A procedure for power consumption estimation of multi-rotor unmanned aerial vehicle

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Abstract. Unmanned aerial vehicles (UAVs) have the potential to find many commercial applications, which may require relatively long mission times. Therefore, it is important to make UAVs that can complete the mission in an efficient and power saving way. To achieve a prescribed flight mission, a UAV has to perform a number of maneuvers/movements, which will consume a certain amount of power. To maximize the cruising time, not only the power source is able to provide enough amount of power to the UAV but also the parts of the UAV can perform efficiently to save power. Before the minimum power capacity can be determined, it is required that the power consumptions of the UAV parts for the required mission be evaluated in a proper way. In this paper, a procedure is presented to estimate the power consumption of a composite UAV. The configuration as well as the fabrication of the UAV using truss-type parts made of carbon strand/epoxy composite material will be briefly introduced. The power consumptions of the propeller system and electric parts will be evaluated in a systematic way. Experiments were conducted to verify the theoretical predictions. Flight tests were also performed to study the power consumption of the UAV and the suitability of the proposed procedure for power consumption calculation.

1. Introduction

UAVs have been used widely for different purposes. For instance, UAVs are used to transport rescue items [1] or spray pesticides [2]. In general, the fact that the present allowable operation time is relatively short has limited the UAV application scope. In particular, for small entertainment UAVs, the flight time is only about 5 to 15 minutes. To tackle this short flight time problem, some researchers have devoted to study the enhancement of UAV flight duration. Jung et al [3] proposed the use of the Photovoltaic Power Management System (PPMS) to provide solar power to a tethered multi-rotor UAV for continuous surveillance missions. In their study, the longest flight time has been increased to 54.14 min. Junaid et al [4] developed an outdoor wireless charge station for UAV. In their work, they have developed a UAV autonomously charge method in which the charge station can provide a stable charge efficiency (75%) in outdoor environment. Verbeke et al [5] developed a hexacopter, which comprises two arms with large propeller in a quadcopter structure. The UAV flight duration improvement is 58%. Except the studies of increasing UAV flight time, some researchers have proposed methods to evaluate UAV flight time. Hwang et al [6] estimated UAV flight time in steady-level flight. In their study, the average error between the estimated and measured values is 2.3%. Kim et al [7] performed UAV analysis and optimal design with the inclusions of propeller aerodynamics, UAV frame structure analysis, and electric system analysis to achieve UAV optimization. Their study has led to the increase of the UAV maximum hovering time from 31 min to 40 min. Furthermore, the
UAV maximum flight range has been extended from 34.5 km to 46.7 km. Although the UAV endurance problem has been tackled by a number of researchers, not much work about UAV energy consumption in flight has been performed. In this paper, we will present a procedure to estimate the power consumption of an Octa-rotor UAV with the weight (self-weight and payload) of 43kg. The contents of the paper consists of two parts, namely, UAV part design and power consumption evaluation for a prescribed flight mission. In the UAV part design, the components of the propulsion system (e.g., motor, propeller, battery etc.) are chosen according to the design load requirement (100kg) and the structure is manufactured using the carbon strand composite material. Regarding UAV power consumption evaluation, the power consumption characteristics of the power related parts are determined experimentally. A prescribed flight mission comprising 4 different types of movement (Lifting up, Landing, Hover, and Tilted flight) is planned for flight test. The measured power consumption is used to verify the correctness of the proposed power consumption evaluation procedure.

2. Design of UAV parts

2.1. Design of UAV propulsion system

Multi-axis UAVs are currently available in a variety of configurations. In this research, we selected the Octa-rotor configuration, which has some advantages like high lifting force and save more volume [8]. The Octa-rotor UAV has 4 arms and 2 rotors are installed on each arm. However, it has one shortcoming, which is that the motor at the lower level has 22% thrust loss [9, 10]. Therefore, the total thrust of the UAV is written as

\[ T_{\text{total}} = T \times N \times 1.78 \]  

where \( T_{\text{total}} \) is total thrust (kgf); \( T \) is motor thrust; \( N \) is number of arm axes.

