Modeling Power Consumptions for Multirotor UAVs

HAO GONG, Member, IEEE
BAOQI HUANG, Member, IEEE
BING JIA, Member, IEEE
INNER MONGOLIA UNIVERSITY, HOHHOT, CHINA
HANSU DAI
AVIC CHENGDU AIRCRAFT DESIGN AND RESEARCH INSTITUTE, CHENGDU, CHINA

Abstract—Unmanned aerial vehicles (UAVs) have various advantages, but suffer from their limited energy in practical applications. Therefore, it is important to establish reasonable power consumption models for further efficient power. However, most existing works either establish theoretical power consumption models for fixed-wing UAVs and single-rotor UAVs or provide heuristic power consumption models for multirotor UAVs without rigorous mathematical derivations. This article aims to establish theoretical power consumption models for multirotor UAVs. To be specific, the closed-form power consumption models for a multirotor UAV in three flight statuses, i.e., forward flight, vertical ascent, and vertical descent, are derived by leveraging the relationship between single-rotor UAVs and multirotor UAVs in terms of power consumptions. On this basis, a generic flight power consumption model for the UAV in a 3-D scenario is obtained. Extensive experiments are conducted in real scenarios by using DJI M210 and a mobile app developed based on DJI Mobile SDK, and confirm the correctness and effectiveness of these models; in addition, power consumption model-based simulations are performed to further investigate the effect of the number of rotors and weight of payload on UAV power consumptions. The proposed power consumption models not only reveal how power consumptions of multirotor UAVs are affected by various factors, but also pave the way for introducing other applications.

1. INTRODUCTION

In recent years, unmanned aerial vehicles (UAVs) have found a significant number of applications in wireless communication, power grid inspection, and so on, due to their decreasing expense and increasing functionality [1], [2], [3], [4], [5], [6], [7]. However, energy limitation is always a key and unavoidable issue in UAV applications [8], [9], [10], which leads to more studies focusing on the power consumption of UAVs. In addition, UAV power consumption mainly consists of two parts: one is the conventional communication-related power consumption due to, e.g., signal transmission, circuits, and power amplification; the other is the flight power consumption to ensure that the UAV remains aloft and supports its movement. In general, the flight power consumption depends on the flight status and is usually much more significant than communication-related power consumptions. Thus, it is important to understand how the UAV power consumption varies with its flight status and also important to model the flight power consumption.

Prior research on UAV power consumption models can be loosely classified into three categories. The first category is simply applying the existing power models of the ground vehicles or robots to UAVs [11], [12], [13], [14], [15]. However, the power consumption models for mobile vehicles or robots moving on the ground are not suitable for UAVs due to their fundamentally different moving mechanisms. Therefore, more effective and feasible models belonging to the second category are proposed, i.e., the experiment-driven heuristic power consumption models based on measured/simulated data [16], [17], [18], [19], [20]. For instance, in [16], some brief experiments were performed to model the power consumptions of a few basic UAV (e.g., quadcopter UAV) maneuvering actions. Similarly, given a quadcopter UAV, a power consumption model involving its speed and operating conditions is given in [17] based on experimental results. However, both the power models in [16] and [17] were simply expressed in relation to speed neglecting the effect of other crucial factors on UAV power consumptions, such as the number of rotors and weight of payload and so on, thus the lack of more accurate closed-form expression limits their applications. Besides, by analyzing battery performance, some power consumption models of electrically powered UAVs were obtained in [18], [19], and [20], and the above defects were found to exist. Therefore, in order to theoretically investigate the power consumptions of UAVs and improve the applicability of the resulting models, the last category considers theoretical power consumption models based on kinematic and aircraft theory [21], [22], [23], such as [24], [25], [26], [27], and [28]. For example, a generic power consumption model as a function of the UAV’s velocity and acceleration was derived for fixed-wing UAVs in [24], which cannot be applied for rotary-wing UAVs due to...
their fundamentally different mechanical designs; in [25], a closed-form power consumption model was derived for single-rotor UAVs in 1-D forward flight at a constant speed without acceleration/deceleration, and have been used to study the energy-efficient UAV communications in [29] and [30] and was also extended in [26] and [27] by deriving an analytical model for single-rotor UAVs in 2-D forward flight; in addition, the model in [25] was further validated in [28] by fitting UAV measurement data collected from wide experiments; moreover, the power consumption model for single-rotor UAVs in vertical flight is also derived in [27]. All the above works provided valuable guidance on establishing power consumption models for UAVs.

However, considering the power consumption models for multirotor UAVs which are the most popular kind of UAVs today, existing works [16], [17], [18], [19] only gave heuristic power consumption models without rigorous mathematical derivation, limiting their applications in many research fields. Therefore, great efforts have to be devoted to deriving theoretical power consumption models for multirotor UAVs. In addition, prior studies [25], [26], [27] on theoretical power consumption models only considered the UAVs’ flight statuses in 1-D or 2-D scenarios, while ignoring general 3-D scenarios motivating studies of the corresponding power consumption characteristics for the UAVs in 3-D scenarios.

This article tackles the problem of lacking theoretical power consumption models for multirotor UAVs in general flight scenarios. To be specific, first, based on the analysis of the relationship between the power consumption of single-rotor UAVs and multirotor UAVs, the 2-D closed-form power consumption models for multirotor UAVs in horizontal and vertical flight statuses are established, which not only promotes the analysis of UAV power consumption performance, but also provides guidance for the study of UAV energy consumption optimization. Then, in order to explore power consumptions of multirotor UAVs in 3-D scenarios, a 3-D power consumption model is extended by integrating the proposed 2-D models.

To verify the effectiveness of the proposed power consumption models, a large number of flight experiments were conducted in real scenarios, and a large amount of UAV flight data were collected. It is shown that the predicted power consumptions of the proposed 2-D models not only exhibit better agreement with the actual power consumptions but also significantly outperform the predicted power consumptions using the existing power models [31]; in addition, the proposed 3-D model also presents good power consumption prediction performance. Based on the proposed power consumption models, simulations are further carried out to analyze the effects of the number of rotors and payload weight on UAV power consumptions, and the results show that power consumptions of UAVs always increase with payload weights increasing, however, the relationship between power consumptions and the number of rotors does not change in the same way under different flight statuses and different flight speeds.

