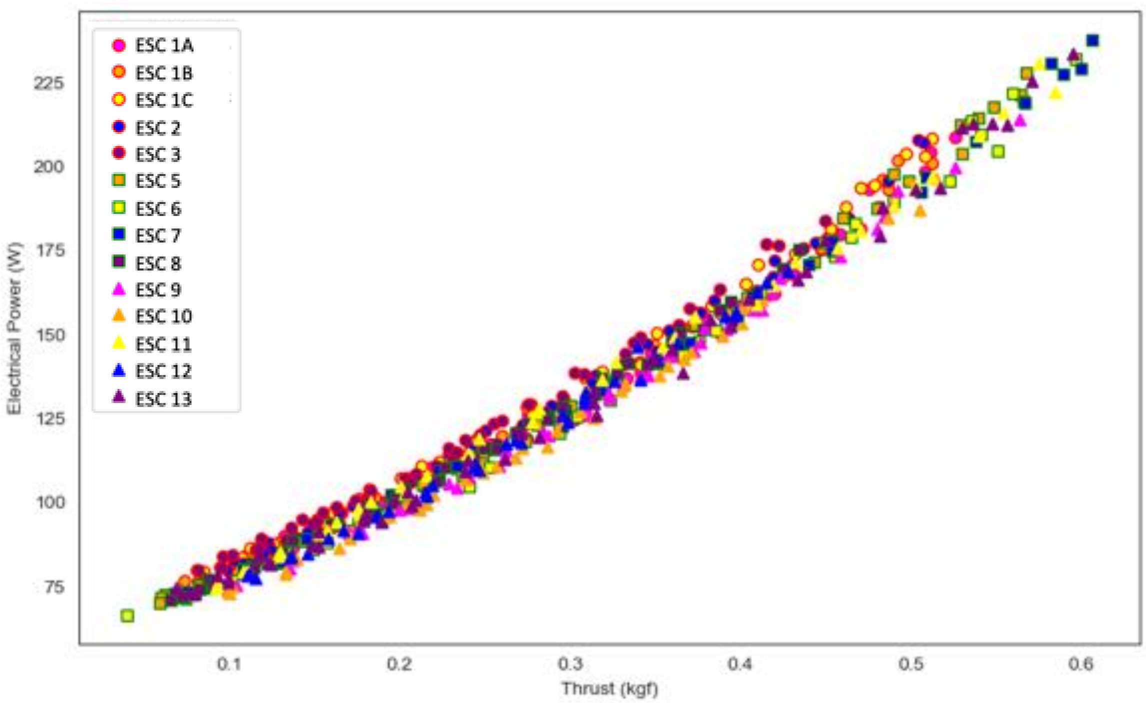


Figure 18: The plot of Thrust (kgf) vs. Electrical Power (W) for each ESC.



Statistical Comparison of First Test Data:

Goals and Parameters:

The goal of the additional statistical methods is to confirm that the data sets are indeed statistically different so conclusions can then be drawn. As mentioned previously, a comprehensive comparison of all the data sets exceeds the scope of this document. However, the following comparisons were conducted as outlined in Table 2. These comparisons assist in drawing conclusions to answer the 5 main questions.

Table 2: The comparisons made are shown in the table below.

Subject 1	1 A	1 A	2	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
Subject 2	1B	1C	3	2	3	5	6	7	8	9	10	11	12	13

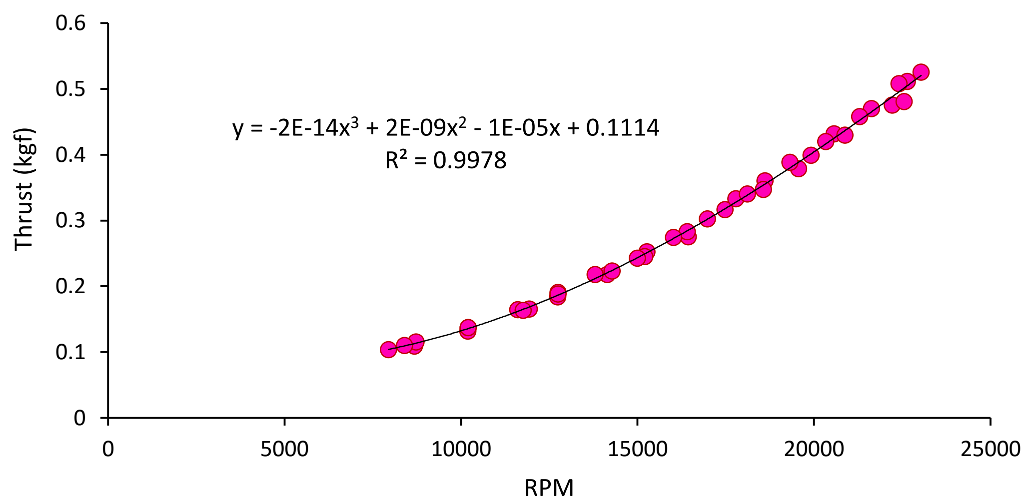
For this statistical analysis, the confidence interval is set at 95%, meaning a 95% confidence in the claims made. To determine if a data set is statistically the "same," proof is needed showing that the averages between the data sets the same. Here, "same" refers to statistical significance. By proving the data sets are in fact different, conclusions can then be drawn from the data.

