A Study on Battery Separation Drones to Extend Endurance

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Abstract

Battery-powered multi-copters have a high proportion of their total weight dedicated to batteries due to the low energy density of current battery technologies. Moreover, the battery weight remains constant regardless of its remaining capacity, necessitating high power requirements and significantly limiting flight time. This study proposes a theoretical framework for designing a new drone capable of extending endurance by separating and discarding used batteries, thereby gradually reducing weight during the mission. The developed model predicts the optimal number of batteries required for a given mission by integrating a weight prediction model based on battery capacity and a blade element momentum theory model that predicts the required power with respect to the variable weight. This study quantitatively compared the increased endurance achievable with the used battery separation technology. Applying this technology to quadcopters with total weights of 7 kg, 15 kg, and 25 kg resulted in expected endurance improvements of 127.3%, 121.0%, and 130.7%, respectively, compared to using a single battery. Additionally, considering the application of this technology to commercial drones, the study applied battery separation technology to the DJI Matrice 300 RTK, a widely used industrial drone. As a result, even with the use of two batteries, an endurance improvement of over 12.5% was achieved compared to the single battery condition.

Keywords: Long-endurance drone, Battery multi-stage separation

1. Introduction

Multi-copters, with their capability to fly at low altitudes, low speeds, and hover in place, are employed in a wide range of applications, including reconnaissance, delivery, and videography. These versatile aerial vehicles are primarily powered by batteries, making them environmentally friendly by eliminating the need for internal combustion engines, thereby significantly reducing noise and carbon emissions. However, the low energy density of batteries imposes significant limitations on flight duration and adds considerable weight, restricting the ability of multi-copters to perform long-duration and long-range missions. To mitigate these limitations and enhance the utility of battery-powered multi-copters, ongoing research efforts aim to improve their endurance and range [1-3].

To overcome the limitations of low energy density in batteries, alternative approaches such as hydrogen fuel cells [4, 5] and wired ground power [6] have been proposed. Hydrogen fuel cells generate power for flight through a chemical reaction between hydrogen and oxygen. With an energy density 92% to 170% higher than that of batteries, hydrogen fuel cells can significantly extend flight times for the same weight. However, the power generated by fuel cells is insufficient for takeoff and climb, necessitating the use of a separate battery. This results in a complex and heavy system, with an efficiency of approximately 60%, compared to over 90% efficiency for batteries [4]. Conversely, the ground-powered method supplies power via an external cable, enabling continuous flight without the need for battery replacement [6]. Despite this advantage, the operational range is limited by the length of the cable, beyond which weight and electrical resistance become problematic, and the flight path must be carefully planned to avoid obstacles, further limiting practical applications [6].

Battery separation is another method designed to address the limitations of low energy density batteries and improve flight time by replacing discharged batteries with fully charged ones during flight. There are two main approaches to battery separation. The first method, known as battery swapping[7], involves a multi-copter called a refueler UAV that delivers and retrieves new batteries from the aircraft on a mission. This method allows for unlimited flight duration as long as new batteries are continuously supplied. However, the flight time of the mission aircraft is constrained by the battery capacity, which is dependent on the payload capacity of the refueler UAV. Consequently, the battery swap method is limited by the performance of the refueler UAV, affecting mission distance and duration. Additionally, the battery replacement device mounted on the mission aircraft adds weight and reduces flight efficiency, resulting in shorter flight times when using a single battery.

The second approach is the battery multi-stage separation method, where installed batteries are sequentially disconnected to reduce weight during flight, similar to how an aircraft burns fuel to reduce weight, as shown in Figure 1. This method enhances endurance time. Karan J. [8] conducted an experiment comparing flight times under Maximum Takeoff Weight (MTOW) conditions and demonstrated that the battery multi-stage separation method increased flight time by 19% compared to using a single battery. However, there is currently a lack of tools for predicting the power requirements of battery separation and analyzing the optimal number of batteries and expected mission time. Despite these challenges, the battery multi-stage separation method increases flight efficiency by sequentially separating used batteries to reduce weight. This method is particularly focused on because it can overcome the limitations of the battery replacement method, which reduces flight efficiency. Previous research [8] indicated that the propeller's efficiency varied due to weight changes during flight, making it challenging to understand performance changes when applying this technology to heavier multi-copters, as the research was conducted on low-weight aircraft. Moreover, the discrepancy between actual and predicted flight times increased as the battery capacity or weight increased. Additionally, while the optimal number of batteries was theoretically infinite, the specific number of batteries required was not identified.

Figure 1 – Conceptual view of battery multi-stage separation technology
(green: charged batteries, red: discharged battery)

To address the limitations arising from the lack of a design tool that considers the optimal number of batteries and the characteristics of the battery multi-stage separation method, this study developed an integrated analysis tool. This tool integrates a required power prediction model, which accounts for propeller efficiency variations with weight changes, and a battery weight prediction model, which accurately reflects the weight variations of different battery types and capacities. This approach aims to identify the optimal number of batteries for enhanced performance. The study focused on determining the optimal number of batteries as a function of endurance time for a high-weight multi-copter, a scenario not addressed in previous research [8]. Furthermore, the impact of increasing the weight of the multi-copter on endurance time was analyzed, and the maximum endurance time for in-place flight was evaluated for a model currently in active commercial use.