The major contributions of this article are as follows.

1) The 2-D closed-form models are developed to characterize the power consumptions of multirotor UAVs in horizontal and vertical flight with respect to speeds and hardware parameters.
2) The 3-D closed-form model is obtained to predict the power consumptions of multirotor UAVs in generic scenarios.
3) Extensive experiments are performed to collect UAV flight data to verify the effectiveness of the aforementioned models.
4) Simulations are conducted to analyze the effect of various parameters on power consumptions of UAVs, including the number of rotors and weight of payload.

The rest of this article is organized as follows. Section II provides an overview of power consumption models of single-rotor UAVs. Section III establishes 2-D and 3-D power consumption models of multirotor UAVs. Section IV carries out the experimental validation of the proposed models. Section V reports the simulation analysis results. Finally, Section VI concludes this article.

II. SINGLE-ROTOR UAV POWER CONSUMPTION MODELS

In order to better analyze and utilize the energy of single-rotor UAVs, various power consumption models have been reported and can be extended for formulating power models for multirotor UAVs due to the fact that multirotor UAVs can be regarded to some extent as an extension of single-rotor UAVs. Therefore, prior to introducing the multirotor UAV case, it is necessary to understand the single-rotor UAV case. To this end, a brief overview of the theoretical power consumption models for single-rotor UAVs is presented in this section. Specifically, the closed-form power consumption models for single-rotor UAVs in horizontal flight and vertical flight shall be elaborated in [25] and [27], respectively. The main notations used in this section are summarized in Table I.

A. Power Consumption Models for a Single-Rotor UAV in Horizontal Flight

In this subsection, the power consumption required for a single-rotor UAV in horizontal flight status is modeled, and in particular, the power consumption of the UAV in hovering status, i.e., the UAV horizontal speed equals to 0, is also modeled.

According to [25], the power consumed by a single-rotor UAV to hover can be expressed as

$$P_h = \frac{\delta}{8} \rho A \Omega^2 R^4 + (1 + k) \frac{W^{3/2}}{\sqrt{2 \rho A}}$$

(1)

where $P_h$ and $P_t$ are two constants representing the blade profile power and induced power, respectively. Based on (1), the power consumption of a hovering UAV is denoted...
TABLE I

List of Main Notations

| Notation | Physical meaning | Simulation value |
|----------|------------------|------------------|
| $\delta$ | Profile drag coefficient | 0.011 |
| $\rho$ | Air density in kg/m$^3$ | 1.168 |
| $s$ | Rotor solidity | 0.045 |
| $A$ | Rotor disc area in m$^2$ | 0.214 |
| $\Omega$ | Blade angular velocity in radians/second | - |
| $R$ | Rotor radius in meter (m) | 0.26 |
| $k$ | Incremental correction factor to induced power | 0.11 |
| $W$ | UAV weight in Newton | 20 |
| $\kappa$ | Thrust-to-weight ratio, $\kappa \triangleq \frac{P_W}{W}$ | 1 |
| $v_0$ | Mean rotor induced velocity in hover | 6.325 |
| $S_{FP\parallel}$ | Fuselage equivalent flat plate area in horizontal status in m$^2$ | 0.009 |
| $S_{FP\perp}$ | Fuselage equivalent flat plate area in vertical status in m$^2$ | 0.377 |
| $C_T$ | Thrust coefficient | 0.001195 |

As $P_1 = P_0 + P_i$, which is a finite value depending on the UAV weight, air density, rotor disc area, and so on.

Furthermore, provided that the single-rotor UAV is flying horizontally at a constant speed, say $V$, the corresponding power consumption in [25] can be expressed as

$$P_2(V, \kappa) = P_0 \left(1 + \frac{3V^2}{\Omega^2r^2}\right) + P_0 \kappa \left(\sqrt{\frac{V^2}{4v_0^2} - \frac{V^2}{2v_0^2}}\right)^{1/2}$$

$$+ \frac{1}{2} S_{FP\parallel} \rho V^3$$

where the first two terms denote the blade profile power and induced power in horizontal flight status, respectively, and are dependent on the specific speed $V$ instead of staying constant as in the hovering status; $S_{FP\parallel} \rho V^3/2$ denotes the parasite power. It can be observed from (2) that the blade profile power and parasite power increase quadratically and cubically with $V$, respectively, and are necessary for overcoming the profile drag of the blades and the fuselage drag [23, eq. (4.5)], respectively. Besides, the induced power can be regarded as the power to overcome the induced drag of the blades, and decreases with $V$ increasing.

B. Power Consumption Models for a Single-Rotor UAV in Vertical Flight

On the basis of the analysis in [25], a closed-form power consumption model for a single-rotor UAV in vertical flight was reported in [27], i.e.,

$$P_3(V, T) = P_1 + \frac{1}{2} TV + \frac{T}{2} \sqrt{V^2 + \frac{2T}{\rho A}}$$

where $T$ is the rotor thrust, and the other parameters are the same as above. The vertical flight of single-rotor UAVs usually includes vertical ascent and vertical descent, which should have different values of $T$ because of the different drag directions. Therefore, given the same speed $V$, the corresponding powers required for a single-rotor UAV in vertical ascent and vertical descent are certainly different. Meanwhile, it follows from (3) that the speed $V$ is assumed nonzero only in the vertical direction.

The above closed-form formulae (1)–(3) describe the power consumed by a single-rotor UAV in different flight statuses, but cannot be directly applied to multirotor UAVs. To this end, power consumption models for multirotor UAVs shall be investigated in Section III.

III. MULTIROTOR UAV POWER CONSUMPTION MODELS

In this section, multirotor UAVs and an abstract representation of power consumptions of multirotor UAVs are first introduced, then closed-form power consumption models for multirotor UAVs in both horizontal flight and vertical flight with a constant speed in 1-D or 2-D scenarios are derived, and finally, 3-D scenarios are taken into consideration.

A. Analysis of Multirotor UAVs

There are different classification methods for multirotor UAVs, e.g., multirotor UAVs with an even or odd number of rotors according to the parity of the number of rotors. However, the application scope of the former is wider than that of the latter due to its simple flight control mechanism. Therefore, for the purpose of conducting tractable analysis, this article only deals with multirotor UAVs with an even number of rotors, such as quadcopter UAVs, hexacopter UAVs, and so on, and does not consider double-layer multirotor UAVs. The extension to general multirotor UAVs is left as future work.