Process:

1. Regression curve fitting

Before conducting any statistical analysis, each ESC must be fitted with a regression curve for each of the four metrics of analysis. For simplicity, a third-degree polynomial regression curve was used for each metric, generated with the LINEST function in Excel. This regression curve employs the least squares method, aiming to create a curve where approximately half of the data points fall above and half fall below the curve. Refer to Figure 19 for an example of this regression curve.

Figure 19: An example regression curve. This curve shows RPM vs. Thrust data points for ESC 1A. The equation for the curve is given as well. The R^2 value indicates the goodness of fit for the curve; a value closer to 1 signifies a better fit, meaning the curve closely approximates the data points.



2. Data bootstrapping

To compare the regression curves, the datasets were expanded using data bootstrapping. Bootstrapping is a data resampling technique where the data is repeatedly sampled with replacement. For this analysis, the data was resampled 1,000 times using Python. A regression curve was fitted to each resampled dataset, and the resulting coefficients were compiled into an Excel spreadsheet for further analysis.

3. Compute descriptive statistics

For each coefficient the average, standard deviation and the confidence interval was found. Computing the confidence interval allowed easy comparison of the coefficients between each pair being compared.

4. Preform F-test and t-test on each coefficient

A F-test was conducted to compare the variation between the coefficients of the bootstrapped data sets. The F-test determined which type of t-test to conduct and returns a probability value. This probability is the likelihood the two datasets have the same amount of variation. The t-test was used after the F-test was used to compare the averages of datasets. It provides a probability indicating how likely the averages are to be the same. For both test, probabilities greater than 0.05 are considered significant, meaning either the variation is the same or the average is the same when either test returns a probability value greater than 0.05. When either test returns values less than that, there is then proof of statistically significant difference between the variation and averages of the coefficients in the regression curve. If there is a statistical difference in the regression curves there is an indication to statistical difference in the data sets used to fit the sets regression curves. However, the t-test and F-test do not specify the nature of these differences. The results of the F-test and t-test are presented in the tables below.

Table 4: The table below shows the results of the F-test and t-test for the 1A to 1B pair coefficients. The results indicate that the two curves are statistically different.

1A vs. 1B	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.085	0.005	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.001	0.075	0.214	0.266
t-test Motor Efficiency (%)	0.000	0.000	0.192	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.046	0.022
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 5: The table below shows the results of the F-test and t-test for the 1A to 1C pair coefficients. The results indicate that the two curves are statistically different.

1A vs. 1C	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.018	0.764	0.649
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 6: The table below shows the results of the F-test and t-test for the 2 to 3 pair coefficients. The results indicate that the two curves are statistically different.

2 vs. 3	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 7: The table below shows the results of the F-test and t-test for the 1C to 2 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 2	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.070	0.201	0.210	0.421
t-test Electrical Power	0.000	0.000	0.111	0.373
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.049	0.345	0.494
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.012	0.022	0.018	0.032
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 8: The table below shows the results of the F-test and t-test for the 1C to 3 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 3	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.001	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 9: The table below shows the results of the F-test and t-test for the 1C to 5 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 5	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 10: The table below shows the results of the F-test and t-test for the 1C to 6 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 6	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.004	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 11: The table below shows the results of the F-test and t-test for the 1C to 7 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 7	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.335	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.050	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.004	0.099	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 12: The table below shows the results of the F-test and t-test for the 1C to 8 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 8	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.965	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.001	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 13: The table below shows the results of the F-test and t-test for the 1C to 9 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 9	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.434	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.070	0.774
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.003	0.716	0.077
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 14: The table below shows the results of the F-test and t-test for the 1C to 10 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 10	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.001
t-test Electrical Power	0.255	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.051	0.705	0.160	0.073
t-test Torque (Nm)	0.005	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 15: The table below shows the results of the F-test and t-test for the 1C to 11 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 11	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.499
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 16: The table below shows the results of the F-test and t-test for the 1C to 12 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 12	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.000	0.000	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.115	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

Table 17: The table below shows the results of the F-test and t-test for the 1C to 13 pair coefficients. The results indicate that the two curves are statistically different.

1C vs. 13	Coefficient 0	Coefficient 1	Coefficient 2	Coefficient 3
F-test Electrical Power	0.033	0.968	0.000	0.000
t-test Electrical Power	0.000	0.000	0.000	0.000
F-test Motor Efficiency (%)	0.067	0.000	0.000	0.000
t-test Motor Efficiency (%)	0.000	0.000	0.000	0.000
F-test Torque (Nm)	0.000	0.000	0.000	0.000
t-test Torque (Nm)	0.000	0.000	0.000	0.000
F-test Thrust (kgf)	0.000	0.000	0.000	0.000
t-test Thrust (kgf)	0.000	0.000	0.000	0.000

As indicated by the tables above, there appears to be a statistical difference in all the regression curves obtained. This suggests that the regression curves for each metric of analysis across all comparison pairs exhibit statistically significant differences. Claims about efficiency can now be made, since there is a statistical difference in the regression curves and hence the data sets.

Visual Analysis:

Now that it is proven that there is a statistical difference, effort can now be made in drawing conclusions from the data sets. For simplicity only one metric will be considered in this section. That is motor efficiency. The series of figures, shown below, aim at drawing conclusions to satisfy the 5 big questions. Each figure provides relevant feedback into the performance characterization of each ESC.

Figure 20: An analysis of ESC 1A and 1B. These are in fact the same ESC, on the same battery base board. This was done as a control but proves that there may be a slight advantage in not using a heat sink on the Kairos ESC. Further repeat testing should be done to confirm this.