2. Development of design tool

It is important to accurately predict the required power and battery weight, considering the changes in propeller and motor efficiency as the weight decreases with each battery separation step. However, previous studies [8] have estimated power requirements using constant propeller efficiency at maximum takeoff weight (MTOW) conditions, which does not account for propeller efficiency changes as weight changes. Due to the non-linear relationship between battery capacity and weight, accurately predicting battery weight, which is a significant contributor to the weight of a multi-copter, is essential. This limitation makes it difficult to accurately predict the required power and battery weight. To address these limitations, this study developed an integrated analysis tool that combines a required power prediction model and a battery weight prediction model. The structure of the developed integrated analysis tool is shown in Figure 2. The integrated analysis model predicts the weight of each battery and subtracts the weight of each stage battery from the total weight. The first model, the power requirement prediction model, predicts the power requirement based on the weight of the multi-copter at a given battery stage. The second model, the battery weight prediction model, predicts the battery capacity and battery weight by considering the required power of the multi-copter, the number of battery stages, and the endurance per battery divided by the target endurance. Next, the Total Endurance, which is the sum of the flight time of all analyzed battery stages, is checked to see if the Target Endurance is reached. If the Target Endurance is not reached, the process of applying the weight of the multi-copter minus the predicted battery weight back into the integrated model is repeated until the Target Endurance is reached. Once the target endurance is reached, all the weights of each battery are added to obtain the total battery weight by battery type. The total number of battery units is determined by identifying the optimal number of batteries when the total battery weight per battery unit is the lightest.

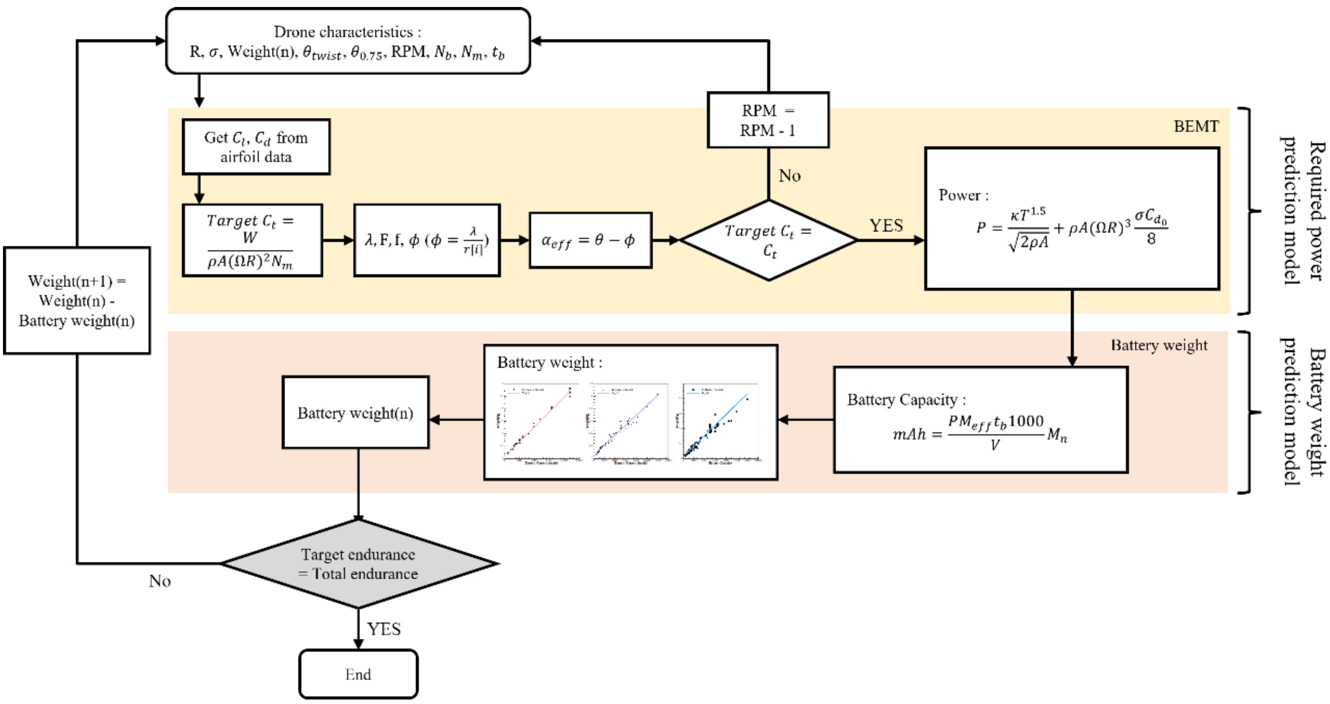


Figure 2 – The structure of numerical tool

2.1 Required Power Prediction Model

For a typical multi-copter whose weight does not change during flight, the airframe is designed without considering propeller efficiency based on weight. However, in a multi-stage battery disconnect scheme, the weight changes and the design must account for the changing propeller efficiency. If this is not taken into account, the power requirement prediction will be inaccurate whenever the batteries are disconnected. Consequently, it becomes impossible to predict the exact mission time and optimal number of batteries, as the error increases with the number of batteries, similar to the optimal number of batteries predicted in previous research [8]. To predict the correct mission time and optimal number of batteries, it is essential to estimate the required power by considering propeller efficiency as a function of weight.

In this study, Blade Element Momentum Theory (BEMT) was employed to predict the efficacy and required power of the propeller, taking into account the weight fluctuations resulting from battery separation. BEMT is based on momentum theory, which posits that thrust is generated by the difference in momentum flowing through the tube from the start of the stream to the end of the stream. This is done under the assumption of a one-dimensional, non-viscous, incompressible, and non-rotating tube around the propeller. This theory posits that thrust is generated by the difference in momentum flowing through the tube from the start of the stream to the end of the stream. It divides the propeller into the elements of the simulation and represents the geometric flow elements generated by each element, as illustrated in Figure 3. Consequently, the lift and drag forces can be obtained in accordance with the relevant equations. The thrust and torque can be obtained according to Equations (1) and (2) by using the lift and drag generated by each element. This is called Blade Element Theory (BET), and the combination of momentum theory and BET is called BEMT.[9]

