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Performance Evaluation of Simulated UAV Mobile Hotspot Modelling

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) have shown significant growth and utilization in several applications like agriculture, construction, and disaster management. Nevertheless, a considerable obstacle that persists is the restricted operational durability, principally attributed to limitations in battery capacity. This study focuses on the issue of enhancing energy efficiency in Unmanned Aerial Vehicles (UAVs) that serve as mobile hotspots. It explicitly targets situations when the UAVs need to operate for extended periods of time to provide coverage for events and emergencies. This project aims to create and verify a simulation model that can accurately forecast energy usage and improve battery efficiency in various operational scenarios. A full UAV model is created using MATLAB Simulink, which integrates characteristics such as flight dynamics, propulsion, hovering positions, battery conditions, and network load. The model is subjected to simulation using different trajectories and scenarios to assess its performance. The key findings suggest that the power used for flight propulsion, communication, and computation has a substantial impact on the operational duration of the UAV. The simulation findings demonstrate several approaches to enhance energy efficiency, prolonging the UAV's durability. This study offers useful insights for future research on energy-efficient UAV designs, highlighting the significance of employing realistic simulation models throughout the first phases of UAV development. The results contribute to advancing unmanned aerial vehicles (UAVs) that maintain consistent performance and safety during long missions, especially when used as mobile internet access points in crucial scenarios.

Keywords:

UAV; Hotspot Wi-Fi; Battery performance

1. Introduction

In the past few years, Unmanned Aerial Vehicle (UAV) have received spotlight attentions to research and development due to its huge application impacts and adaptation in diverse applications. The UAVS have drawn significant implementations into broad range of applications such in agricultural [1-3], constructions [4,5], power surveillance [6-9], post disasters [10], traffic

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monitoring [11] etc. Due to this massive grow of applications, research on UAVs have seen rapid convergence and diversities in the areas of its applications [12,13], designs [14,15], and performance evaluations [16,17]. Nowadays, research on incorporating the 5G technology with UAVs [18-20] has also been taken step of advancement, resulting in the of UAV enabled-wireless hotspot as a candidate to be considered in boosting resilience against faults, natural disasters, and unexpected traffic. In order to demonstrate their capabilities in diverse applications, most work in UAV research frequently undergo rigorous validation and flight-testing. Testing for performance validation, however, is not always a timely or economically feasible solution. The requirement for trustworthy and suitably realistic simulation programs has become an increasingly significant component for analysing the performance characteristics of UAVs in the early stages of their design. A simulation model of a small size UAV represented in different conditions and scenarios could build up a prediction model of energy consumption of a UAV to further improve the limitations of battery lifetime as UAV's application drawbacks [21].

Integrating 5G technology with UAVs offers a substantial possibility to improve their performance and dependability in delivering wireless hotspots in different situations. UAVs can be used as base stations in 5G networks, allowing a cost-efficient method for improving wireless connectivity and expand network coverage, particularly in regions with inadequate cellular infrastructure [22]. By deploying 5G technology, UAVs may operate as base stations, providing fast Internet access and long-range control. This makes them appropriate for purposes that require control beyond the visible horizon [23]. In addition, the utilization of UAVs in 5G networks can facilitate the establishment of energy-efficient opportunistic networks. This is achieved by delivering 5G base stations to locations that lack enough coverage, thereby enabling the provision of bandwidth-intensive applications such as Ultra High Definition (UHD) video streaming [24].

Furthermore, the integration of UAVs with 5G technology may enhance security by utilizing blockchain-enabled secure communication. This ensures mutual authentication in UAV networks that operate within 5G environments. Ensuring the security of communication is essential for preserving the accuracy and privacy of data sent between UAVs and base stations. In addition, the use of UAVs as User Equipment (UE) in 5G networks requires the development of specialized antennas, such as highly focused single-band arrays, to enable smooth and uninterrupted connectivity and communication inside the network [25].

The recently developed MATLAB Simulink simulation model for energy-efficient UAVs is an important advance in the field of UAV research and development. This simulation model allows researchers to analyse and improve the energy consumption patterns of UAVs in different operating environments, facilitating the development of more energy-efficient aerial platforms. Researchers can utilize MATLAB Simulink to develop intricate models that replicate the dynamics of UAV systems, encompassing propulsion systems, energy storage components, and control algorithms [26]. This simulation environment offers a significant tool for studying the influence of various design parameters on the energy efficiency of UAVs and for creating new approaches to improve their performance.