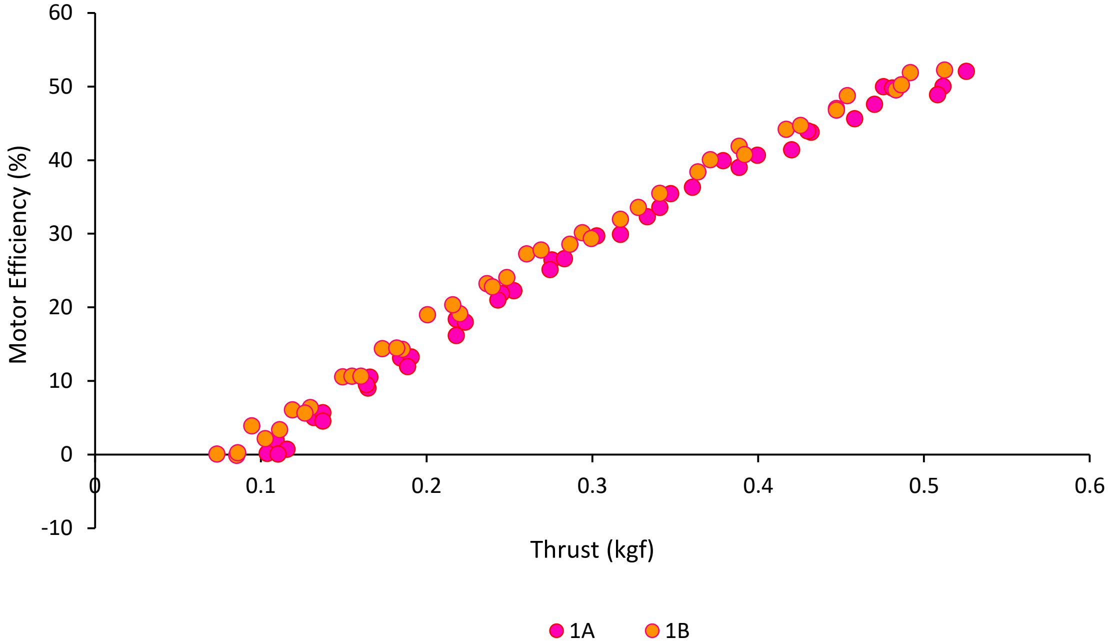


Figure 21: An analysis of ESC 1A and 1C. These are in fact the same ESC, on the different battery base boards. This was done as a control but proves that there may be a slight advantage in using battery baseboard B over the other battery baseboard A. Further repeat testing should be done to confirm this.

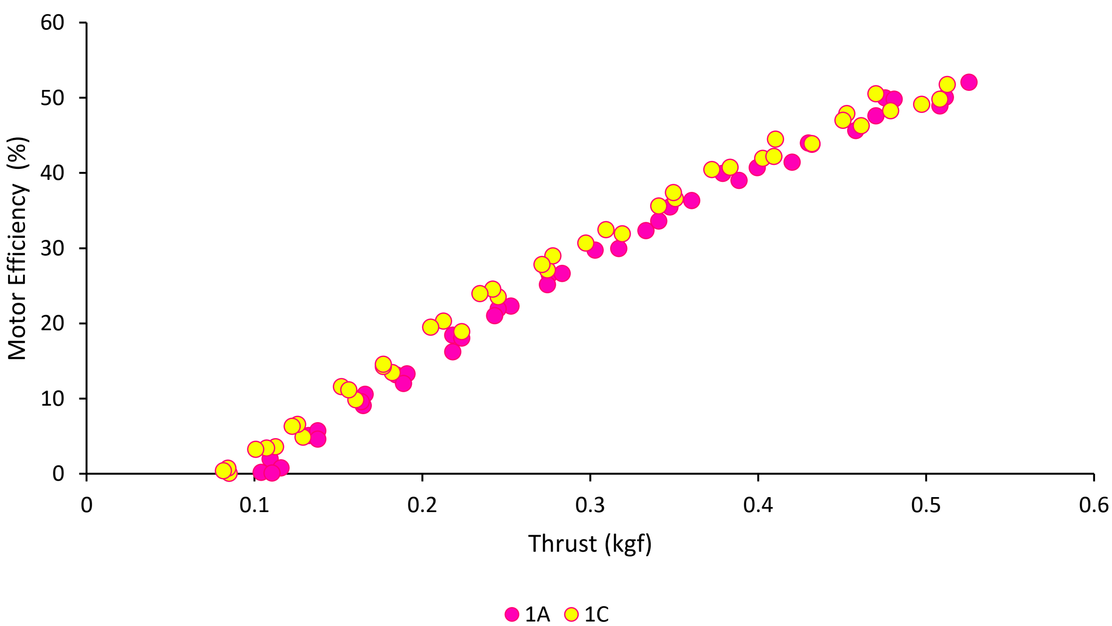


Figure 22: An analysis of ESC 1C, 2, and 3. These are the Kairos branded ESCs with the same battery base boards. Comparison between them shows they are very close in performance, but 1C seem to preform just slightly better than the rest.