$$dT = N_b(dL\cos\phi - dD\sin\phi) \tag{1}$$

$$dQ = N_b(dL\sin\phi + dD\cos\phi) \tag{2}$$

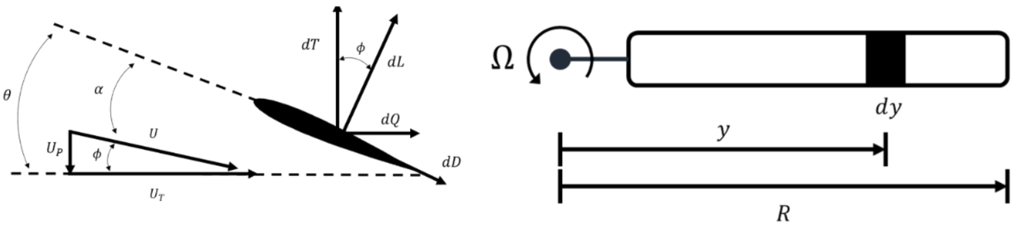


Figure 3 – Blade Element Momentum Theory

In actual propellers, the tip loss effect causes zero lift at the blade tip. However, since the Blade Element Momentum Theory (BEMT) does not account for this tip loss effect, we incorporated Prandtl's tip loss equation, as shown in equations (3)-(5), into BEMT to consider the tip loss. for this tip loss, we incorporated Prantl's tip loss equation into BEMT to consider the tip loss. Here, 'solidity' is defined as the ratio of the area of the blade. 'λ' is inflow ratio. 'r' is radius of the blade. 'C_{l_a}' is section lift-curve slope. 'N_b' is number of rotor blade. 'ϕ' is inflow angle of attack. 'F' is Prandtl's tip-loss function. 'f' is effective flow separation point as a fraction of chord.

$$\lambda(r) = \frac{\sigma C_{l_a}}{2\left(\sqrt{1 + \frac{32F}{\sigma C_{l_a}}\theta r} - 1\right)} \tag{3}$$

$$F = \left(\frac{2}{\pi}\cos^{-1}\left(e^{-f}\right)\right) \tag{4}$$

$$f = \frac{N_b}{2\left(\frac{1-r}{r\phi}\right)} \tag{5}$$

The BEMT developed in this study was validated by comparing it with the experimental Figure of Merit (FM) data for the UH-1 helicopter [10, 11]. W. Mantay [10] conducted experiments by mounting the UH-1 main rotor on a spin tower at NASA's Langley Research Center. J. Berry [11] carried out experiments under conditions of hover and forward flight using a scaled-down UH-1 helicopter main rotor in a 4×7-meter wind tunnel test facility. Validation was performed using the main rotor of the UH-1 helicopter under hover conditions. Figure 4 shows the overlap of FM predicted by the BEMT developed in this study with the experimental data [10, 11] in the thrust coefficient range of 0.001 - 0.0045, confirming that FM is accurately predicted with a maximum error of 5% across various thrusts. The required power prediction model using BEMT can consider propeller efficiency with weight reduction during flight, making it useful for predicting the optimal number of batteries and mission time.

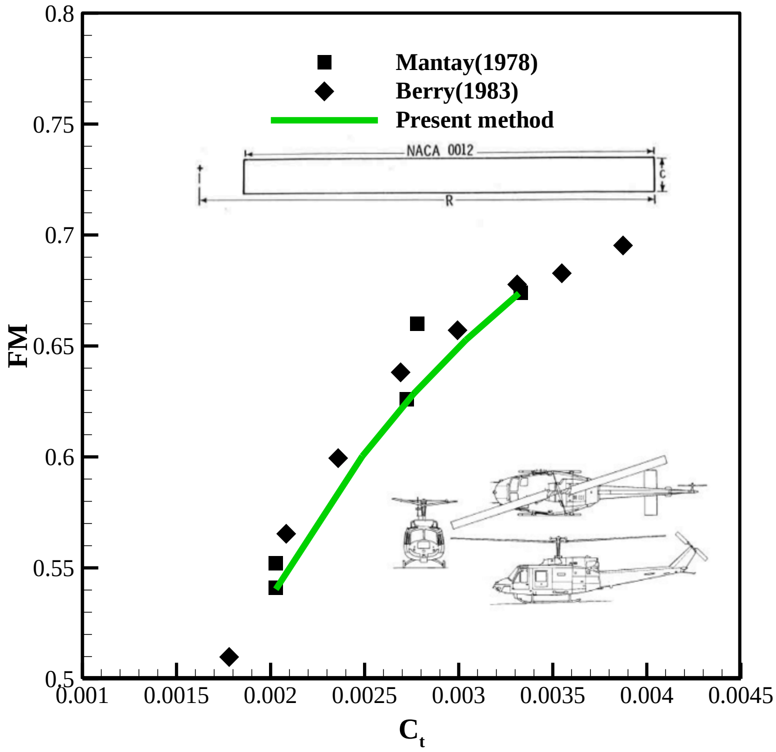


Figure 4 – Figure of Merit of UH-1 blade: experimental [9] and numerical results.

2.2 Battery Weight Prediction Model

To determine the optimal number of batteries for a multi-copter with a multi-stage battery separation method, it is crucial to accurately predict battery weight and flight time. Previous research [8] predicted the estimated flight time for a quadcopter with a weight of 975g based on an energy density of 130 Wh/kg. However, to confirm the feasibility of the multi-stage battery separation method, it is necessary to analyze the performance changes of heavy multi-copters. Additionally, previous research[8] suggested that an infinite number of batteries would be optimal. However, the predicted battery weight based on an energy density of 130 Wh/kg tends to be overestimated for capacities above 2000 mAh and underestimated for capacities below 2000 mAh. This discrepancy arises because the battery structure, as shown in Figure. 5, was not considered. The battery structure comprises energy storage parts and non-energy storage parts such as circuits, cases supporting the battery pack, and the Battery Management System (BMS) that optimizes the safety, lifetime, and performance of the battery through functions such as charge and discharge management, voltage and current monitoring, temperature control, and cell balancing. Even if the total weight of the battery decreases, the weight of the components that do not contribute to energy storage does not decrease linearly. Instead, the reduction in weight is primarily concentrated in the energy storage components. Therefore, linear prediction using energy density results in errors depending on the battery capacity, which hinders the accuracy of the model in predicting total weight and flight time.

