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Power Consumption Analysis of UAVs with Varying Payloads for Next Generation Wireless Networks

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) are emerging as an important component for enhancing the coverage and capacity of next generation wireless networks. However, the use of UAVs is challenging because of crucial power management. The power management becomes more sophisticated for rotary-wing UAVs, the most commonly used ones, which require more energy as payload and flight actions increase. The current study investigates the energy consumption of UAVs with varied payloads during hovering and moving operations. The effects of payloads such as cameras, sensors, GPS modules, communication systems, and flight controllers on UAV power consumption are investigated in this study. It is very much necessary to comprehend these energy dynamics for optimal UAV design and maximizing operational effectiveness. Key findings show how payload configuration and flying conditions affect energy requirements. Two regression-based empirical mathematical models for hovering and moving conditions representing the relationship between the power consumption of UAV and its weight with payloads are proposed. This rigorous analysis of power consumption of UAV provides valuable insights into optimizing UAV design and operation in next-generation wireless networks. The findings of the work, including the proposed mathematical models, are expected to help researchers and engineers develop more energy-efficient UAVs, resulting in extended flight periods and improved operational reliability.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), sometimes known as drones, have emerged as critical technologies in a variety of fields such as communication, surveillance, disaster management, and logistics. Their ability to work autonomously, navigate difficult terrain, and deliver cost-effective solutions for a variety of applications makes them important in today's technological environments (Jiang *et al*., 2021). With the emergence of next-generation wireless networks such as 6G, UAVs are being envisioned as a revolutionary instrument for improving communication coverage, maintaining seamless connectivity, and meeting the ever-increasing need for high-speed, low-latency networks (Zeng *et al*., 2016). These UAV-based aerial systems are anticipated to provide support for ultra-reliable low-latency communication (URLLC), massive machine type communication (mMTC), and enhanced mobile broadband (eMBB) services (Horsemanheimo *et al*., 2022). The use of UAV in wireless networks tends to make a dramatic impact in this field. The importance of UAVs in wireless communication has changed dramatically over the previous decade. In fact, integrating UAVs as communication equipment represents a paradigm shift in 6G wireless networks. Traditional communication networks sometimes fail to provide coverage in distant, disaster-prone, or densely populated urban regions. UAVs, which serve as aerial base stations or relays, can bypass these constraints by providing dynamic and adaptable communication platforms, as suggested by (Huang *et al*., 2020) and (Na *et al*., 2020). UAVs' flexibility allows them to address major difficulties like line-of-sight communication, interference mitigation, and network densification, all of which are required for the successful deployment of 6G networks (Huang *et al*., 2020). Another promising use of UAV can be as an aerial base station (Ahmed *et al*., 2020). UAVs can be deployed for remote sensing applications (Bhardwaj *et al*., 2016). However, despite their enormous advantages, significant problems remain in integrating UAVs into next-generation networks. One of the most significant challenges is energy efficiency, which has a direct impact on operating reliability, coverage area, and flight endurance (Chowdhury *et al*., 2020).

Rotary-wing UAVs, such as quadcopters and hexacopters, are extremely useful since they can take advantage of VTOL (vertical take-off and landing) capabilities. Such properties make them appropriate for applications requiring positioning in place, precision maneuvering, or deployment in very limited spaces (Zeng *et al*., 2019). However, these UAVs consume more power than their fixed-wing equivalents, owing to the constant energy demand required to oppose gravity and sustain lift (Gong *et al*., 2023). The addition of payloads such as cameras, sensors, communication modules, and batteries increases energy consumption, reducing the operational endurance (Kottat *et al*., 2023). This involves a thorough examination of the elements that influence power consumption, as well as strategies for optimizing energy usage, particularly under various payload combinations and flight conditions.

Payloads have an important role in defining UAV capability and power requirements. The variety of payloads used in UAV operations reflects the wide range of their applications. Cameras and sensors are essential for surveillance, mapping, and environmental monitoring (Almalki *et al*., 2020). GPS and communication modules provide real-time navigation and data transmission, which is essential for maintaining network connectivity and dependability (Jin *et al*., 2022). Flight controllers and other onboard electronics are required to ensure UAV stability and control, which adds to the total weight and energy needs. The interaction of payload weight, power consumption, and flight dynamics highlights the necessity for a thorough investigation to optimize UAV performance, particularly in scenarios requiring lengthy flight durations and large payload capacity (Mozaffari *et al*. 2016). Apart from energy, meeting sustainable and ecologically friendly solutions concerning both network and technological aspects is simultaneously fostering the growing need for UAV wireless communication. How critical these become factors in enabling a trend like this – that is, solar or hybrid UAVs remain under intensive investigation by authors of related works: Lee *et al*. (2017) and Sun *et al*. (2019). On the other hand, solar-powered UAVs become practical options for extending flight times by exploiting such technologies, and due regard must be given to efficiency in gathering energy and payload limits. According to Huang *et al*. (2020), understanding the complex balance between energy generation, storage, and consumption shall be the key towards developing UAV systems for next-generation wireless networks. Some other challenges related to it were also pointed out by Kathole *et al*. (2022) and Ye *et al*. (2020).

Several studies have acknowledged the critical impact of payload and energy consumption on the operational performance of UAVs. However, the works offered limited insights into detailed power consumption modelling under varying payload conditions. (Chowdhury *et al*., 2020) emphasized the importance of energy efficiency in determining UAV coverage, endurance, and reliability. While this study successfully identified energy consumption as a constraint in UAV-enabled communication networks, it did not provide a deep analysis of how various payload configurations affect power consumption. (Huang *et al*., 2020) emphasized the energy constraints of UAVs as a major technical impediment and concentrated on the integration of UAVs into next-generation wireless networks, particularly 6G. Although their work emphasized the significance of establishing a balance between payload, communication needs, and power, it lacked a thorough examination of the patterns of power consumption related to payloads under various operating situations. Due to the continual energy needed to provide lift, rotary-wing UAVs are inherently energy inefficient, as addressed by (Gong *et al*., 2023). The importance of power consumption characteristics in hovering and maneuvering activities was reaffirmed by this investigation. However, their works did not include any empirical or simulation-based evaluation of various payload scenarios. Kottat *et al*. (2023) explicitly investigated the impact of payload augmentation, such as the addition of sensors and communication modules, on UAV energy consumption and flying time. Although it acknowledged that energy requirements increase with higher payloads, the study lacked quantitative modelling or systematic comparisons of power consumption with various payload settings.