Substituting the maximum weight 100kg and 4 axes in Eq. (1), the single motor thrust requirement is found to be 14.2kgf for satisfying the maximum load requirement of 100kg. Based on the motor thrust requirement, we selected 100KV DC brushless motor together with the #3295 propellers (Figure 1) and two 6S lipo-battery packages (50V/22000mAh) to supply the electric power. Also use T-motor FLAME 80AHV ESC (Figure 2) to control the motor speed.

2.2. Manufacture of Carbon strand/epoxy composite fuselage

The reduction of UAV self-weight can help save electric power. A truss is a robust light weight structure which, if used to make the UAV fuselage, can save more electricity and increase payload for the UAV. Therefore, regarding UAV fuselage design, a 3D truss-type structure (Figure 3) which
consisted of several plan trusses was adopted. The plane truss members were made using a carbon strand/epoxy material via a winding technique. Each node of the plane truss was also formed from the carbon strand/epoxy composite material so that it can resist bending moment. The 3D carbon strand composite fuselage is shown in Figure 4. The mass estimation of the parts of the carbon strand composite Octarotor UAV is listed in Table 1.

![Figure 3. Carbon fiber truss design & manufacture](image1.png)

![Figure 4. Carbon fiber fuselage design & manufacture](image2.png)

| Components | Weight (kg) | Numbers | Total weight (kg) |
|------------|------------|---------|------------------|
| Crazy Motor 8320 100KV | 0.75 | 8 | |
| 3295 propeller | 0.12 | 8 | |
| Tattu 22000mAh 6S 25C | 2.5 | 2 | |
| T-motor FLAME 80A HV ESC | 0.1 | 8 | 30 |
| Pixhawks & Other components | 0.2 | 1 | |
| Carbon fiber fuselage | 1 | 1 | |
| Landing gear | 2.75 | 4 | |

Table 1. Mass estimation of UAV parts
3. Propeller Performance Analysis

3.1. Blade Element Momentum Theory

In this study, the UAV flight patterns under consideration consist of 4 types, i.e., lifting up, landing, hovering, and tilted flight. The aerodynamic performance of the propeller is analysed based on the Blade Element Momentum Theory (BEMT) [11]. Consider the UAV propeller thrust \( T \), airflow velocity \( (V_1) \), UAV flight speed \( (V_0) \), and propeller induced velocity \( (v_1) \) in the aerodynamic analysis. The flight velocities for different flight patterns are shown, respectively, in Figure 5a–d. The relations among the propeller parameters in each flight pattern are expressed as

\[
T = 2\rho \pi R^2 (V_0 + v_1)v_1
\]

where \( \rho \) is air density (kg/m³); \( R \) is radius of propeller (m).

To make calculation procedure simple, use \( \rho \pi R^2 (\Omega \cdot R) \) in propeller thrust to make a dimensionless parameter thrust coefficient \( (CT) \) which is expressed as

\[
CT = 2(V_0 + v_1) \cdot \frac{v_1}{v_0}
\]

with \( v_0 = \frac{V_0}{\Omega R}, v_1 = \frac{V_1}{\Omega R} \).

Therefore, the propeller induced velocity in lifting up condition \( v_1 \) is expressed as

\[
v_1 = -\frac{v_0}{2} + \sqrt{\left(\frac{V_0}{2}\right)^2 + \frac{CT}{2}}
\]

In the Landing condition, because the UAV moving direction is opposite to the lifting up condition, the propeller parameters are then expressed as

Landing thrust: \( T = -2\rho \pi R^2 (V_0 + v_1)v_1 \)

Landing airflow velocity: \( V_1 = v_1 - |V_0| \)

Landing thrust coefficient: \( CT = -2(V_0 + v_1) \cdot \frac{v_1}{v_0} \)