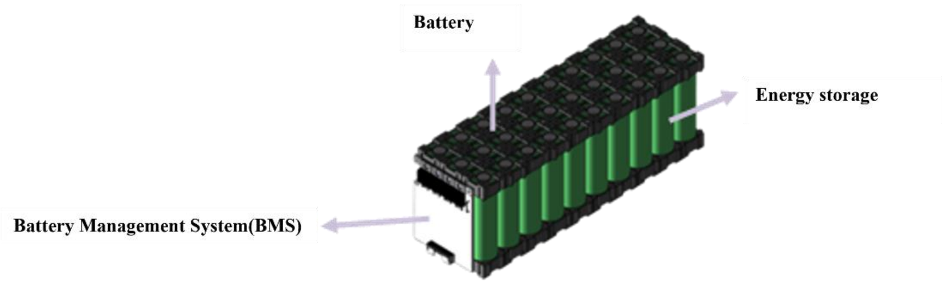
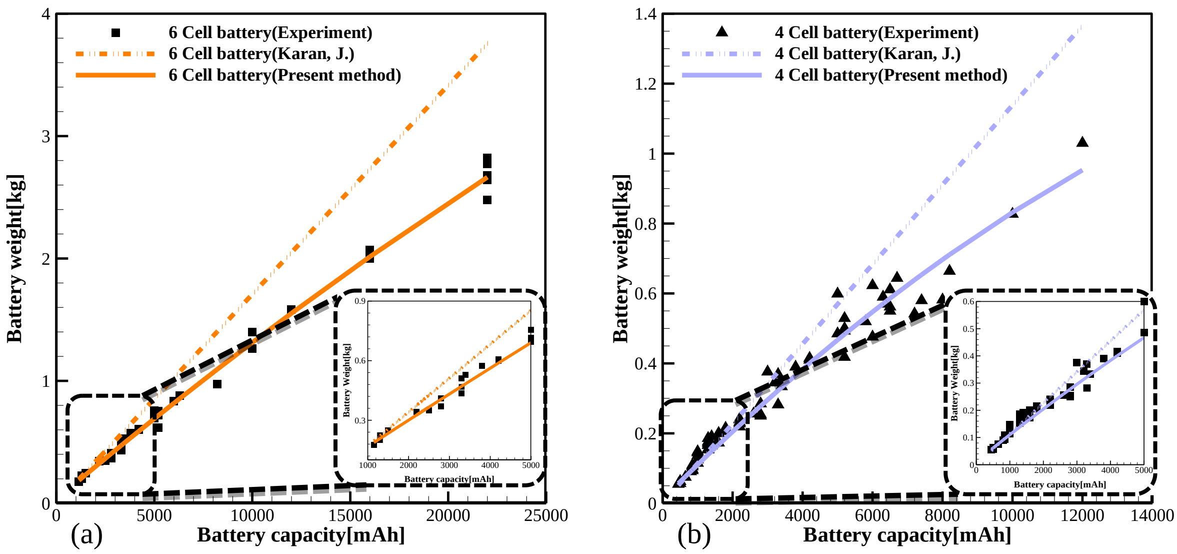


Figure 5 – Battery structure

This research focused on developing a battery weight prediction model in multi-copter, considering the use of 3-cell, 4-cell, and 6-cell batteries. The primary objective was to investigate the performance impact of multistage battery separation in multi-copter with a weight exceeding 1 kg. This study aims to address a gap in existing literature, as previous research [8] has excluded such multi-copter from analysis. As the weight of a multi-copter increases, the number of cells in the battery also increases. This is because a heavier multi-copter requires more power, which necessitates higher battery voltage and efficiency. To improve the accuracy of battery weight prediction, this study analyzed data from 249 commercially available batteries sold online. This extensive analysis aims to enhance the findings of previous studies on this subject [8]. Figure 6 illustrates the relationship between battery weight and capacity for 6-cell, 4-cell, and 3-cell batteries. The dotted line represents the battery weight predicted based on the energy density from previous studies [8], while the solid line represents the results from our battery weight prediction model. These are plotted alongside the actual battery weights, shown as dots. As illustrated in Figure 6, the battery weight predicted by the previous study [8], which assumes a constant battery energy density, exhibits an increasing discrepancy as battery capacity increases, regardless of the number of battery cells. Specifically, for a 4-cell 8000 mAh battery, the prior study shows an error of 56.49% compared to the actual battery weight. In contrast, our battery weight prediction model demonstrates a smaller error, averaging 14% for 3-cell, 10% for 4-cell, and 5% for 6-cell batteries, irrespective of the number of cells and capacity. The coefficient of determination (R^2) for the 3-cell, 4-cell, and 6-cell models is 0.951, 0.9664, and 0.9952, respectively, confirming the high prediction accuracy of our battery weight prediction model. This developed model can predict the total battery weight according to the number of battery stages when the battery multistage separation method is applied to a heavy multi-copter. Additionally, it identifies the optimal number of batteries with the smallest weight among the predicted total battery weights. The optimal number of batteries for multi-copter weighing 7 kg, 15 kg, and 25 kg was also determined. Finally, the maximum endurance was analyzed as the weight varied.



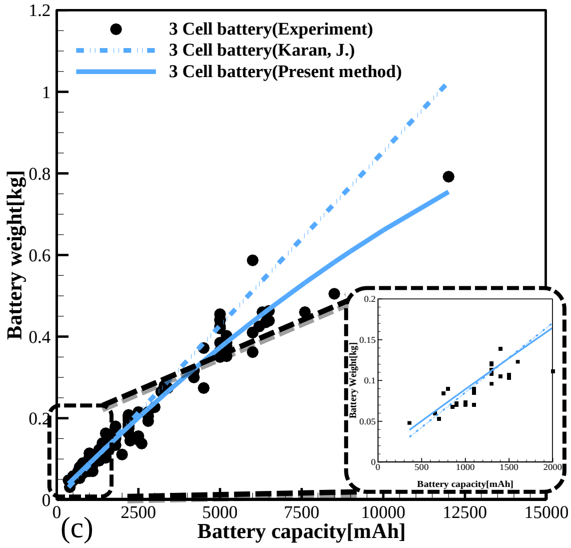


Figure 6 – The data points on each 6-cell (a), 4-cell (b), and 3-cell (c) graph depict the commercialized battery weights based on battery capacity.

