

Received August 23, 2018, accepted September 24, 2018, date of publication October 9, 2018, date of current version October 31, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2875040

# Comprehensive Energy Consumption Model for Unmanned Aerial Vehicles, Based on Empirical Studies of Battery Performance

HASINI VIRANGA ABEWICKRAMA<sup>ID</sup>, BEESHANGA ABEWARDANA JAYAWICKRAMA<sup>ID</sup>, YING HE<sup>ID</sup>, AND ERYK DUTKIEWICZ<sup>ID</sup>

Global Big Data Technologies Centre, University of Technology Sydney, Ultimo, NSW 2007, Australia

Corresponding author: Hasini Viranga Abewickrama (hasini.v.abewickrama@student.uts.edu.au)

**ABSTRACT** Unmanned aerial vehicles (UAVs) are fast gaining popularity in a wide variety of areas and are already being used for a range of tasks. Despite their many desirable features, a number of drawbacks hinder the potential of UAV applications. As typical UAVs are powered by on-board batteries, limited battery lifetime is identified as a key limitation in UAV applications. Thus, in order to preserve the available energy, planning UAV missions in an energy efficient manner is of utmost importance. For energy efficient UAV mission planning, it is necessary to predict the energy consumption of specific UAV manoeuvring actions. Accurate energy prediction requires a reliable and realistic energy consumption model. In this paper, we present a consistent and complete energy consumption model for UAVs based on empirical studies of battery usage for various UAV activities. We considered the impact of different flight scenarios and conditions on UAV energy consumption when developing the proposed model. The energy consumption model presented in this paper can be readily used for energy efficient UAV mission planning.

**INDEX TERMS** Energy consumption, energy consumption model, power consumption, UAV.

## I. INTRODUCTION

Unmanned Aerial Vehicles (UAV) are fast gaining popularity. Their many desirable features like the ability to hover, the ability to fly over dangerous and inaccessible areas and ease of deployment enable UAVs to be widely used in many commercial applications [1].

Despite the increasing popularity and their many advantages, UAVs have inherent limitations that hinder the full potential of UAV applications. Limited battery lifetime is identified as a key drawback in UAVs [2]. As typical UAVs are electric devices powered by on-board batteries with a limited lifetime, most UAV applications are unable to reach their full potential.

To reduce the impact of limited flight time of UAVs caused by limited battery lifetime, it is important to minimize the energy consumption in UAV missions. Thus, to plan energy efficient UAV missions and to identify and reduce high energy consuming manoeuvring actions, following a reliable and complete energy consumption model for UAVs is mandatory. An accurate model of battery performance in different scenarios would allow further flight mission planning and recharging optimization for UAVs [2]. The work presented

in [3], further emphasises the importance of battery life prediction, based on energy consumption of UAV missions, for autonomous battery maintenance systems for UAVs.

In this paper, we present an energy consumption model for UAVs that profiles energy needs for commonly used UAV manoeuvring actions. The model is based on empirical studies of battery performance which will be described in detail later in this paper.

There are two common approaches for modelling and predicting power consumption of ground electric vehicles: white-box approach and black-box approach. In the white-box approach understanding of energy consumption of electric vehicles is based on specific vehicle dynamics [4]. In the black-box approach a general statistical approach using regression model, without vehicle dynamics model, is used to model the power consumption of vehicles [5]. The black-box approach is easy, convenient and provides all necessary information for energy and power consumption predictions for UAV missions. Hence, we employ the black-box approach to model the energy consumption of UAVs, considering different flight scenarios and conditions but not taking vehicle dynamics into account.

In literature there appear to be limited studies on the battery performance of UAVs [2]. Ahmed *et al.* [6] present experimental results of a few basic UAV manoeuvring actions: hovering, flying vertically upward and flying vertically downward. More detailed studies on battery performance have been carried out in [2]. Tseng *et al.* [2] have conducted studies to determine the impact of movement (hovering, vertical movement and horizontal movement), payload and wind on the power consumption of a UAV.

However, both [2] and [6] cannot be considered complete energy models for UAVs. The authors of [2] overlook energy consumed for factors such as communication, take-off and speed, while Ahmed *et al.* [6] do not consider the effect of payload, speed and communication, in addition to some basic movements such as taking-off. Further, in both [2] and [6] sufficient quantitative experiments have not been performed to obtain sufficient empirical data to determine the impact of studied factors on energy consumption of UAVs. Thus, they do not contain enough information for energy predictions or comparisons.

To the best of our knowledge, our previous work presented in [7] is the first power consumption model on Intel Aero Ready to Fly Drone [8]. In this paper, we propose an enhanced energy consumption model, based on experiments performed on the same UAV model. The method we use for power calculations and energy predictions can be used on other UAV models for similar applications. The energy consumption model presented in this paper can be readily used for energy efficient UAV path planning and obstacle avoidance purposes.

The rest of this paper is structured as follows. Section II gives an overview of the empirical studies of UAV power and energy consumption. The measurement results of the studies and energy consumption model are presented in Section III. Section IV presents a more comprehensive energy consumption model. Section V describes the evaluation of the accuracy of the proposed energy consumption model. Section VI concludes the paper.

## II. OVERVIEW OF THE EMPIRICAL STUDY OF UAV POWER AND ENERGY CONSUMPTION

We conducted a series of studies focused on understanding the impact of several factors on power/energy consumption of UAVs. The factors taken into consideration are stated below.

- 1) On-ground power consumption
- 2) Impact of communication
- 3) Impact of distance on energy/power consumption for communication
- 4) Impact of taking-off
- 5) Impact of movement - hovering, horizontal movement, vertical movement
- 6) Impact of payload
- 7) Impact of speed
- 8) Impact of wind

The different UAV operating modes used in the studies are shown in Table 1.

**TABLE 1. UAV operating modes.**

Mode	Description
Idle mode	Powered on, kept on ground without propellers rotating
Armed mode	Powered on, kept on ground with propellers rotating
Take-off	Leave the ground and begin to fly
Horizontal movement	Move parallel to the ground
Vertical movement	Move at a right angle to the ground (upward and downward)
Hover	Remain in one place in air

**TABLE 2. Intel aero ready to fly drone specifications [8].**

Parameter	Measurement
Weight (without battery)	865 g
Dimensions (hub-to-hub)	360 mm
Height	222 mm
Propeller length	230 mm

**TABLE 3. Dualsky LiPo battery specifications [9].**

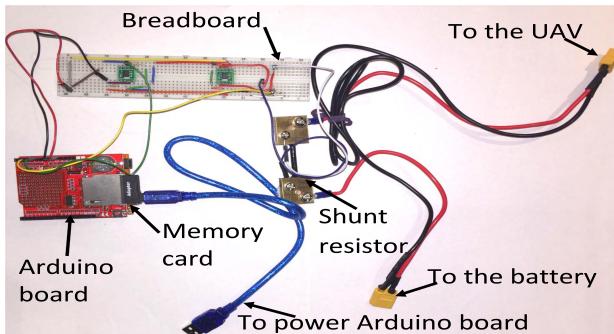
Parameter	Measurement
Capacity	4000 mAh
Voltage	14.8 V
Weight	399 g
Dimensions (LengthxWidthxDepth)	141 x 44 x 31 mm

All experiments were performed on Intel Aero Ready to Fly Drone [8] with new Dualsky 4000 mAh 4S 25c, ECO-S LiPo batteries [9], in obstacle free outdoor environments, where wind was minimal (except for the experiments conducted to understand the impact of wind on UAV power/energy consumption). The specifications of the UAV and the batteries used are listed in Table 2 and 3. A QGroundControl software [10] installed laptop, was used as the ground station to control the UAV.