In this paper, an extensive analysis of the power consumption of UAVs has been presented with various payload configurations. The significant contributions of our work are noted below.

i. This analysis examines the power consumption of rotary-wing UAVs with different payload configurations, with a focus on future wireless networks.

ii. A MATLAB simulation model is used to analyze the power consumption of UAVs with various payloads.

iii. Unlike earlier studies that analyze the effect of payload on UAV energy consumption only quantitatively, this paper provides two empirically validated regression models for power consumption in both hovering and movement modes, based on realistic payload configurations and actual component weights.

Such findings will help engineers and researchers to develop energy-efficient UAV systems so that these fulfil the exacting demands of next-generation wireless networks.

2. UNMANNED AERIAL VEHICLE (UAV)

Unmanned Aerial Vehicles (UAVs) are remotely piloted or autonomous aircraft for different purposes. Although originally developed for military operations, UAVs nowadays are in wide use for civilian applications like surveillance, disaster management, environmental monitoring, and next-generation wireless networks (Zeng *et al*., 2016). Without an onboard human operator, UAVs are able to accomplish tasks in hazardous or unreachable areas, which enhances safety and efficiency. UAVs have evolved from specialist uses to mainstream technologies, altering industries including logistics, telecommunications, and disaster management. Their ability to adapt to various operational requirements is an important component of their expanding utility. For example, in next-generation wireless networks, UAVs act as aerial base stations,

ensuring continuous connectivity in locations where terrestrial networks are unavailable or insufficient. UAVs can be used for many works, such as aerial base stations and IoT applications. It can be used in mobile crowd sensing, as suggested by (Zhou *et al*., 2018). In crisis events, they provide immediate situational awareness, aiding rescue teams in traversing difficult terrain and locating victims.
The critical factors of energy consumption in UAV operations are linked to the payload weight, flight dynamics, and environmental conditions. Rotary-wing UAVs, especially, need much power for hovering and vertical take-off. Further work in the area is aimed at energy harvesting and lightweight material advancement that might improve flight endurance.

2.1 Types of UAV

UAVs can be broadly divided into two categories based on their structure and working principle. These are:

A) Rotary-wing UAV: A rotary-wing UAV, a drone, or a helicopter type of UAV has lifting and propulsion created by rotating wings. These can be very nimble, taking off and landing vertically, enabling this class to work in minimal areas. Since their rotor system creates their lift force, they also are capable of hovering, omnidirectional flight, and precise translation. Rotary-wing UAVs are widely used in surveillance, aerial photography, search and rescue operations, and environmental monitoring (Zeng *et al*., 2019). They can be equipped with various sensors for performing various specialized tasks. They vary in size, from small hobbyist models to large industrial systems, and offer flexibility for both civilian and military operations. These types are the commonly used UAVs. However, they can be used for various state-of-the-art applications, like aerial base stations and IoT-based functions. In this study, the analysis is carried out with rotary-wing UAVs.

B) Fixed -wing UAV: A fixed-wing UAV is similar to a standard airplane, providing lift through its fixed wings and can't hover or stop in a position like its rotor-wing family since lift generation doesn't occur through stillness and needs forward movement. They come designed for more fuel-efficient long over the distance distances and higher airspeeds, making them ideal candidates for mapping, surveying, environmental monitoring missions and military scout work. The flight endurance and range of fixed-wing UAVs are generally longer than that of rotary-wing drones, and therefore they are more appropriate for area coverage at a large scale (Templin *et al*., 2017). A fixed-wing UAV consists of a fuselage, wings, and a propulsion system that normally includes a small internal combustion or electric engine. Fixed-wing UAVs can take off from runways or catapult systems and land autonomously on prepared surfaces or with parachutes. Fixed-wing UAVs are normally used in applications that require long flight times and large coverage areas due to their effective aerodynamics.

3. POWER CONSUMPTION IN UAV

Power consumption in UAVs is a significant element that can influence flying performance, endurance, and operating capabilities. Most UAVs are powered by batteries, fuel cells, or hybrid power systems, which combine multiple sources of energy. A UAV's power consumption is determined by a variety of factors, including its design, weight, flight circumstances, and the activities it performs. Understanding power consumption is critical for increasing flight duration, improving energy efficiency, and achieving mission objectives. It has been already stated that UAVs can play a significant role in wireless communication. However, various applications in this field need to satisfy various requirements and thus require a considerable amount of power (Solyman *et al*., 2021). The main power consumption in rotary-wing UAVs is for the rotation of the rotors and is also enhanced by the use of payloads to some extent. Temperature, altitude, and turbulence are some of the environmental elements that affect battery performance and UAV efficiency. To overcome these issues, UAV developers are looking into advanced solutions such as high-density batteries, solar-powered propulsion, and energy harvesting devices. Flying path optimization and adaptive energy allocation systems, sometimes powered by artificial intelligence, are being used to reduce waste and increase flying time. As UAVs play more intricate roles in industries such as telecommunications, agriculture, and emergency services, understanding their power consumption dynamics is critical to realizing their full potential.

