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Original Article

Analysis of Battery-based and Direct Current Generator Drone Power System

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Abstract - *Conventional power sources for Unmanned Aerial Vehicles (UAVs) are primarily battery-based. However, tethered drones represent a unique establishment from the norm, which will ensure a continuous power supply and data connection. Throughout this unique attribution it is highly suitable for protracted surveillance operations for inaccessible maintenance areas, vigilant oversight of populous events, systematically examining critical infrastructure, and rapidly assessing disaster-stricken areas with real-time aerial perspectives. Nonetheless, it is essential to note that their operational range is significantly limited compared to the untethered UAV, and they possess inherent mobility constraints. Development of a tethered drone is challenging as the suitable motor should be selected appropriately to ensure the energy produced by the DC Generator can provide enough energy to generate the required motor performance. In this research, performance analysis was conducted to understand the differences in electrical characteristics between the battery-based power supply and the developed DC Generator and their impact on the thrust performance of the drone. The experimental study was conducted using several power systems: 4S 100C Battery-based, 4S 75C Battery-based, 3S 25C Battery-based, 3S 5C Battery-based, and DC Generator. The electrical properties of the power provided through a tethered source differ from those of a battery-based power supply. The research noted a significant influence of battery cell count and c-rating on the thrust produced. The highest thrust was recorded at 48.02N for a 4S battery and 36.98N for a 3S battery; interestingly, the study revealed that applying the same voltage as the 4S and 3S batteries to the DC Generator did not yield a similar thrust. To achieve comparable performance to the battery-based system, a higher voltage input was necessary. The research observed that the battery-based system generally had a lower voltage-to-current ratio compared to the DC Generator system. Specifically, a 2.3 times lower ratio was observed between the 3S battery and the DC Generator while maintaining similar thrust levels.*

Keywords - *Tethered drone, Unmanned Aerial Vehicle (UAV), Quadrotor, Power characteristics, Thrust testing.*

1. Introduction

Within the agriculture sector, micro-light aircraft and the cutting-edge technology of Unmanned Aerial Vehicles (UAVs) are currently used for various tasks. It is possible to do crop monitoring of any sort and in any place with the assistance of a drone [1]. The use of drone technology may potentially improve long-term performance, increase agricultural yields, reduce time, and contribute to land management in a more environmentally responsible manner. In recent years, drone power supply has become one of the main topics in the drone industry [2][3]. A lot of research and development has been conducted to make an alternative power supply for the drone to increase flying time for the drone [4][5]. Because of that, many alternative power supplies have been developed from solar to hybrid system power supplies. All these alternative power supplies have advantages and limitations, and their suitability will rely on many factors, including the power consumption and size of the drones [7].

The hybridization of the power supply, which involves combining a variety of different types of power supply, is another method that can be used to increase the flying time of UAVs. This method is the most effective way to ensure that unmanned aerial vehicles have a high level of endurance, considering all these different factors. To put it another way, the hybridization of the power supply is the direction that could be taken. To generate the required amount of power, the power supply can be hybridization by combining several different types of power supply in combination with one another. [8] investigates the configuration of Unmanned Aerial Vehicle (UAV) systems and provides an in-depth review of the technical research and academic advancement of fuel, fuel-electric hybrid, and pure electric UAV propulsion systems. Specifically, the research focuses on fuel, fuel-electric hybrid, and pure electric UAV propulsion systems. This research was done so that there would be a better opportunity to optimise the configuration of UAV systems.

The findings of this investigation are presented within the framework of an analysis of how UAV systems are configured. After that,[8] discusses the power unit of electric propulsion UAVs before moving on to a discussion of the future vital technologies and development directions of electric propulsion UAVs.

The principles and theories applied in battery power supply differ from those used in DC power generators or hybrid systems. The distinctions in energy characteristics, such as the voltage-to-current ratio, between battery-based systems and DC power generators or hybrid systems remain unclear. This presents a challenge in the development of generator-based drones, as it is crucial to carefully choose the appropriate motor to ensure that the energy generated by the generator can adequately power the desired motor performance.

Hence, this research was carried out to provide clear power system design guidelines by understanding the energy characteristics of several power systems involved. Although there are several power supply alternatives discussed in many research studies, understanding the electrical characteristics and performance differences highlighted in this research remains essential for optimizing efficiency, ensuring safety, enhancing flight dynamics, and ultimately maximizing the performance and reliability of drone systems.

2. Literature Review

2.1. Drone Power Management

One of the problems when designing a drone is flight time estimation. In general, calculating the maximum take-off weight is the priority when designing drones. The flight time is directly proportional to the battery storing capacity and C-rating. Hence, the longer the flight time required by the drones, the more batteries required which resulted in reducing the drone payload allocation. On the other hand, adding more weight will increase the requirement of using more powerful motors. In considerations of choosing powerful motors, thrust calculation matters the most because the current consumption will significantly increase. This problem is circling in the same situation, without any real solution to overcome the problem.