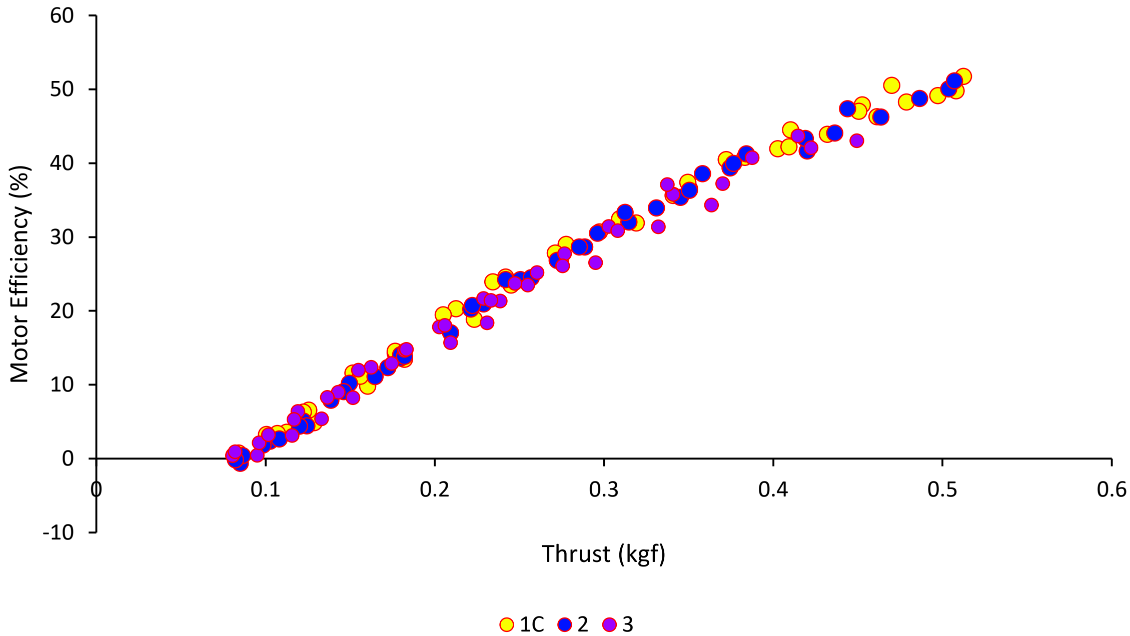


Figure 23: An analysis of ESC 8, 9,10, 12, and 13. These are the Simon K branded ESCs with the same battery base boards. Comparison between them shows they are very close in performance, but 13 seem to preform just slightly better than the rest.

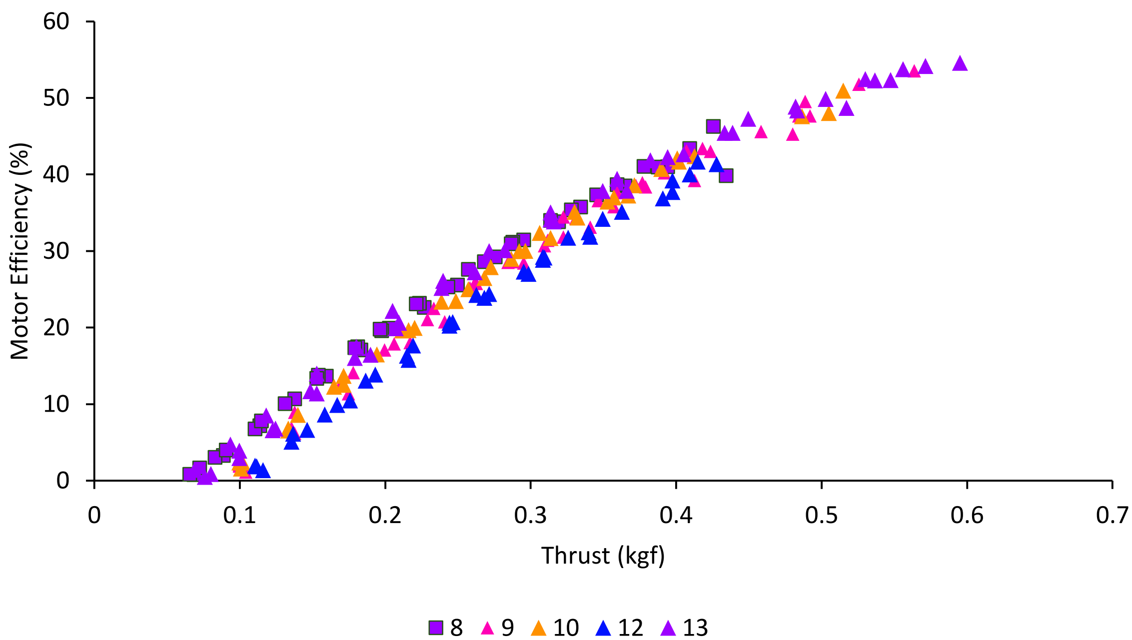


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Figure 24: An analysis of ESC 5, 6, 7, and 11. These are the BL-Heli branded ESCs. Comparison between them shows they are very close in performance, but 5 seem to preform just slightly better than the rest.