3.1 Power Consumption Factors in UAV

A. Weight and Payload: The UAV's overall weight, including its payload, has a big influence on how much power it uses (Kottat *et al*., 2023). UAVs can be of various sizes and weights. A list of different classes of UAV based on their weights is given in (Lykou *et al*., 2020). Especially when carrying extra gear like cameras, sensors, or communication systems, heavier UAVs need more energy to take off and stay in the air. In addition to increasing drag, larger payloads demand more power to overcome air resistance.

B. Flight Speed and Altitude: Flight speed and altitude determine the energy usage for UAVs. As the speed is increased, more aerodynamic drag is encountered. This results in higher power requirements. At a higher altitude, the energy expenditure is higher as the air becomes denser, leading to reduced lift. Most of the UAVs flying at a lower altitude operate with a greater efficiency of energy usage since there is denser air, making lift easier to sustain.

C. The Nature of Flight Duration and The Type of Mission: In general, power consumption is related to mission and flight duration; long-endurance flights, as it were, to be used in either surveillance or observing the environment sustainably keep UAVs flying, whereas short, intensive missions, such as finding and rescuing a target, may make use of bursts of high power and quick maneuvering.

D. Aerodynamics: It is very important in terms of power consumption; the more a UAV is designed to be aerodynamic, the less drag it produces, hence less use of energy to maintain flight. Besides, it is in the design of the wings, the fuselage, and rotor systems that together give the general efficiency of the UAV. More efficient UAVs aerodynamically will have longer flight times using the same amount of energy input.

If rotary-wing UAV is considered, the power consumption during hovering can be given by the equation (Dorling *et al.*, 2016),

$$P_{hover} = \frac{T^{\frac{3}{2}}}{\sqrt{2 \times \rho \times A_{rotor} \times n}} \quad (1)$$

where,
P_{hover} = Power required for hovering by the UAV
T = Thrust required to keep the UAV in air = Weight of the UAV in Newton
ρ = Air density
A_{rotor} = Area of the rotor of the UAV
n = No. of rotors
The UAV will also need to move when necessary. The power consumption during movement can be calculated by using the equation (Thibbotuwawa *et al.*, 2019),

$$P_{flight} = \frac{1}{2} \times C_D \times A_{rotor} \times \rho \times v^3 + \frac{W^2}{\rho \times b^2 \times v} \quad (2)$$

where,
P_{flight} = Power required during movement by the UAV
C_D = Drag coefficient
W = Weight of the UAV in Newton
ρ = Air density
A_{rotor} = Area of the rotor of the UAV
b = width of the UAV
v = velocity of the UAV

3.2 Payloads Used in UAV

UAV payloads are the equipment carried for special missions in addition to the flight components. These payloads consist of cameras, sensors, communication devices, and delivery systems. They enable UAVs to perform a variety of activities, including airborne photography, surveillance, environmental monitoring, and disaster response. Advanced payloads such as LiDAR and thermal imaging broaden UAV applications to include precision agriculture, infrastructure inspection, and search and rescue operations. The kind and weight of the payload have a considerable impact on the UAV's flight duration, power consumption, and range. Modern UAVs are designed to carry modular payloads, providing flexibility and adaptation across industries and mission needs. In this work, the use of the following five payloads is considered.

A. Camera: UAV cameras can collect photos and videos which can be used in applications including surveillance, mapping, and aerial photography. They range from basic RGB cameras to complex models such as thermal and multispectral cameras. The quality of the camera used is determined by the mission's requirements, with characteristics such as zoom, stabilization, and resolution adapted to individual applications. Lightweight cameras are commonly used in UAV applications to minimize payload weight. For instance, the Raspberry Pi Camera Module v2.1 weighs approximately 3g. However, more advanced cameras can weigh around 75g (Douklias *et al.*, 2022).

B. Sensor: Sensors in UAVs gather data for navigation, stability, and environmental awareness. Gyroscopes, accelerometers, barometers, and ultrasonic sensors are among the most common types. Light Detection and Ranging (LiDAR) and infrared sensors provide advanced applications such as obstacle detection, 3D mapping, and environmental monitoring. Different types of sensors are used for performing different types of work. (Sørensen *et al.*, 2017) provided the weights of various sensors that are used with UAVs ranging from 2 to 4 gm. A Teensy 3.1 development board, often used in sensor modules, weighs around 30g. Combining such a board to use various sensors can total around 60g.

C. GPS Module: GPS modules offer location data to UAVs, allowing for accurate navigation and flight path execution. They provide autonomous flight, waypoint tracking, and geofencing. This function is of great importance in wireless communications. Advanced GPS systems, such as RTK (Real-Time Kinematics), provide centimetre-level accuracy, which is essential for precision agriculture, surveying, and other jobs that need great positional accuracy. GPS modules designed for UAVs are typically lightweight. GPS modules can weigh from 20g to 30 g (Ukaegbu *et al.*, 2021).

D. Communication Module: Communication modules enable data flow between UAVs and ground control stations. Telemetry and command communication are carried out by technologies such as Wi-Fi, Bluetooth, and RF. Advanced modules enable long-distance connection and real-time video streaming, providing effective control and monitoring even in demanding conditions. Modern communication modules enable high data speeds and minimal latency by leveraging modern technologies such as 5G/6G transceivers, software-defined radios, and millimetre-wave communication. These modules, which account for a considerable portion of the UAV's total power consumption, must strike a balance between performance and energy economy. Optimizing their architecture is critical for long-term UAV operation and stable connectivity in next-generation networks. The weight of communication modules can vary greatly depending on their capabilities (Douklias *et al.*, 2022). Although the precise weight isn't stated, a total weight of about 200g can be considered for a complete communication setup when taking into account extra parts like antennae and housings.