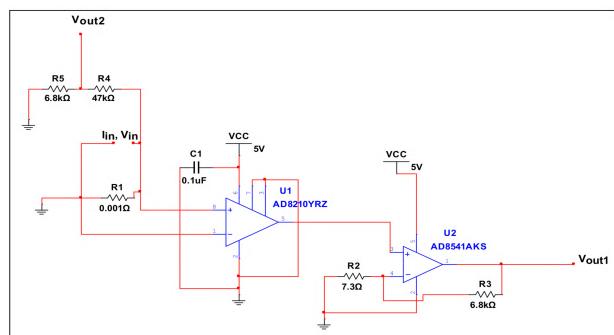
### A. CUSTOM, HIGH ACCURACY, LIGHTWEIGHT DIGITAL MULTIMETER

To calculate the power and energy consumption, it was necessary to log instantaneous voltage and current draw of the UAV. Due to the limited payload capacity of the UAV, most of the commercially available data loggers were too heavy for the UAV to carry onboard (Maximum gross weight of Intel Aero Ready to Fly Drone is 1900 g [8]). UAV manoeuvring actions are swift, thus, for increased accuracy it was necessary for the data logger to have a high sampling and logging frequency. Most of the commercially available loggers do not support this preferred accuracy.

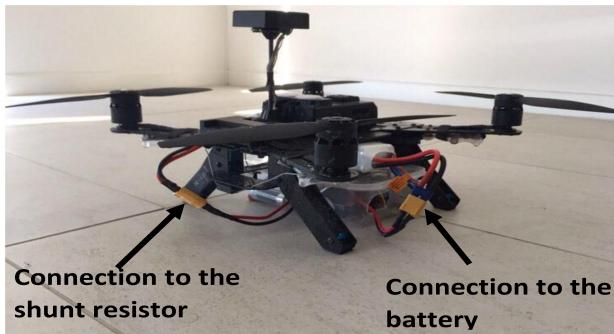
Thus, for collecting and recording current and voltage data, we developed a custom digital multimeter and data logger (Figure 1), with a logging interval of 20 ms. The circuit diagram of the developed multimeter is shown in Figure 2. The set up of the system of circuit and UAV is shown in Figure 3.



**FIGURE 1.** Circuit to measure and log instantaneous current and voltage every 20 ms.



**FIGURE 2.** Circuit diagram of custom digital multimeter.



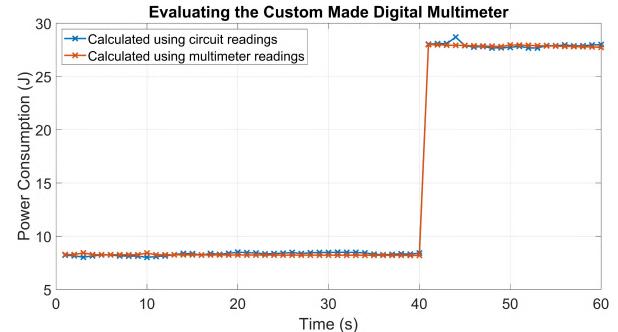
**FIGURE 3.** Set up of the circuit and UAV.

Based on the specifications of the integrated circuits (IC) used, the current that flows through the UAV  $I_{in}$ , can be calculated by (1), where  $V_{out1}$  is output voltage,  $R1$ ,  $R2$  and  $R3$  are resistors used as shown in the circuit diagram in Figure 2.

$$I_{in} = \frac{V_{out1}}{(20 \times R1)} \times \frac{R3}{R1 + R2} \quad (1)$$

A voltage divider is used to measure the voltage applied to the UAV. The voltage through the UAV can be calculated using (2).  $V_{in}$  is the voltage through the UAV,  $V_{out2}$  is output voltage of the voltage divider,  $R4$ ,  $R5$  are resistors as shown in Figure 2.

$$V_{in} = \frac{V_{out2}(R4 + R5)}{R5} \quad (2)$$



**FIGURE 4.** Evaluating the accuracy of the custom digital multimeter.

The circuit was evaluated by comparing the power calculations in Idle and Armed modes of the UAV, using the voltage and current readings of a standard multimeter and readings of the custom-made digital multimeter. The results are shown in Figure 4. Based on the results, the errors of the power calculations based on the custom-made digital multimeter, in comparison to the readings of a standard multimeter are within 5%.

### III. MEASUREMENT RESULTS AND ENERGY CONSUMPTION MODEL

Based on the studies carried out, it was noted that the UAV battery was always able to cater to the instantaneous power demand of the UAV. Accordingly, the limiting factor in a UAV mission would be the amount of energy the battery can provide. Thus, to make the model more general and applicable to a wide variety of scenarios we present the energy consumption of the UAV for various manoeuvring activities, along with the instantaneous power requirements.

The total energy consumption for a certain flight scenario can be calculated by the integral of power over the period of flying. This is shown in (3), where  $E$  is the energy consumption in joules.  $P$  is the instantaneous power consumption in watts.  $t$  is the time interval of flight scenario in seconds.

$$E = \int_0^t P dt \quad (3)$$

In special scenarios where instantaneous power consumption is stable over time, the energy consumption for 1 s, is equal to the instantaneous power consumption. This is further shown by (4). The symbols  $E$ ,  $P$  and  $t$  have the same meanings as above.

$$E = \int_0^1 P dt = P \quad (4)$$

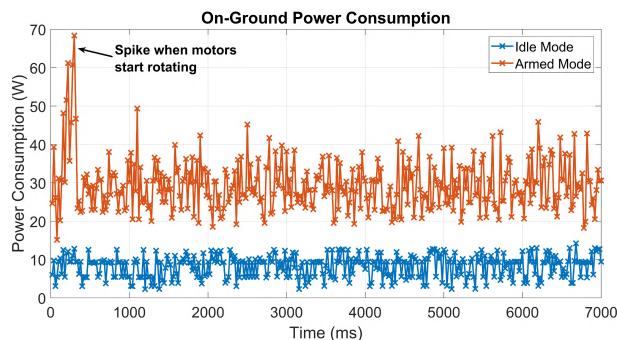
#### A. ON-GROUND POWER CONSUMPTION

Two basic experiments were conducted, to understand the power consumption of the UAV when it is on ground.

The power consumption statistics related to this section are shown in Table 4.