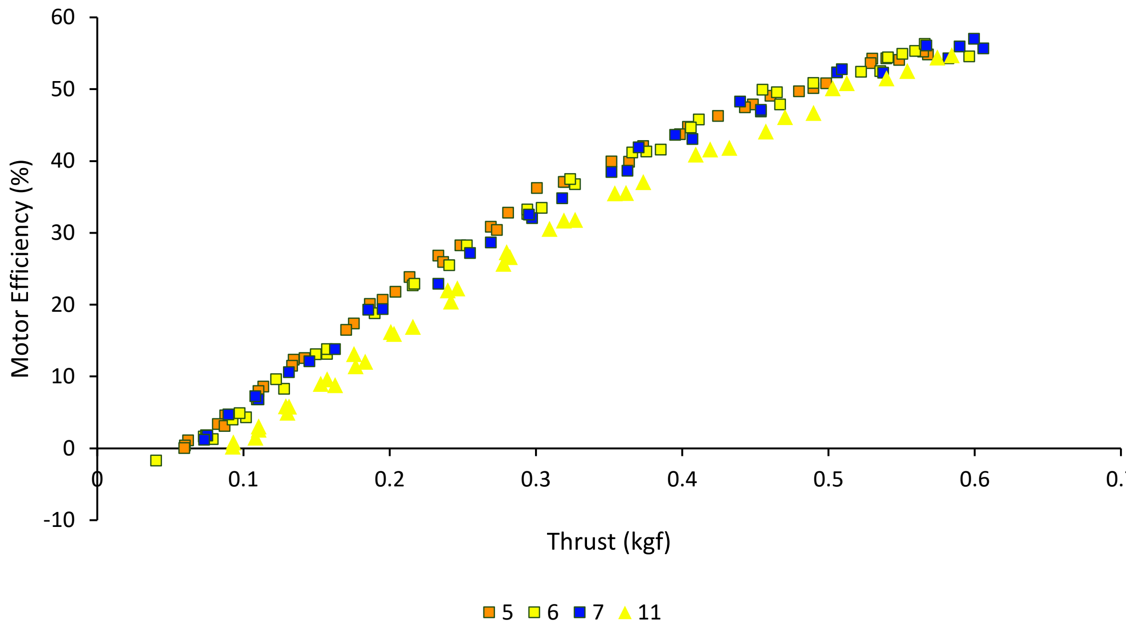


Figure 25: An analysis of ESC 1C, 5, and 13. These three ESCs are the top preforming ESCs. Comparing all of them shows that the ESC 5 from BL-Heli has a slight edge in performance over the other branded ESCs.

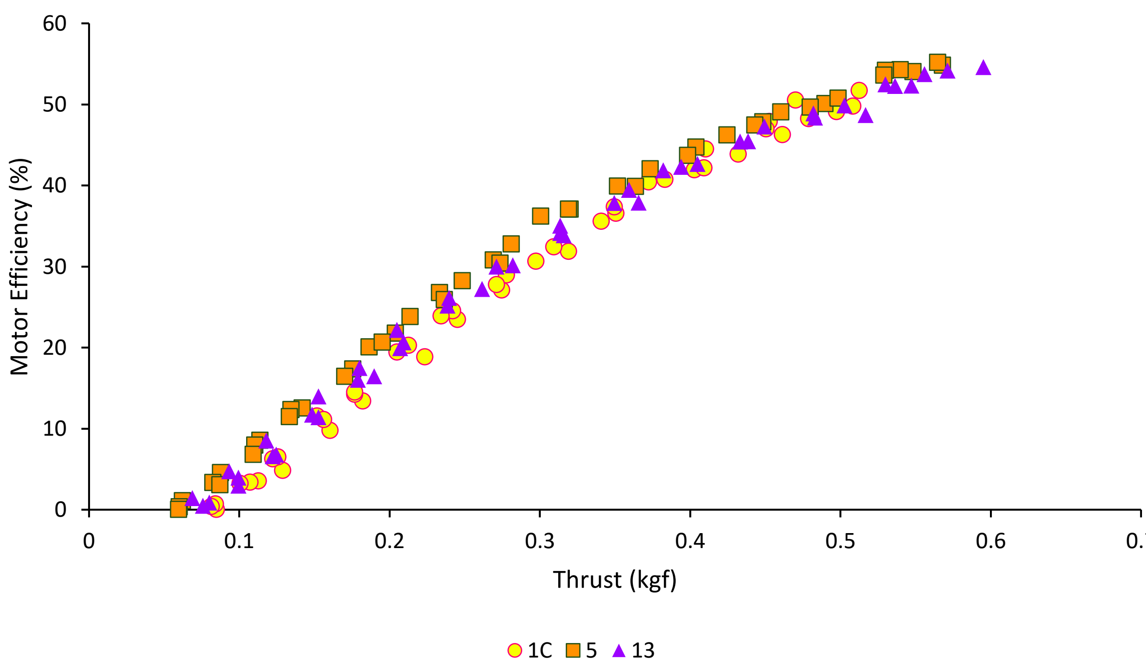


Figure 26: The figure below shows all models of the Kairos ESC compared with the best and worst Simon-K brand ESC. This proves that The Kairos ESC has an efficiency on par with Simon-K ESCs, preforming better than the worst and slightly less efficient than the best Simon-K ESCs.