Although the MATLAB Simulink simulation model for energy-efficient UAVs offers some benefits, it is important for researchers to take into account certain limitations. An important constraint lies in the complicated nature of incorporating renewable energy integration and energy storage technologies into the simulation environment. Developing accurate representations for renewable energy sources and energy storage components can be difficult and may necessitate a comprehensive understanding of the fundamental physics and dynamics of the system [27]. Moreover, the processing resources needed for executing complicated simulations in MATLAB Simulink can be substantial, particularly when simulating extensive UAV systems that consist of numerous components and subsystems [28]. The computational load can have an impact on the performance of the simulation and may necessitate the use of optimization techniques to ensure optimal performance of the simulation.

This research work aims to model a UAV as a mobile hotspot and investigates the parameters that affect the endurance of the UAV, in expectations to foresee the energy efficiency of such system. The power consumed by flight propulsion, communication and computation limit the operation duration of UAV hotspot powered by rechargeable battery. This includes consideration of comprehensive system parameters such as flight dynamics, propulsion, hovering position, battery status and network load status to improve the overall energy efficiency on the go. In this work, an initial UAV model is developed in Simulink, that includes specific parameters for a UAV that could carry a mobile hotspot. Then, this model will be simulated based on its trajectory and its operation in specific scenarios/conditions with various system parameter range. The evaluation of the simulated model is hoped to support future research work on energy efficient UAV to provide temporary hotspot for mass events and to provide emergency coverage for disaster-stricken areas.

This study provides significant advancements in the realm of UAV research. Firstly, it entails creating a complete UAV model in MATLAB Simulink that combines several system factors, such as flight dynamics, propulsion, hovering locations, battery condition, and network load. This model accurately replicates the energy usage of the Unmanned Aerial Vehicle (UAV) in various operational situations and flight paths. Furthermore, the study offers useful insights into the aspects that have the greatest impact on energy consumption by simulating the functioning of the UAV under various scenarios. This includes thoroughly investigating the power needed by flight propulsion, communication, and computing.

2. Methodology

One of the most important stages in planning and creating a drone is modelling an unmanned aerial vehicle (UAV). UAV modelling is constructing a mathematical model of the physical behaviour and dynamics of the drone. The performance, behaviour, and responsiveness of the drone may be simulated using this model under various inputs and conditions.

Improving control and navigation, lowering the risk of accidents, and optimizing performance all depend on having an accurate and trustworthy UAV model. Designing autopilot algorithms, forecasting flight characteristics, and testing control schemes are just a few of the many uses for a UAV model.

A combination of theoretical research, empirical testing, and computer simulations are frequently used to model a UAV. When creating the model, consideration is given to the physical characteristics of the UAV, such as mass, inertia, aerodynamics, and propulsion. The model might additionally consider variables related to the drone's environment, such as wind, temperature, and altitude.

State-space models, linear and nonlinear models, and system identification approaches are just a few of the modelling methods and tools that can be applied. The complexity of the UAV, the goal of the model, and the information and resources at hand all play a role in choosing the modelling approach.

UAV modelling, in general, is a crucial step in the design and development of a drone since it enables engineers to anticipate and optimize the drone's performance and behaviour in a safe and effective way. Figure 1 shows the step involved in designing the UAV.

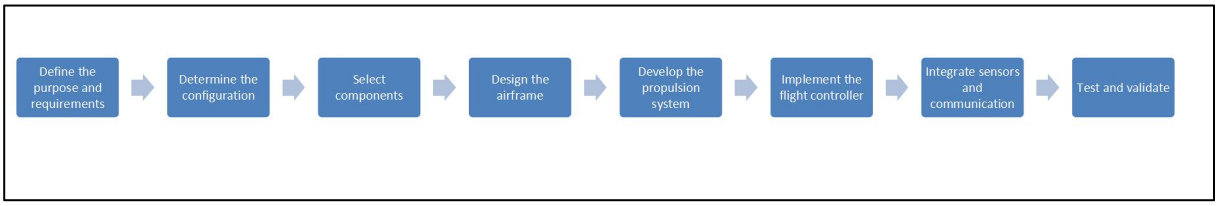

Fig. 1. Steps involved in designing a UAV

2.1 UAV Purpose and Requirements

In this project, a UAV will be used as a mobile Wi-Fi hotspot to connect places that are hard to reach or hard to get to the internet. This can be especially helpful in emergencies or during short-term events where a regular internet connection might not be available or work well. Table 1 tabulated the size of the hotspot used in this project.

