Energy Consumption in Unmanned Aerial Vehicles: A Review of Energy Consumption Models and Their Relation to the UAV Routing

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Abstract. The topic of unmanned aerial vehicle (UAV) routing is transitioning from an emerging topic to a growing research area with UAVs being used for inspection or even material transport as part of multi-modal networks. The nature of the problem has revealed a need to identify the factors affecting the energy consumption of UAVs during execution of missions and examine the general characteristics of the consumption, as these are critical constraining factors in UAV routing. This paper presents the unique characteristics that influence the energy consumption of UAV routing and the current state of research on the topic. This paper provides the first overview of the current state of and contributions to the area of energy consumption in UAVs followed by a general categorization of the factors affecting energy consumptions of UAVs.

Keywords: Unmanned Aerial Vehicles · UAV routing
Energy consumption of UAVs

1 Introduction

Transportation problems and their associated solution strategies has long been a study of interest for both academia and industry [1–3]. In recent years, unmanned aerial vehicles (UAVs) have become the subject of immense interest and have developed into a mature technology applied in areas such as defense, search and rescue, agriculture, manufacturing, and environmental surveillance [4–9]. Without any required alterations to the existing infrastructure such as deployment station on the wall or guiding lines on the floor, UAVs are capable of covering flexible wider areas in the field than ground-based equipment [10].

However, this advantage comes at a price. To efficiently utilize this flexible resource, it is necessary to establish a coordination and monitoring system for the UAV or fleet of UAVs to determine their outdoor route and schedule in a safe, collision-free, and time-efficient manner, that takes their operating environment into account [7, 11, 12]. Following recent advances in UAV technology, Amazon [13], DHL [14], Federal

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Express [15], and other large companies with an interest in package delivery have begun investigating the viability of incorporating UAV-based delivery into their commercial services. It seems very likely that future multi-modal transportation networks will include UAVs as they are less expensive to maintain than traditional delivery vehicles such as trucks, can lower labor costs by performing tasks autonomously [16, 17], and are fast and able to bypass congested roads. This gives rise to a new problem category: the UAV routing problem (UAVRP). To support varied applications of UAV routing in practice, this paper presents several contributions for energy consumption of UAVs.

1.1 Important Factors to Consider in Deriving Energy Consumption of UAVs

In UAV routing, the majority of studies either assume unlimited fuel capacities [18] or do not consider the fuel in their approach at all. The authors have only been able to identify a few studies which consider fuel constraints in UAV routing [19, 20]. To achieve a realistic and efficient routing, understanding the factors that determine the energy consumption is critical in deriving energy consumption models.

In vessel routing fuel consumption is typically considered to be a function of speed [21] and are heavily non-linear [22]. In the existing research of UAV routing linear approximations for consumption are used [16]. However, we know from industry that this is not reasonable for UAVs, as the weight of the payload in combination with speed and weather conditions are critical.

In the following sections of this contribution, we discuss the main factors as identified in the literature: weather conditions, flying speed, and payload. The aim is to define what UAV routing problems should take into account and how this differs from traditional routing problems.

1.2 Impact of Weather

In outdoor routing for UAVs, one must deal with the stochastics of weather conditions that influence energy consumption of UAVs [23–26]. These elements have some characteristics that potentially can strongly influence the solution strategy for the UAV routing problem. Two main factors for weather's influence on UAV routing are listed below.

a. Wind: The major environmental factor that affects the UAV is wind in the form of wind direction and speed. Wind may benefit the energy consumption or give increased resistance to the movement in other cases [27].
b. Temperature: Temperature conditions can affect the UAV's battery performance as it is linked to battery drain and capacity [16].

Ignoring the impact of weather will not provide more realistic solutions as flying with the wind could reduce energy consumption and cold temperatures may adversely affect battery performance [28]. Most existing research in UAV routing does not consider weather factors and, therefore, ignores the impact of weather on the performance [16, 20, 29, 30]. Furthermore, as weather changes over time in a stochastic manner [31], one must assume that a particular route will have different fuel consumption at different times.

1.3 UAV Flying Speed and Payload

The relative flying speed of the UAV is a critical factor in determining the fuel consumption. Wind speed and direction are linked with the flying speed because, depending on the wind direction, it may affect the flying status of UAV either positively or negatively. The flying status of UAV can be any of the following:

a. hovering,
b. horizontal moving or cruising or level flight, and
c. vertical moving: vertical take-off/landing/altitude change.

Hence, the flying status of the UAV should be considered as well as the flying speed in calculating the energy consumption [27], and relevant models are proposed in Sect. 3 in relation to these flight statuses.