Landing induced velocity: \( v_1 = -\frac{v_0}{2} - \sqrt{\left(\frac{V_0}{2}\right)^2 - \frac{CT}{2}} \)

In the hovering condition, the UAV flight speed \( (V_0) \) is zero. Hence, the hover thrust and airflow velocity are expressed as

Hover thrust: \( T = 2\rho \pi R^2 v_1^2 \)

Hover thrust coefficient: \( CT = 2v_1^2 \)

Hover airflow velocity: \( V_1 = \frac{v_1}{\sqrt{\frac{CT}{2}}} \)

In the Tilted flight condition, the tilted angle \( (\alpha) \) must be considered. The propeller parameters in the tilted flight are expressed as

Tilted flight thrust: \( T = 2\rho \pi R^2 V_1 v_1 \)
Tilted flight airflow velocity: \( \overrightarrow{V_1} = \overrightarrow{V_0} + \overrightarrow{V_1} = V_0 \sin \alpha_2 + v_1 \cos(\alpha_1 - \alpha_2) \) (7b)

Tilted flight thrust coefficient: \( CT = 2 \overrightarrow{V_1} \cdot \overrightarrow{v_1} \) (7c)

\[
\begin{align*}
\text{Tilted flight} \\
\text{thrust coefficient: } CT &= 2 \overrightarrow{V_1} \cdot \overrightarrow{v_1} \quad \text{(7c)}
\end{align*}
\]

\[
\begin{align*}
\text{Tilted flight airflow velocity: } \overrightarrow{V_1} &= \overrightarrow{V_0} + \overrightarrow{V_1} = V_0 \sin \alpha_2 + v_1 \cos(\alpha_1 - \alpha_2) \quad \text{(7b)}
\end{align*}
\]

Figure 5. Propeller momentum theory model: (a) Lifting up, (b) Landing, (c) Hovering, (d) Tilted flight

According to the BEMT (Figure 6), the equations of airfoil lift and drag forces \((dL_i, dD_i)\) on each section are represented as

\[
\begin{align*}
\text{Lift force: } dL_i &= \frac{1}{2} C_{Li} \rho U_i^2 c_i \text{dr} \quad \text{(8a)} \\
\text{Drag force: } dD_i &= \frac{1}{2} C_{Di} \rho U_i^2 c_i \text{dr} \quad \text{(8b)}
\end{align*}
\]

As a consequence, the equations of the propeller thrust \((T)\), torque \((Q)\) and power \((P)\) for \(N\) propeller blades are represented as

\[
\begin{align*}
T &= N \sum_{i=1}^{n} dL_i \cos \varphi - dD_i \sin \varphi \quad \text{(9a)} \\
Q &= N \sum_{i=1}^{n} dL_i \sin \varphi + dD_i \cos \varphi \cdot r_i \quad \text{(9b)} \\
P &= N \sum_{i=1}^{n} dL_i \sin \varphi + dD_i \cos \varphi \cdot r_i \Omega \quad \text{(9c)}
\end{align*}
\]
4. Power Analysis of Propulsion System

4.1. Power transmission loss

In the propulsion system, the Li-po battery provides the electric power ($P_{in}$) to eight DC-brushless motors which transform the electric power to the mechanical power ($P_M$) of the propellers. In the transmission process (Figure 7), the Li-po battery may have different power losses, such as Back EMF loss ($P_m$), iron loss ($P_I$), and Copper loss ($P_C$) [12]. Therefore, the propeller mechanical power ($P_M$) is represented as

$$P_M = M \cdot \omega$$  \hspace{1cm} (10)

where $M$ is torque; $\omega$ is rotational speed (rad/s).

