Drone Power Consumption Model using in Delivery Task

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Abstract

In recent years, the drone has become highly active for making a last mile delivery to save effort and time for delivery operations. The drone is powered by a small battery size, which make power consumption a critical constraint for drone delivery tasks. In this paper, a power consumption model is driven based on theories of the aerodynamics of the drone. This model is implemented in MATLAB/SIMULINK to obtain the relation between the payload weight and the power consumed by the drone. Three experiments have been done on this model for a different number of rotors in order to see their power consumption. The results show that this model is fairly good and can be used to obtain the power consumed per Kg weight and also the power needed to keep the drone in hover which can be used for route planning when the drone makes the delivery task.

Keywords: energy constraint; drone routing problem; power consumption; UAVs.

الملخص

في السنوات الأخيرة أصبحت الطائرات بدون طيار المستخدم في عمليات التوزيع النهائية تلاقي اهتماما كبيرا و ذلك لأنها تقلل من الوقت و الجهد في عملية التوزيع. يتم تزويد الطيارات بدون طيار بالطاقة بواسطة بطاريات صغيرة مما يجعل استهلاك الطاقة من القيود الحساسة في عملية التوزيع التي تقوم بها الطيارات بدون طيار. في هذه الورقة تم نمذجة عملية استهلاك الطاقة بناء على النظريات الديناميكية الهوائية لهذه الطيارات.

تم تنفيذ هذا النموذج في برنامج MATLAB/SIMULINK وذلك للحصول على العلاقة ما بين وزن الحمولة والطاقة المستهلكة للطائرة بدون طيار. النتائج المتحصل عليها اثبت

أن هذا النموذج جيد ويمكن استخدمه لحساب الطاقة المستهلكة لكل وحدة وزن وكذلك حساب الطاقة المطلوبة للطائرة في وضع الطيران العمودي والتي نحتاجها عند تصميم المسارات التي تستهلكها الطائرة إثناء عملية تنفيذ مهام التوزيع.

الكلمات المفتاحية: قيد الطاقة؛ مسألة توجيه الطيارات بدون طيار ؛ استهلاك الطاقة؛ الطائرات بدون طيار.

Introduction

In the last few years, the use of Unmanned Aerial Vehicles (UAV), also known as drones, has been greatly increased in many military and civilian applications due to numbers of features, which has them, perform human work at high levels of reliability and with greater effectiveness. The drone is rotary-wing type with numbers of characteristics, such as small size, takeoff and landing in a small area, good relationship between total weight and payload, simple mechanical structure and high maneuverability. These characteristics make it an ideal candidate for the distribution of goods in 3D space. There are many companies in the logistic area working to involve drones in delivery systems to make delivery processes more efficient at lower cost and in less time[1] [2] [3]. Regular delivery trucks cannot easily reach some locations, especially in the rural areas; therefore, a drone would be a suitable solution in such cases.

On the other hand, the small size of the drone makes the battery also small and the power of it is limited. This leads to limited flight time, which will impact that the drone cannot complete his mission, as well as the possibility of crashing to the ground if batteries are not recharged or replaced during a journey. The objective of this paper was to drive a power consumption model utilizing to compute the power consumed by the drone as a function with payload weight. To reach the goal the aerodynamic theories are used to drive the mathematical model. This model is implemented in MATLAB with three experimental for three types of drones, four, six and eight rotors.

Literature review

The power requirement of the drone depends on the payload weights, weather condition and the speed of the drone. The power consumption is a critical issue when the drone does his missions and need more investigation. Many studies were investigated to extend the flight time by improves energy efficiency or reducing the energy consumed by drone. In [4] the authors proposed a work that extend the mission duration by investigates the factors impact the power consumption of drone such as, motions, wind and payload weight. In [5], [6], and [7] they introduce an automated battery platform system that can solve the problem by replacing or charging the battery many times during a mission. The authors in [8], suggest a technique that extends the endurance of drones by dumping consumed batteries out of the drone while in flight. In [9] introduces a method that extends the endurance of a rotorcraft by decreasing the payload; this is achieved by subdividing the battery into multiple smaller capacity batteries which are sequentially discharged and released. However, this is limited by the additional weight of the switching circuitry and release mechanism.