2.3 System verification

To validate the integrated analysis tool developed by combining the demand power prediction model with the battery weight prediction model, the results of the analysis were compared with those of experiments conducted in a previous study [8]. In order to validate the integrated analysis tool developed by combining the demand power prediction model and the battery weight prediction model, which takes into account the weight loss during flight due to battery separation, the analysis results were compared with experiments performed in a previous study [8]. The validation was conducted under identical conditions as those employed in the previous study [8], which presented the time spent in operation with two batteries and the change in power demand over time. The weight of the quadcopter utilized in the experiments conducted by Element is as follows: The weight of the multi-copter without batteries is 595 grams, each battery weighs 190 grams, and the total weight of the two batteries combined is 380 grams, for a total weight of 975 grams. The experimental results of using two batteries on this aircraft were 9.3 minutes of flight time using only the first battery and 13.5 minutes of flight time using only the second battery, for a total of 22.8 minutes of flight time. The required power was measured to be 159 W before battery separation and 112 W after battery separation. Such detailed information on flight time, required power, and battery weight provides valuable data for validating the integrated analysis tool.

The validation of the integrated analysis tool developed in this study was carried out through flight experiments conducted in a previous study [8], focusing on two aspects. The first aspect of the validation process involved verifying the accuracy of the tool in predicting the required power demand based on the remaining weight after disconnecting the battery. The tool predicted a power demand of 120 W after separation of the battery, which exhibited a 7% discrepancy compared to the experimental value of 112 W. The discrepancy is attributed to the lack of specific information on the propeller in the current experiment [8], where only the NACA0012 airfoil with twist was applied. It is likely that a thin cambered airfoil, specifically designed for low Reynolds numbers, was used in the actual experiments. If the developed required power prediction model considers the propeller with higher efficiency used in the experiments, it is expected that the error will be reduced to less than the current 7% discrepancy. The second aspect involved verifying the accuracy of the total battery weight prediction. In the experiment using a 3-cell battery, two 2200mAh batteries weighing 190g each were used, resulting in a total battery weight of 380g. The predicted total battery weight in this study was 388g, showing a minor error of 2.1%, confirming the accuracy of the total battery weight prediction. Figure 7 compares the developed integrated analysis tool with the experimental measurements. Consequently, the accuracy of both the power demand prediction and the battery weight prediction was validated, confirming the accuracy of the power demand variation and total battery weight prediction in a multi-copter applying the actual multi-stage battery separation method. This completed the validation of the integrated analysis tool developed in this study. Subsequently, the maximum endurance time and the optimal number of batteries were analyzed for multi-copter weighing 7kg, 15kg, and 25kg. The tool was also applied to the DJI Matrice 300 RTK, a model actively used in commercial fields, to determine the maximum flight time and the optimal number of batteries.

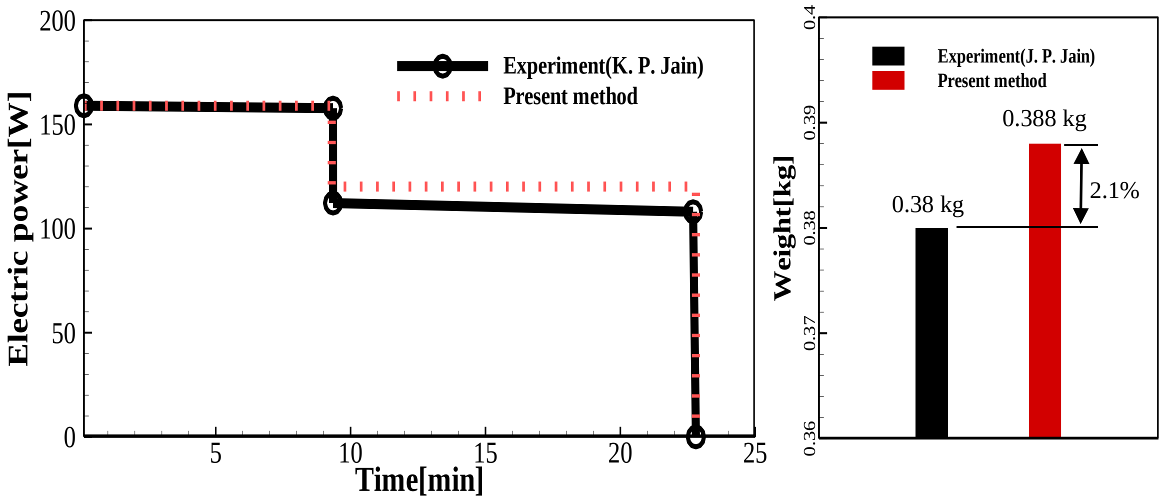


Figure 7 – Comparison of electric power(left) and total battery weight(right) between flight tests [8] and numerical model.

3. Results

Until recently, battery separation technology has primarily been applied to lightweight drones with a Maximum Take Off Weight (MTOW) of 1 kg [8]. However, there is a significant commercial demand for 7 kg multi-copter due to their high viability in the market. In this study, a 7 kg multi-copter with the longest possible hovering time was designed using battery separation technology. An analysis was conducted to predict flight times based on varying numbers of batteries, identifying conditions that minimized battery weight while maximizing the hovering endurance. Furthermore, the application of battery separation technology was extended to drones of different weights, including 15 kg and 20 kg models. By applying this technology to these heavier drones, the optimal number of battery stages required to maximize the hovering endurance was predicted. Finally, the impact of battery separation technology on mission times for DJI's commercially successful Matrice 300 RTK was examined. This study aimed to evaluate the performance enhancements in mission duration brought about by this innovative battery technology.