E. Flight Controller: The flight controller is the UAV's brain, managing stability, navigation, and sensor integration. It processes input from sensors and user commands to control motors and actuators. Modern flight controllers support autonomous features like obstacle avoidance, GPS-based navigation, and real-time adjustments, ensuring efficient and safe UAV operation. Different lightweight flight controllers are suitable for use in a UAV system. Flight controllers typically weigh from 100g to 120g (Unmanned Systems Technology, 2024).

4. OVERVIEW OF THE SYSTEM

4.1 UAV System Description

In this work, a rotary-wing UAV is considered for carrying

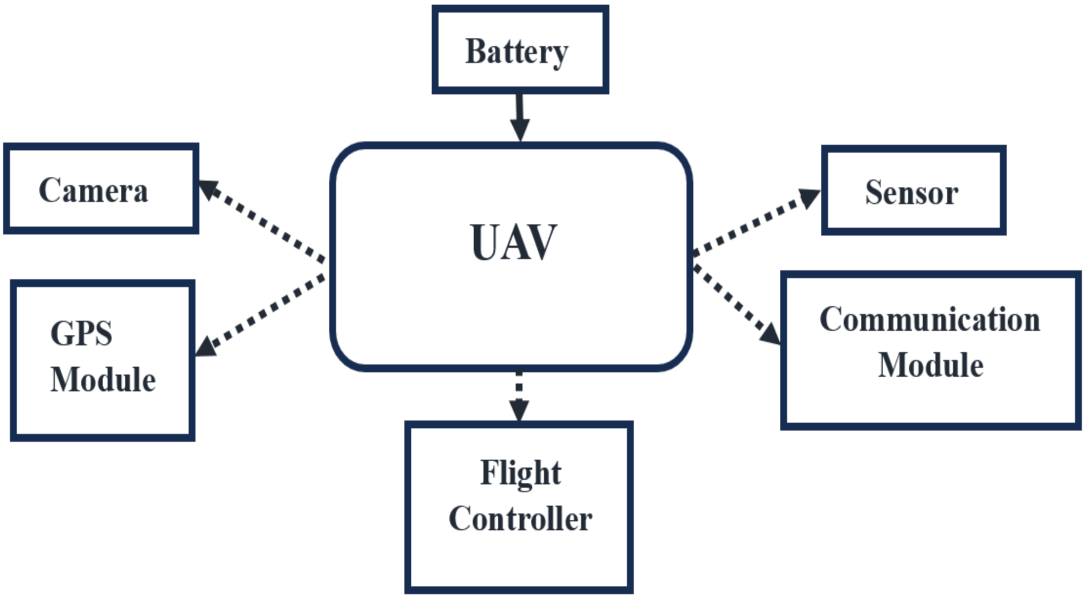

Figure 1: Block diagram of the UAV system

out the analysis. The UAV is equipped with some payloads necessary for performing specific tasks. A simple block diagram of the considered system is shown in Figure 1. The simulation and the power consumption analysis of the system are carried out using MATLAB. After that, an empirical model is suggested denoting the relationship between the power consumption of UAV and the payload weights.

4.2 Weights of Different Payloads

In this system, one rotary-wing UAV weighing 1.5 kg (with a battery) and five payloads with different weights are used. The used payloads are a camera, a sensor, a GPS module, a communication module and a flight controller. The weights of these payloads are listed in Table 1 according to (Douklias *et al*., 2022), (Sørensen *et al*., 2017) and (Ukaegbu *et al*., 2021).

Table 1
Weights of the components used in the model

Payload	Weight (g)
UAV (with battery)	1500
Camera	75
Sensor	60
GPS Module	25
Communication module	200
Flight controller	110

5. METHODOLOGY OF WORK

In this paper, the power consumption analysis of UAV is performed in a systematic way. First, a UAV of weight 1.5 kg (with battery) and five different payloads shown in Table 1 are selected. Then simulation of the UAV system is done with different payload configurations. After obtaining the power consumption values from the simulation, a regression-based empirical model is developed to denote the relationship between power consumption and overall weight of UAV. The flow of work is shown in Figure 2.