**TABLE 4.** Power consumption statistics.

Mode	Average Power Consumption (W)	Standard Deviation (W)
Idle	8.241	2.870
Armed	28.900	5.761
Wi-Fi in Idle mode	8.262	2.012
GPS in Idle mode	8.264	2.024
Horizontal flying	310.576	53.720

**FIGURE 5.** On-ground power consumption of the UAV.

### 1) IDLE MODE

The UAV was powered on and kept on ground without the propellers rotating and with no connection with the ground station (communication modules disabled). Internal processing, on-board fan, attached multimeter and data logging circuit and LED indicators would basically consume power in this scenario. The instantiations power consumption was calculated and is shown by the blue line in Figure 5. The power consumption in the Idle mode is reasonably stable over time as observed in Figure 5.

The above study was conducted multiple times, and the energy consumption over time was calculated using (3). The best fit line shown by the green line in Figure 6 was obtained considering the average energy consumption of all studies. A perfect line that goes through the origin was not obtained due to the slight fluctuations in power consumption and errors in measurements. This is true to all relevant scenarios throughout the paper.

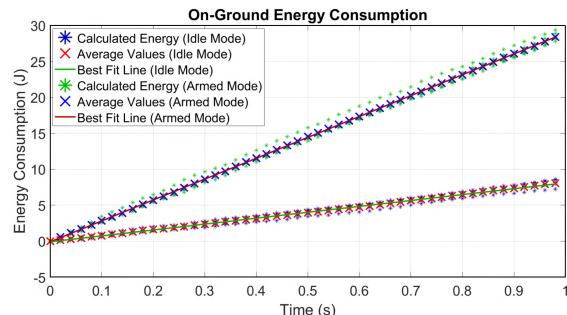
The energy consumption in Idle mode increases linearly with time. The Idle mode energy consumption shown in Figure 6 is given by (5), where  $E$  is the energy in joules and  $t$  is the time in seconds. Symbols  $E$  and  $t$  have the same meaning throughout the paper.

$$E = 8.195t - 0.087 \quad (5)$$

### 2) ARMED MODE

The UAV was powered on and kept on ground with the propellers rotating. In this scenario, the UAV would need power to rotate the four motors, in addition to the power requirements mentioned in the previous subsection.

The power consumption in Armed mode is shown by the red line in Figure 5. The initial spike in power consumption

**FIGURE 6.** On-ground energy consumption of the UAV.

is due to the high draw of current when starting the rotation of four motors.

The energy consumption for Armed mode, once stabilized (calculated using the average of data obtained through multiple studies) is shown by the red line in Figure 6. The linear increase in energy consumption over time in this scenario is given by (6).

$$E = 29.027t - 0.087 \quad (6)$$

The power and energy consumption in Armed mode is considerably higher than that of Idle mode. The high power consumption in the motors for rotating propellers causes increased power consumption in Armed mode. Thus, designing energy efficient motors and propellers for UAVs would be advantageous energy-wise.

## B. IMPACT OF COMMUNICATION

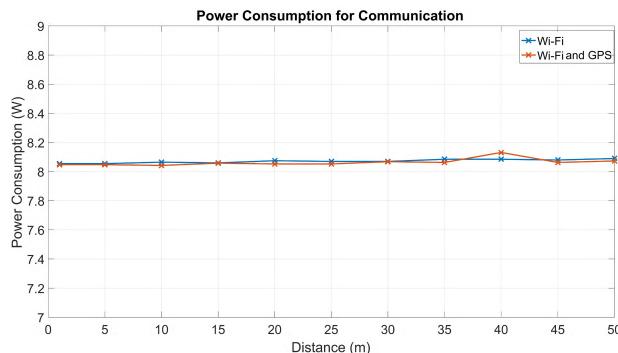
The studies in this section were performed in the ‘Idle mode’ mentioned in *Section A Subsection 1*. The power measurements for this section (shown in Table 4) are equal to the total power consumption of the UAV in the given scenarios, which is the sum of the power consumption discussed in *Section A Subsection 1* and power consumption for communication that is stated below.

### 1) WI-FI COMMUNICATION

In indoor UAV missions, Wi-Fi is mostly the key mode of communication between the UAV and ground station. Thus, it is important to quantify the power consumption for Wi-Fi communication.

The UAV was made to maintain Wi-Fi with the ground station. In this study, the ‘node mode’ was used on the UAV and the ground station was used as an Access Point (AP). The UAV would share its calibration information, status information (armed, disarmed, landed etc.), battery information and basic set up parameters including take-off altitude, speed etc. with the ground station using Wi-Fi.

The total power consumption of the UAV while maintaining Wi-Fi with the ground station does not have a significant difference with that of when not communicating with the ground station (based on the results given in Table 4).



**FIGURE 7.** Impact of distance on UAV power consumption for communication.

2) GLOBAL POSITIONING SYSTEM (GPS) COMMUNICATION  
The same study as above was carried out with the GPS module of the UAV enabled, and with the UAV having a 3D GPS lock with 20 satellites. With the experimental results for this scenario, shown in Table 4, it can be noted that power consumption for GPS communication is negligible.

### C. IMPACT OF DISTANCE ON ENERGY/POWER CONSUMPTION FOR COMMUNICATION

While maintaining a clear line of sight between the UAV and ground station at all times, the distance between ground station and UAV was gradually increased (up to 50 m) to quantify the impact of distance on communication. The instantaneous power at each point was calculated for a period of 20 minutes, and the average power consumption at each point was considered in plotting the graph in Figure 7. The blue line represents the total power consumption with Wi-Fi communication and the red line represents the total power consumption with both Wi-Fi and GPS. A stable power consumption can be observed over the distance considered.

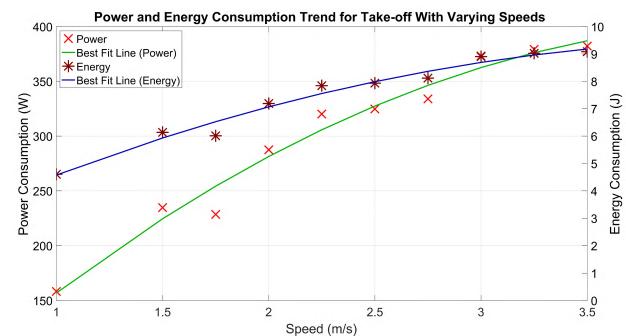
Based on the above studies, it can be noted that in comparison to the Idle mode power consumption in *Section A Subsection 1*, the power consumption for both Wi-Fi and GPS communication is negligible. Thus, in flight scenarios where the UAV is no further than 50 m away from the ground station, the power consumption for communication can be ignored, so is the energy consumption.

### D. IMPACT OF TAKING-OFF

When the UAV takes off, there is a sudden spike in power consumption when it starts to overcome inertia and move against gravitational force, as marked in Figure 9.

Several studies with different take-off speeds were conducted to determine the relationship between the spike in power consumption and take-off speed. The results are plotted in Figure 8, in the green line with respect to left-hand side y-axis. As observed in Figure 8 the power consumption for taking-off increases with the take-off speed.