Table 1
Hotspot Parameters

Parameters	Value
Mass (kg)	1.5
Weight (m)	0.14
Length (m)	0.14
Height (m)	0.14

2.2 UAV Propulsion System

The propulsion system is an integral part of a UAV because it generates the thrust necessary to lift and propel the drone forward. The propulsion system for this endeavour consists of four electric motors, four propellers, and a battery as the power source. The motors generate rotational force, which is then transmitted to the propellers, which generate a lifting force and forward propulsion. The design and configuration of the propulsion system are determined by variables such as the drone's mass and size, the intended flight duration, velocity, and altitude. The choice of the propulsion system and its components is crucial for determining the UAV's overall performance, including its top speed, range, and endurance. As UAV technology continues to advance, more efficient and advanced propulsion systems are developed and implemented. Parameters for the UAVs utilized in this project are listed in Table 2.

Table 2
UAV Parameters

Parameters	Value
Mass of UAV (kg)	1.276
Battery capacity (A.h)	7.6*3
Wind speed	12 m/s

Table 3 and 4 tabulated the propeller and motor parameters used in this project.

Table 3
Propeller Parameters

Parameters	Value
Diameter (m)	0.254
KTrust	0.1072
KDrag	0.001

Table 4
Motor Parameters

Parameters	Value
Maximum Torque (Nm)	0.8
Maximum Power (w)	160
Efficiency (%)	83.33
Speed (rpm)	5000
Rotor damping (rad/s)	1 x 10^{-7}

2.2 Test and Validate

In this project, the UAV was tested and verified using several procedures to make sure it complies with the necessary requirements and operates as intended.

2.2.1 Flight testing

The drone was tested in a controlled environment. The UAV's performance, stability, and control were assessed during flight testing while operating at a variety of speeds, altitudes, and manoeuvres. In this project, the trajectory of the drone was set as shown in Figure 2.

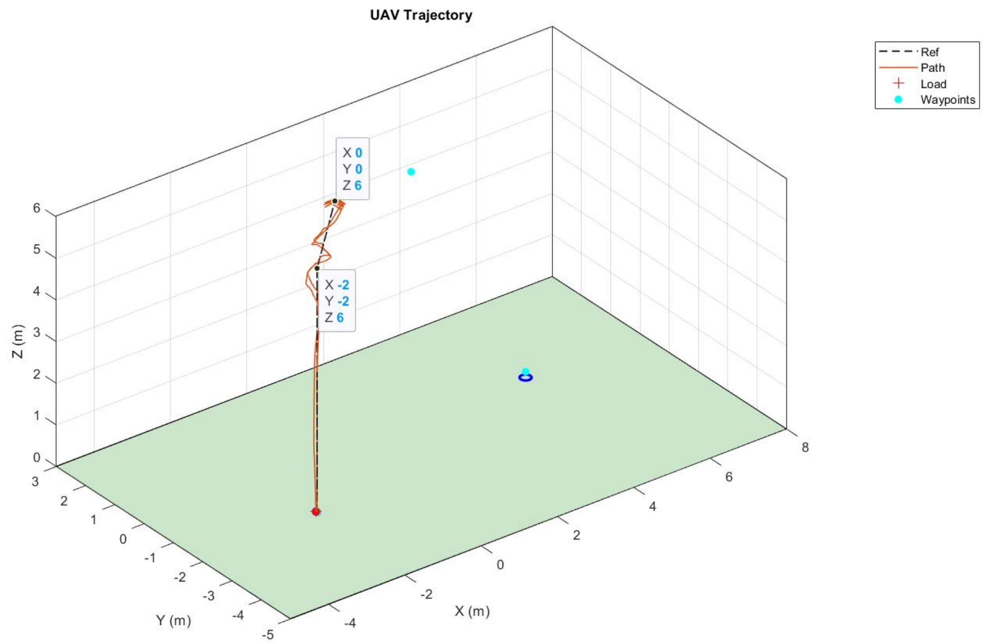

Fig. 2. UAV trajectory

About 140 seconds are needed for this UAV trip. From the coordinates (-2, -2, 0.4), the UAV has climbed vertically to position (-2, -2, 6). Traveling from point A to B takes 29 seconds before making a 180-degree turn (0,0,6). The UAV hovers for 60 seconds at location (0,0,6) before returning to the starting coordinate along its previous route.