The drone routing problem (DRP) is a new issue related to using the drone in the logistics of distributing goods to customers [10], and it is comparatively similar to the vehicle routing problem (VRP). The VRP was first applied in the field of logistics distribution by Dantzig and Ramser in the early 1959 [11]. The role of the VRP is to determine the minimum cost such that the delivery time or distance travelled of the routes for several vehicles which departure from the depot with a certain capacity to serve a number of customers and return to the depot. The DRP is different from the VRP such that the DRP uses a small autonomous aerial vehicle powered by a small battery, which adds some limitations to the problem, such as limited flight times and limited carrying capacity. This adds more constraints when we model the problem, such as energy constraint, maximum flight time, and the number of customers on the route. This allows the drone to perform multi-trips with a fixed number of customers, possibly one, two or three customers.

The energy constraint is a critical constraint in the drone routing problem and can be written as the following [12]:

$$y_j \leq y_i - p(m_{ij})\left(\frac{d_{ij}}{v} + \lambda\right) \quad (1)$$

Where, y_j is the remaining energy at customer j after visiting customer i and complete the delivery task, and y_i is the previous current energy. $p(m_{ij})$, is the power consumed by the drone for payload and battery weight between customer i, and customer j. d_{ij} represents the distance matrix. v is the speed of drone in $\mathrm{m/s}$, λ is the time in second spent at each customer, landing, serve the customer and take off. This constraint forced the current energy available y_j is equal to the total power consumed along the route to reach the customer j. From the previous constraint the power consumed $p(m_{ij})$, is depended on the payload, so it is important to calculate this power when the drone makes the delivery task.
In this study, we propose a model called a drone power consumption model. This model can be using for drone routing problem to compute the power consumed by the drone when it carries the payload weight.

Drone Power Consumption Model.

The drone is powered by a lithium-ion polymer (LiPo) small battery, which strongly limits the class of missions that a drone can successfully carry out. The power consumed by the drone is affected by distance traveled, payload carried, environment condition and the speed of the drone[12]. The power consumption model is derived when the drone in hovering case. The power required for hovering is considered as an upper limited power consumption [13]. At the forward speed, an event called translational lift will occur, when the air passes horizontally through the rotor system due to forward speed. This will improve the rotor efficiency and the required power at the rotor, which considerably lower than in the hover case [13]. The power consumed by the drone during takeoff, flight and landing are assumed on the average approximate and is amounting to the power consumed during hover [14]. Refer to [13] "the main purpose of the rotor in the hover are to provide a vertical lifting force in opposition to the weight of the helicopter". This force need a power required to be induced in the air called an ideal power and given by:

$$P = T v_h \tag{2}$$

Where, T is the thrust generated by the rotor to endure the vehicle in hover and it is equal the weight of the vehicle, vh is the induced velocity in the air at hover condition, and by using momentum theory [13] [15] it is given by:

$$v_h = \sqrt{\frac{T}{2\,\rho\,A_p}} \tag{3}$$

By substituting equation (3) in (2)

$$P = T\sqrt{\frac{T}{2\,\rho A_p}} = \frac{T^{3/2}}{\sqrt{2\,\rho\,A_p}} \tag{4}$$