In order to apply the models in relation to single-rotor UAVs, the relationship between multirotor UAVs and single-rotor UAVs in terms of power consumptions should be understood. Given a multirotor UAV, it is commonly assumed that each rotor is identical and symmetrically distributed [32], such that the axial momentum theory applies [23]; moreover, the multirotor UAV is assumed to be composed of multiple identical single-rotor UAVs, the number of which equals to the number of rotors of the multicopter UAV. On this basis, the power consumption of the multirotor UAV can be approximately evaluated by summing up the power consumptions of multiple single-rotor UAVs. In order to facilitate the subsequent analysis, define the following notations.

1) The multirotor UAV of weight $W$ has $n$ rotors.
2) The weight assigned to each rotor is $W_r$, i.e., $W_r = \frac{W}{n}$.
3) The thrust of the multirotor UAV is defined as $T_r$, i.e., $T_r = \sum T_i$.

4) The thrust of the $i$th rotor in the multirotor UAV is $T_i$, i.e., $T = \sum T_i$.

Given the multirotor UAV, the parameters associated with each rotor include $\delta, A, s, C_T, k, v_0, \rho, S_{FP\parallel}$ and $S_{FP\perp}$, where $C_T$ is the thrust coefficient, $S_{FP\parallel}$ is the fuselage equivalent flat plate area in horizontal status, and the others are the same as those in Table I.
B. Power Consumption Models for the Multirotor UAV in Horizontal Flight

Prior to presenting the models, consider the angular velocity of rotors in (1)–(3), namely $\Omega$. It is known that the flight of the multirotor UAV is implemented by controlling the angular velocity of each rotor, such that different thrusts are produced by setting different angular velocities of the multiple rotors. Since the thrust $T$ is proportional to the squared blade angular velocity $\Omega$, i.e., $\Omega = \sqrt{\frac{T}{c_T p A \rho}}$ given by [23, eq. (11.1)], $\Omega$ can be substituted by this formula involving $T$ and other parameters.

In actual flight, the thrust provided by each rotor of the multirotor UAV varies according to different flight statuses. When the multirotor UAV is hovering, the thrust $T$ balances the UAV’s weight, so that each rotor of the UAV shall provide the same thrust, namely that the thrust of the $i$th rotor $T_i$ equals $W_t$, which is $W/n$. Based on (1), the power consumed by the $i$th rotor of the hovering multirotor UAV, denoted $P_{ih}$, can be formulated by

$$P_{ih} = W_{r}^{3/2} C_T^{-3/2} \frac{\delta_s}{8 \sqrt{\rho A}} + (1 + k) \frac{W_{r}^{3/2}}{2 \sqrt{\rho A}}.$$  

Thus, the power consumed by the multirotor UAV in hovering can be obtained by summing up the power consumptions of all rotors, denoted $P_{mh}$, as follows:

$$P_{mh} = \sum_{i=1}^{n} P_{ih} = n \times W_{r}^{3/2} \times \left( C_T^{-3/2} \frac{\delta_s}{8 \sqrt{\rho A}} + (1 + k) \frac{W_{r}^{3/2}}{2 \sqrt{\rho A}} \right) = \frac{\delta_s}{8 \sqrt{n \rho A}} \left( W_{r}^{3/2} \frac{C_T}{C_T} \right) + (1 + k) \frac{W_{r}^{3/2}}{2 \sqrt{n \rho A}}$$  

where $P_{hm}$ and $P_{in}$ denote the blade profile power and induced power of the hovering UAV, respectively. It can be found that $P_{hm}$ increases with $n$ decreasing, and when $n$ decreases to 1, $P_{hm}$ is equal to $P_{ih}$ in form; in addition, $P_{ih}$ and $P_{nh}$ are usually approximated as two constants due to their parameter expressions for the UAV hovering at a fixed height.

Furthermore, provided that the multirotor UAV is in horizontal flight, the simplified schematic of the forces acting on the straightforwardly flying UAV at a fixed height is shown in Fig. 1, where $\alpha_T$ is the tilt angle of the rotor disc and the forces include the rotor thrust $T$, fuselage drag $D$ and UAV weight $W$. Given a constant speed $V$, the following formulae will hold:

$$T \cos \alpha_T = W,$$

$$T \sin \alpha_T = D$$  

(6)

which indicates that $T$ is equal to $\sqrt{W^2 + D^2}$, but since $\alpha_T$ is usually very small when the UAV flies at a constant speed [25], it can be obtained that $T \approx W$, so that the corresponding thrust-to-weight ratio (TWR) of each rotor is also approximately 1. Therefore, based on (2) and (4),

when the multirotor UAV flies horizontally with a constant speed $V$, the power consumption $P_f(V)$ associated with the $i$-th rotor of the UAV can be formulated as

$$P_{f}(V) = \frac{\delta_s}{8 \sqrt{\rho A}} \left( W_{r} \frac{C_T}{C_T} \right)^{3/2} + \frac{3 \delta_s}{4 \sqrt{\rho A}} \left( W_{r} \frac{C_T}{C_T} \right) V^2 + (1 + k)$$

$$\times \frac{W_{r}^{3/2}}{2 \sqrt{\rho A}} \left( \sqrt{1 + \frac{V^4}{4 V_0^2}} - \frac{V^2}{2 V_0^2} \right)^{1/2} + \frac{1}{2} S_{FP} \rho V^3.$$  

(7)

Accordingly, the corresponding power consumption, denoted $P_{mf}(V)$, of the multirotor UAV can be derived as follows:

$$P_{mf}(V) = \sum_{i=1}^{n} P_{f}(V)$$

$$= n \times \left[ \frac{\delta_s}{8 \sqrt{\rho A}} \left( W_{r} \frac{C_T}{C_T} \right)^{3/2} + \frac{3 \delta_s}{4 \sqrt{\rho A}} \left( W_{r} \frac{C_T}{C_T} \right) V^2 + (1 + k) \right]$$

$$+ \frac{W_{r}^{3/2}}{2 \sqrt{\rho A}} \left( \sqrt{1 + \frac{V^4}{4 V_0^2}} - \frac{V^2}{2 V_0^2} \right)^{1/2} + \frac{1}{2} S_{FP} \rho V^3$$

(8)

C. Power Consumption Models for the Multirotor UAV in Vertical Flight

According to the aforementioned discussions, the determination of the thrust is key to deriving the power consumption models for the multirotor UAV. Thus, the corresponding thrusts for the multirotor UAV in vertical flight are first formulated. Specifically, two schematics with respect to vertical ascent and vertical descent are illustrated in Fig. 2 by involving the forces acting on the UAV, where $T_a$ ($T_d$)
and \(D_a (D_d)\) denote the thrust and fuselage drag of the UAV associated with vertical ascent (descent), respectively.