As unmanned aircraft have become a critical part of human life, for example, in surveillance, agricultural, and medicine delivery missions, obtaining the optimum and efficient flight time is vital. This research proposes a novel approach to maximum take-off weight calculation that is needed when designing the aircraft by looking at the complete map of motor specifications.

2.2. Battery Based

Drones in the market nowadays are powered mostly by batteries[2]. They supply most small drones that provide the propulsion system with versatility and simplicity[9]. Although it uses a specific energy source, it can still not guarantee long, continuous drone missions. It is primarily because of their relatively low density of energy[10]. Unfortunately, multiplying batteries is not a practical solution because, intuitively, bigger batteries lead to longer flight time; however, lifting heavy batteries requires more electricity and thus decreases endurance.

Drones must also have an external energy source to compensate for the limitations of batteries and enhance their endurance[11][12][13]. The flight time limitation restricts the drone from doing the task continuously for commercial purposes such as agriculture and aerial photogrammetry. In addition, the performance and life of the batteries are influenced by many factors, such as operating temperatures, discharge, and rechargeable currents[14][15].

2.3. Battery C-Rating

The charging or discharging rate over time determines the C-rating of a battery. Adjusting the C-Rating can either speed up or slow down the charging or discharging process. The time taken for a battery to charge or discharge varies based on its C Rating. Technically, 1C takes 60 minutes, 0.5C takes 120 minutes, and 20C corresponds to a 30-minute charging or discharging time. In activities like FPV racing, where speed is crucial, having a battery with a high C-rating is important because it allows for a quick burst of power. However, batteries with higher C-ratings may also be heavier, potentially affecting overall performance.

$$\mathrm{I} = \mathrm{C}_r \times E_r \tag{1}$$

Where I represent Current capacity in (A), C_r is the battery C-Rating and E_r is the Energy rated (Ah)

2.4. Tethered Based

Tethering a drone to a ground station is a tried-and-true method of limiting a UAV flight area. By restricting the space of flight, UAVs can function autonomously or under human supervision so that a flight away does not occur. These tethered UAVs are generally equipped with monitoring or other data collection sensors. In addition to limiting the flight area of the UAV, the tether can be used to provide power and/or data communications to/from the UAV[16]. Several attempts to develop a tethered UAV have been seen before; several designs have been deployed all over the globe.

Figure 1 depicts the illustrations of the tethered drone system. The key motivation for developing the tethered system was to reduce the flight time limit imposed by the battery power. To this end, the system was invented to empower drones from the ground station, which theoretically would allow endless flight duration. Tethered DC generators and battery-based power supply construction are typically considered during drone development, considering parameters such as reliability, dimensions, performance, mobility, and the cost of the analysed solution [17].

Fig. 1 Tethered drone system

Table 1. Drone specifications

Flight controller		Pixhawk 2.0
Propeller length		13, 14 & 15-inch
Arm length		46 cm
Motor	Model	Tarot 4006 (Brushless)
	Rating (Kv)	620
	Idle Current (A)	0.8
	Max Continuous current (A)	17.5
	Weight (g)	82

3. Materials and Methods

3.1. Drone Features

Quadcopters are one of the most common and popular configurations for consumer and commercial drones due to their simplicity of design. Hence, the quadcopter drone was chosen for this experiment and drone specifications are shown in Table 1.

3.2. Testing Rig

The load cell was used to measure the thrust produced by the drone during the testing rig process, which was installed on the platform. A display panel (load cell reader) works with the load cell to give the reading value of the force applied to the load cell while the drone is operated on the testing rig table (drone holder). Figure 2 shows the illustration of the Testing Rig Diagram, while Table 2 is the testing rig parameter and its properties.

3.3. Testing Parameter

3.3.1. Lithium Polymer Battery

A lithium polymer battery (LiPo), or more precisely a lithium-ion polymer battery, is a lithium-ion rechargeable battery that uses a polymer electrolyte rather than a liquid electrolyte [6], [18], which was utilised in this research. The experimental study was conducted using LiPo battery power systems, 4S 100C battery-based, 4S 75C battery-based, 3S 25C battery-based and 3S 5C battery-based. The specification of the battery-based power system used in this experiment is described in Table 3.

3.4. Direct DC Power Supply

DC power supply has been used for this research to compare it with the battery-based power system. The power output for this DC power supply can be adjusted to meet the same voltage as the LiPo battery voltage. The DC power supply specification is described in Table 4.