2.2.2 Battery performance

A series of tests and measurements were done on a UAV's battery to make sure that it meets the needed specifications and works as expected. The battery voltage, charging rate, and power dissipated were observed during the drone operation.

3. Results

3.1 UAV Positions

Figure 3 depict the position of the UAV at different points along the x, y, and z axes as time progresses. Each graph illustrates the location of the UAV, with the dotted line representing the reference position and the red line indicating the actual position controlled by the PID controller.

The Position x displays the UAV's spatial coordinates along the x-axis as a function of time. From the beginning, the UAV is positioned around 1 m below the reference point. At around the 20 s point, it tries to attain the reference location, fluctuating around a distance of 1.5 m. Although the PID controller successfully brings the UAV to the intended location, it demonstrates instability or overshooting caused by oscillations. After around 100 s, the reference location falls back to approximately -1 m, and the UAV responds to this shift by demonstrating oscillations once again. This suggests that while the PID controller is successful in getting the UAV close to the intended location, it still encounters difficulties in keeping a steady position without oscillations.

The Position y has a comparable pattern to the x-axis. The UAV starts its movement from a distance of -2 m and, after approximately 20 s, tries to reach the target point of around 2 m. The current location of the system meets the desired reference point, but it shows significant oscillations, which suggest that the system is overshooting and the PID controller requires frequent corrections. After around 100 s, the reference location reverts to approximately -2 m, and the UAV replicates this change with comparable oscillating behaviour. This implies that although the PID controller is successful in navigating the UAV to the intended location, it has difficulties in maintaining stability, resulting in oscillations around the reference point.

Conversely, the Position z exhibits distinct dynamics. The initial position is set at 0 and gradually raises to around 5 m at the 20 s mark. It remains at this level until around 100 s before returning to 0. The current position closely tracks the reference position with minimal oscillations, suggesting that the PID controller effectively maintains stability and precision in controlling the z-axis. This implies that the PID settings for the z-axis are more finely adjusted or there is vertical motion in comparison to horizontal motion.

In general, the PID controller efficiently controls the UAV's locations along the x, y, and z axes, ensuring that the actual positions closely match the desired reference positions. Nevertheless, there are discernible fluctuations in both the x and y coordinates, suggesting the presence of instability or overshooting. This is a typical occurrence when using PID controllers to regulate dynamic systems. The z position control exhibits enhanced stability with low oscillations, indicating improved tuning of the PID parameters for vertical movement or less external disturbances in the z-direction. To enhance stability and minimize oscillations, it may be essential to fine-tune the settings of the PID controller or adopt more sophisticated control techniques, particularly for the x and y axes. and y axes.

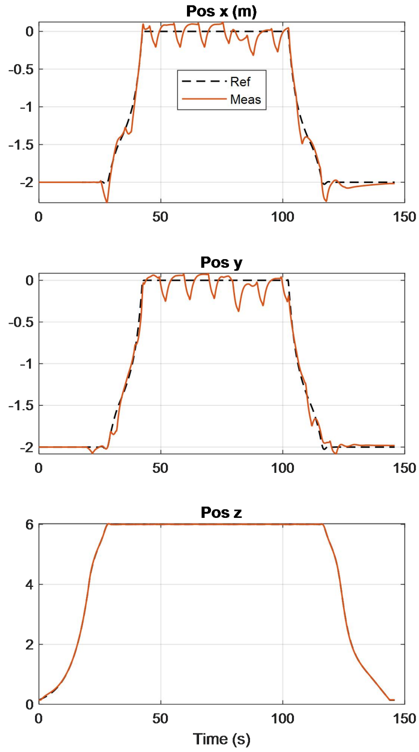

Fig. 3. UAV Position in x, y and z axes

3.2 UAV Velocity

Figure 4 depicts the velocity of the UAV along the x, y, and z axes as a function of time. Each graph displays the velocity of the UAV. A dotted line represents the reference velocity, while a red line shows the actual velocity regulated by the PID controller.