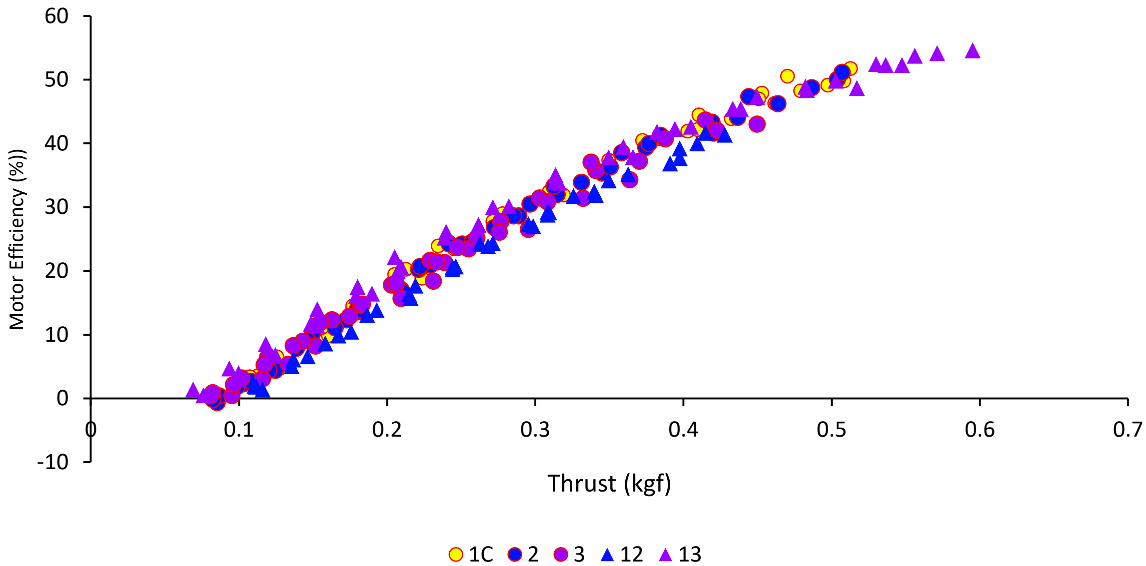
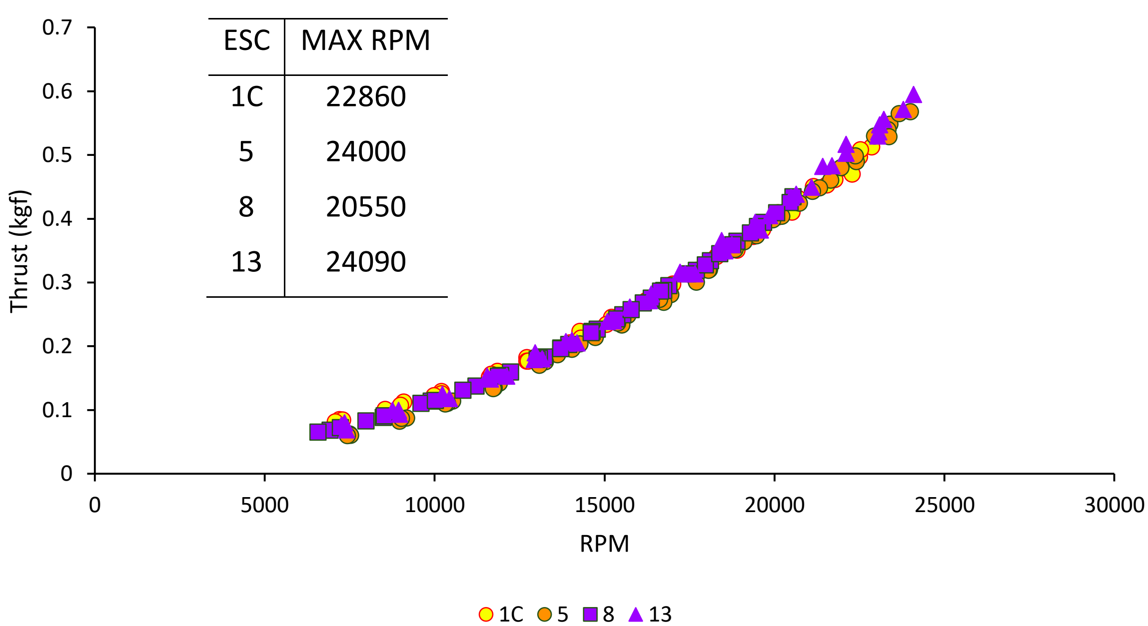


Figure 27: The figure below highlights the differences in maximum switching frequency between the branded ESCs. The switching frequency is higher at higher RPM values. As seen, Kairos ESC has the third highest RPM out of the samples. Concluding that it has smaller switching frequency capability than the BL-Heli and some Simon-K ESCs.



ESC	MAX RPM
1C	22860
5	24000
8	20550
13	24090

The result of the visual analysis answers all 5 of the main questions. The results of the visual analysis are given in the table below.

Question:	Finding:
Does adding the heatsink significantly impact motor efficiency?	The heat sink on the Kairos ESC has a slight disadvantage to motor efficiency.
Does a different battery baseboard impact motor efficiency?	Using the newer model battery baseboard increases efficiency.
Is there a difference in performance between models of the same brand?	The 1C ESC, preforms best among the Kairos ESC. The 5 ESC preforms best among the BL-Heli ESC. The 13 ESC preforms best among the Simon K ESC.
Does the Kairos Autonomi ESC have similar performance to other ESCs?	ESC 5 offers a slight edge in performance over the other top preforming brand ESCs. Kairos ESCs preforms on par with Simon-K ESCs.
How does the Kairos phase switching frequency compare to other brands?	The Kairos ESC has smaller switching frequency capability than the BL-Heli and some Simon-K ESCs.

Second Test Data Results:

The objective of the second test was to simplify testing and identify broader trends in the data. While this test did not achieve its goal of reducing complications, it provided valuable insights into how different ESCs interpret signals. Figures 19-22 illustrate the variations in throttle percentage interpretation as set by the mission planner. Calibration attempts for the different ESCs were unsuccessful, which led to varying motor outputs at the same throttle percentage.