Table 2. Testing rig specifications

Thrust meter		ProAce A20
Load cell	Model	Mavin NA4 (Single point)
	Max thrust	2000N
Watt Meter	Model	ABS
	Max Current	150

Table 3. Battery-based system specification

Parameter		
4S 100C	Number Of Cells	4 Cell
	C-Rate	100 C
	Voltage Rating	14.8 V
	Battery Capacity	5200 mAh
4S 75C	Number Of Cells	4 Cell
	C-Rate	75 C
	Voltage Rating	14.8 V
	Battery Capacity	5200 mAh
3S 25C	Number Of Cells	3 Cell
	C-Rate	25 C
	Voltage Rating	14.8 V
	Battery Capacity	2200 mAh
3S 5C	Number Of Cells	3 Cell
	C-Rate	5 C
	Voltage Rating	14.8 V
	Battery Capacity	2200

Table 1. DC Generator specification

Parameter		
Input	Maximum Power Output	2000w
	Input Voltage	180-264 VAC
	Frequency	45-63 Hz
Output	Dc Voltage	27 V
	Rated Current	74 A
	Voltage Adjustable Range	0-27 V
	Current Adjustable Range	0-74A

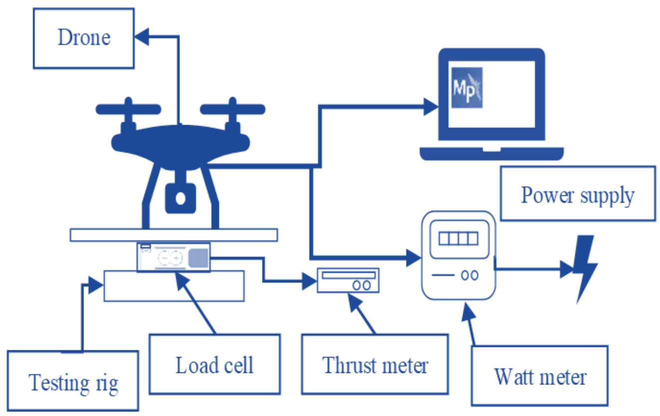

Fig. 2Testing rig diagram

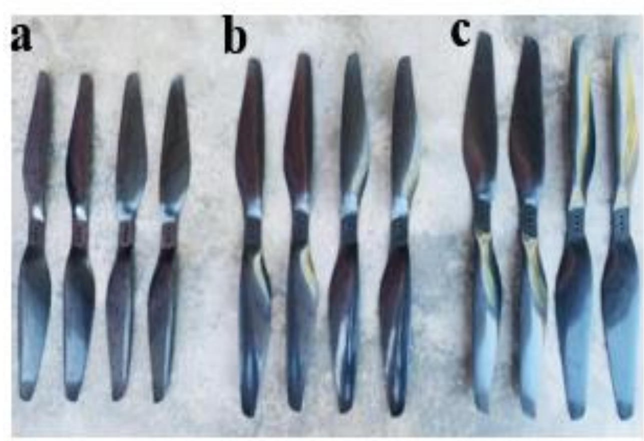

Fig. 3 Sizes of propeller (a) 13-inches, (b) 14-inches and (c) 15-inches

3.5. Propeller

Manufacturers of drone propellers generally include two primary dimensions in the manner A × B [6]. The first number represents the propeller's entire length from end to end. The second factor is the pitch, which is connected to the propeller's angle and is described as how far the propeller will travel forward under ideal conditions for each rotation.

The propellers' length is 13 inches, 14 inches and 15 inches, as shown in Figure 3. This obeys the recommended size of the propeller to be used with the type of motor, which is from 11 to 15 inches in length.

4. Results and Discussion

In the early investigation, the maximum thrust produced by the system was determined. This operation recorded the maximum thrust at 100% throttle percentage. For consistency, the maximum thrust reading is taken at the stable condition while the motor is running for the duration of 10s. The maximum output current was also the response of interest in this experiment. As expected, the current increases are due to demand from the system concerning the load from the propulsion system. The higher the mechanical load is, the higher the energy required to overcome the resistance.Hence, the output voltage and output current were taken from the multi-meter reading of the system at the maximum thrust condition. Although the number of battery cells in the battery-based power system indicates the voltage rating (1 cell battery is equivalent to 3.75V), the voltage drop happened.

This voltage drop was caused by the capacity reduction due to the usage and energy losses. Thus, taking the voltage rating instead of the multi-meter reading would not indicate an accurate power output value. In this research, the output power was calculated using the following formula,

$$P_o = V_o I_o$$

Where P_o is power output, V_o is voltage output and I_o is current output.In the case of a DC power generator, the input voltage was manually adjusted to achieve the required voltage output as displayed by the multi-meter while the motor was running.Table 5, Table 6, and Table 7 show the response for 4S Battery, 3S Battery system and DC power generator, respectively.