Therefore, provided that the multirotor UAV is in vertical flight with a constant speed, it can be obtained as

\[
T_a - W = D_a
\]  \hspace{1cm} (9)

for vertical ascent and

\[
W - T_d = D_d
\]  \hspace{1cm} (10)

for vertical descent. Although the multirotor UAV ascends or descends both at a constant speed, the corresponding thrusts \(T_a\) and \(T_d\) will be different, and in particular, since both \(D_a\) and \(D_d\) are greater than 0, the former will be larger than the latter regardless of the speed.

As was discussed in the preceding subsection, the power consumed by the multirotor UAV in vertical flight can be calculated by summing up the power consumptions of all rotors. As such, it is necessary to obtain the power consumption of each rotor by determining its thrust. To be specific, due to the equality among the thrust of each rotor given the vertical flight of a multirotor UAV, their corresponding power consumed by the thrust of each rotor, denoted \(P^i\), can be abbreviated as

\[
P_d^i (V, T_a^i) = P_{ho}^i + \frac{1}{2} T_d^i V + \frac{T_d^i}{2} \sqrt{V^2 + \frac{2 T_d^i}{\rho A}}
\]  \hspace{1cm} (12)

which can be found that the difference between the two is caused by the thrusts in (11), and will become more obvious with \(V\) increasing.

According to (12), the corresponding power consumed by the multirotor UAV, denoted \(P_{ma}(V, T_a)\) or \(P_{md}(V, T_d)\), can be calculated as follows:

\[
P_{ma}(V, T_a) = \sum_{i=1}^{n} P_d^i (V, T_a^i)
\]

\[
= n \times \left( P_{ho} + \frac{1}{2} T_d V + \frac{T_d}{2} \sqrt{V^2 + \frac{2 T_d}{\rho A}} \right)
\]

\[
= P_{hvo} + \frac{1}{2} W V + \frac{n}{4} S_{FP, \perp} \rho V^3 + \left( \frac{W}{2} + \frac{n}{4} S_{FP, \perp} \rho V^2 \right) \left( 1 + \frac{S_{FP, \perp}}{A} \right) V^2 + \frac{2 W}{n \rho A}
\]  \hspace{1cm} (13)

or

\[
P_{md}(V, T_d) = \sum_{i=1}^{n} P_d^i (V, T_d^i)
\]

\[
= n \times \left( P_{ho} + \frac{1}{2} T_d V + \frac{T_d}{2} \sqrt{V^2 + \frac{2 T_d}{\rho A}} \right)
\]

\[
= P_{hvo} + \frac{1}{2} W V - \frac{n}{4} S_{FP, \perp} \rho V^3 + \left( \frac{W}{2} - \frac{n}{4} S_{FP, \perp} \rho V^2 \right) \left( 1 - \frac{S_{FP, \perp}}{A} \right) V^2 + \frac{2 W}{n \rho A}
\]  \hspace{1cm} (14)

Since \(T_a\) and \(T_d\) only vary with \(V\) according to (11), \(P_{ma}(V, T_a)\) and \(P_{md}(V, T_d)\) can be abbreviated as \(P_{ma}(V)\) and \(P_{md}(V)\), respectively. It follows that \(P_{ma}(V)\) increases with \(V\) increasing, but the change in \(P_{md}(V)\) is difficult to be observed due to the complicated formulation. Besides, although both vertical ascent and vertical descent belong to the vertical flight of a multirotor UAV, their corresponding power consumptions are significantly different, and particularly, the former is theoretically larger than the latter for the given speed \(V\) (see Appendix A), inspiring careful consideration of the choices of ascent or descent for energy consumption aware path optimization.

D. Generic Flight Power Model

In previous subsections, the power consumption models for the multirotor UAV in horizontal flight and vertical flight in 1-D or 2-D scenarios have been obtained. But in practice, UAVs usually operate in 3-D scenarios, which involve not only horizontal or vertical flight, but also other statuses, including forward ascent, forward descent, and so
on. Therefore, it is necessary to extend the power consumptions of UAVs in 3-D flights and establish a more generic power consumption model.

Prior to the extension, the following factors should be taken into consideration. First, velocity is the most critical factor in determining the power consumptions of UAVs according to the aforementioned discussions. Second, the total power consumed by the multirotor UAV can be studied by analyzing the corresponding vertical and horizontal power consumptions [26]. Supposed that the multirotor UAV flies in a 3-D scenario with the velocity \( \mathbf{V}_v \), as shown in Fig. 3, which can be decomposed into three velocities in three distinct directions, namely \( \mathbf{V}_x, \mathbf{V}_y \), and \( \mathbf{V}_z \), respectively, with the three axes of X, Y, and Z representing the three directions of east, north, and up, respectively; for ease of presentation, let \( \mathbf{V}_h \) and \( \mathbf{V}_v \) denote the horizontal velocity and vertical velocity of the UAV, respectively.

According to a similar analysis in [33], the power consumed by the UAV can be expressed by using the power consumption increments in horizontal and vertical directions. On this ground, the power consumption of the multirotor UAV in any steady flight (i.e., without acceleration or deceleration) can be modeled as

\[
P_{\text{total}}(\mathbf{V}_u) = P_{\text{min}} + \Delta P_h(\mathbf{V}_h) + \Delta P_v(\mathbf{V}_v) \tag{15}
\]

where \( \Delta P_h(\mathbf{V}_h) \) is the power consumption increment in the horizontal direction with horizontal velocity \( \mathbf{V}_h \), and \( \Delta P_v(\mathbf{V}_v) \) is the power consumption increment in the vertical direction with vertical velocity \( \mathbf{V}_v \).