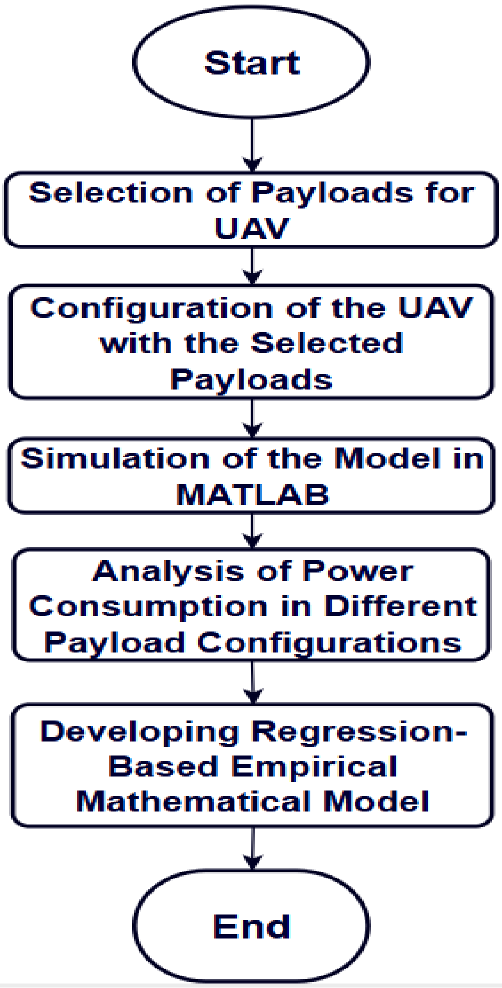

Figure 2: Flowchart representing the workflow

6. RESULTS AND DISCUSSIONS

6.1. Simulation Results of the System:

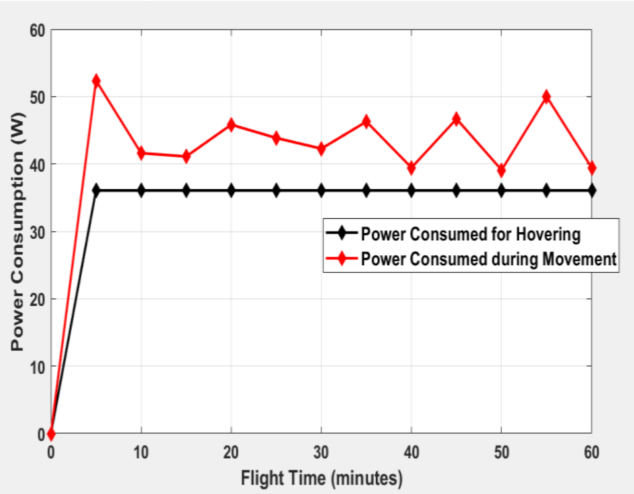

Figure 3: Power consumption of UAV without payloads

Figure 3 depicts power consumption in a UAV without payloads. It displays the consumed power without payloads in two scenarios: hovering and movement. Figure 1 shows that the power usage when hovering remains constant throughout the flight time. The UAV's constant power requirements for hovering are 36.06 W. If the UAV is only hovering, it will consume 36.06 W of power during its flight. However, power does not remain constant while moving. The drag constant is the parameter that causes it to vary in our considered system in moving state.

The drag constant varies according to the changing nature of the air and the UAV's movement. When no payload is employed, the UAV's power consumption during movement ranges between 39.10 W and 52.38 W. Figure 1 shows that the largest power consumption while movement occurs during a 5-minute flight time, which is 52.38 W. The power consumed during the 20-minute bout is 45.82 W. The minimum power consumption of 39.1 W occurs during a 50-minute trip. The graph shows that power consumption during movement is always greater than hovering power.

The UAV system used here is equipped with a 14.8 V, 5000 mAh battery. So, the battery has a capacity of 74 Wh or 4,440 watt-minutes. Figure 4 shows the state of the battery with the charge of the battery during both hovering and movement without payloads throughout its flight.

Figure 4 shows that after 60 minutes of hovering in one position, the energy left in the UAV's battery is 2276 watt-minutes (37.93 Wh). If the UAV moves during its flight, the battery will have 1800 watt-minutes, or 30 Wh, left after an hour. This graph verifies results of Figure 1 that power consumption during movement exceeds that during hovering. During hovering, the battery charge is 3358 watt-minutes after 30 minutes, decreasing to 2276 watt-minutes after 60 minutes. The battery charge is 3105 watt-minutes after 30 minutes of movement and reduces to 1800 watt-minutes at the end of an hour of flight.

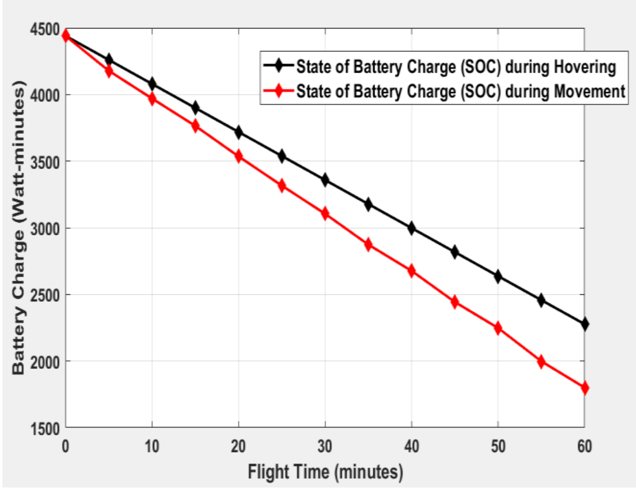

Figure 4: State of battery charge (SOC) without using payloads

Now, the analysis of power consumption is carried out by using payloads. The analysis is carried out for hovering and moving conditions separately. The analysis is done for the hovering condition first.

In Figure 5, the consumption of power with and without payloads during hovering is illustrated. It is seen that the power consumption is fixed throughout the flight of the UAV. As seen from Figure 1, the power consumption remains fixed during hovering. The main focus of this graph is to provide a picture of how power consumption increases when payloads are used. When the five payloads, with a total weight of 470 g, are used, the power consumption gets increased. The consumption of power gets increased to 54.28 W, which is 36.06 W when no payload is used. So, an increase in power consumption by 18.22 W can be seen when an additional weight of 470 g is used with the UAV.

Now, an analysis of the state of battery charge is provided for this case. Figure 6 shows the remaining battery charge in the UAV at different times during 1 hour of hovering in the air. It shows a gradual decrease in battery power.