4.1. Battery-based Responsiveness

Table 5. 4S Battery response

		Factor 1	Factor 2	Response 1	Response 2	Response 3
Std	**Run**	**A: Battery Specs**	**B: Propeller Size (inch)**	**Thrust (N)**	**Max. Current (A)**	**Power Output (W)**
1	3	4S 75C	13	47.48	84.50	1328.34
2	16	4S 75C	13	47.97	81.17	1246.77
3	9	4S 75C	13	46.89	86.26	1377.57
4	10	4S 100C	13	48.07	86.60	1414.18
5	13	4S 100C	13	47.58	78.44	1266.81
6	11	4S 100C	13	46.70	85.05	1336.99
7	12	4S 75C	15	47.09	108.52	1639.74
8	4	4S 75C	15	46.60	106.92	1705.37
9	5	4S 75C	15	46.11	105.15	1550.96
10	6	4S 100C	15	45.81	100.03	1447.43
11	7	4S 100C	15	45.81	111.94	1683.58
12	18	4S 100C	15	46.10	108.60	1602.94
13	1	4S 75C	14	46.89	108.19	1718.06
14	15	4S 100C	14	46.50	97.82	1463.39
15	14	4S 75C	14	46.70	102.02	1538.46
16	8	4S 100C	14	45.62	95.38	1496.51
17	2	4S 75C	14	46.50	101.75	1540.49
18	17	4S 100C	14	46.21	91.12	1315.77

Table 6. 3S Battery response

		Factor 1	Factor 2	Response 1	Response 2	Response 3
Std	Run	A: Battery Specs	B: Propeller Size (inch)	Thrust (N)	Max. Current (A)	Power Output (W)
1	16	3S 5C	13	33.06	62.39	752.42
2	18	3S 5C	13	32.37	52.16	597.75
3	2	3S 5C	13	31.66	57.36	667.10
4	17	3S 25C	13	28.35	49.63	535.011
5	5	3S 25C	13	27.96	48.30	568.97
6	8	3S 25C	13	27.96	47.05	489.79
7	11	3S 25C	15	36.98	73.43	822.42
8	6	3S 25C	15	36.10	76.91	906.00
9	10	3S 25C	15	35.61	75.47	858.09
10	13	3S 25C	15	32.08	68.59	741.46
11	7	3S 25C	15	31.69	68.81	761.73
12	15	3S 25C	15	31.59	68.43	773.26
13	14	3S 25C	14	33.84	65.61	736.14
14	9	3S 25C	14	29.04	62.50	679.38
15	4	3S 25C	14	33.65	71.70	833.87
16	12	3S 25C	14	29.23	56.72	560.96
17	3	3S 25C	14	33.06	65.71	733.98
18	1	4S 100C	14	28.45	55.15	540.47

4.2. DC Supply Responsiveness

Table 7. DC Generator response

		Factor 1	Factor 2	Response 1	Response 2	Response 3
Std	Run	A: Output Voltage	B: Propeller Size (inch)	Thrust (N)	Max. Current (A)	Power Output (W)
1	11	14.8	13	19.03	30.52	451.70
2	14	14.8	13	19.13	30.82	456.14
3	15	14.8	13	18.84	31.46	465.61
4	7	22.2	13	31.88	49.25	1093.35
5	4	22.2	13	31.49	49.04	1088.69
6	8	22.2	13	31.20	47.13	1046.29
7	9	14.8	15	18.54	36.34	537.83
8	3	14.8	15	18.54	34.16	505.57
9	6	14.8	15	18.54	34.88	516.22
10	13	22.2	15	29.72	55.62	1234.76
11	12	22.2	15	28.74	54.22	1203.68
12	16	22.2	15	28.94	53.68	1191.70
13	1	18.5	14	24.23	44.45	822.33
14	10	18.5	14	23.94	43.36	802.16
15	5	18.5	14	23.94	43.07	796.80
16	2	18.5	14	23.94	44.85	829.80
17	24	14.8	14	18.54	35.6	526.88
18	22	22.2	14	29.63	54.84	1217.45
19	23	18.5	13	25.02	39.85	737.23
20	17	18.5	15	24.13	44.75	827.88
21	20	18.5	14	24.23	43.68	808.08
22	19	18.5	14	23.94	42.97	794.95
23	18	18.5	14	24.13	44.24	818.44
24	21	18.5	14	24.13	43.6	806.60
25	25	18.5	14	24.03	44.98	832.13