UAVs typically carry some form of payload such as camera equipment or parcels. The impact of different weights of payloads can be significant enough that they should be considered when deriving the energy consumption models [27, 28]. From the airline industry, it is known that fuel/energy consumption depends on certain factors. For example, maximum flight distance or flight time of UAV could be constrained by take-off gross weight, empty weight, thrust to weight ratio [32], fuel weight, and payload [33]. From the airline industry, one can find comparable models for flight such as available fuel models for multirotor helicopters [34] that indicate that linear approximation of the energy consumption is not applicable for large variations of the payload carried [28].

2 Energy Consumption Models for UAVs

Based on the main factors influencing the energy consumption, different energy models can be proposed based on the context of the UAV routing. Theoretical understanding of flight identifies the primary design parameters for achieving the minimum lift for takeoff of a flying object. These include power, weight, width, air density, drag coefficient, and surface area of the flying object. Beyond the primary design parameters, there are numerous other critical secondary design issues regarding, for example, balance, control, and shape that must also be correct to achieve flight [35]. The implication is that each type of UAV in a particular configuration of these parameters has a unique behavior regarding fuel consumption.

These parameters must be considered when calculating a UAV's energy consumption for a particular route under a particular set of circumstances as the flight time of a UAV is defined by these parameters and its energy storage capacity. An energy consumption model helps balance these parameters by providing a function of energy consumed by the UAV. Such models are critical during UAV routing to compare the energy consumed by alternative routes. The aim of this study is not only to provide a global fuel consumption model for UAVs but also to identify the link and influence of the main factors on the consumption.

When the UAV is flying at a constant speed in a horizontal moving state, we have an example of Newton's first law of motion. In this flying state, all the forces cancel each other to produce no net force and so the UAV continues moving in a straight line [36–40]. The upward lift on the UAV equals the downward force of gravity; the forward thrust of the propeller or rotors is matched by the backward drag on the UAV (Fig. 1).

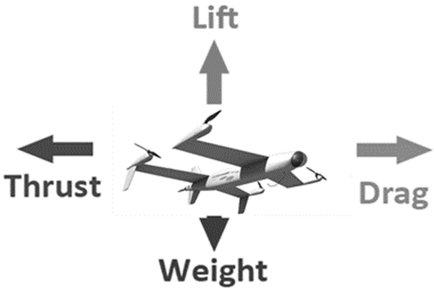

Fig. 1. Different forces act on UAV.

From Newton's second formula we can derive the following equation.

$$F = V\left(\frac{d\mathrm{m}}{dt}\right) \tag{1}$$

Because in horizontal moving the weight of the UAV is equal and opposite to the lifting force, this lifting force is the reaction to diverting the air downward. This lifting force is the reaction to diverting the air downward. So, the weight of the UAV is equal to the speed of the air being thrown down multiplied by the mass of air per unit of time that is being affected by the UAV [38, 41].

$$W = F_L = V\left(\frac{dm}{dt}\right) \tag{2}$$

W is the weight of the UAV, V is the downward speed of the air, and $\frac{d\mathrm{m}}{dt}$ is the mass of the air being thrown down per unit of time.

Let b denote the width of UAV. We can now calculate the mass of air per time unit as the density of the air multiplied by the speed of the UAV multiplied by the area influenced by the UAV [37, 38, 41].

$$\frac{d\mathrm{m}}{dt} = \frac{1}{2}Db^2v \tag{3}$$

Substituting this into our main lift Eq. (2) gives:

$$W = V\frac{1}{2}Db^2v \tag{4}$$

Where W is the weight of the UAV, V is the speed of the air being thrown down, D is the density of the air, v is the relative speed of the UAV through the air, and ½ b^2 is the effective area affected by the UAV body.

2.1 Power Consumption in Horizontal Moving

Power is required to lift the UAV into the air and some power is needed to overcome the parasitic drag that is impeding its forward movement through the air [38, 39, 42, 43]. Let us first focus on the power required to overcome parasitic drag. The parasitic drag can be modeled as [37]:

$$F_P = \frac{1}{2}C_DADv^2 \tag{5}$$

Where F_P is the parasitic drag, C_D is the aerodynamic drag coefficient, A is the front facing area, D is the density of the air, and v is the UAV's relative speed through the air. The general equation for power is [41]:

$$P = Fv \tag{6}$$

Hence, the power needed to overcome the parasitic drag is:

$$P_P = \frac{1}{2}C_DADv^3 \tag{7}$$

The UAV needs power both to overcome parasitic drag and for lifting the UAV [44].

$$P_T = P_P + P_L \tag{8}$$

The power needed to overcome parasitic drag is the greatest at high speeds while the power needed for lift is the greatest at the low speeds. Between these two extremes, the power requirement is the lowest, that is, there is an optimal cruising speed (Fig. 2). Because the power requirement is greater at slower speeds, it does not make sense to travel at a speed lower than where this power requirement is the lowest, unless the UAV does not wish to arrive early at a destination [45, 46].