The experiments showed that the sudden spike of power consumption in take-off lasts approximately 40 ms. Based on



**FIGURE 8.** UAV power and energy consumption for take-off with varying speeds.

the time approximations and power consumption, the energy required for taking-off was calculated and is shown by the blue line with respect to the right-hand side y-axis, in Figure 8. The relationship between the take-off energy consumption and speed is given by (7), where  $E$  is the energy requirement in joules and  $V$  is the take-off speed in m/s.

$$E = -0.432V^2 + 3.786V - 1.224 \quad (7)$$

### E. IMPACT OF MOVEMENT

The power measurements shown in this section are the total power consumed by the UAV in performing the stated actions. This includes power for basic arming mentioned in *Section A Subsection 2*, the power for communication mentioned in *Section B* and the power for movements discussed in this section.

#### 1) HOVERING

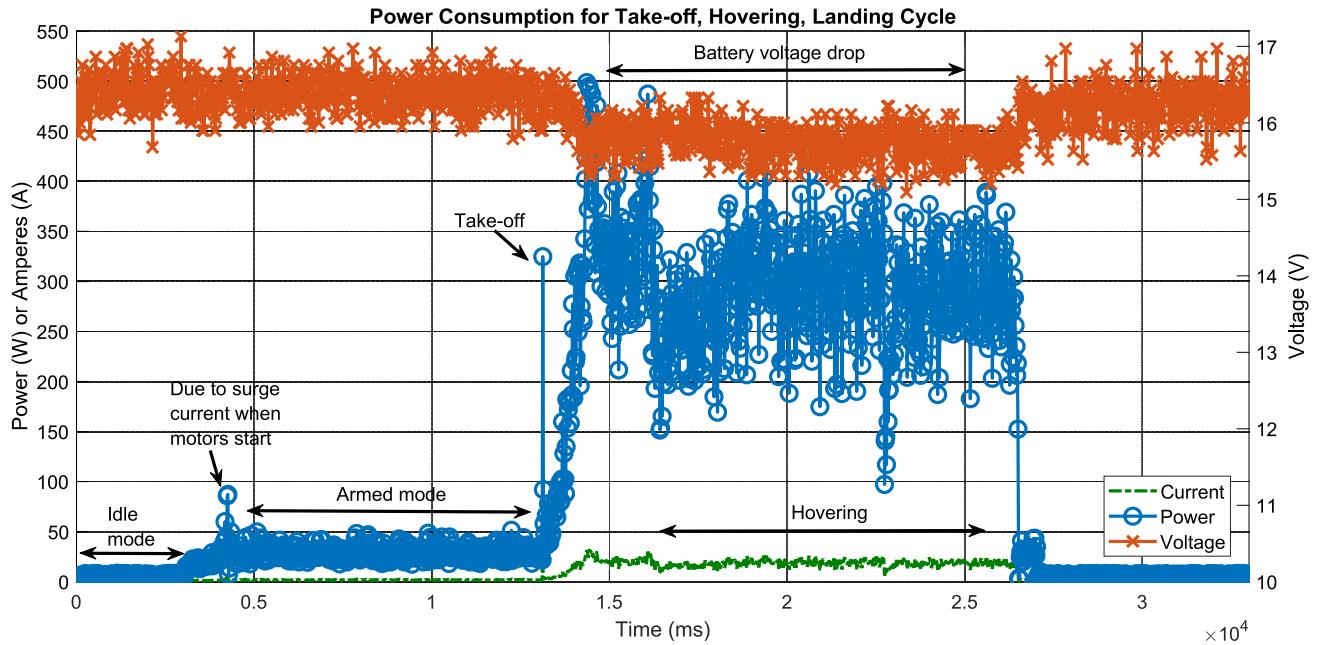
The UAV was made to take-off and hover at different altitudes to understand the behaviour of power consumption when hovering and the impact of altitude on it.

Figure 9 shows voltage, draw of current and power consumption pattern for a full cycle of taking-off, hovering and landing. The reasonably stable power consumptions in Idle mode, Armed mode and hovering and the sudden spikes in power consumption due to the motors starting to rotate the propellers and when taking-off can be seen.

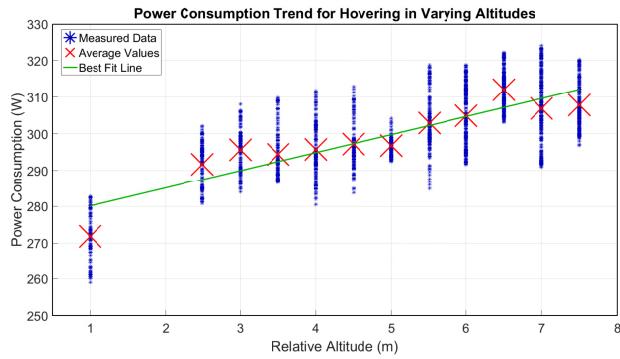
The battery voltage drop due to the very high current draw of the UAV when it is above ground, can be observed in the voltage plot.

The average power consumption for 1 s remains reasonably stable over the time period of hovering. When a UAV hovers, it remains static and the forces acting on the UAV are ideally balanced. In perfect environmental conditions, the forces acting on a UAV remain stable over time. Thus, the forces generated by rotating the propellers of the UAV remain stable over time, resulting in stable power consumption over the period of hovering.

Figure 10 shows the instantaneous power measurements and average power consumption for hovering in different relative altitudes, along with the best fit line based on the average power consumption at each relative altitude.



**FIGURE 9.** Voltage, current and power consumption of the uav for taking-off, hovering and landing.



**FIGURE 10.** UAV power consumption for hovering in different altitudes.

Based on (4), the energy consumption trend for hovering at different altitudes for 1 s takes the same form as the best fit line in Figure 10.

The relationship between the relative altitude and energy consumption for hovering for 1 s is given by (8), where  $E_1$  is the energy requirement for hovering for 1 s in joules and  $H$  is the relative hovering altitude in meters.

$$E_1 = 4.917H + 275.204 \quad (8)$$

Based on (8), the energy requirement  $E$  for hovering at a relative altitude of  $H$  for  $t$  seconds is given by (9).

$$E = (4.917H + 275.204)t \quad (9)$$

The power requirement to hover a UAV in air can be theoretically calculated using basic physics, as shown below.

The kinetic energy the UAV produces by moving air using one propeller  $E$  is given by (10), where  $m_{air}$  is the mass of air

being moved and  $v$  is the speed of propellers.

$$E = \frac{1}{2} m_{air} v^2 \quad (10)$$

Since the UAV has four rotating propellers, the total kinetic energy produced,  $E_{total}$ , is given by (11).

$$E_{total} = 2m_{air} v^2 \quad (11)$$

If  $r$  is the radius of a propeller,

$$m_{air} = \pi r^2 v t \rho \quad (12)$$

where  $\rho$  is the density of air in the given height and temperature.