It is important to note that this test did not encompass all ESCs as in the previous test. This limitation arose for two reasons: firstly, significant statistical differences were observed early, reducing the need for extensive testing; and secondly, some ESCs failed to connect properly to the flight controller and mission planner.

Figure 28: A plot of the Throttle Percentage vs. Thrust (kgf). There is great variation within the same throttle percentage, though the plots do seem to converge at 95%. This is likely due to the motor reaching maximum power output.

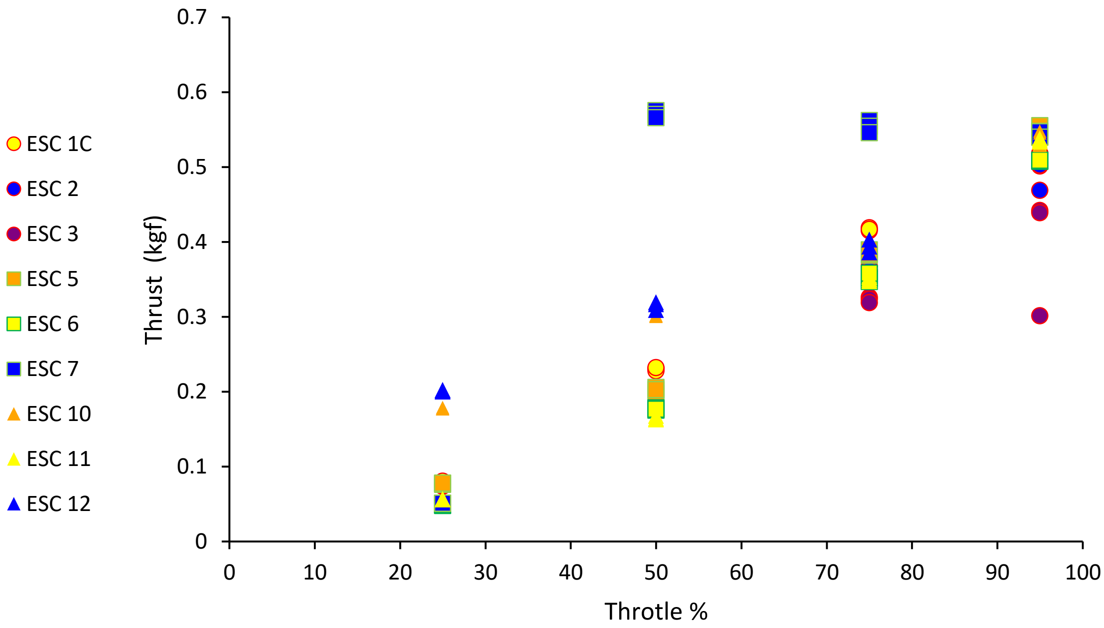


Figure 29: A plot of the Throttle Percentage vs. RPM. There is great variation within the same throttle percentage, though the plots do seem to converge at 95%. This is likely due to the motor reaching maximum power output.

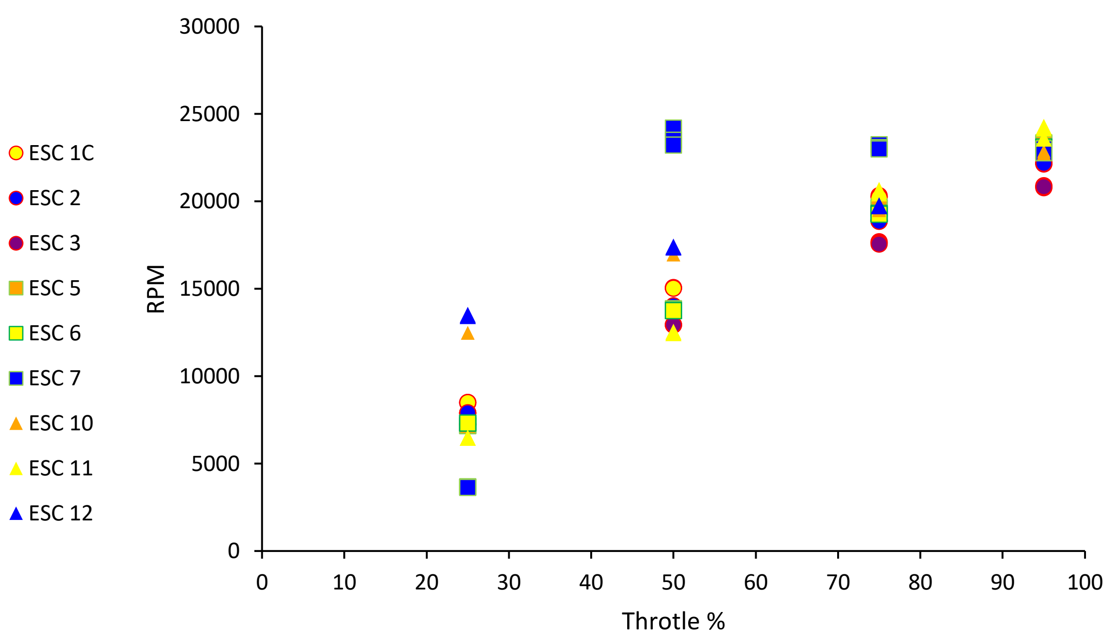


Figure 30: A plot of the Throttle Percentage vs. Electrical Power (W). There is great variation within the same throttle percentage, though the plots do seem to converge at 95%. This is likely due to the motor reaching maximum power output.