3.1 Optimal number of battery stages

The total weight of the battery is contingent upon the number of batteries utilized in the multi-stage battery separation scheme. The optimal number of batteries is the number that results in the lowest total battery weight. Previous studies [8] have posited that when the number of batteries is infinite, continuous weight reduction leads to the optimal number of batteries. However, flight time predictions for different battery counts (5, 15, 25, 50, 100, 500), as shown in Figure 8, indicate that the maximum endurance decreases as the number of batteries increases. As shown in Figure 9, which illustrates the total battery weight by number of batteries for a target flight time of 2.5 hours, the total battery weight tends to decrease as the number of batteries increases until it reaches 13 batteries, similar to previous studies [8]. However, when the number of batteries exceeds 13, the overall battery weight increases. Moreover, when the number of batteries reaches 500, the battery weight surpasses the total weight (7 kg) to achieve the target flight time of 2.5 hours.

The reason why the total battery weight increases is because the battery weight was predicted by considering the battery structure. In previous research [8], the battery weight was estimated to approach zero when the battery capacity becomes very small using energy density. However, due to non-energy storage components such as BMS, casing, and wiring, there is a minimum weight that exists even if the battery capacity is very small. The battery weight prediction model developed in this study can account for this minimum weight by considering the battery structure. Therefore, beyond a certain number of batteries, the influence of non-energy storage components on the total weight increases, causing the total battery weight to rise. This specific number of batteries is referred to as the optimal number of batteries. For a multi-copter weighing 7 kg, the optimal number of batteries is 13, as shown in Figure 9.

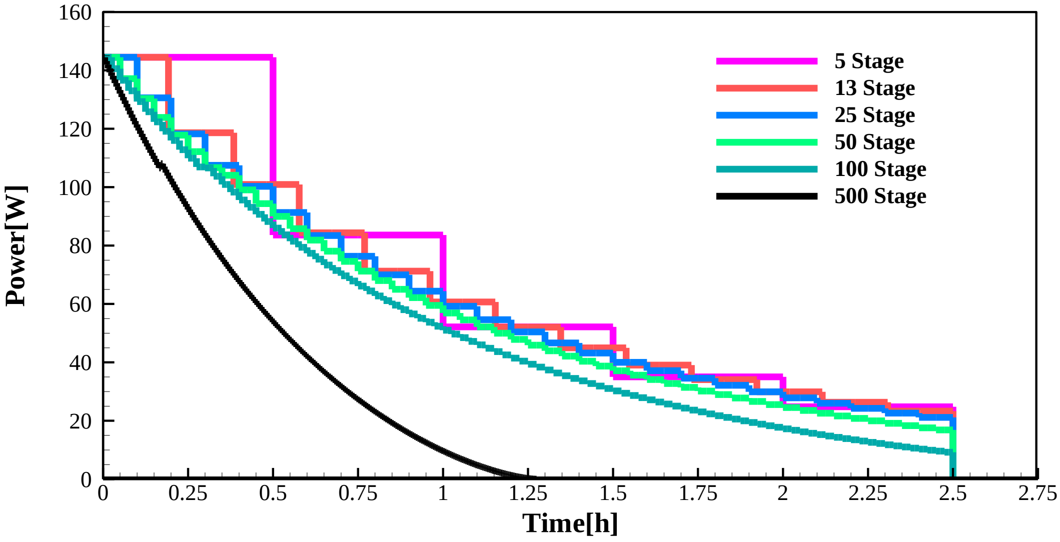


Figure 8 – Changes in required power according to flight time per battery.

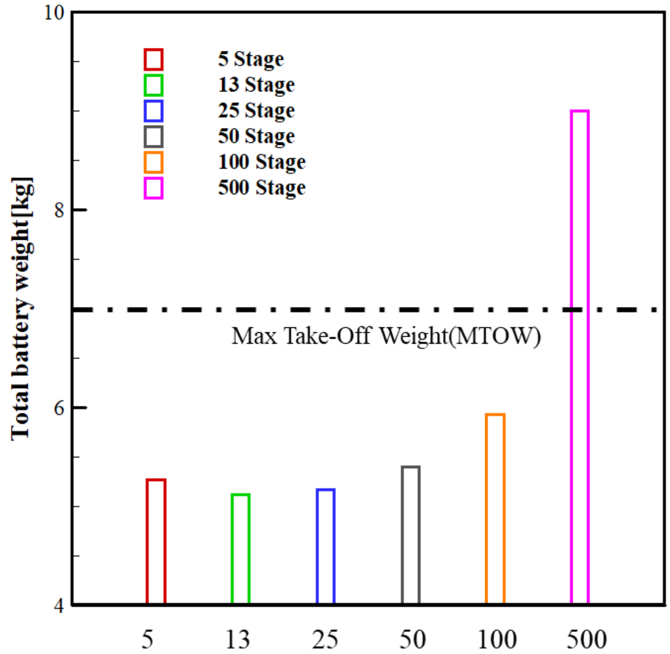


Figure 9 – battery weight based on the number of batteries.

3.2 Weight effect of multi-copter

The elevated power requirements of heavy multi-copter necessitate larger batteries to achieve a desired endurance level. Consequently, the added battery weight contributes to an overall increase in the weight of the multi-copter, which in turn escalates the required power, creating a snowball effect. This phenomenon arises from the low energy density of the batteries. The scatter diagram in Figure 10 shows the weight and hovering endurance (flight time) of currently available multi-copter. It is apparent from the Figure 10 that the endurance decreases rapidly with increasing weight. Therefore, improving the endurance of high-weight drones is a challenging task.