Since (13), where  $E$  is energy,  $P$  is power and  $t$  is time,

$$dP = \frac{dE}{dt} \quad (13)$$

from (11) and (12),

$$P = 2\pi r^2 v^3 \rho \quad (14)$$

The relationship between power  $P$ , speed  $v$  and force  $F$  is given by (15)

$$P = Fv \quad (15)$$

For hovering, since UAV is stationary, the forces should balance. Therefore,

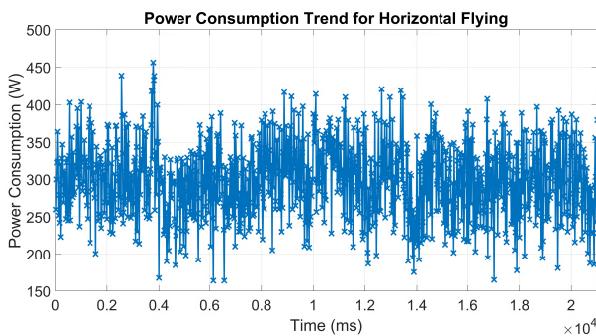
$$F = mg \quad (16)$$

where  $m$  is the mass of the UAV and  $g$  is gravitational force. Substituting (15) and (16) in (14).

$$P = \sqrt{\frac{(mg)^3}{2\pi r^2 \rho}} \quad (17)$$

**TABLE 5.** Parameters affecting power consumption for hovering.

Parameter	Value
$m$ (total mass including the digital multimeter)	1.73 kg
$\rho$	$1.225 \text{ kg/m}^3$ [12]
$r$	115 mm
$g$	$9.796 \text{ ms}^{-2}$ [11]

**FIGURE 11.** UAV power consumption for horizontal flying.

According to [11] and [12], the gravitational force and density of air do not change within the considered altitude. Thus, theoretically (as shown in (17)) for fixed mass, the power consumption, and therefore energy consumption for hovering should remain constant over altitude. However, in comparison to the theoretical power consumption given by (17), using the values given in Table 5, the practical power consumption for hovering, calculated using (8) shows an increase in power consumption approximately by 1.5% with height, due to UAV efforts in retaining stability against the changing environmental conditions with the altitude.

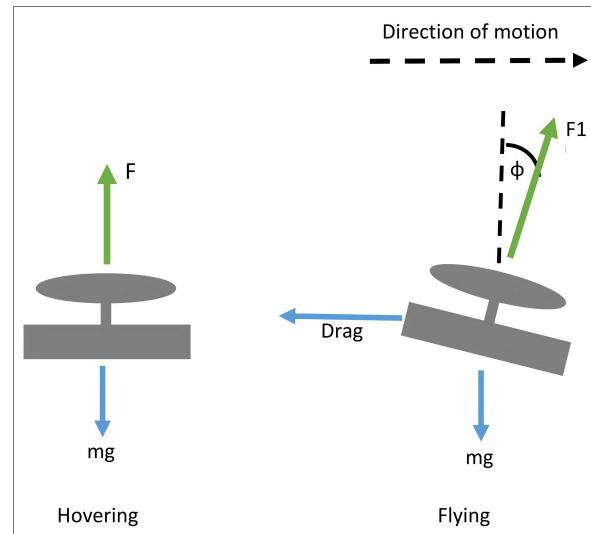
## 2) HORIZONTAL MOVEMENT

The UAV was made to fly horizontally at a constant speed of 1 m/s, in a straight line at a relative altitude of 5 m. The instantaneous power consumption was calculated and plotted in Figure 11.

As observed in Figure 11, the average power consumption for 1 s remains reasonably stable over time, except for minor fluctuations due to slight vertical movements. Power consumption statistics for this scenario is given in Table 4.

Since the UAV is flying at a constant speed, the forces acting on the UAV should balance. Hence, the force created by the UAV should have the same magnitude as the magnitude of the resultant force acting on the UAV. In perfect environmental conditions, the forces acting on the UAV would remain constant. Therefore, the force created by UAV by rotating the propellers should remain stable, resulting in stable power consumption over time when flying horizontally in constant speed.

When both hovering and flying horizontally at a constant speed, UAV power consumption is stable. However,

**FIGURE 12.** Forces acting on a UAV when hovering and flying horizontally in constant speed.

the power consumed when flying horizontally is slightly higher than the power consumed when hovering at the same altitude. This is due to the difference of the magnitude of thrust generated by the UAV in the two scenarios.

Figure 12, shows the forces acting on the UAV when hovering and flying horizontally in constant speed.  $F$  is the thrust generated by the UAV when hovering.  $F_1$  is the thrust generated by the UAV when flying horizontally in the direction shown in Figure 12. The UAV tilts by an angle of  $\phi$  and  $mg$  is the weight of the UAV.

When hovering,

$$F = mg \quad (18)$$

When flying horizontally in constant speed

$$F_1 \cos \phi = mg \quad (19)$$

From (18) and (19),

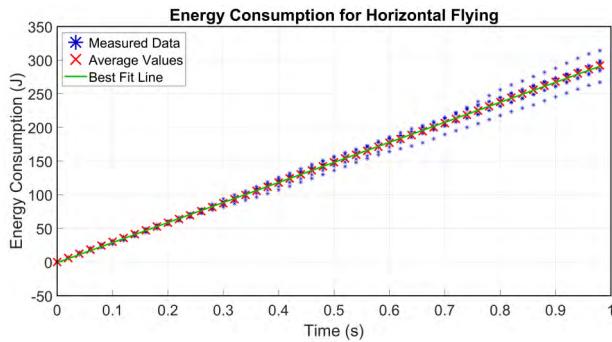
$$F_1 = F \sec \phi \quad (20)$$

According to (20), the thrust UAV needs to generate when flying horizontally is higher than that when hovering. As the power consumption increases with the thrust, UAV consumes more power when flying horizontally.

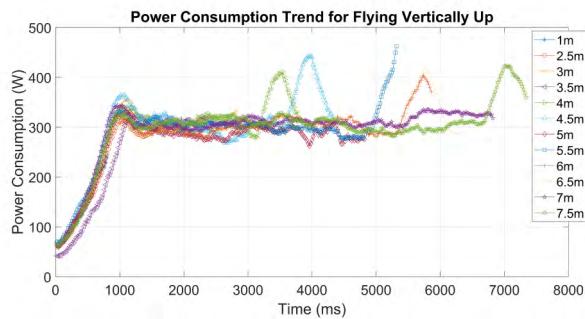
The energy consumption for flying horizontally at constant speed is given by Figure 13. Several studies were conducted and the average energy consumption in each study was considered when plotting the graph.

The energy consumption increases linearly with time as seen in Figure 13 and the increase is represented by (21).

$$E = 308.709t - 0.852 \quad (21)$$



**FIGURE 13.** UAV energy consumption for horizontal flying.



**FIGURE 14.** UAV Power consumption for flying vertically upward to reach different relative altitudes.

### 3) VERTICAL MOVEMENT

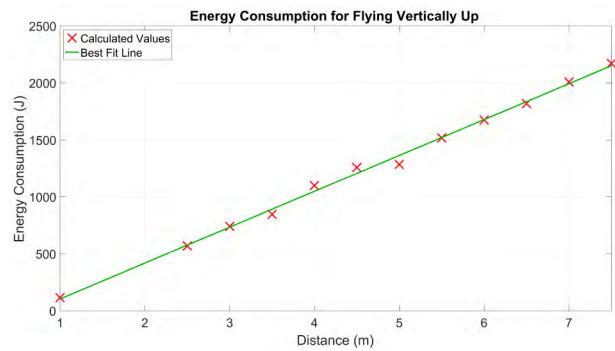
The UAV was made to take-off and fly vertically upward to reach different relative altitudes. All the studies were performed with a take-off velocity of 1 m/s. The instantaneous power consumption was calculated every 20 ms and plotted in Figure 14.