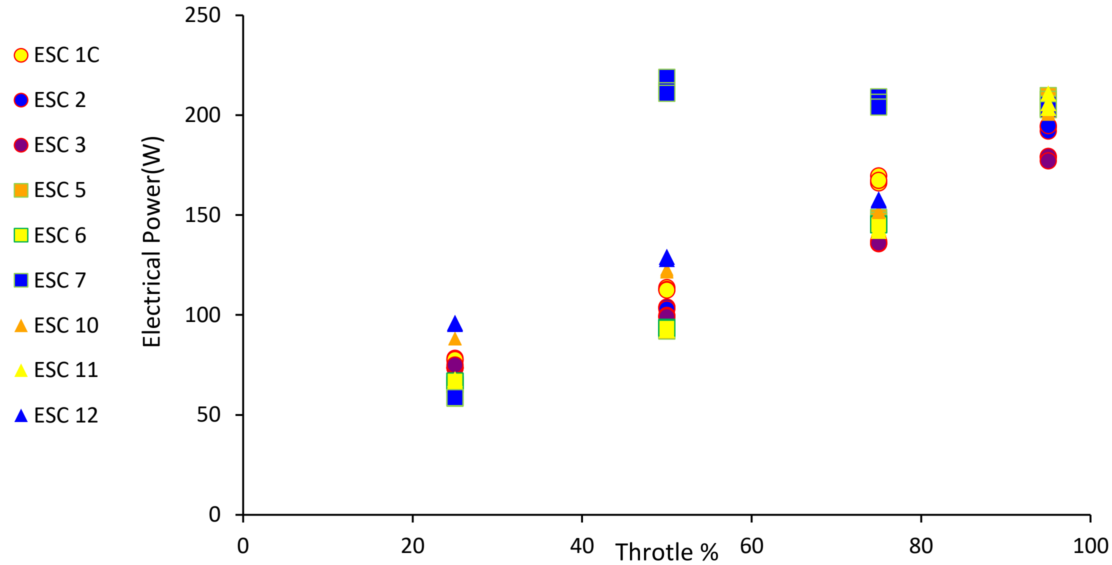
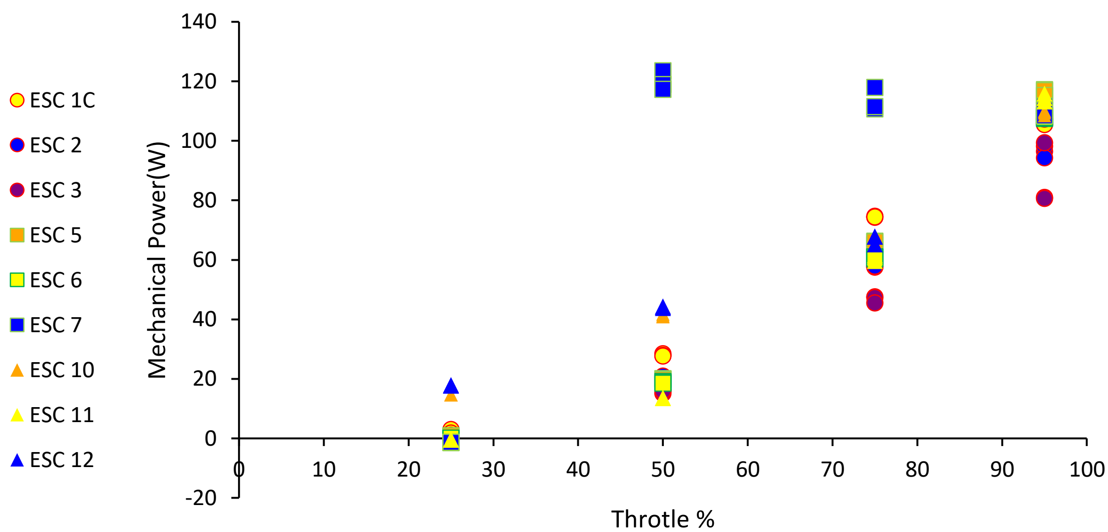


Figure 31: A plot of the Throttle Percentage vs. Mechanical Power (W). There is great variation within the same throttle percentage, though the plots do seem to converge at 95%. This is likely due to the motor reaching maximum power output.



Conclusion

In conclusion, there appears to be a statistically significant difference in the performance of the different ESCs. Although visual analysis suggests that these differences are small, they are nonetheless significant. Further analysis reveals that:

1. Adding a heat sink to the Kairos ESC decreases the efficiency (Figure 20).
2. The newer battery base board seems to improve efficiency (Figure 21).
3. The 51 Amp BL-Heli 32-Bit Lumenier ESC seems to preform best out of all ESCs tested (Figure 25).
4. Each different model, and brand of ESC is going to behave differently based on interpretation of signals (Figure 28).
5. The Kairos ESC has a lower operating switching frequency than the BL-Heli and some Simon-K ESCs (Figure 27).

Further testing is needed to provide greater evidence to these differences and in supporting these claims. Testing would require collecting data at different RPM levels for each ESC, ensuring minimal RPM differences at those levels, and requiring instantaneous readings of frequencies set within a range of less than 10 hertz. Doing more testing would provide greater support to the claims made.

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Revisions

Name/Signature	**Date**	**Description**
Cameron	7-18-24	Content addition
Cameron	7-23-24	Content editing, improvements to clarity and flow.