The DC-brushless motors power losses are represented as

$$P_m = V_m \cdot I_m$$  \hspace{1cm} (11)

where $V_m$ is voltage of Back EMF; $I_m$ is current of Back EMF. The iron loss ($P_I$) is expressed as

$$P_I = k \cdot f \cdot B^2$$  \hspace{1cm} (12)

where $k$ is Steinmetz coefficients; $B$ is the peak magnetic flux density (tesla, T); $f$ is frequency (Hz).

The copper loss ($P_C$) is expressed as

$$P_C = I^2 \cdot R_m$$  \hspace{1cm} (13)

where $R_m$ is resistance of the propulsion system circuit.

The equation of propulsion system power transmission is then represented as

$$P_{in} = P_M + P_m + P_I + P_C$$  \hspace{1cm} (14)

Figure 7. Propulsion system power transmission process
4.2. Calculation of UAV energy consumption

In this study, the propulsion system power consumption is converted to energy consumption ($E_{pro}$) so that the difference between $E_{pro}$ and Li-po battery energy storage ($E_{bat}$) can be calculated. The UAV energy consumption is represented as

\[ E_{pro} = P_m * t = (P_M + P_m + P_I + P_C) * t \]  \hspace{1cm} (15)

where $E_{pro}$ = propulsion system energy consumption(J); $P_m$ = battery power (W); $t$ = time (sec).

The equation of Li-po battery energy storage is represented as

\[ E_{bat} = V_{bat} * C_{bat} * 3600(\text{secs}) \]  \hspace{1cm} (16)

where $V_{bat}$ is voltage supply of battery (V), $C_{bat}$ is capacity of battery (Ah).

Therefore, the UAV energy consumption percentage ($C$) in a flight process is represented as

\[ C = 100 - \left( \frac{E_{bat} - E_{pro}}{E_{bat}} \right) * 100 \% \]  \hspace{1cm} (17)

5. Experimental Investigation

5.1. Relation between PWM value and throttle percentage

Before performing flight experiment, because the Remote Controller (RC) throttle input (%) will be converted to the PWM signal in Pixhawk flight controller (Figure 8) to decide motor output, the relation between PWM signal (motor output) and RC throttle percentage (input) must be established. The APM official Ground Controller Station software “Mission planner” can be used to simulate the output PWM signal of each movement (Figure 9). After the simulation, the PWM values can be converted to the RC throttle percentage as listed in Table 2.

![Figure 8. Pixhawk flight controller](image1)

![Figure 9. Motor output simulation via the Mission Planner](image2)

**Table 2. Conversion of PWM value to Throttle percentage**

| PWM Signal | percentage of throttle(%) |
|------------|---------------------------|
| 1900       | 100                       |
| 1860       | 96                        |
| 1820       | 90                        |
| 1780       | 85                        |
| 1740       | 80                        |
| 1700       | 75                        |
| 1660       | 70                        |
| 1620       | 65                        |
| 1580       | 60                        |
| 1540       | 55                        |

| PWM Signal | percentage of throttle(%) |
|------------|---------------------------|
| 1900       | 100                       |
| 1860       | 96                        |
| 1820       | 90                        |
| 1780       | 85                        |
| 1740       | 80                        |
| 1700       | 75                        |
| 1660       | 70                        |
| 1620       | 65                        |
| 1580       | 60                        |
| 1540       | 55                        |
5.2. Experimental set up

The experimental apparatus similar to the one in [13] is shown in Figure 10. The propulsion system (propeller and motor) is situated on the left top end of the steel beam. The load cell underneath the steel beam and Arduino will be used to attain the propeller thrust value when the propulsion system pushes the beam downward. The voltage, current, and power values of the motor during the operation time are measured using the Wattmeter.

![Figure 10. Propulsion system test apparatus](image)

**Figure 10. Propulsion system test apparatus**

5.3. Analysis of propulsion system performance

In the propulsion system performance analysis, the propeller airfoil type is treated as NACA 2409 (Figure 11). The software “Javafoil” is used to determine the lift and drag force coefficients ($C_L$, $C_D$) at different sections the blade in the BEMT analysis.