The Velocity x represents the speed at which the UAV moves in the x-direction. The current velocity displays periodic fluctuations around the reference velocity, especially during the initial 100 seconds. The oscillations indicate that the UAV is consistently modifying its speed to match the reference velocity. After reaching the 100-second mark, the oscillations decrease, suggesting that the unmanned aerial vehicle (UAV) achieves a more stable velocity that is closer to the desired reference value. This behaviour indicates that there may be challenges in keeping a consistent speed, which might be caused by excessively reactive PID settings or external disruptions.

Similarly, the y-component of velocity exhibits oscillating behaviour around the reference velocity. The oscillations persist consistently throughout the whole length, showing that the UAV is actively adapting its speed to accurately follow the reference. At around the 20-second point, there is a notable alteration followed by ongoing oscillations, indicating consistent dynamic adjustments. The predictable oscillation pattern indicates that the PID controller is performing frequently modifications, perhaps in reaction to external stimuli or inherent system dynamics.

The Velocity z has distinct characteristics in contrast to the x and y axis. At first, there is a sudden increase in velocity, peaking at around 0.4 m/s, and then quickly returning to zero. The reference velocity remains constant at zero throughout, whereas the real velocity exhibits oscillations around these zero references. Remarkably, at about the 100-second point, there is a substantial divergence in which the velocity decreases to a value below -0.2 m/s before returning to zero. This implies that the UAV encountered a considerable disruption or necessitated a large modification during this timeframe. The initial surge and subsequent divergence indicate instances of instability or external influence on the UAV's vertical velocity.

The PID controller's efforts to regulate the UAV's velocities along all three axes demonstrate a recurring pattern of oscillations around the desired velocities. The regular fluctuations in the x and y velocities suggest that the UAV regularly modifies its speed to align with the reference, maybe as a result of too-sensitive PID settings or external disturbances. The vertical velocity of the UAV, which exhibits an initial sudden increase and noticeable deviation at around 100 seconds, indicates instances of instability or external factors affecting its speed in the upward or downward direction. The consistent oscillations observed in all three plots indicate that more tweaking of the PID controller may be necessary to obtain more fluid velocity control. Minimizing these fluctuations can improve the stability and overall efficiency of the UAV. In addition, the utilization of tactics like as feed-forward control, advanced control algorithms, or the application of filters to external disturbances might enhance velocity control, resulting in more steady and precise motions of the UAV.

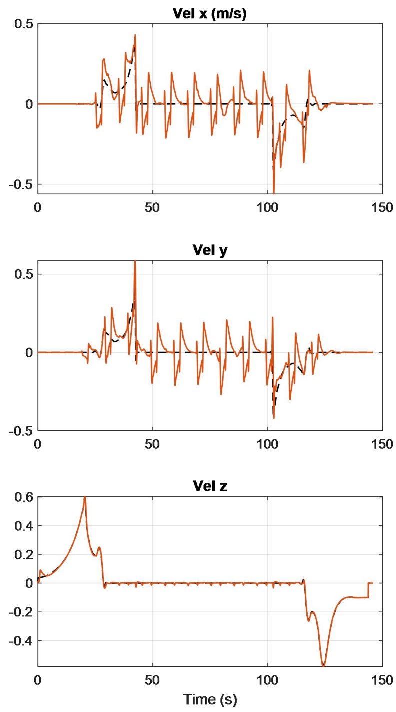

Fig. 4. UAV Velocity

3.3 UAV Movements

Figure 5 exhibits the changes in the roll, pitch, and yaw of the UAV over time. It specifically highlights a period of wind disturbance that occurred between 29 and 115 s. Each graph displays the orientation of the UAV. The dotted line represents the reference angle, while the red line represents the actual angle regulated by the PID controller.

The Roll (deg) displays the UAV's roll angle as it changes over a period. The current roll angle displays substantial fluctuations around the reference value during the whole time. During the period of wind disturbance, these oscillations intensify, suggesting that the UAV is having trouble in maintaining the correct roll angle. These findings indicate that the PID controller is actively attempting to adjust the roll angle, but its performance is significantly affected by the wind, resulting in amplified aberrations. The continuous oscillations indicate that the UAV's ability to control its roll is being affected by an external disturbance, leading to a less stable roll angle.