Where, P is the hover power, ρ is the air density and A_p is the propeller disk area. The thrust, T for a single rotor is equal to the drone weight when the drone in hovering phase [13], that is:

$$T = (m_D + m_L)g \tag{5}$$

Where, m_D and m_L are the weight of the drone frame (including battery and propeller) and the weight of payload respectively and g is the gravity, so the equation (4) for one rotor becomes:

$$P = (m_D + m_L)^{3/2}\sqrt{\frac{g^3}{2\,\rho\,A_p}} \qquad (6)$$

On the other hand, the total weight of the drone frame and payload is distributed evenly on nr rotors, so we can calculate the power consumption in hover for n_r rotors as following:

$$P = Pn = (m_D + m_L)^{3/2}\sqrt{\frac{g^3}{2\,\rho\,A_p n_r}} \qquad (7)$$

We considered the DJI Phantom 3 quadrotor [16] with specification to agree to drone that used in delivery system, the physical parameters of DJI Phantom 3 are listed in table (1) and for missing ones, we reckoned on the values reported in [17], for similar drone.

TABLE 1. The physical parameters values of the quadrotor[16] [17].

Parameter	Description	Value	Units
m_D	mass	1.3	kg
v	Max speed	16	m/s
	Max flight time	23	min.
g	Gravity	9.81	m/s^2
ρ	Air density	1.225	Kg/m^3
A_p	propeller disk area	0.2	m^2
n_r	Number of rotor	4	-

Experiment

In this section, the drone power consumption model is verified by implement the equation (7) in MATLAB/SIMULINK to perform three experiments. The first, one is to obtain the relation between the payload weight and the power consumed by the drone for the drone with four rotors which called Quadrotor. The second is to find the relation between the payload weigh, and the power consumed for the drone with six rotors, and the last experiment is to determine the relation between the payload weight and the power consumed for the drone with eight rotors. The parameters ρ , A_p and n_r in equation (7) are under a square root, that is mean a slight adjustment to them will have a restricted influence on power P. So we can use the data in table 1. for all small multi-rotors drones in our simulation.

Power Consumption and Payload Weight Relationship.

Figure 1 shows SIMULINK model to implemented equation (7) in three experiments, the payload weight is variant from 0 to 4 Kg to find the power consumption at each weight. The result obtain from this model is used to drive the relation between the payload weight and the power consumption.

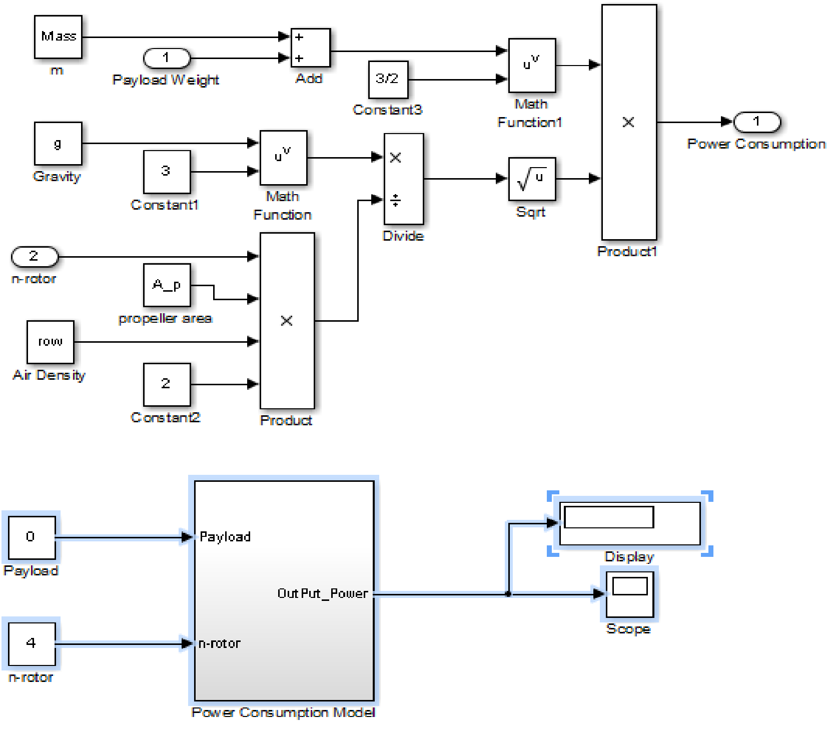

Figure 1. The power consumption model in SIMULINK.