The purpose of lift is to transfer energy from the UAV to surrounding air to lift the UAV. This energy is the kinetic energy that the air is given as it is thrown downward [37, 41, 43]. For individual objects, this is calculated as:

$$E = \frac{1}{2}mV^2 \tag{9}$$

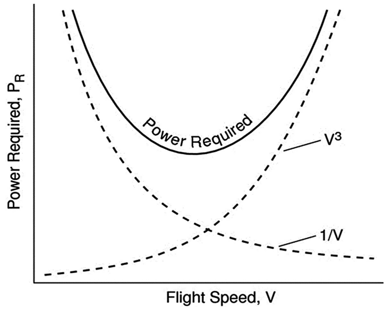

Fig. 2. Power vs Flight Speed

The power required for lift is the amount of energy given to the air per unit of time and substituting (8) we have:

$$P_L = \frac{dE}{dt} = \frac{d\left(\frac{1}{2}mV^2\right)}{dt} = \frac{1}{2}\left(\frac{dm}{dt}\right)V^2 \tag{10}$$

From substituting (7) and (8) we can have the power required to lift as [41]:

$$P_L = \frac{W^2}{Db^2v} \tag{11}$$

Where P_L is the power needed for lift, W is the total weight of the UAV, D is the density of the air, b is the width of UAV, and v is the relative speed of the UAV through the air. Recalling our total power Eq. (8), the power needed for flight is as follows.

$$P_T = \frac{1}{2}C_D A D v^3 + \frac{W^2}{Db^2v} \tag{12}$$

Where P_T is the power needed for flight in watts, C_D is the aerodynamic drag coefficient, A is the front facing area in m^2, W is the total weight of the UAV in kg, D is the density of the air in $kg/m^{3,}$ b is the width of UAV in meters, and v is the relative speed of the UAV in m/s considering the wind speed and direction.

The speed cube is in the numerator of parasitic power term, and speed is in the denominator of the power for lift term.

By taking the derivative of the total power equation with respect to speed then setting the result equal to zero, we can find the speed for minimum power [37, 38, 41, 42, 47].

$$v_{\min} = \left(\frac{2W^2}{3C_D A b^2 D^2}\right)^{0.25} \tag{13}$$

We can now take the calculated minimum power speed and substitute it into the total power equation to calculate the minimum power needed for flight [37, 41, 42, 47].

$$P_{\min} = \frac{4}{3}\left(\frac{W^2}{Db^2 v_{\min}}\right) \tag{14}$$

The minimum power speed is not the normal cruising speed of the UAV, but rather, it would be the bare minimum speed to use.

2.2 Optimum Flying Speed

Optimum speed is the speed that gives the least amount of drag (Fig. 3). The speed that has the least amount of drag on the aircraft is the optimum cruising speed [38, 41, 43, 47]. The total drag is the parasitic drag that was calculated earlier plus the drag generated in throwing the air down.

$$F_T = F_P + F_I \tag{15}$$

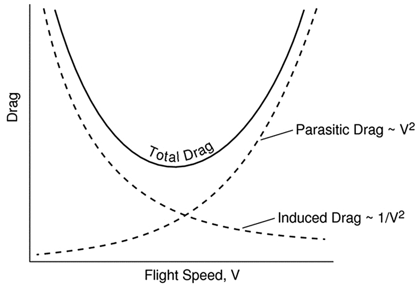

Fig. 3. Drag vs Flight Speed

The drag generated in throwing the air down, or induced drag, is simply a way to account for the fact that more force is needed to move the UAV through the air [38, 44, 46]. The induced drag is calculated by starting with the power lift equation and applying the standard power Eq. (11). The induced drag is then just the power lift equation divide by speed [38, 41, 47]. We can now add the parasitic drag and the induced drag.

$$F_T = \frac{1}{2} C_D A D v^2 + \frac{W^2}{Db^2 v^2} \tag{16}$$

Like before when we found the minimum power speed, we determine the cruising speed by taking the derivative of the total force equation with respect to speed then setting the result equal to zero we can find the speed for the minimum drag force [37, 41, 42, 47].

$$v_{\text{optimum}} = \left(\frac{2W^2}{C_D A b^2 D^2} \right)^{0.25} \tag{17}$$

Where v_{optimum} is the optimum cruising speed, W is the weight of the flying object, D is the density of the air, A is the frontal area, C_D is the drag coefficient, and b is the width of the UAV. With this relatively simple equation, we can input data about a UAV and the density of the air to calculate the correct speed to fly.