The Pitch (deg) exhibits a comparable pattern to the roll angle, characterized by significant oscillations about the reference angle. During the wind disturbance phase, the oscillations of the UAV grow more intense, demonstrating that the pitch of the UAV is greatly influenced by the external disturbance. The PID controller tries to rectify these aberrations, although the impact of the wind poses challenges in stabilizing the pitch angle, leading to persistent adjustments and oscillations. These observations indicate that the UAV's ability to regulate its pitch is also affected under windy circumstances, resulting in a less stable pitch angle and requiring the PID controller to make more corrective measures.

The Yaw (deg) has a distinct pattern in contrast to roll and pitch. The current yaw nearly tracks the reference until around the 20 s point. During the duration of wind disturbance, there are observable variations from the reference, particularly between 80 and 120 s, where the yaw angle exhibits substantial alterations. The wind has a greater impact on the yaw control of the UAV, resulting in higher deviations and slower adjustments. This suggests that the PID controller is less efficient in preserving the target yaw angle when there are wind disturbances. The significant variations in the yaw angle indicate that the UAV's ability to regulate its yaw is especially susceptible to external disturbances.

The PID controller actively strives to regulate the roll, pitch, and yaw angles of the UAV by the reference values. Nevertheless, the turbulence caused by the wind throughout the period of 29 to 115 s has a substantial effect on all three rotational motions, resulting in amplified oscillations and deviations from the desired angles. The roll and pitch angles display persistent oscillations, suggesting that the UAV has difficulty maintaining stability in the presence of wind conditions. The PID controller continuously performs changes, but, the external disturbance surpasses its corrective efforts. The yaw angle exhibits more prominent fluctuations, indicating that the yaw control is less resilient to wind disturbances in comparison to roll and pitch. In general, the performance of the PID controller is greatly affected by the wind, suggesting that further tuning or the adoption of more sophisticated control techniques is necessary to enhance stability and resilience against external disturbances.

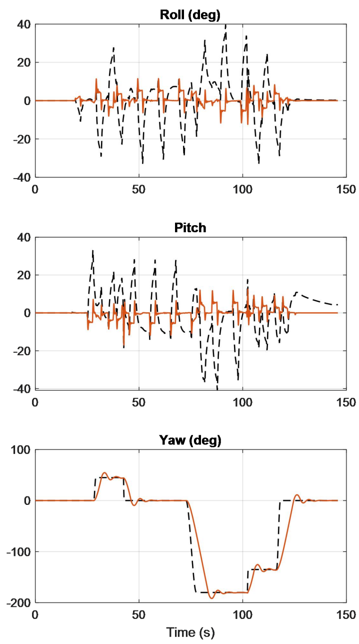

Fig. 5. UAV Roll, Pitch and Yaw

3.4 Battery Performance

Figure 6 depicts how the battery performed while the UAV was in motion. The Vbatt graph depicts the variation in the battery voltage of the UAV throughout different stages of motion. During the first vertical rise, the voltage begins at around 16.8V and gradually lowers to roughly 15.6V. The progressive decrease in power consumption suggests a substantial amount of energy being used by the UAV to take off and gain altitude. During the shift to horizontal movement, the voltage consistently decreases from 15.6 V to around 14.5 V, indicating the continuous energy needed for propelling the UAV sideways. During the hovering phase, the Unmanned Aerial Vehicle (UAV) maintains a stationary position in the air, and the rate of voltage drop decreases somewhat from 14.5 V to around 13.8 V. This implies that hovering requires less power than active movement. During the return phase, the voltage decreases from 13.8 V to around 12.5 V as the UAV returns to its initial location. In general, the steady decrease in voltage throughout all phases highlights the ongoing energy usage needed for different UAV motions.

The State of Charge (SOC) graph exhibits a gradual decline in battery capacity over time, reflecting the energy usage of the Unmanned Aerial Vehicle (UAV) throughout its operation. At the start of the upward climb, the state of charge (SOC) is 100%, gradually decreasing to around 90% after this stage. This refers to the amount of energy used to increase elevation. Throughout the horizontal movement phase, the State of Charge (SOC) steadily decreases from 90% to 75%, indicating significant energy use to sustain lateral flight. During the hovering phase, the state of charge (SOC) declines from 75% to 65%, indicating continuous energy use to maintain the unmanned aerial vehicle (UAV) in the air. During the return phase, the state of charge (SOC) decreases from 65% to 50%, indicating the amount of energy consumed to navigate back to the initial location. The consistent decrease in state of charge (SOC) over the different stages of movement emphasizes the anticipated trend of energy consumption by the unmanned aerial vehicle (UAV), where uninterrupted operation results in a gradual decrease in battery capacity.