Results and Discussion

Figure 2, figure 3 and figure 4 shows the results for three types of UAVs, quad-rotor with 4 rotors, hexa-copter with 6 rotors and UAV with 8 rotors. The result indicates that the model line is a nonlinear solid line, and we used the least square method to fit a line to represent the linear approximate model. The least square method is a mathematical regression used to find the best fit line for a set of data points. We implemented the method in MATLAB and find the linear approximate model dashed thin lines in the Figures, and from that model, we find a liner equation as following:

$$P(m_L) = \mu\, m_L + \alpha \qquad (8)$$

Where, μ is the power consumed rate per unit weight of payload, and α is the power required to keep the body drone in the air.

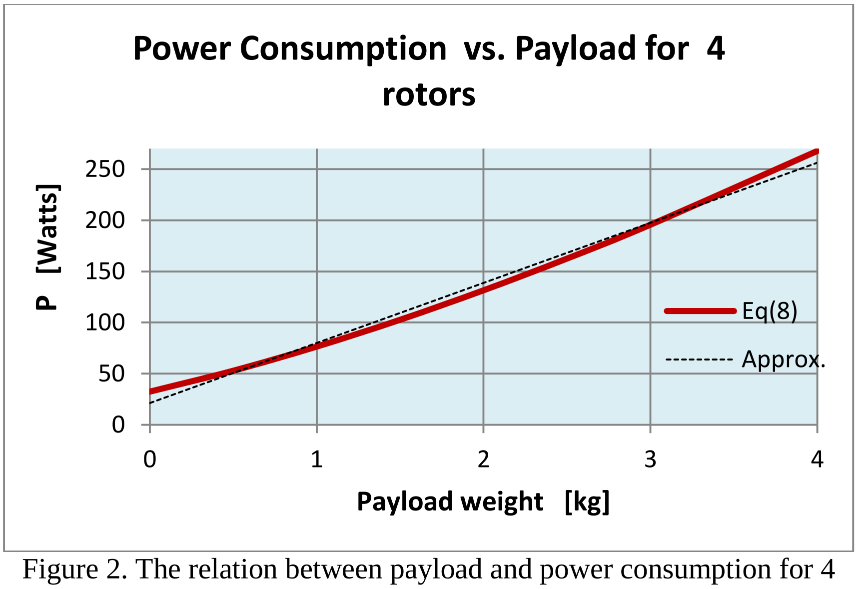

Figure 2. The relation between payload and power consumption for 4 rotors. The continuous thick line represents Eq. (7) and the dashed thin line represents the approximate.

For a drone with 4 rotors (quadrotor), figure 2. demonstrates, there is a difference between an actual model and the approximate model with the largest difference being 11.6 watt, and a mean percent error of 4.9 %, as the payload variant from 0 to 4 Kg. Moreover, the power required to keep the drone frame in the air $\alpha = 21.44\ watt$, which obtain when the payload equal to zero, and the power consumed rate per Kg is, $\mu = 58.7\ watt/Kg$.

Figure 3 the difference between the actual and approximate models with the largest variance being 9.5 watt for the drone with 6 rotors when the payload is variant from 0 to 4 Kg. This result establish that the mean percent error is 4.5%, and the power required to keep the drone frame in the air $\alpha = 17.52\ watt$, while the power consumed rate per kg is, $\mu = 58.7\ watt/Kg$.