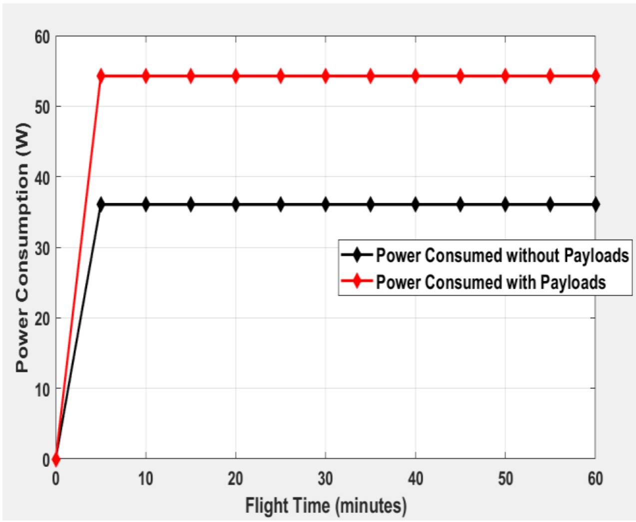

Figure 5: Power consumption of UAV during hovering

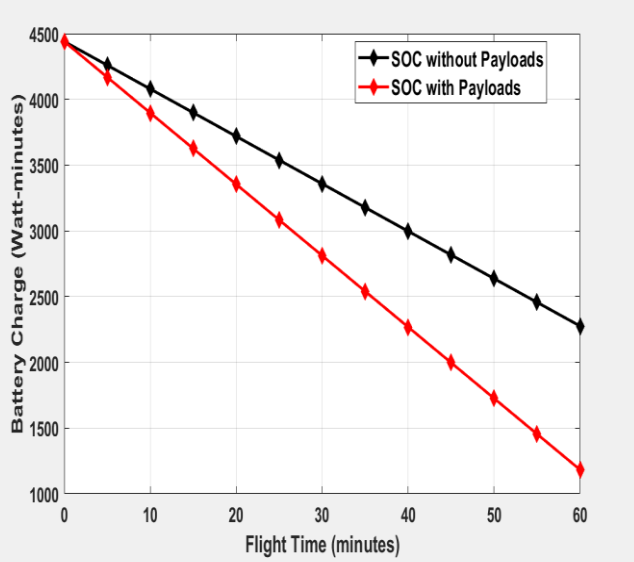

Figure 6: State of battery charge (SOC) during hovering

Figure 6 shows that the charge remaining in the UAV's battery after hovering for 60 minutes is 2276 watt-minutes (37.93 Wh). The battery power after 20 minutes of flying is 3719 watt-minutes. After 20 minutes, or 40 minutes of flight, the battery capacity drops to 3538 watt-minutes. After another 20 minutes, or one hour of flight, the power lowers to 2276 watt-minutes (37.93 Wh). When payloads are employed, the battery charge after an hour of hovering is 1183 watt-minutes (19.72 Wh). After 20 minutes of flight, the battery charge level is 3354 watt-minutes. After 40 minutes of flight, the battery power reaches 2269 watt-minutes. When it flies for more than 20 minutes, it drops again, eventually reaching 1183 watt-minutes (or 19.72 Wh).

When payloads are utilized, the remaining battery charge after an hour of hovering is lower than when no payload is used. It is less because more power is required to operate the UAV while carrying payloads. As payloads are employed with UAVs, their weight increases, and they require more thrust to stay in the air by overcoming gravitational force.

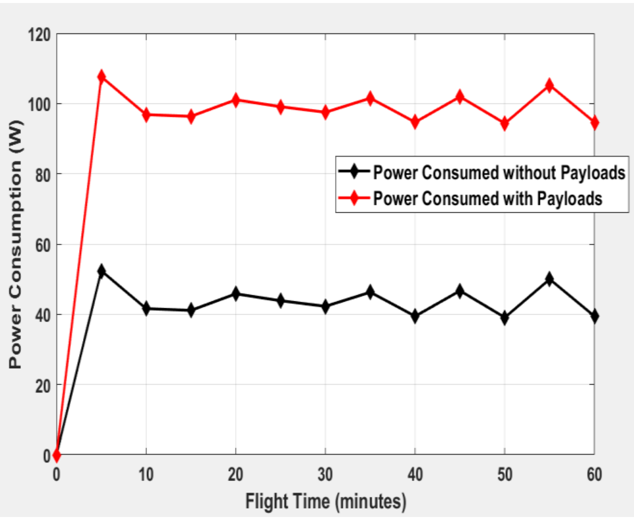

Figure 7: Power consumption of UAV in moving condition

In Figure 7, the power consumed by the UAV during movement is illustrated. When the UAV moves without using any payload, the maximum power consumption is 52.38 W, while it increases to 107.6 W when the mentioned payloads are used. So, a significant increase in power consumption is seen when payloads are used. The power consumption increases by 55.22 W. The increase is so high, as the power consumption in moving condition depends on the square of the total weight of the UAV. That means, while moving, payloads play a vital impact on power consumption. So, the weight of the payload needs to be carefully determined by looking at the energy constraints.

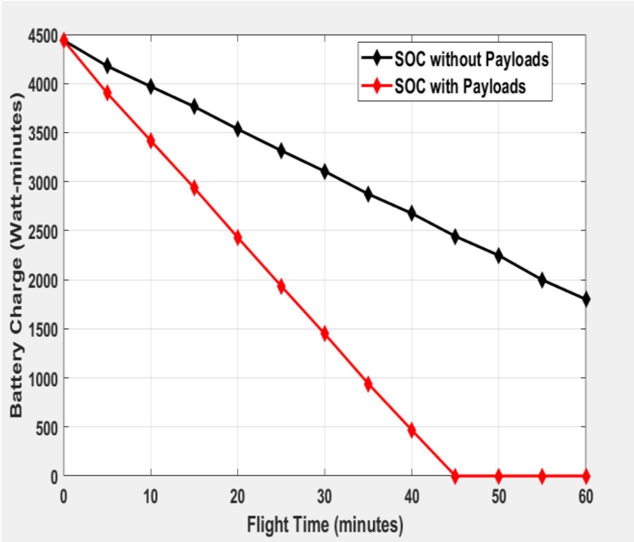

Figure 8: State of battery charge (SOC) in moving condition

In Figure 8, the state of battery charge is shown for moving condition. Without payload, after completing a flight of 1 hour, the remaining battery capacity is 1800 watt-minutes or 30 Wh. But when the payloads are used, the battery capacity is 1448 watt-minutes or 24.13 Wh after 30 minutes of flight. So, in this case, a power of 49.87 W has been consumed in 30 minutes. With the remaining power in the battery, it cannot continue to fly for 1 hour. The battery power becomes 0 after 45 minutes of flying. That means, the weight of payloads significantly affects the flight time of UAV. So, while configuring a UAV, the payload weights must be carefully fixed by considering the flight requirements and the availability of power.