As observed in Figure 14, at the beginning of the flight, power consumption increases steadily with time, and remains reasonably stable until the UAV reaches required relative altitude. Random increases in power consumption can be seen as the altitude increases, due to UAV reactions to the changing environmental conditions while trying to maintain stability.

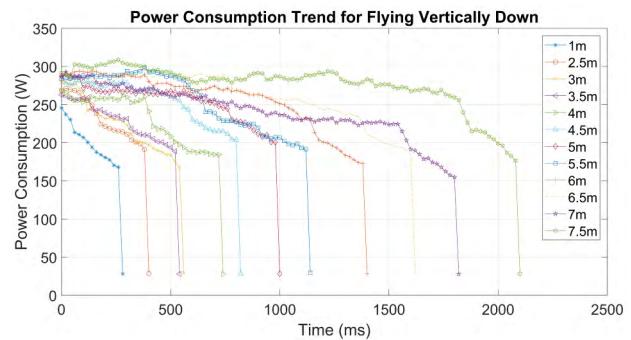
The energy consumption of the UAV when reaching different altitudes, was calculated and is shown in Figure 15, along with the best fitting relationship between the energy consumption and vertical distance travelled, which is given by (22), where  $D$  is the vertical distance travelled upward in meters.

$$E = 315D - 211.261 \quad (22)$$

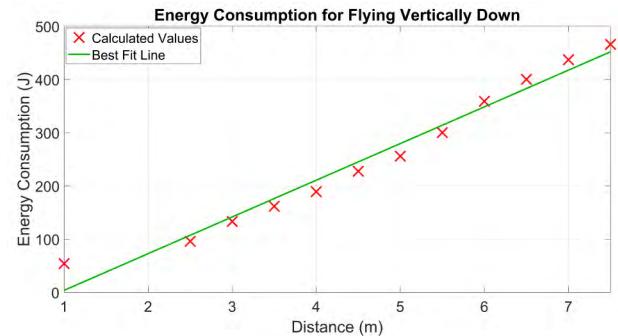
The UAV was stationed at different altitudes and made to fly vertically downward to determine the impact of flying vertically downward on the power and energy consumption of the UAV. The instantaneous power for each altitude scenario is shown in Figure 16. The energy consumed in each scenario is calculated and shown in Figure 17 along with



**FIGURE 15.** UAV energy consumption for flying vertically upward to reach different relative altitudes.



**FIGURE 16.** UAV power consumption for flying vertically downward.



**FIGURE 17.** UAV energy consumption for flying vertically downward.

the best fit line. The relationship between the distance of flying vertically downward and the consumed energy, shown in Figure 17 is given by (23), where  $D$  is the vertical distance travelled downward in meters.

$$E = 68.956D - 65.183 \quad (23)$$

The energy required to fly downward is considerably less than the energy required to fly upward. When flying upward, the UAV has to work against the gravitational force. On the other hand, when flying downward, the gravitational force acts towards the direction of movement and the UAV has to perform comparatively less work to maintain stable and safe velocity.

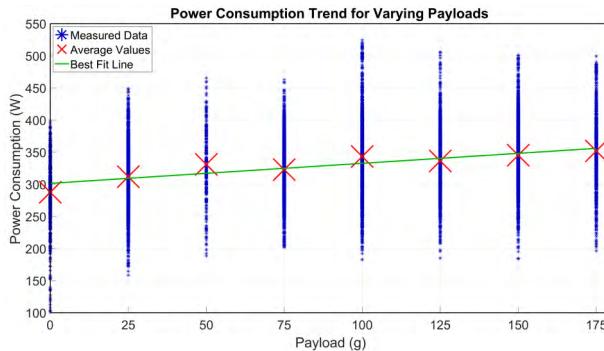


FIGURE 18. Impact of payload on UAV power consumption.

#### F. IMPACT OF PAYLOAD

The UAV was mounted with different payloads and made to hover at a relative altitude of 5 m. The UAV was able to handle an external weight only up to 175 g and steadily reach the required altitude. When mounted with 200 g, the UAV became unstable.

The power consumption for hovering with payloads is shown in Figure 18. A clear relationship between power consumption and payload can be observed. As the payload of the UAV increases, the power consumption of the UAV increases accordingly.

Based on (4), the energy consumption trend for hovering with different payloads for 1 s takes the same form as the best fit line shown in Figure 18.

The relationship between the payload and energy consumption for hovering for 1 s is given by (24), where  $E$  is the energy requirement for hovering for 1 s in joules and  $L$  is the payload in grams.

$$E = 0.311L + 301.524 \quad (24)$$

Based on the results of the studies carried out to understand the energy consumption of hovering, we can eliminate the energy consumption for hovering at a relative altitude of 5 m and isolate the impact of payload. Hence, based on (8) and (24), the isolated impact of payload is given by (25).

$$\begin{aligned} E &= (0.311L + 301.524) - (4.917 * 5 + 275.204) \\ &= 0.311L + 1.735 \end{aligned} \quad (25)$$

Based on (25), the energy requirement for hovering with a payload of  $L$  in grams for  $t$  seconds is given by (26).

$$E = (0.311L + 1.735)t \quad (26)$$

#### G. IMPACT OF SPEED

UAV was made to fly 5 m vertically upward in different speeds to determine the relationship between speed and power consumption. The instantaneous power consumption for each scenario is shown in Figure 19. The energy consumption for each scenario is calculated and shown in Figure 20. Although the instantaneous power increases with speed, since the total time taken to reach a certain altitude decreases,

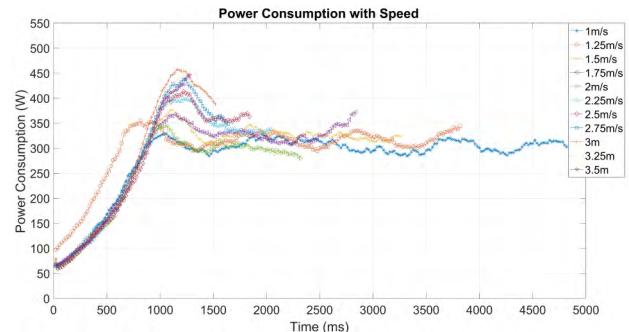


FIGURE 19. Impact of speed on UAV power consumption.