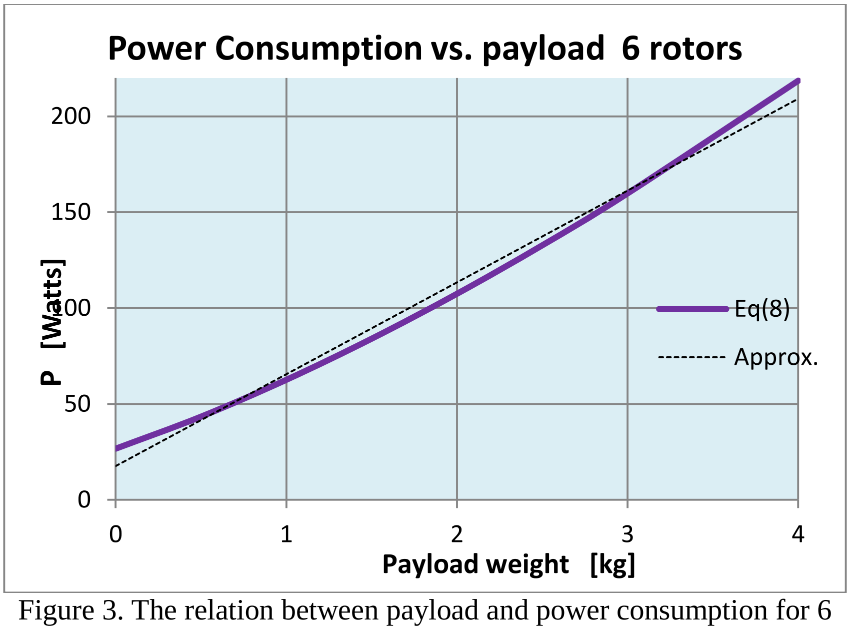

Figure 3. The relation between payload and power consumption for 6 rotors. The continuous thick line represents Eq. (7) and the dashed thin line represents the approximate.

Figure 4 show that the variance is 4.62 $watt$ between the actual and approximate models for drone with 8 rotors. The mean percent error is 4 %, and the power required to keep the drone frame in the air $\alpha = 18.38\ watt$, however the power consumed rate per kg is, $\mu = 38.57\ watt/Kg$.

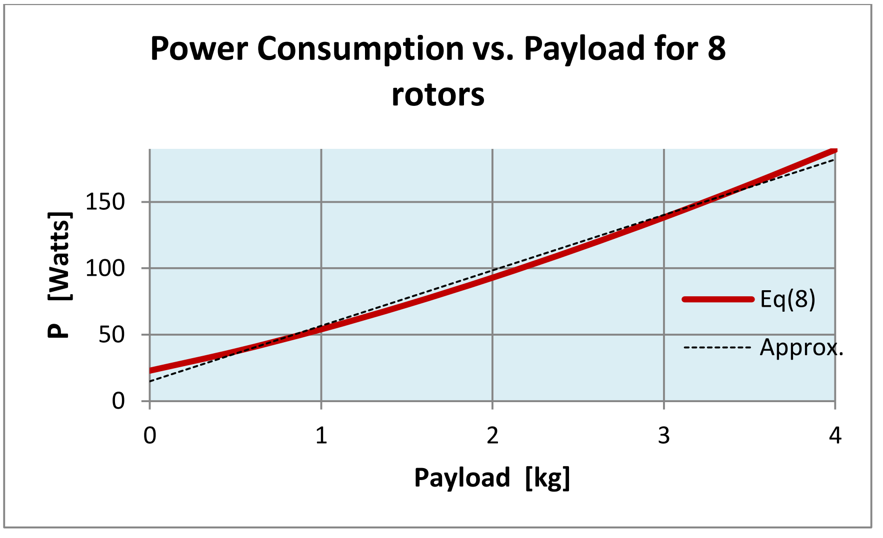

Figure 4. The relation between payload and power consumption for 8 rotors, the continuous thick line represents Eq. (7) and the dashed thin line represents the approximate.