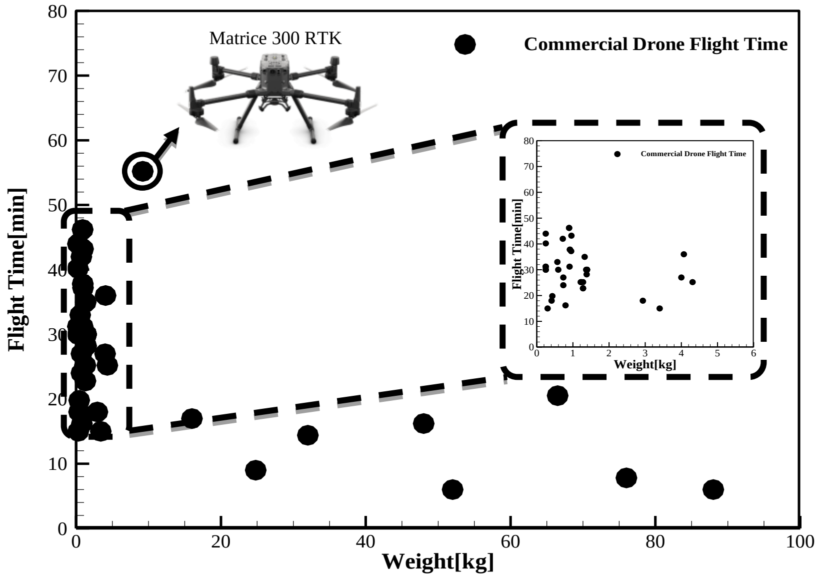


Figure 10– Flight time according to weight of commercial multi-copter

This study analyzes the change in endurance when the battery separation method is applied to two types of heavy multi-copter weighing 15 kg and 25 kg. The maximum endurance for both the 15 kg and 25 kg multi-copter is predicted to be 2 hours, as shown in Figure 11. The optimal number of batteries is 20 for the 15 kg multi-copter and 27 for the 25 kg multi-copter. Although the number of batteries increases compared to the 7 kg multi-copter, the endurance decreases for both heavier weights. As a result, the maximum endurance time for multi-copter weighing 15kg and 25kg was reduced to 2 hours, which is a 20% decrease compared to the 7kg multi-copter. This is because, in the case of heavy multi-copter, the overall weight of components such as motors, frames, and ESCs increases in addition to the battery, leading to higher power requirements. To achieve the same flight time as the 7kg multi-copter, more energy is needed. However, in the case of heavy multi-copter, the weight of components such as motors, frames, and ESCs increases, resulting in a relatively lower proportion of battery weight. Due to the low energy density of the battery, it is not possible to store enough energy for a flight time of 2.5 hours, reducing the endurance time to 2 hours. On the other hand, the optimal number of batteries increased compared to the 7kg multi-copter. This is because the flight time per battery decreases, and rapid battery separation leads to a quick reduction in weight, enabling efficient flight. Therefore, it was observed that the optimal number of batteries increases as the weight of the multi-copter increases.

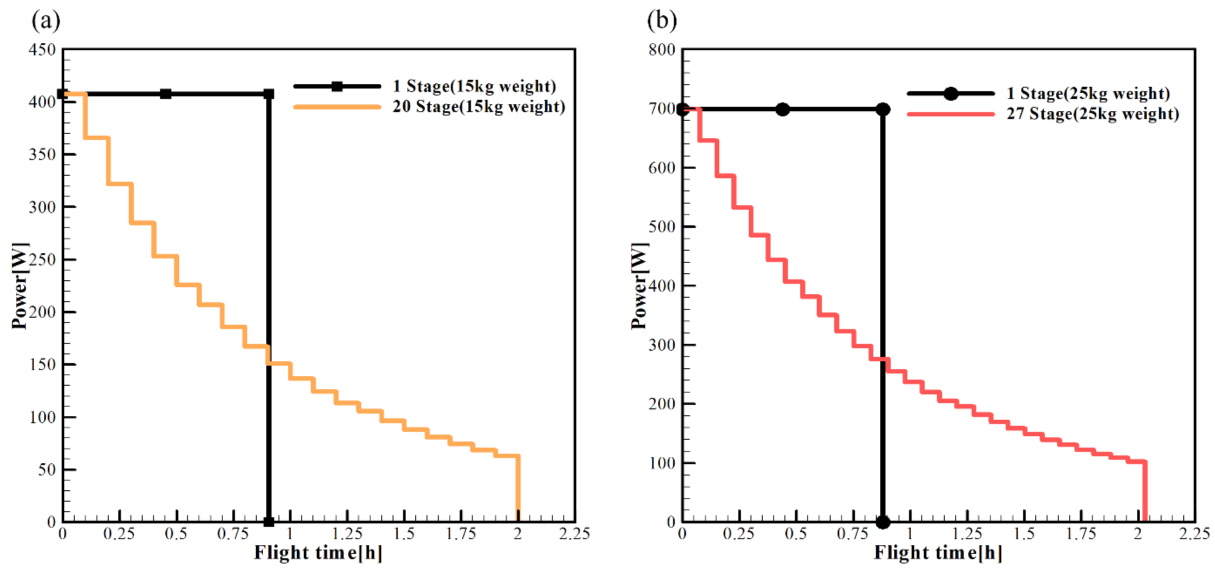


Figure 11 – The change in required power with respect to flight time. 15 kg (a), 25 kg (b).

3.3 Applying commercial Drone

The battery separation method was applied to the DJI Matrice 300 RTK model, which is in high demand for commercial drone markets used in construction, infrastructure management, security, and surveillance. The Matrice 300 RTK can carry a payload of 2.7 kg, with the battery weighing 2.7 kg and the airframe (excluding the battery and payload) weighing 3.6 kg, resulting in an MTOW (Maximum Takeoff Weight) of 9 kg. In this study, under MTOW conditions, the payload and airframe weight were kept constant, while the battery weight varied with flight time using the multi-stage battery separation method. This approach was compared to the single battery method to determine the maximum flight time and the optimal number of batteries. To predict the power requirements of the propeller, only the propeller diameter of 21 inches for the Matrice 300 RTK was available, with no information on airfoil shape, twist, solidity, or RPM. Therefore, this study applied a custom-designed propeller. The propeller airfoil used was NACA0012, with a diameter of 21 inches, solidity (σ) of 0.16, and a twist angle ($\theta twist$) of 27.5°. Based on this information, it was found that the proportion of battery weight to the total weight, including the payload, was only 30%, leading to shorter endurance times. Upon comparing the use of 1, 2, and 3 batteries, it was determined that using 2 batteries provided the best performance.