Figure 9 illustrates how the weight of the UAV affects its power usage. The payload weight has already been shown to have a substantial impact on the power consumption of UAVs. So, it is very vital to understand the link between weight and power consumption of UAVs.

In this study, the UAV's body weight with battery is 1.5 kg. At a weight of 1.5 kg, the power consumption for hovering is 36.06 W, whereas it is 72.02 when moving. When the UAV's total weight with camera reaches 1.575 kg, the power consumption for hovering and movement is 38.80 W and 77.05 W, respectively. When the sensor module is added with this, the power consumption becomes 41.04 W and 81.25 W, respectively, in hovering and moving conditions.

When the UAV is equipped with a camera, sensor, GPS module, and communication module, the overall weight is 1.86 kg. The power consumption in this case is 49.8 W for hovering, and for movement, the power is 98.41 W. When all the payloads are used, the total weight of the UAV is 1.97 kg. In this case, the consumed power during hovering is 54.28 W, and it is 107.6 W for movement.

Thus, an increase in weight of UAV by 31.33% accounts for an increase in power consumption by 50.53% and 49.40% for hovering and movement respectively. This relationship between power consumption and weight of UAV is summarized in Table 2.

6.2. Regression-based Empirical Mathematical Model:

In this part of the work, regression analysis is employed to establish an empirical connection between the weight of the UAV (with various payloads) and the power it uses for movement and hovering. This model assists in forecasting power requirements for various payload configurations without requiring repeated experiments. The power consumption in both cases shows an apparent linear relation with the weight. However, as payloads increase, the power increase is not always constant. So, the analysis of these obtained data is performed with both linear and 2^{nd}-degree polynomial regression to develop the desired relation.

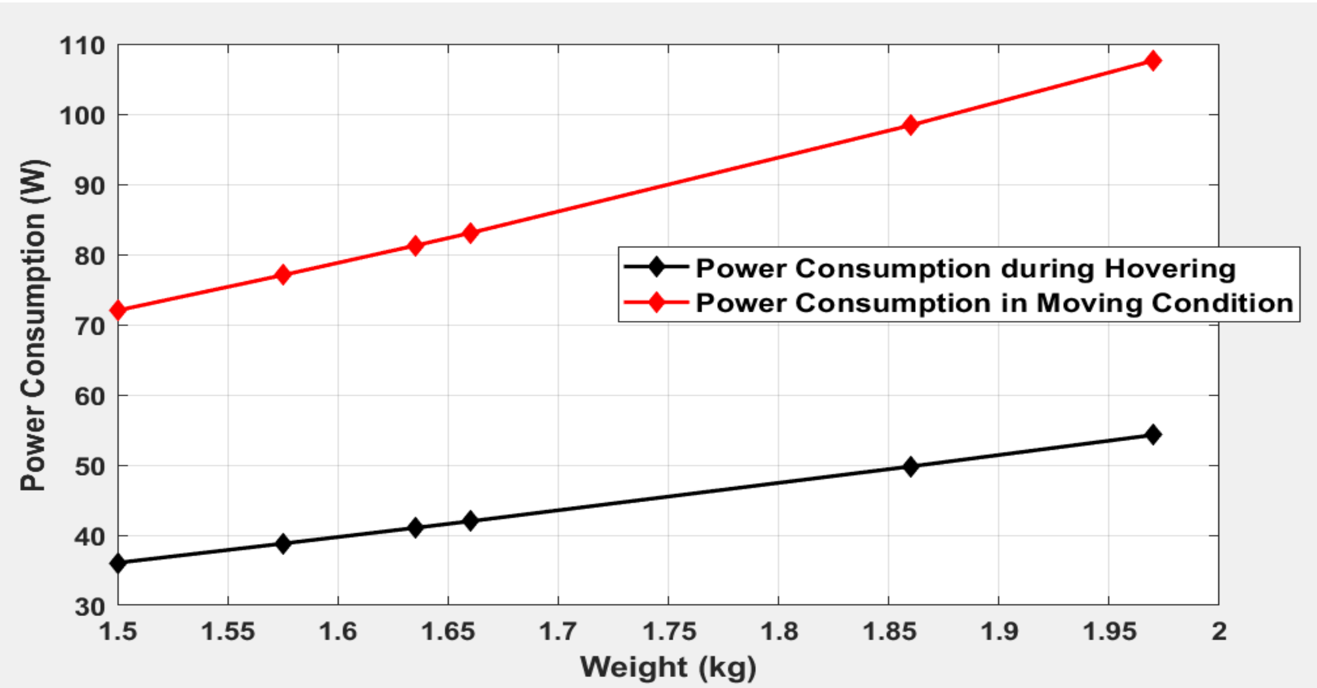

Figure 9: Influence of payload weights on power consumption of UAV

Table 2
Influence of payload weights on power consumption of UAV

Component	Weight (kg)	Power Consumption for Hovering (W)	Power Consumption for Movement (W)
UAV	1.5	36.06	72.02
UAV + Camera	1.575	38.80	77.05
UAV + Camera + Sensor	1.635	41.04	81.25
UAV + Camera + Sensor + GPS Module	1.66	41.98	83.05
UAV + Camera + Sensor + GPS Module + Communication Module	1.86	49.8	98.41
UAV + Camera + Sensor + GPS Module + Communication Module + Flight Controller	1.97	54.28	107.60