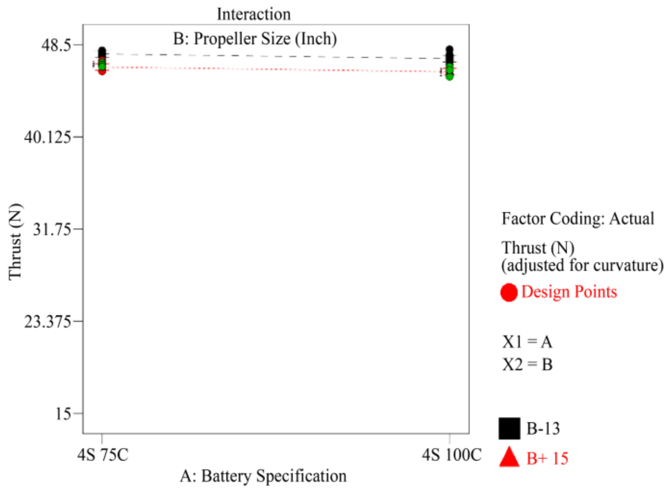

Fig. 4 The influence of interaction factors A and B on the thrust - 4S Battery

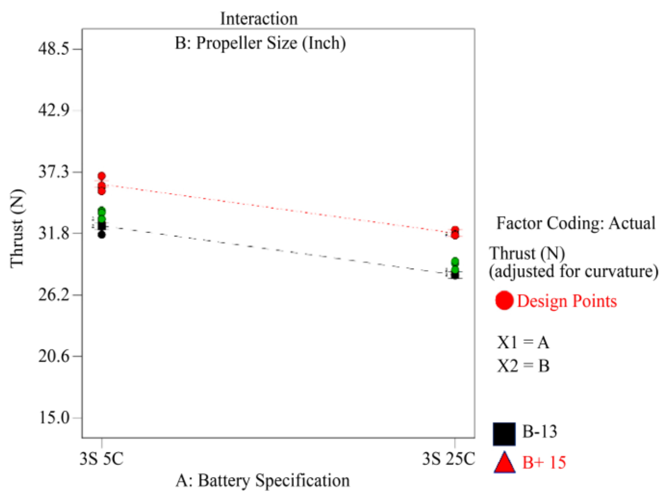

Fig. 5 The influence of interaction factors A & B on the thrust - 3S Battery

Figure 4 shows the graphical representation of the maximum thrust produced by the 4S Battery system. The maximum thrust produced by the system is approximately 48N. However, the maximum thrust was achieved by the smallest propeller of 13 inches. With the same energy sources, a higher efficiency configuration with means of a better thrust to power ratio was obtained by the smaller propeller. This inferred that the maximum electrical power generated by the 4S battery-based power supply has achieved the optimum level thrust. The power available has achieved the threshold limit of torque produced.

Although the bigger propeller size can produce a bigger thrust, the available torque is unable to efficiently handle the drag forces induced on the propeller surface during the lifting process. Differently, for the 3S Battery, the bigger propeller has produced a bigger thrust value to the propulsion system, as shown in Figure 5.

Table 8. Rate of voltage drown by Different C-Rating

		Rate of Voltage Drown (mV/s)		Average Rate of Voltage Drown (mV/s)	
Run	**Propeller Size (in)**	**25C**	**5C**	**25C**	**5C**
1	13	2.2	1.0	1.8	1.0
2		1.8	0.7		
3		1.4	1.3		
4	14	2.3	1.0	1.8	0.9
5		1.5	1.0		
6		1.7	0.7		
7	15	2.9	1.0	2.1	1.1
8		2.1	1.2		
9		1.2	1.1		

Due to a lower voltage rating, at any parameter combinations, the thrust produced by the 3S Battery is lower than the thrust produced by the 4S Battery. Interestingly, the study indicates that the C rating of the battery significantly influences the thrust produced. With a bigger C Rating, lower thrust is produced.The phenomenon has drawn up another hypothesis that the C Rating will determine the rate of voltage drawn from the power system. The faster the voltage drawn is (indicated by the bigger C Rating), the higher the rate of power losses due to the usage.

An additional study on the voltage losses during the operation supported the hypothesis. The thrust test is conducted at a constant duration of 10s. The initial voltage and final voltage readings were extracted for every experimental run. As shown in Table 8, the rate of voltage drown for the 3S 25C battery is higher than the 3S 5C battery.

Similar to the 4S Battery, the smaller propeller produced a bigger thrust than the 15-inch propeller while using the voltage output of 18.5V and 22.2V. At 14.8V voltage output, a closely similar thrust of approximately 19N was produced by all propeller sizes used in this investigation. Although the 14.8V voltage output used by the DC power generator is similar to the 4S Battery-based power supply voltage rating, a significant difference in thrust value was obtained. At any parameter combination, the DC power supply produces approximately 2.5 times lower thrust than the 4S Battery-based power supply. The reason for lowering the thrust value will be further elaborated with refer to the analysis of the current output and power generated by the system.