Furthermore, according to (8), \( \Delta P_h(\mathbf{V}_h) \) can be easily expressed as

\[
\Delta P_h(\mathbf{V}_h) = \frac{3}{8} \sqrt{n} \delta \sqrt{\frac{W}{C_T}} s \left\| \mathbf{V}_h \right\|^2 + P_{\text{in}} \left( \sqrt{1 + \frac{\left\| \mathbf{V}_h \right\|^4}{4v_0^4}} - \frac{\left\| \mathbf{V}_h \right\|^2}{2v_0^2} \right) - 1
\]

+ \frac{n}{2} S_{FP} \rho \left\| \mathbf{V}_h \right\|^3 \tag{16}
\]

where \( \left\| \mathbf{V}_h \right\| \) is the norm of the horizontal velocity \( \mathbf{V}_h \).

Generally, the power consumptions of the UAV in vertical flight, denoted \( P_v(\mathbf{V}_v) \), only involves \( P_{ma} \) and \( P_{md} \), and does not hold when \( \mathbf{V}_v = 0 \); in order to ensure the integrity of \( P_v(\mathbf{V}_v) \) and facilitate the following analysis, the case of \( \mathbf{V}_v = 0 \) is supplemented as follows:

\[
P_v(\mathbf{V}_v) = \begin{cases} P_{ma}(\left\| \mathbf{V}_v \right\|) & \mathbf{V}_v > 0 \\ P_{\text{min}} & \mathbf{V}_v = 0 \\ P_{md}(\left\| \mathbf{V}_v \right\|) & \mathbf{V}_v < 0 \end{cases} \tag{17}
\]

where \( \left\| \mathbf{V}_v \right\| \) is the norm of the vertical velocity \( \mathbf{V}_v \).

Based on (13), (14), and (17), \( \Delta P_v(\mathbf{V}_v) \) can be concisely formulated as

\[
\Delta P_v(\mathbf{V}_v) = \frac{1}{2} W \left\| \mathbf{V}_v \right\| + sgn(\mathbf{V}_v) \frac{n}{4} S_{FP} \rho \left\| \mathbf{V}_v \right\|^3 + \left( \frac{W}{2} + sgn(\mathbf{V}_v) \frac{n}{4} S_{FP} \rho \left\| \mathbf{V}_v \right\|^2 \right) \times \sqrt{1 + \frac{sgn(\mathbf{V}_v) S_{FP}}{A} \left\| \mathbf{V}_v \right\|^2} + \frac{2W}{n\rho A} \left( \frac{\left\| \mathbf{V}_v \right\|}{2} \right) + (sgn(\left\| \mathbf{V}_v \right\|) - 1) \frac{W}{2} \frac{2W}{n\rho A} \tag{18}
\]

where \( sgn(\mathbf{V}_v) \) is the sign function with respect to \( \mathbf{V}_v \) to distinguish the powers consumed by the UAV in vertical ascent and vertical descent. As a result, given the multirotor UAV flying in 3-D scenarios with the velocity \( \mathbf{V}_u \), \( P_{\text{total}}(\mathbf{V}_u) \) can be further expressed by (19) shown at the bottom of the next page, which integrates the proposed 2-D power consumption models for the multirotor UAV and theoretically extends it to 3-D scenarios, enriching the research in the field of UAV power consumptions.

IV. EXPERIMENTS

In this section, extensive experiments were conducted to validate the theoretical power consumption models for multirotor UAVs derived in the previous section. Then, the details of the experimental data processing are presented, and the experimental results are reported.

A. Experimental Setup

The experiments were conducted by using DJI M210 RTK V2, a quadcopter UAV (see Fig. 4), in the square of Inner Mongolia University in Hohhot, China, which is an open field surrounded by buildings minimizing the effect of winds, as depicted in Fig. 5. Besides, an Android app was developed based on DJI Mobile SDK to record real-time UAV flight data samples, i.e., instantaneous UAV flight speeds and instantaneous current/voltages of the UAV battery, at frequencies of 1 and 10 Hz (which is faster than the sampling frequency in [28]), respectively, which can be used to calculate power consumptions and make an experimental analysis.

In order to validate four different power consumption models, four different flight experiments were carried out. First, the UAV was controlled to fly along a straight line with a constant speed (which takes integer values from the range between 0 m/s (hovering status) and 15 m/s)
at a fixed height of 20 m. Due to the limited site space (i.e., the red area in Fig. 5), the UAV was maneuvered to fly several round trips (which is not fixed) to collect sufficient data given each specified speed. Then, the second and third flight experiments were performed by controlling the UAV to ascend or descend vertically with a constant speed between the heights of 0 and 110 m; the specified ascent speed and descent speed ranged from 0 to 5 m/s in the step of 0.5 m/s and from 0 to 3 m/s in the step of 0.5 m/s, respectively. In order to save the energy of the UAV, the two experiments were conducted jointly in such a round trip, as shown in Fig. 6, where the UAV first starts ascending at $t_0$ and reaches the height $H_{\text{max}}$ at $t_0$ (i.e., the second flight experiment), then hovers until $t_1$, and descends with a constant speed to height $H_0$ at $t_2$ (i.e., the third flight experiment) with $H_0$ being the minimum safety height for the UAV in continuous descent and finally lands at $t_3$; the process of the round trip was repeated and only the data corresponding to the time period highlighted with the red lines in Fig. 6 were recorded. Last, differently from the first three flight experiments, the UAV was controlled to fly in an arbitrary steady flight status in the fourth flight experiment (which was conducted in the red area in Fig. 5); specifically, the speeds of the UAV in horizontal and vertical directions were controlled to be nonzero at the same time, and follows the range aforementioned. Note that all experimental data was recorded only if the UAV reached a specified speed or was in a steady flight.