2.3 UAV Energy Consumption in High Speeds

From the literature according to [41], in steady level flight, the thrust of the UAV is equal to the drag of the UAV, and the lift is equal to the total weight of UAV, in which case the propulsive thrust power can then be given as follows.

$$T = W * \frac{C_D}{C_L} \tag{18}$$

From Power Eq. (10), we can derive that

$$P_P = Tv \tag{19}$$

C_D is the Drag coefficient, and C_L is Lift coefficient of the UAV.

$$P_P = \frac{C_D}{C_L} * Wv \tag{20}$$

From (12), the total power in higher speeds is;

$$P_T = \frac{C_D}{C_L} * Wv + \frac{W^2}{Db^2 v} \tag{21}$$

2.4 Energy Consumption in Hovering, Vertical Takeoff and Landing

Studies have used the following equation in calculating the energy consumption of UAVs, which is derived using power consumed by a multirotor helicopter, and they have proved that the power it consumes is approximately linearly proportional to the weight of its battery and payload under practical assumptions [16, 34].

$$p^* = \frac{T^{\frac{3}{2}}}{\sqrt{2D\varsigma}} \tag{22}$$

Also, this study has assumed that the power consumed during takeoff and landing is, on average, approximately equivalent to the power consumed during hover. Power $p*$ in watts and the thrust T in Newtons. Air density of air D in kg/m^3, and the facing area ς of the UAV is in m^2, where the thrust $T = W g$, given the UAV total weight W in kg, and gravity g in N.

As air density is dependent on temperature, different temperature conditions will lead to different air densities and thus will affect the power consumption of UAVs.

3 Relationship of Factors Affecting UAV Energy Consumption

Figure 4 presents an overview of the relationships between different factors which are linked with energy consumption of UAVs. Among these factors, speed of UAV and wind direction has a correlation as speed of the UAV is affected by the wind speed and direction. Based on the existing research, smaller power consumptions were observed when flying into headwind [38, 48], which is due to the increasing thrust by translational lift, when the UAV moves from hovering to forward flight [27]. When flying into a headwind, translational lift increases due to the relative airflow increases, resulting in less power consumption to hover the UAV [49]. When the wind speed exceeds a certain limit, the aerodynamic drag may outweigh the benefit of translational lift [27].

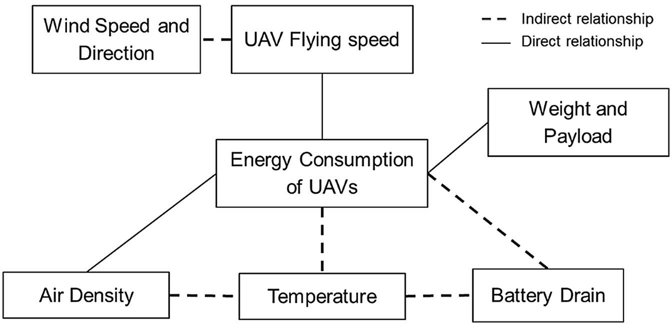

Fig. 4. Factors that affect energy consumption of UAVs

Moreover, temperature and air density have a relationship and this is linked with the battery drain. Air density influences the lifting capacity of aircraft and varies with temperature [50]. On the other hand, studies have shown that in cold conditions at or below zero degrees, shorter flying times and increased risk of UAV malfunction are observed [51]. In contrast to all other factors, weight and payload act as an individual factor which influences the energy consumption of UAVs in general.

4 Conclusion

This paper focuses mainly on deriving the energy consumption of UAVs, which is highly non-linear and dependent on weather, speed, and payload. This makes UAV routing differ significantly from all other types of routing we traditionally deal with, as

UAVs are expected to travel in certain high altitudes, and are, therefore, significantly susceptible to wind and weather conditions.

We have presented equations to calculate the total power consumption of UAVs in different flight scenarios including horizontal moving, vertical moving, and hovering based on the existing literature. In the future, we will further analyze these models by experimenting with industrial data and different models of available UAVs.

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