The maximum thrust produced by the system is approximately 19N for 14.8V, 24N for 18.5V and 31.8N for 22.2V. However, the maximum thrust was achieved by the smallest propeller of 13 inches and the highest output voltage of 22.2V. This shows that by increasing the output voltage, the thrust will also increase if the drag force does not exceed the torque produced by the brushless motor.

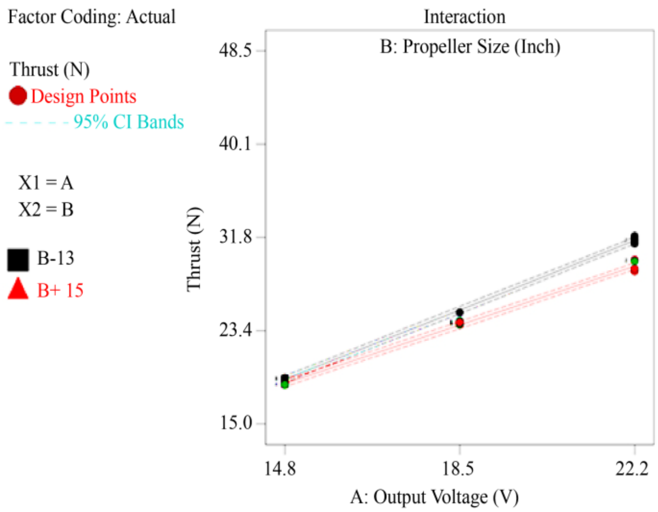

Fig. 6 The influence of interaction factors A and B on the thrust - DC Generator

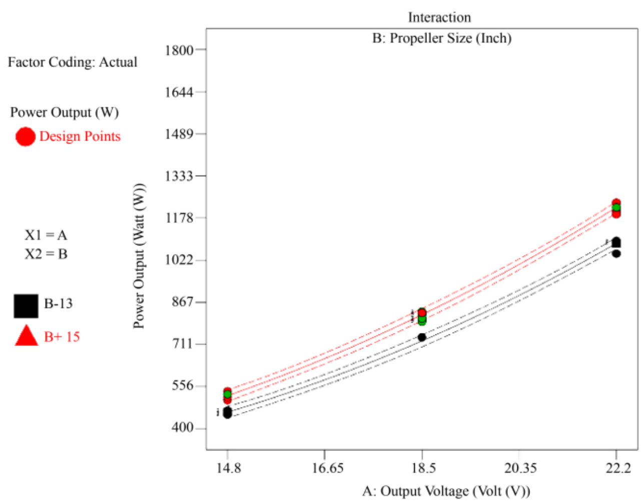

Fig. 7 The influence of interaction factors A and B on the maximum power output - DC Generator

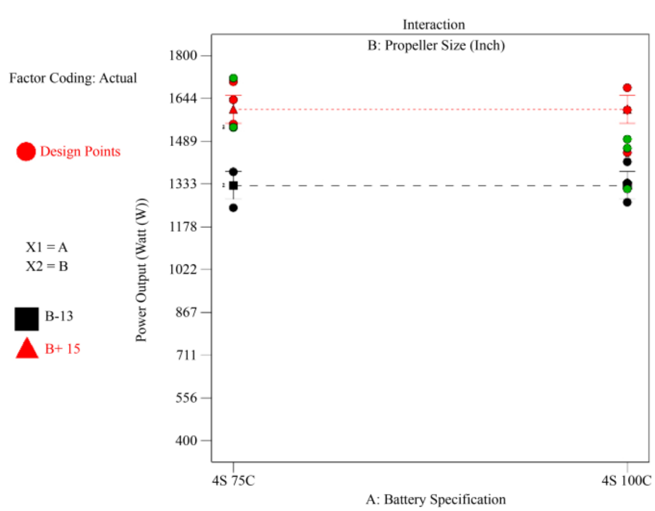

Fig. 8 The influence of interaction factors A and B on the maximum power output - 4S Battery-based