Over the course of the experiments, more than 11 000 flight data samples were recorded; on this ground, the instantaneous UAV power consumption, including both the flying power and the communication-related power, can be easily obtained by multiplying the current and the voltage. However, according to both existing studies and our experiments, the power for the experimental UAV in hovering status is around 300 W, which is much larger than that for wireless communications (which are normally around several hundreds of milliwatts [34], [35]). Therefore, in the four experimental measurements, the communication-related power consumptions are ignored, and the obtained power consumption of the UAV is approximately treated as the flying power consumption, as was adopted in [28]. Besides, since the UAV in our experiments flew in steady flight status, the resulting power consumptions incur relatively small and slow changes, say with almost identical power consumption data during one second, so that the sampling

\[
P_{\text{total}}(V_v) = P_{\text{motor}} + \frac{3}{8} \sqrt{n} \left[ \frac{W \rho A}{C_T} \right] s \|V_h\|^2 + P_{\text{in}} \left[ \left( \frac{W}{2} + \frac{n S_{FP}}{4} \rho \|V_v\|^2 \right) + \frac{n}{2} \frac{S_{FP}}{A} \rho \|V_v\|^2 \right] \\
+ \frac{1}{2} W \|V_v\| + \text{sgn}(V_v) \frac{n}{4} S_{FP} \rho \|V_v\|^2 + \left( \frac{W}{2} + \text{sgn}(V_v) \frac{n}{4} S_{FP} \rho \|V_v\|^2 \right) \\
\times \left[ \left( 1 + \frac{\text{sgn}(V_v) S_{FP}}{A} \right) \|V_v\|^2 + \frac{2 W}{n \rho A} + (\text{sgn}(\|V_v\|) - 1) \frac{W}{2} \sqrt{2 W n \rho A} \right]. \tag{19}
\]
frequency of 10 Hz is sufficient according to the Nyquist sampling theory.

B. Data Processing

In order to choose proper flight data for further validation purposes, the following three data processing steps, including data alignment, data filtering, and data fitting, are adopted in sequence.

First, data alignment is conducted to derive the one-to-one relationship between one power consumption sample and one speed sample, termed one power-speed sample, so as to facilitate further validation and performance evaluation of power consumption models. To be specific, on account of the sampling frequency of speeds being one tenth that of power consumptions (which are 1 and 10 Hz, respectively), ten power consumption samples are averaged to be related to one speed sample to compose one power-speed sample.

Second, due to the instability of manually controlling the UAV, there exist fluctuations in the speed values of the aligned power-speed samples in the first experiment [see Fig. 7(a)], such that data filtering is applied to exclude those samples significantly deviating from the specified speed values. Following the data filtering method in [28], given the judgment condition \(|V_{i+1} - V_i| > a_0\) where \(f_s = 1\) Hz is the sampling frequency, \(a_0 = 0.5 \text{ m/s}^2\) is a horizontal acceleration/deceleration threshold and \(V_i\) denotes the speed of the \(i\)th power-speed sample), the power-speed samples in which speeds satisfy the condition will be filtered out, as shown in Fig. 7(b). From the figure, it is intuitive that there are variations in power consumptions at the same speeds for the power-speed samples. According to the best understanding, it is mainly caused by the wind, and some other factors, e.g., the temperature and air pressure.

Moreover, similar data filtering is also applied to the power-speed samples of the fourth experiment.

Third, for the purposes of determining the parameter values in these models, including (8), (13), and (14), for further validation and analysis, data fitting is carried out. However, due to the large number of parameters in these models, they are simplified by combining multiple parameters into one, as follows:

\[
P_{mf}'(V) = C_1 + C_2V^2 + C_3 \left( \frac{V^4}{C_4^2} - \frac{V^2}{C_4} \right)^{1/2} + C_5V^3, \tag{20}
\]

\[
P_{ma}'(V) = C_6 + C_7V + C_8V^3 + (C_7 + C_8V^2) \left( 1 + \frac{4C_9}{C_9} \right) V^2 + \frac{4C_7}{C_9}, \tag{21}
\]

and

\[
P_{md}'(V) = C_6 + C_7V - C_8V^3 + (C_7 - C_8V^2) \left( 1 - \frac{4C_9}{C_9} \right) V^2 + \frac{4C_7}{C_9}. \tag{22}
\]

where \(C_j\) with \(j = 1, \ldots, 9\), is the combinatorial parameter. Furthermore, according to the least squares fitting method, these combinatorial parameters can be estimated by solving the following minimization problems in MATLAB:

\[
\min_{C_j, j=1, \ldots, 5} \sum_{i=1}^{N_1} \left[ P^i - P_{mf}'(V^i) \right]^2, \tag{23}
\]

\[
\min_{C_j, j=6, \ldots, 9} \sum_{i=1}^{N_2} \left[ P^i - P_{ma}'(V^i) \right]^2, \tag{24}
\]

\[
\min_{C_j, j=6, \ldots, 9} \sum_{i=1}^{N_3} \left[ P^i - P_{md}'(V^i) \right]^2 \tag{25}
\]

where \(N_k, V_k\), and \(P_k\) with \(k = 1, \ldots, 3\), respectively, denote the numbers, speeds, and power consumptions of the power-speed samples in the three experiments.

Based on the estimation results of \(C_1 - C_9\), the physical parameter values in (8), (13), (14), and (19) are further obtained, as outlined in Table I, which are consistent with the results in [25].

C. Experimental Results and Discussions

In this subsection, the first three proposed 2-D power consumption models are validated and analyzed, and on this ground, the fourth 3-D power consumption model is evaluated.

1) Validation of the 2-D Models: In order to validate the effectiveness of the proposed 2-D models, the variations of both power consumptions and energy efficiency (i.e., the energy consumption per unit flight distance) with respect to speed are investigated, using the power-speed samples obtained in our experiments and the aerodynamic-based
power models (APM) reported in [31] as a comparison method, respectively.

First, the experimental data (i.e., the power-speed samples) of the actual flight power consumptions of the UAV in the three flight states are compared with the prediction results of the proposed 2-D models and APM. As shown in Fig. 8, the proposed 2-D models have better agreement with the experimental data in most cases, while the APM significantly deviates from the experimental data in the cases of forward flight and vertical ascent, thus demonstrating the advantage of the proposed 2-D models. In addition, to provide more accurate comparison information, Table II gives the ratio of the absolute difference between the actual flight power consumptions of the UAV under three flight statuses and the predicted values of the two models to the mean value of the actual flight power consumptions (termed the average relative difference). Obviously, the proposed 2-D models have smaller ratio values, which also reflects the superiority of the proposed 2-D models over APM.