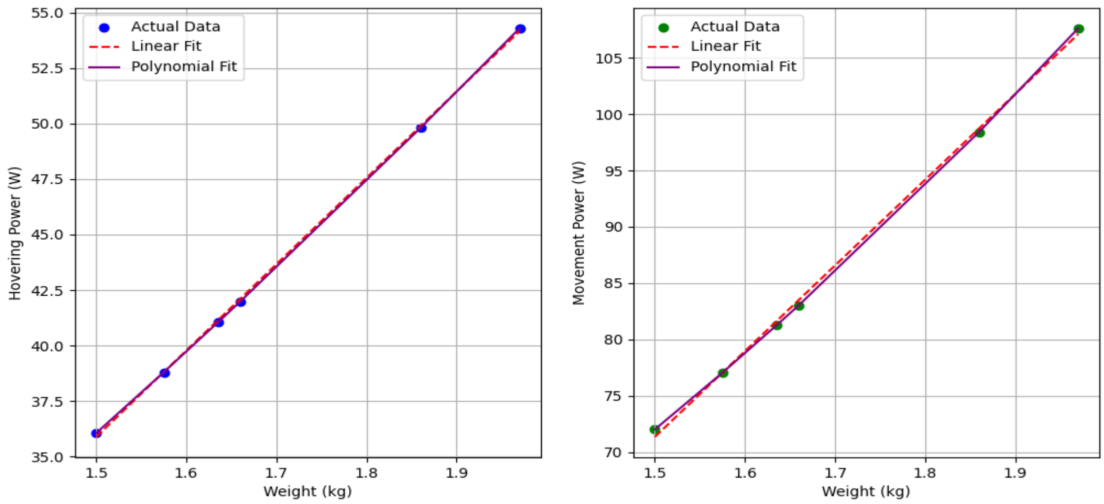

Figure 10: Regression analysis to develop an empirical relation between UAV power consumption and its overall weight

In case of linear regression, the models will be:

For hovering power,

$$P_{hover}(W) = a_{hover}W + b_{hover} \tag{3}$$

For movement power,

$$\boldsymbol{P_{move}(W) = a_{move}W + b_{move}} \tag{4}$$

where W is the overall weight of the UAV, a is the coefficient of W or slope, and b is the intercept

In case of 2nd degree polynomial regression, the models will be:

For hovering power,

$$P_{hover}(W) = \alpha_{hover}W^2 + \beta_{hover}W + \delta_{hover} \tag{5}$$

For movement power,

$$\boldsymbol{P_{move}(W) = \alpha_{move}W^2 + \beta_{move}W + \delta_{move}} \tag{6}$$

where α is the coefficient of W^2, β is the coefficient of W, and δ is the intercept.

Now, the linear and the 2nd degree polynomial regressions are implemented in Python using the data in Table 2. The results found are shown in Figure 10.

Using linear regression, the R^2 values are found to be 0.97 and 0.98 respectively. Although these are good results, better values are obtained with 2nd degree polynomial regression. The R^2 values are 1 in both cases, which represents a proper fit. So, the polynomial regression model is used to represent the desired empirical relationship. Using polynomial regression, the values of the coefficients are obtained as follows:

$\alpha_{hover} = 5.61, \beta_{hover} = 19.31, \delta_{hover} = -5.53,$

$\alpha_{move} = 21.83, \beta_{move} = -0.06, \delta_{move} = 22.98,$

Therefore, our desired empirical equations showing the relationships between power consumption and weight of UAV can be written from the equations 5 and 6.

For hovering power, the equation is,

$$P_{hover}(W) = 5.61W^2 + 19.31W - 5.53 \tag{7}$$

For movement power the equation is,

$$P_{move}(W) = 21.83W^2 - 0.06W + 22.98 \tag{8}$$

The equations 7 and 8 describe the desired relation between UAV weight and its power consumption.

CONCLUSIONS

This paper aims to provide a rigorous analysis of the power consumption of Unmanned Aerial Vehicles (UAVs) with different payload configurations, focusing on the potential use of UAVs in next-generation wireless networks. According to the study, payload weight and type have a significant impact on how much energy is used when hovering and moving - two crucial UAV operating scenarios. Two empirical mathematical models are also proposed in the work which denote how the power consumption depends on the overall weight of UAV. Rotary-wing UAVs, considered in this work, are particularly suitable for applications that require precise positioning and hovering, such as serving as aerial base stations in 6G networks. The findings of this study have significant implications for UAV deployment and design plans. The researchers can optimize UAV design and its deployment to increase flight durations of UAV by utilizing the empirical models provided here. In this work, the environmental factors, such as wind, temperature, and altitude, are not considered, which can have a significant impact on UAV energy consumption. Addressing these factors will be an important direction for future work to enhance this analysis. The analysis performed here is simulation-based. Researchers can conduct analysis by incorporating real UAV systems to increase the credibility of the proposed model. Future studies should focus on creating adaptive scheduling algorithms that take mission needs and real-time energy availability into account. Research on fabricating efficient and lightweight materials for UAVs and for the payloads of UAVs can be very beneficial for developing next-generation efficient UAVs. By overcoming these obstacles, UAVs can serve the next-generation 6G wireless network in an efficient way. This study serves as a framework for developing energy-efficient UAVs to meet the demands of future wireless technologies.

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DATA AVAILABILITY STATEMENT

Datasets generated during the current study are available from the corresponding author upon reasonable request.

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ETHICS APPROVAL

This study is an engineering experimental investigation. The MIJST Research Ethics Committee has confirmed that formal ethical approval was not required.

ETHICS, CONSENT TO PARTICIPATE, AND CONSENT TO PUBLISH

Not applicable.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHOR CONTRIBUTIONS

Author 1: Saif Ahmed - Conducted the literature review, developed the conceptual framework, designed the system and performed the result analysis.

Author 2: Nimul Islam Emon - Contributed to the preparation and writing of the manuscript.

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Portions of this manuscript were assisted by an artificial intelligence language model (ChatGPT, OpenAI). The tool was used solely for language editing, text refinement, and clarity improvement. All content, data interpretation, analysis, conclusions, and final decisions were generated, verified, and approved by the authors. The authors take full responsibility for the accuracy and integrity of the manuscript.

CONFLICT OF INTEREST DECLARATION

The authors declare that they have no conflicts of interest.

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