If the payload weight changes from 0 to 9 Kg, in the experiments the accuracy of approximate model will decrease with mean percent error 5.1% for drone with 4 rotors and 6.8 % for drone with 6 rotors. The results show that the model is agreeable to calculate the power consumed by the drone when delivery tasks are carried out. Finally, the other parameters may impact the power consumption and necessity to investigation such as, the weather condition, and the speed of the drone.

Conclusion

The drone is powered by a small battery which make the power consumption is the challenges when carry out the delivery tasks. A mathematical formulation of the drone power consumption model was driven by using the theories of aerodynamics of the rotor-wing aircraft. The model was implemented in MATLAB/SIMULINK for drones with different number of rotors. This model is used to obtain the relation between the payload weight and the power consumed by the drone. Three experiments were done for three classes of drones: 4 rotors, 6 rotors and 8 rotors. The result shows that we can find the power consumption rate per kilogram and the power required to keep the drone frame in the air for various type of rotor-wing of drones. This result can be used in the drone routing problem (DRP) to calculate the power consumed by the drone when it makes the delivery work.

References

[1]. DHL launches its first regular urban drone delivery service.(accessed on 19 May 2019); Available from: https://www.smartcitiesworld.net/news/news/dhl-launches-its-first-regular-urban-drone-delivery-service-4189.
[2]. Amazon wins FAA approval for Prime Air drone delivery fleet. (accessed on AUG 31 2020); Available from: https://www.cnbc.com/2020/08/31/amazon-prime-now-drone-delivery-fleet-gets-faa-approval.html.
[3]. UPS launches new drone technology for speedier, heavier deliveries. (accessed on 27 March, 2020).
[4]. Citroni, R., F. Di Paolo, and P.J.S. Livreri, A novel energy harvester for powering small UAVs: Performance analysis, model validation and flight results. 2019. **19**(8): p. 1771.
[5]. Ure, N.K., et al., An automated battery management system to enable persistent missions with multiple aerial vehicles. IEEE/ASME Transactions on Mechatronics, 2015. **20**(1): p. 275-286.
[6]. Lee, D., J. Zhou, and W.T. Lin. Autonomous battery swapping system for quadcopter. in Unmanned Aircraft Systems (ICUAS), 2015 International Conference on. 2015. IEEE.
[7]. Michini, B., et al., Automated battery swap and recharge to enable persistent UAV missions, in Infotech@ Aerospace 2011. 2011. p. 1405.

[8]. Chang, T. and H. Yu, Improving electric powered UAVs' endurance by incorporating battery dumping concept. Procedia Engineering, 2015. **99**: p. 168-179.
[9]. Abdilla, A., A. Richards, and S. Burrow. Endurance optimisation of battery-powered rotorcraft. in Conference Towards Autonomous Robotic Systems. 2015. Springer.
[10]. Gatteschi, V., et al., New Frontiers of Delivery Services Using Drones: A Prototype System Exploiting a Quadcopter for Autonomous Drug Shipments. 2015: p. 920-927.
[11]. Dantzig, G.B. and J.H. Ramser, The truck dispatching problem. Management science, 1959. **6**(1): p. 80-91.
[12]. Zhang, J., et al., Energy consumption models for delivery drones: A comparison and assessment. 2021. **90**: p. 102668.
[13]. Leishman, G.J., Principles of helicopter aerodynamics with CD extra. 2006: Cambridge university press.
[14]. Torabbeigi, M., et al., Drone delivery scheduling optimization considering payload-induced battery consumption rates. 2020. **97**(3): p. 471-487.
[15]. Hoffmann, G., et al. Quadrotor helicopter flight dynamics and control: Theory and experiment. in AIAA guidance, navigation and control conference and exhibit. 2007.
[16]. PROFESSIONAL, P. PHANTOM 3 PROFESSIONAL. (accessed on 2022); Available from: https://www.dji.com/phantom-3-pro/info#specs.
[17]. Pounds, P., R. Mahony, and P.J.C.E.P. Corke, Modelling and control of a large quadrotor robot. 2010. **18**(7): p. 691-699.