Second, a method similar to that in [25] is adopted to calculate the flight energy efficiency of the UAV, and compares the actual flight energy efficiency based on experimental data with the predicted results based on the proposed 2-D models and APM under three flight statuses. It can be visually seen from Fig. 9 that the predicted energy efficiency based on the proposed 2-D models and APM show good agreement with the real energy efficiency based on experimental data in all three flight statuses. However, according to the average relative difference between the actual flight energy efficiency of the UAV and the predicted energy efficiency of the two models under three flight states shown in Table II, it can be observed that the proposed 2-D models still have a better prediction effect, further confirming the effectiveness of the proposed 2-D models.

2) Analysis of the 2-D Models: Both the experimental results of actual flights and the proposed 2-D models reveal that UAVs incur different energy consumption characteristics under different flight statuses and different flight speeds, which will be carefully investigated in what follows.

In the first place, the power consumptions of the UAV are obviously different in terms of their growing trends with speed increasing in the three flight statuses.
In the forward flight status, as shown in Fig. 8(a), the power consumption of the UAV does not vary significantly with speed, only slightly decreasing around 8 m/s, which is consistent with the theoretical results in [25]; interestingly, the power consumption of the UAV in the hovering status (i.e., the speed is 0 m/s) tends to be larger than that in other speed cases, which is consistent with the experimental results in [28]; this is because the induced power is significantly reduced when the UAV’s status changes from hovering to forward flight, leading to a reduction in overall power consumption.

In the vertical ascent status, as illustrated in Fig. 8(b), the power consumption of the UAV increases in a nonlinear manner with increasing speed and is always greater than the power consumption of the UAV in hovering status; on the contrary, in vertical descent status, the power consumption of the UAV decreases slowly with increasing speed and is always less than that in the hovering status, as shown in Fig. 8(c). The main reason causing this difference is that the UAV will generate different thrusts in these two flight statuses [refer to (11)], and the larger the thrust, the higher the power consumption of the UAV.

In the second place, the energy efficiency (or energy consumption per unit distance) of the UAV increases (or decreases) rapidly with increasing speed in all three flight statuses, but will remain relatively stable when a certain speed is exceeded.

In particular, existing theoretical studies [25], [36] reveal the existence of an optimal flight speed (not necessarily the maximum speed) maximizing the energy efficiency of the UAV in the forward flight status, but limited by the speed range in which the DJI M210 can safely fly (i.e., up to 15 m/s), this theoretical optimal speed is not observed in the experimental results.

Besides, in both vertical ascent and vertical descent statuses, the energy efficiency of the UAV at the same flight speed [see Fig. 9(b) and (c)] is significantly lower than that of the UAV in forward flight status, indicating that the UAV will consume less energy in forward flight for a given flight distance.

3) Evaluation of the 3-D Model: The diversity of flight statuses of UAVs in 3-D scenes makes it difficult to comprehensively analyze the relationship between power consumptions and speeds of UAVs in 3-D flights. Therefore, the proposed 3-D model is evaluated based on actual flight power consumptions of the UAV in arbitrary steady flights.

As shown in Fig. 10, when the UAV is in the ascent status (i.e., the vertical velocity is greater than 0), the predicted power consumptions are often smaller than the actual power consumptions; however, when the UAV is in the descent status (i.e., the vertical velocity is less than 0), the predicted power consumptions are often greater than the actual power consumptions. The reason causing such prediction differences might be that there was a downward wind field in the experimental environment that affected the actual power consumption of the UAV; to be specific, when the UAV ascended (or descended), the wind produced resistance (or impetus) to the UAV, which in turn led to higher (or lower) actual power consumption of the UAV. However, the proposed 3-D model does not take into account such situations. In addition, the average relative differences between the actual power consumptions and the power consumptions predicted by the proposed 3-D model is 13.20%, which is acceptable according to the prediction results of the existing theoretical power consumption models [21], [31].

To further verify the stability of the power consumption prediction accuracy of the proposed 3-D model, the average relative differences between the actual power consumptions and those predicted by the proposed 3-D model for five groups of experimental data of different sizes (i.e., 100, 200, 400, 500 power-speed samples) are compared. Specifically, the samples in each group were randomly selected from the samples of the fourth experiment (see Fig. 10), which is repeated ten times, and the average relative differences are further averaged over the ten sample selections. As listed in Table III, revealing that the power consumption prediction accuracy does not scale with the sizes of the experimental data, and confirming the stability of the proposed 3-D model in power consumption prediction.

V. MODEL-BASED SIMULATION RESULTS

In order to further discuss the effects of factors other than speeds on the power consumptions of UAVs, simulations based on the proposed power consumption models are conducted due to the difficulty of performing actual experiments.

A. Simulation Setup

In the simulation, the proposed power consumption models are used to calculate the power consumptions with respect to different numbers of rotors and payload weights of a UAV in five flight statuses, respectively, where six different flight speeds are considered in each flight status. The
maximum values of the forward flight speed, vertical ascent speed, and vertical descent speed are set to be 15 m/s, 6 m/s, and 3 m/s, respectively, and the main physical parameters of the UAV power consumption models are the same as those in Table I; in addition, the number of rotors of the UAV is set to be even numbers between 4 and 12, and the maximum payload weight of the UAV is 1 kg.

B. Analysis of the Effect of the Rotors Number

The power consumptions of UAVs are often different given different numbers of rotors under different flight statuses and different flight speeds, which will be carefully analyzed in what follows.

In both forward flight and vertical ascent statuses, as shown in Fig. 11(a) and (b), the power consumption of the UAV decreases with the increasing number of rotors when the speed is small; however, when the speed rises up, the power consumption of the UAV turns out to slowly decrease, and then promptly increase with the increasing number of rotors. This is mainly due to the following reasons: 1) when the speed is small, the overall power consumption of the UAV is mainly influenced by the induced power, so when the induced power decreases with the increasing number of rotors, the overall power consumption decreases; 2) however, when the speed is large enough, the parasitic power starts to dominate and increases significantly with the increasing number of rotors, which leads to the increase of the overall power consumption.