![Figure 11. NACA 2409 airfoil](image)

**Figure 11. NACA 2409 airfoil**

5.4. Comparison of theoretical and experimental data

After the analysis and testing of the UAV parts have been conducted, the data of UAV propulsion system thrust (Figure 12) and power consumption (Figure 13) are used to estimate UAV energy consumption in the actual flight test. In the rotor test, the thrust errors between BEMT analyses and test results are in the range of 15.8%~25.6%. With respect to the power consumption results, the theoretical prediction which includes BEMT propeller power and motor losses (e.g., Back EMF losses, Iron losses, and Copper losses) is compared with the test value measured using the wattmeter. The error between the theoretical and experimental predictions in the range of power consumption is 1.1%~27.1%. The errors for different cases are given as
Thrust:

![Thrust chart]

| Throttle (%) | Motor speed (RPM) | Measurement (gf) | Estimation (gf) | Errors (%) |
|--------------|-------------------|------------------|-----------------|------------|
| 30           | 1465              | 1800             | 2419.8          | 25.6       |
| 40           | 1824              | 2900             | 3725.7          | 22.2       |
| 50           | 2250              | 4800             | 5702.4          | 15.8       |
| 60           | 2600              | 6300             | 7576.3          | 16.8       |

Figure 12. Propulsion system analysis result (Thrust)

Power:

![Power consumption chart]

| Throttle (%) | Motor speed (RPM) | KV  | BEMT Propeller power (w) | Back EMF losses (w) | Iron losses (w) | Copper losses (w) | Estimation (w) | Measurement (w) | Errors (%) |
|--------------|-------------------|-----|---------------------------|---------------------|-----------------|-----------------|----------------|----------------|------------|
| 30           | 1465              | 100 | 92.35                     | 60.07               | 37.79           | 10.34           | 200.6         | 275            | 27.1       |
| 40           | 1824              |     | 177.19                    | 101.96              | 37.79           | 26.48           | 343.4         | 415            | 18.0       |
| 50           | 2250              |     | 329.9                     | 160.88              | 37.79           | 57.79           | 586.4         | 650            | 9.8        |
| 60           | 2600              |     | 499.91                    | 207.2               | 37.79           | 94.22           | 839.2         | 830            | -1.1       |

Figure 13. Theoretical and experimental predictions of power consumption

5.5. Flight test plan

The composite Octarotor UAV (Figure 14) was used in the flight test. In the experimental study, two flight tests (Figure 15.) were performed to determine the energy consumptions of the UAV under different payload conditions. The two flight tests basically have the same flight pattern except that for the first test the total UAV weight is 30kg while the second 35kg.
6. Result & Discussion

6.1. UAV power consumptions in flight tests 1 and 2

The test results of the two flight missions are listed in Table 3 for comparison. It is noted that, as expected, the power consumption will increase when the payload increases. Furthermore, the battery power consumption record for flight tests 1 and 2 are shown in Figures 16 and 17, respectively. It is noted that the battery power consumptions for flight tests 1 and 2 are 2757mAh and 3040mAh, respectively, which are 12.53% and 13.82 % of the full amount (22000mAh).

| Movement          | Throttle (%) | Rotation speed (RPM) | Power consumption (w) | Numbers of motor operation | Throttle (%) | Rotation speed (RPM) | Power consumption (w) | Numbers of motor operation |
|-------------------|--------------|----------------------|-----------------------|---------------------------|--------------|----------------------|-----------------------|---------------------------|
| Lifting up        | 50           | 2250                 | 586.4                 | 8                         | 54           | 2392                 | 673.9                 | 8                         |
| Hover             | 47           | 2150                 | 501.0                 | 8                         | 50           | 2250                 | 586.4                 | 8                         |
| Tilted flight-high | 54           | 2392                 | 673.9                 | 4                         | 57           | 2525                 | 771.9                 | 4                         |
| Tilted flight-low | 40           | 1950                 | 343.4                 | 4                         | 43           | 1980                 | 419.6                 | 4                         |
| Landing           | 37           | 1790                 | 324.4                 | 8                         | 40           | 1824                 | 343.4                 | 8                         |
Figure 16. Battery consumption record of flight test 1