The power dissipation graph offers a comprehensive understanding of the dynamic power consumption patterns shown by the UAV. Power dissipation during the vertical rise varies from 150 W to 200 W, occasionally reaching spikes close to 190 W. These surges are most likely a result of the greater amount of energy required to counteract the effects of gravity. During the horizontal movement phase, power dissipation varies between 100 W and 200 W, with periodic spikes reaching around 190 W. These variations indicate the need for changes in velocity or trajectory, resulting in a temporary increase in power requirements. During the hovering phase, the amount of power dissipated varies between 90 W and 160 W, often experiencing sudden increases up to around 150 W. The oscillations seen during this period suggest that the unmanned aerial vehicle (UAV) consistently makes minor modifications to sustain its location, resulting in fluctuations in power usage. During the return phase, the power dissipation is similar to that of the horizontal movement phase, ranging from 100 W to 200 W, with occasional spikes reaching up to 190 W. This pattern demonstrates that the UAV consistently expends energy in order to return to its initial location, with intermittent surges in power consumption resulting from alterations in movement or external influences.

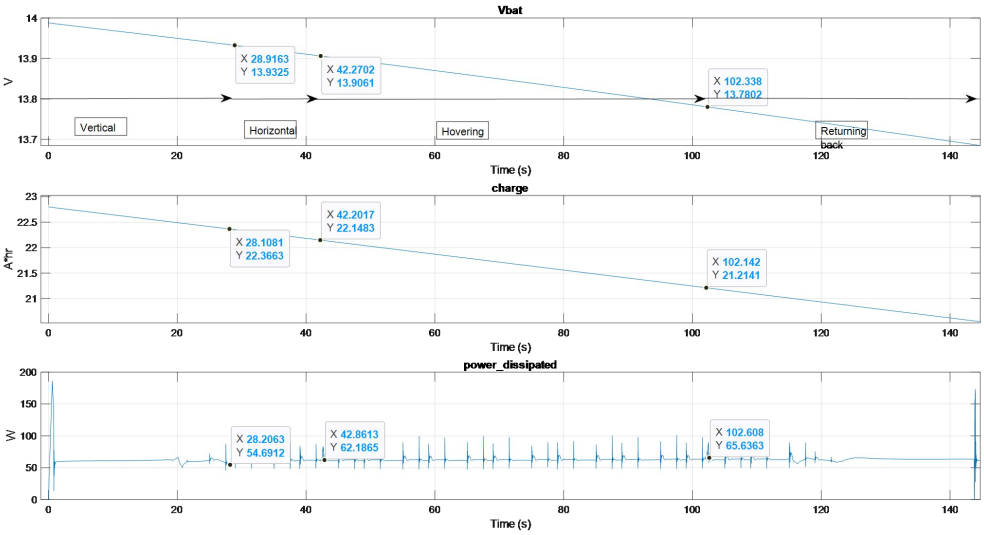

Fig. 6. Parameter for battery performance

4. Conclusions

In conclusion, the results of the flight-testing show that the UAV works effectively and complies with the necessary requirements. The UAV was able to accomplish the necessary manoeuvres, including take-off, landing, and hovering, during the flight testing, which demonstrated that it could maintain stable flight at a variety of altitudes, speeds, and weather conditions. The data analysis demonstrated that the UAV could achieve the necessary flight range and duration, as well as transmit the necessary data and video. The UAV's navigation and control systems were discovered to be accurate and responsive, allowing for exact control of the UAV while in flight. Additionally, the UAV was determined to be secure and dependable, with no major problems or malfunctions noted during the testing. In addition, the results of the tests and measurements show that the UAV's battery performance satisfies the necessary requirements and works as anticipated. The battery's ability to store and provide the appropriate amount of energy was confirmed through capacity testing, and its ability to discharge energy at the required rate was confirmed through discharge rate testing. The battery can function within the necessary temperature range without experiencing any significant performance difficulties, according to the temperature testing. The battery has enough safety measures and can operate safely under various circumstances, according to the results of the safety testing. Overall, the battery's performance was successfully validated, and the battery can now be trusted to operate the UAV and the UAV can be considered appropriate for the purpose for which it was designed.

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