In the vertical descent status, the power consumption of the UAV always decreases with the number of rotors increasing [see Fig. 11(c)]. This is expected for the reason that the increase in parasitic drag at this point leads to a decrease in the UAV thrust and thus, the overall UAV power consumption will decrease.

In the forward ascent status, it can be found from Fig. 11(d) that when the speed is great, the power consumption of the UAV increases significantly with the number of rotors increasing, and the changing trend is close to linear, which illustrates that reducing the number of rotors will save more energy when UAVs are flying at high speed.

In the forward descent status, as the number of rotors increases, the trend of power consumption of the UAV is similar to that of the UAV in forward flight [see Fig. 11(e)]; this is since more power consumption of the UAV is used to maintain its stability in the horizontal direction at this time.

C. Analysis of the Effect of the Payload Weights

The relationship between UAV power consumptions and payload weights at different flight speeds in different flight statuses is further analyzed. To simplify the analysis, only a UAV given four rotors is discussed.

First, the power consumptions of UAVs often increase with payload weights increasing in all five flight statuses, and the trends are nearly linear.

In particular, in the vertical ascent, forward ascent, and forward descent statuses, there is a significant increase in UAV power consumption with increasing payload weight when the speed is small [see Fig. 12(b), (d), and (e)]. Taking the vertical ascent status as an example, as shown in Fig. 12(b), the power consumptions of the UAV increase by about 67.8% and 32.5% for given speeds of 1 m/s and 6 m/s, respectively, when the payload weight increases.
from 0.1 to 1 kg. This is expected because the power consumptions of the UAV vary significantly with speed in these three statuses, but at the same time, the variation in power consumptions due to the payload weight is small.

In addition, in both forward flight and vertical descent statuses, the increase of the payload weight changes the original power consumption relationship between some speeds [see Fig. 12(a) and (e)]. Taking the forward flight status as an example, as shown in Fig. 12(a), when the payload weight is less than 0.6 kg, the power consumption of the UAV at 9 m/s is higher than that at 3 m/s; however, when the payload weight reaches 0.7 kg or more, the power consumption of the UAV at 3 m/s will become higher compared to the power consumption of the UAV at a speed of 9 m/s. Therefore, reasonable planning of the speed and payload weight of the UAV in these two flight statuses can effectively save energy.

VI. CONCLUSION

This article is in an effort to establish theoretical power consumption models for multirotor UAVs. To be specific, the power consumption models with closed-form expression for a multirotor UAV in three flight statuses, including forward flight, vertical ascent, and vertical descent, were derived by analyzing the relationship between single-rotor UAVs and multirotor UAVs in terms of power consumptions, and after that, a generic flight power consumption model for the UAVs was obtained to satisfy the power consumption expression for the UAV in generic flight statuses. Extensive experiments confirmed the correctness of these models, the proposed 2-D models improve the prediction accuracy by about 50% compared to existing studies in terms of power consumption prediction; the average relative difference between the predicted power consumptions of the proposed 3-D model and actual power consumptions is only around 13%, and in order to investigate the influences of the number of rotors and payload weight, simulations were further conducted, it is shown that power consumptions of UAVs always increase with payload weights increasing, and when the load weight reaches 1 kg, the power consumption of the UAV will be increased by around 74% at most compared with the unloaded status; the relationship between power consumptions of UAVs and number of rotors does not change in the same way under different flight statuses and different flight speeds, it can be found that power consumptions of UAVs change significantly with the number of rotors increasing in the same flight status at the same speed, and can be increased by around 82% (or decreased by around 61%) at most.

APPENDIX A

COMPARISON BETWEEN THE POWER CONSUMPTIONS OF UAVS IN VERTICAL ASCENT STATUS AND VERTICAL DESCENT STATUS DESCRIBED IN (13) AND (14) RESPECTIVELY

Given the UAV speed \( V \), the difference between the power consumptions in the vertical ascent and descent, denoted \( \Delta P_{a,d}(V) \), can be formulated as

\[
\Delta P_{a,d}(V) = P_{ma}(V) - P_{md}(V)
= \frac{n}{2} S_{FP,\perp} \rho V^3 + \frac{W}{2} \left( 1 + \frac{S_{FP,\perp}}{A} \right) V^2 + \frac{2W}{n \rho A}
\]
Evidently, the first two terms on the right-hand side of (26) are larger than 0, and the third term is intuitively positive according to its equivalent form in (27) shown at the top of this page.

In summary, since $\Delta P_a(V)$ is always larger than 0 regardless of the value of $V$, $P_{md}$ is definitely greater than $P_{md}$.

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**Hao Gong** received the B.E. degree in computer science from the Beijing University of Chemical Technology, Beijing, China, in 2019. He is currently working toward the Ph.D. degree in computer science with Inner Mongolia University, Hohhot, China.

His research interests include UAV energy modeling and UAV path planning.

**Baoqi Huang** (Member, IEEE) received the B.E. degree in computer science from Inner Mongolia University (IMU), Hohhot, China, the M.S. degree in computer science from Peking University, Beijing, China, and the Ph.D. degree in information engineering from The Australian National University, Canberra, ACT, Australia, in 2002, 2005, and 2012, respectively.

He is currently a Professor with the College of Computer Science, IMU. His research interests include indoor localization and navigation, wireless sensor networks, and mobile computing.

Dr. Huang was the recipient of the Chinese Government Award for Outstanding Chinese Students Abroad in 2011.

**Bing Jia** (Member, IEEE) received the Ph.D. degree in computer architecture from Jilin University, Changchun, China, in 2013.

She is currently an Associate Professor with the College of Computer Science, Inner Mongolia University, Hohhot, China. Her research interests include indoor localization, crowdsourcing, wireless sensor networks, and mobile computing.

**Hansu Dai** received the B.E. degree in aircraft design and engineering from Beihang University, Beijing, China, and the M.S. degree in computer science from Tsinghua University, Beijing, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree in aircraft design with Beihang University.

He is currently a Director of the Development Office of the Department of Air and Space, AVIC Chengdu Aircraft Design and Research Institute (Institute 611), Chengdu, China. His research interests include operational use and overall design of aircraft.