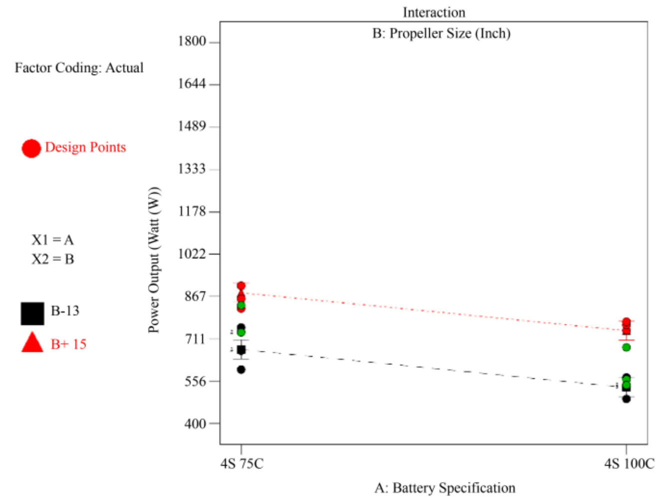

Fig. 9 The influence of interaction factors A and B on the maximum power output - 3S Battery-based

Figure 6 shows the graphical representation of the influence of interaction factors A and B on the thrust for the DC Generator. The highest thrust, observed at 22.2V, was 31.5N for the 13-inch propeller, while the 15-inch propeller produced a lower thrust of 29.7N at a similar voltage. The power output observation in Fig. Figure 7 indicates that the 15-inch propeller demands higher power than the 13-inch propeller but is unable to provide a larger thrust. This observation provides additional support for the previous discussion that these occurrences are a result of energy losses due to drag forces, which are also influenced by the motor torque capability.

The comparison between the maximum power output of the DC generator and the 4S LiPo batteries (Figure 8 and Figure 9) indicates that, despite using the same voltage value for both, the power output of the DC generator is lower than that of the LiPo battery. This discrepancy arises from the C-rating of the LiPo battery, which delivers burst current to the brushless motor, in contrast to the DC generator that supplies current linearly. The 3D surface in Figure 10 shows the relationship between Factor A (Output Voltage) and Factor B (Propeller Size) on thrust for a DC Generator. The figure shows that decreasing voltage and using a larger propeller size leads to a reduction in thrust value. The application of a higher voltage (22.2 V) with a 13-inch propeller size results in the maximum thrust value of 31.89 N. The lower thrust observed with a larger propeller may be attributed to the motor's kV rating. It becomes inappropriate for larger propeller sizes, requiring more energy to overcome drag forces and potentially hindering the motor's rotation from reaching its optimum speed. The differences between DC generators and battery-powered drones in terms of energy characteristics were also analysed in this study. Table 9 shows the comparison of current output and power output at similar voltages for low-voltage power systems.