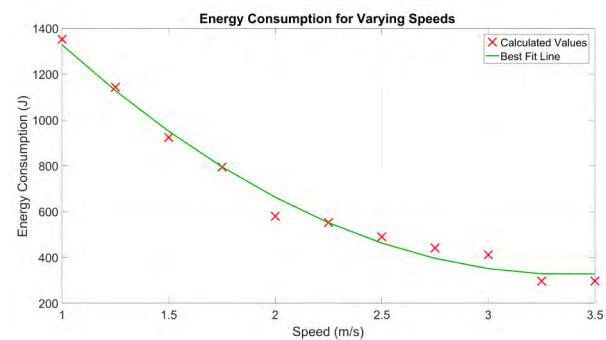


FIGURE 20. Impact of speed on UAV energy consumption.

the total energy consumption does not increase with speed. The best fitting relationship between speed and energy consumption shown in Figure 20 is given by (27), where  $E$  is the energy requirement in joules and  $V$  is the speed in m/s.

$$E = 176.7V^2 - 1.195V + 2.346 \quad (27)$$

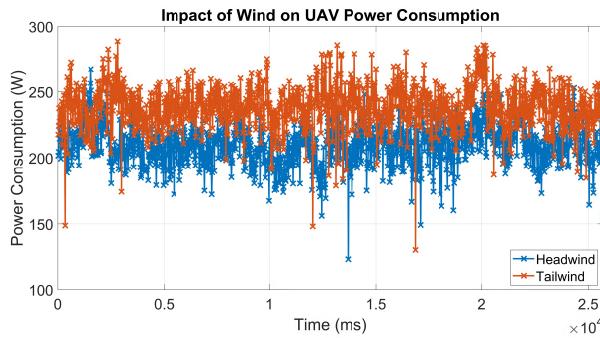
#### H. IMPACT OF WIND

It is important to have an understanding of the impact of environmental factors on the power/energy consumption of UAVs. However, controlling factors such as humidity, thermal effects and wind to understand their effect on UAV power/energy consumption, is deemed impossible in the outdoor environment the experiments were carried out. For this reason, in this paper, the effects of humidity and thermal factors are not considered.

Two experiments were carried out to understand the impact of wind on UAV power/energy consumption. However, due to practical difficulties, different wind speeds were not considered and the below experiments were carried out on the same day, at the same location under same wind conditions, where the speed of wind was 15 km/h.

##### 1) FLYING INTO HEADWIND

The UAV was made to take-off, hover at a relative altitude of 3 m and fly against the direction of the wind (headwind) at 1 m/s. The power consumption for flying headwind is shown by the blue line in Figure 21.



**FIGURE 21.** Impact of wind on power consumption of the UAV.

## 2) FLYING INTO TAILWIND

The UAV was made to take-off, hover at a relative altitude of 3 m and fly in the direction of the wind (tailwind) at 1 m/s. The power consumption for flying tailwind is shown by the red line in Figure 21.

The power consumption when flying into headwind is considerably lesser than when flying into tailwind, as seen in Figure 21. When the UAV flies into headwind, the translational lift increases due to the increase in relative airflow over the propellers [2], [13], resulting in low power requirement when flying into headwind.

## IV. COMPREHENSIVE ENERGY CONSUMPTION MODEL FOR UAVS

The impact of considered factors on energy consumption of the UAV discussed in the previous section is summarized in Table 6.

Based on the equations (5)-(9) and (21)-(27) the total energy consumption of a UAV mission carried out in a wind-free environment can be calculated using (28), as shown at the bottom of this page.

The meanings of the symbols used in (28) are shown in Table 7, along with the conditions for validity.

## V. EVALUATION OF THE PROPOSED ENERGY CONSUMPTION MODEL

In order to assess the accuracy of the proposed energy consumption model, a UAV mission was planned and executed. The power consumption throughout the mission was recorded and the energy consumption was calculated using measured data. The total energy consumption for the planned mission was estimated using the proposed energy

**TABLE 6.** Impact of the Factors Considered on UAV Energy Consumption.

Factor	Equation	Validity Condition
Idle mode	$E = 8.195t - 0.087$	N/A
Armed mode	$E = 29.027t - 0.087$	N/A
Taking-off	$E = -0.432V^2 + 3.786V - 1.224$	$0 < V \leq 3.5 \text{ m/s}$
Hovering	$E = (4.917H + 275.204)t$	$0 < H \leq 7.5$ $t \leq 900 \text{ s}$
Flying horizontally	$E = 308.709t - 0.852$	$t \leq 900 \text{ s}$
Flying vertically upward	$E = 315D - 211.261$	$0 < D \leq 7.5 \text{ m}$
Flying vertically downward	$E = 68.956D - 65.183$	$0 < D \leq 7.5 \text{ m}$
Payload	$E = 0.311L + 1.735$	$0 < L \leq 175 \text{ g}$
Speed	$E = 176.7V^2 - 1.195V + 2.346$	$0 < V \leq 3.5 \text{ m/s}$

**TABLE 7.** Parameters of UAV Energy Model on.

Symbol	Meaning	Unit	Condition
$E$	Total energy	Joules	N/A
$t_1$	Total time in 'Idle mode', on ground	Seconds	N/A
$t_2$	Total time in 'Armed mode', on ground	Seconds	N/A
$V$	Take-off speed	Meters per second	$0 < V \leq 3.5 \text{ m/s}$
$D$	Distance of vertical flying upwards	Meters	$0 < D \leq 7.5 \text{ m}$
$H$	Relative altitude of hovering	Meters	$0 < H \leq 7.5 \text{ m}$
$t_3$	Total hovering time	Seconds	$t_3 \leq 900 \text{ s}$
$L$	Payload	Grams	$0 < L \leq 175 \text{ g}$
$t_4$	Total horizontal flying time	Seconds	$t_4 \leq 900 \text{ s}$
$D_1$	Distance of vertical flying downwards	Meters	$0 < D_1 \leq 7.5 \text{ m}$

consumption model, by (28). The measured energy consumption and estimated energy consumption were compared.

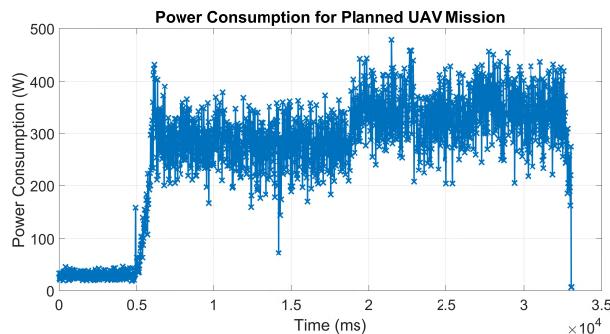
### A. UAV MISSION

UAV was kept on ground in the Armed mode for 5 s and was made to take-off at a speed of 1 m/s. The UAV was made to fly vertically upward for 5 m and hover for 10 s. Finally, the UAV was made to fly horizontally at a constant speed of 1 m/s for 10 s and made to land on ground.

The measured power consumption for this mission is shown in Figure 22.

Based on the area under the graph in Figure 22, the energy consumption of the UAV for the entire mission is 8.22 kJ.

$$\begin{aligned}
 E &= \text{Idle mode} + \text{armed mode} + \text{Take off} + \text{flying vertically upward} + \text{hovering} + \text{payload} \\
 &\quad + \text{flying horizontally} + \text{flying vertically downward} \\
 &= (8.195t_1 - 0.087) + (29.027t_2 - 0.087) + (0.432V^2 + 3.786V - 1.224) + (315D - 211.262) \\
 &\quad + [(4.917H + 275.204)t_3] + [(0.311L + 1.735)t_3] + (308.709t_4 - 0.852) + (68.956D_1 - 65.183) \\
 &= -278.695 + 8.195t_1 + 29.027t_2 - 0.432V^2 + 3.786V + 315D \\
 &\quad + (4.917H + 275.204)t_3 + (0.311L + 1.735)t_3 + 308.709t_4 + 68.956D_1
 \end{aligned} \tag{28}$$

**FIGURE 22.** Power consumption for planned UAV mission.**TABLE 8.** Parameter values for the UAV mission.

Parameter	Value
$t_1$	00 s
$t_2$	5.0 s
$V$	1.0 m/s
$D$	5.0 m
$H$	5.0 m
$t_3$	10.0 s
$L$	00 g
$t_4$	10.0 s
$D_1$	5.0 m

### B. ESTIMATED ENERGY CONSUMPTION

The energy consumption for the above planned mission was estimated using (28), with the parameters listed in Table 8.