For the maximum flight time analysis of the Matrice 300 RTK with a 2.7 kg payload, resulting in a total weight of 9 kg, Figure 12 shows the changes in power requirements over hover time for both the single battery method and the multi-stage battery separation method. The single battery method achieves a maximum hover time of 0.48 hours, while the multi-stage battery separation method achieves a maximum hover time of 0.54 hours, an improvement of 12.5%. The optimal number of batteries in this case is 2. The reason for the improved hover time is that the first battery, weighing 1.56 kg, is separated from the Matrice 300 RTK, reducing the total weight by 17.4%, which decreases the power requirement. Consequently, the reduction in energy consumption leads to an extended hover time.

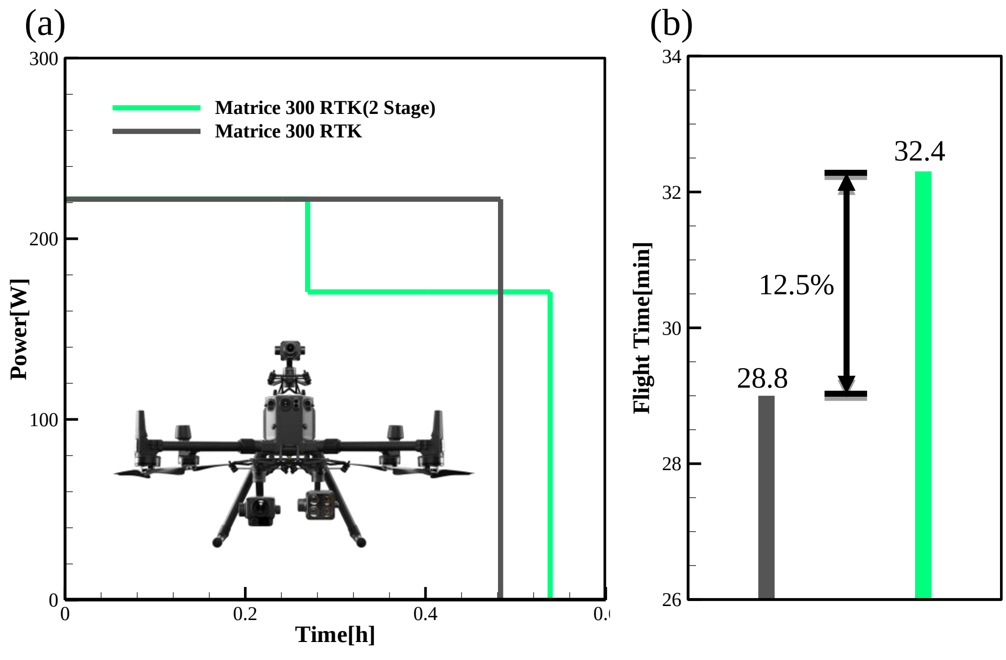


Figure 12 – Graphs of power changes (a) and flight time changes (b) over time.

4. Conclusions

In order to overcome the short flight time, which is a limitation of battery-based multi-copter due to the low energy density of the battery and the unchanging weight of the battery during flight, this study investigated the battery multi-stage separation method. In this study, an integrated analysis tool was developed by combining a battery energy management system (BEMT)-based power demand prediction model and a battery weight prediction model in consideration of the changing weight at each battery separation point. The tool yielded three results. It was found that there is an optimal number of batteries due to the structure of the battery. The optimal number of batteries for multi-copter weighing 7 kg, 15 kg, and 25 kg was predicted to be 13, 20, and 27, respectively. The application of the battery multi-stage separation method to the multi-copter with a higher weight resulted in an increase in the optimal number of batteries and a decrease in flight time compared to the multi-copter with a lower weight. This confirms the effectiveness of increasing the number of batteries for multi-copter with a higher weight. Finally, we analyzed the maximum flight time of a Matrice 300 RTK, the most widely used drone in the commercial drone market today, with a 2.7 kg payload. Our findings indicate that the flight time of a single battery and a multi-stage battery separation method was 0.48 hours and 0.54 hours, respectively. This represents a 12.5% improvement in flight time with the multi-stage battery separation method.

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6. Copyright Statement

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References

[1] Ching-Fuh, Lin. et al. Solar power can substantially prolong maximum achievable airtime of quadcopter drones, *Advanced Science*, vol. 7, no. 20, pp. 2001497, 2020.

[2] Sunghun, J. Yonghyeon, J. and Yong-hyeon, J. Aerial surveillance with low-altitude long-endurance tethered multi-copter uavs using photovoltaic power management system, *Energies*, vol. 12, no. 7, pp. 1323, 2019.

[3] Tommaso, C. et al. High efficiency and lightweight wireless charging system for drone batteries. *in 2017 AEIT International Annual Conference (IEEE)*, pp. 1–6, 2017.

[4] M. B. et al. Power supply architectures for drones - a review, *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, Lisbon, Portugal, Vol. 1, pp 5826-5831, 2019.

[5] Apeland J, Pavlou D., and T. Hemmingsen. "State-of-technology and barriers for adoption of fuel cell powered multirotor drones." 2020 International Conference on Unmanned Aircraft Systems (ICUAS). IEEE, 2020.

[6] Karan J, et al. Tethered power supply for quadcopter: architecture, analysis and experiments. *arXiv*, 2022.

[7] Yoad G. and Amir S. On-Board physical battery replacement system and procedure for drones during flight. *in IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp 9755-9762, 2022.

[8] Karan J, et al. Staging energy sources to extend flight time of a multi-copter UAV. *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, NV, USA, pp 1132-1139, 2020.

[9] Betz A. Screw propellers with minimum energy loss. Göttingen Reports, 193-213, 1919.

[10] John B. Wind tunnel testing of an advanced UH-1 type rotor system. *Journal of the American Helicopter Society*, Vol. 28, No. 2, pp 19-23, 1983.

[11]Wayne M, et al. Full-scale testing of an Ogee tip rotor. *Helicopter Acoustics*, 1978.

[12]Gordon, Leishman, J. *Principles of Helicopter Aerodynamics*, Second edition, Cambridge University Press, 2006.