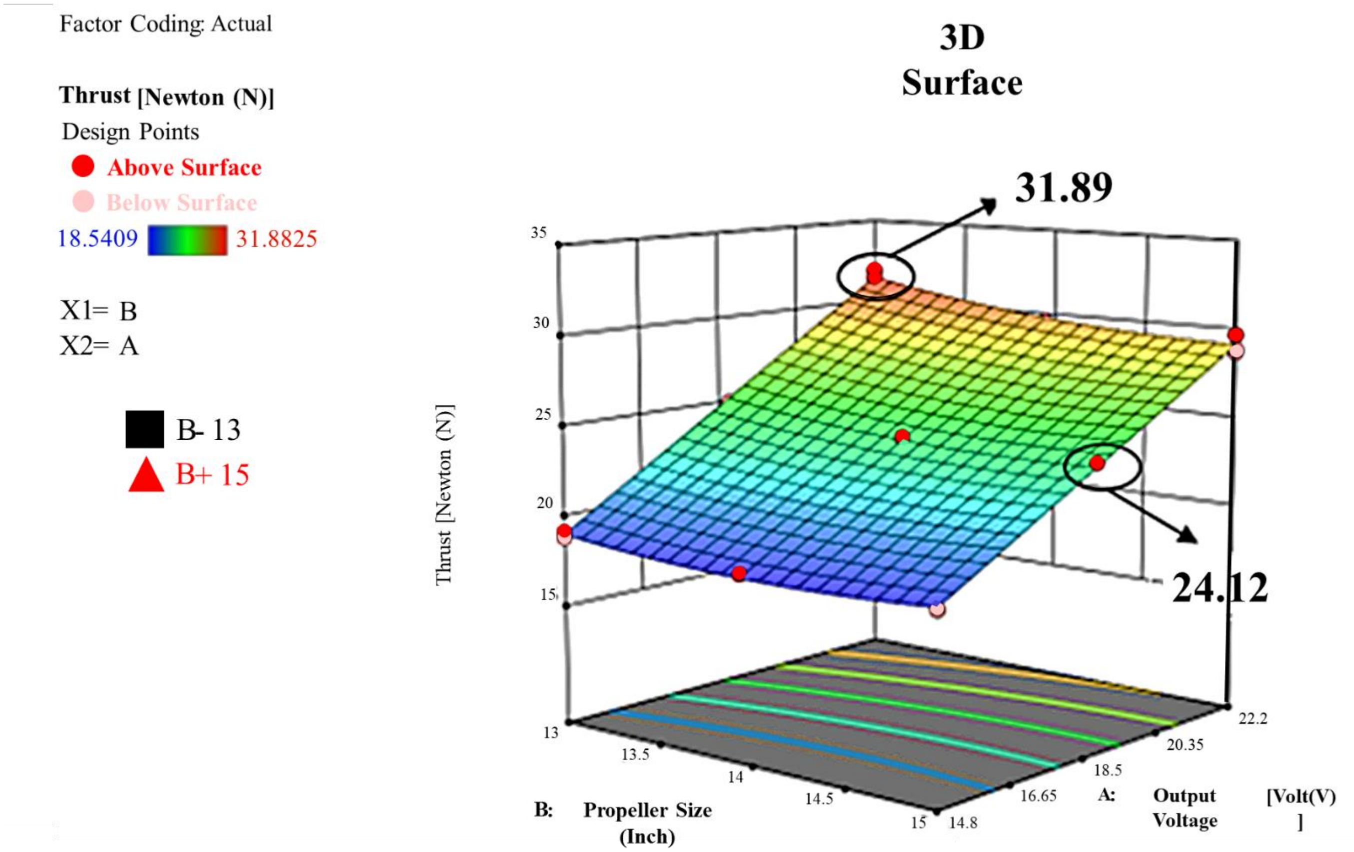

Fig. 10 The relationship between Factor A (Output Voltage) and Factor B (Propeller Size) on thrust for DC Generator

Table 9. Comparison of power characteristics at a similar voltage (Low voltage Power System)

Voltage Input (V)	Propeller Size (in)	Output Current (A)			Power Output (W)		
		Battery Based		DC Generator	Battery Based		DC generator
		4S 75C	4S 100C		4S 75C	4S 100C	
14.8	13	83.88	83.36	30.92	1242.84	1233.76	457.80
	14	104.00	94.76	35.60	1453.80	1402.64	526.88
	15	106.88	106.84	35.12	1581.56	1581.48	519.88

Table 10. Comparison of power characteristics closely similar thrust and propeller size

Thrust (N)	32	
Propeller size (in)	13	
Type of Power supply	3S 5C	DC Generator
Voltage Input (V)	44.40	88.80
Current Output (A)	57.36	49.24
Power (W)	848.93	1093.36
Voltage-to-Current Ratio (V/A)	0.774	1.803

From the analysis result, a battery-based system generates more current than a DC Generator does while using the same amount of input voltage. Since the current value is directly proportional to the overall power output, a higher current also implies that the battery-based system generates higher power than a DC Generator at a similar voltage input. In this case, it can be inferred that a higher voltage is required for the DC Generator to get similar power as the battery-based power system. The phenomenon can be further elaborated by observing the voltage-to-current ratio of different systems at similar thrusts.

Table 10 presents the characteristics of power obtained by different power systems while achieving closely similar thrust. Considering the data at similar propeller sizes, a closely similar power is needed to achieve a similar thrust. However, at any stage of the power system used (low voltage power system), the battery-based system typically owned a bigger voltage-to-current ratio than the DC-generator system.

5. Conclusion

The findings indicate that tethered drones can potentially offer equivalent performance to battery-based drones while operating under different power constraints. This is particularly advantageous in scenarios where continuous or extended flight time is required, as tethered drones can remain powered indefinitely as long as they are connected to a stable power source. The electrical characteristic of the tethered power supply is different from the battery-based power supply. However, the maximum energy generation will depend on the power system capability as discovered in this investigation.

Observations revealed that battery-based systems typically exhibit a lower voltage-to-current ratio compared to DC-generator systems when producing similar levels of thrust. A new rating of the brushless motor could be determined by utilizing the maximum power output as a new indicator. However, it is also crucial to consider the optimum propeller size, as this factor significantly influences the thrust value. Moreover, the ability to manipulate the power parameters of the DC generator system provides a unique level of control and adaptability in tethered drone operations. Operators can fine-tune the drone's performance characteristics to suit specific tasks or environmental conditions, enhancing its overall versatility and utility.

Overall, the research findings serve as a valuable guideline for the future development and deployment of tethered drone technology. Understanding the intricacies of power generation and propulsion in tethered drones can optimize performance, enhance reliability, and unlock new applications in various fields, such as surveillance, monitoring, and aerial photography.

However, establishing a new standard procedure is imperative to safely handle tethered drone systems, especially considering the utilization of high-voltage power supplies, which can pose significant risks without proper protocols in place.

Consequently, further research is warranted to develop a low-voltage, high-current tethered power supply for drones. Such advancements not only mitigate risks but also enhance the practicality and modularity of the system.

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