The estimated energy consumption using the proposed model is 7.87 kJ. Based on this experiment the error of the estimated energy consumption using the proposed model is 4.3%

Based on the above results, it can be seen that the proposed energy model is accurate enough for widely used UAV mission planning.

### VI. CONCLUSION AND FUTURE WORK

A comprehensive energy consumption model for UAVs, is highly necessary for energy efficient mission planning. Identifying the factors that affect the energy consumption of a UAV and manipulating them to achieve energy efficiency is important.

In this paper, we have presented a complete energy consumption model for UAVs based on empirical studies of battery performance. We quantify the impact of on-ground power consumption, impact of communication, hovering, vertical and horizontal movements, speed, payload and wind on a UAV's energy consumption. The proposed model can be efficiently used for prediction of energy requirements and energy efficient UAV mission planning.

Employing UAVs for 5G communications, UAV mounted base stations to provide coverage for example, would require extensive knowledge of energy consumption patterns. The model presented in this paper can be readily used for deriving the optimal height, speed and the favourable payload in such

instances. UAV aided data collection in wireless sensor networks is currently being thoroughly researched. The model proposed in this paper can be used to design the optimal paths for the UAVs to minimize the energy spent on flying while covering the entire sensor network. In addition, the model presented can be used to minimise the energy consumption in UAV aided delivery, coverage and surveying scenarios.

We intend to use the energy model presented in this paper, in our work related to energy efficient inter-UAV collision avoidance, and UAV aided coverage. In addition, it would be advantageous to study the similarities and differences of the behaviour of power/energy consumption in different UAV models.

### REFERENCES

- [1] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Algorithm for energy efficient inter-UAV collision avoidance," in *Proc. 17th Int. Symp. Commun. Inf. Technol.*, Cairns, QLD, Australia, Sep. 2017, pp. 1–5.
- [2] C.-M. Tseng, C.-K. Chau, K. Elbassioni, and M. Khonji. (2017). "Autonomous recharging and flight mission planning for battery-operated autonomous drones." [Online]. Available: <https://arxiv.org/abs/1703.10049>
- [3] N. K. Ure, G. Chowdhary, T. Toksoz, J. P. How, M. A. Vavrina, and J. Vian, "An automated battery management system to enable persistent missions with multiple aerial vehicles," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 275–286, Feb. 2015.
- [4] E. Kim, J. Lee, and K. G. Shin, "Real-time prediction of battery power requirements for electric vehicles," in *Proc. IEEE/ACM Int. Conf. Cyber-Phys. Syst.*, Philadelphia, PA, USA, Apr. 2013, pp. 11–20.
- [5] A. Cappiello, I. Chabini, E. K. Nam, A. Lue, and M. A. Zeid, "A statistical model of vehicle emissions and fuel consumption," in *Proc. IEEE 5th Int. Conf. Intell. Transp. Syst.*, Singapore, Sep. 2002, pp. 801–809.
- [6] S. Ahmed, A. Mohamed, K. Harras, M. Kholief, and S. Mesbah, "Energy efficient path planning techniques for UAV-based systems with space discretization," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2016, pp. 1–6.
- [7] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Empirical power consumption model for UAVs," in *Proc. IEEE 88th Veh. Technol. Conf. (VTC-Fall)*, 2018.
- [8] Intel Australia. (2017). *Specifications for the Intel Aero Ready to Fly Drone*. [Online]. Available: <https://www.intel.com.au/content/www/au/en/support/articles/000023272/drones/development-drones.html>
- [9] DUALSKY Advanced Power Systems. *Dualsky Xpower ECO-S V2 Series 25-30C*. [Online]. Available: [http://www.dualsky.com/ECO\\_Series/Xpower\\_ECO-S.shtml](http://www.dualsky.com/ECO_Series/Xpower_ECO-S.shtml)
- [10] QGroundControl Home. [Online]. Available: <http://qgroundcontrol.com>
- [11] G. A. Bell, D. L. H. Gibbons, and J. B. Patterson, "An absolute determination of the gravitational acceleration at Sydney, Australia," *Metrologia*, vol. 9, no. 2, p. 47, 1973.
- [12] National Aeronautics and Space Administration. (2018). *Earth Atmosphere Model*. [Online]. Available: <https://www.grc.nasa.gov/www/k-12/rocket/atmos.html>
- [13] United States Federal Aviation Administration. (2017). *Helicopter Flying Handbook*. [Online]. Available: [https://www.faa.gov/regulations\\_policies/handbooks\\_manuals/aviation/helicopter\\_flying\\_handbook/](https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/helicopter_flying_handbook/)



**HASINI VIRANGA ABEWICKRAMA** received the B.Sc. (Eng.) degree (Hons.) from the University of Moratuwa, Sri Lanka, in 2014. She is currently pursuing the Ph.D. degree with the University of Technology Sydney, Australia. She was with the industry as a Senior Software Engineer for over two years. Her research interests include multi-UAV systems and energy efficient UAV mission planning.



**BEESHANGA ABEWARDANA JAYAWICKRAMA** received the B.E. degree (Hons.) in telecommunications engineering and the Ph.D. degree in electronic engineering from Macquarie University, Sydney, Australia, in 2011 and 2015, respectively. He is currently a Lecturer with the School of Electrical and Data Engineering, University of Technology Sydney. He was extensively involved in spectrum sensing and interference mitigation in spectrum access systems. His research interests include resource allocation, cognitive radio, and signal processing.



**Ying He** received the B.Eng. degree in telecommunications engineering from the Beijing University of Posts and Telecommunications, China, and the Ph.D. degree in telecommunications engineering from the University of Technology Sydney, Australia, in 2009 and 2017, respectively. She is currently a Lecturer with the School of Electrical and Data Engineering, University of Technology Sydney. Her research interests are physical layer algorithms in wireless communication networks, spectrum sharing, interference mitigation, and multiple radio access technologies coexistence.



**ERYK DUTKIEWICZ** received the B.E. degree in electrical and electronic engineering and the M.Sc. degree in applied mathematics from The University of Adelaide in 1988 and 1992, respectively, and the Ph.D. degree in telecommunications from the University of Wollongong in 1996. His industry experience includes management of the Wireless Research Laboratory, Motorola, in early 2000's. He is currently the Head of the School of Electrical and Data Engineering, University of Technology Sydney, Australia. He is also a Professor with Hokkaido University, Japan. His current research interests cover 5G and IoT networks.

• • •