Figure 17. Battery consumption record of flight test 2

6.2. Comparison of theoretical and experiment results for flight mission 1

The theoretical prediction of the energy consumption for flight mission 1 is listed in Table 4. It is noted that the theoretically predicted percentage of energy consumption is 13.5%. As compared with the experimental result listed in Table 5, the error is 7.2%. The small difference between the theoretical and experimental predictions has indicated that the proposed procedure for energy consumption estimation of UAV is feasible and acceptable.

Table 4. Theoretical Octarotor energy consumption estimation for flight mission 1

| Movement         | Operation time (s) | Energy consumption (kJ) | Theoretical total energy consumption (kJ) | Ratio of total energy consumption to maximum energy (%) |
|------------------|--------------------|-------------------------|------------------------------------------|-------------------------------------------------------|
| Lifting up       | 28                 | 131.3                   |                                          |                                                       |
| Hover            | 34                 | 136.3                   |                                          |                                                       |
| Tilted flight -high | 58               | 156.3                   | 535                                      | 13.5                                                  |
| Tilted flight -low | 58                | 79.7                    |                                          |                                                       |
| Landing          | 12                 | 31.1                    |                                          |                                                       |
Table 5. Comparison of theoretical and experimental predictions (Flight mission 1)

| Theoretical estimation (%) | Experiment (%) | Error (%) |
|-----------------------------|----------------|-----------|
| 13.5                        | 12.53          | 7.2       |

Error = 100 x (Estimation – Experiment)/Experiment (%)

6.3. Comparison of theoretical and experiment results for flight mission 2

The theoretical prediction of the energy consumption for flight mission 2 is listed in Table 6. It is noted that the theoretically predicted percentage of energy consumption is 14.92%. As compared with the experimental result listed in Table 7, the error is 7.38%. Again, the small difference between the theoretical and experimental predictions has indicated that the proposed procedure for energy consumption estimation of UAV is feasible and acceptable.

Table 6. Theoretical Octarotor energy consumption estimation for flight mission 2

| Movement         | Operation time (s) | Energy consumption (kJ) | Theoretical total energy consumption (kJ) | Ratio of total energy consumption to maximum energy (%) |
|------------------|--------------------|-------------------------|------------------------------------------|-------------------------------------------------------|
| Lifting up       | 22                 | 118.6                   |                                          |                                                       |
| Hover            | 44                 | 206.4                   |                                          |                                                       |
| Tilted flight -high | 50               | 154.4                   | 591                                      | 14.92                                                |
| Tilted flight -low | 50                | 83.9                    |                                          |                                                       |
| Landing          | 10                 | 27.5                    |                                          |                                                       |

Table 7. Comparison of theoretical and experimental predictions (Flight mission 2)

| Theoretical estimation (%) | Experiment (%) | Error (%) |
|-----------------------------|----------------|-----------|
| 14.92                       | 13.82          | 7.38      |

Error = 100 x (Estimation – Experiment)/Experiment (%)

7. Conclusion

An Octarotor UAV fabricated using carbon strand/epoxy composite material was developed for flight testing. A procedure has been presented to estimate the power consumption of the UAV. Appropriate equations and testing techniques have been used to estimate the power consumptions of the essential parts of the UAV. The power consumptions of the essential parts have been used to predict the total energy consumptions of the UAV for different flight missions. Two flight tests have been performed to measure the energy consumptions of the UAV. The experimental results have validated the accuracy and feasibility of the proposed energy consumption estimation procedure. It has been shown that the proposed procedure can produce good predictions with percentage errors less than 7.4%. The proposed procedure may find applications in UAV design and flight mission planning.
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