

Research and Development of the Conceptual Design Methodology for Battery-Powered Mini-UAV

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Abstract. The present study develops a conceptual design methodology for battery-powered mini-UAVs. The methodology is adapted to address the peculiar characteristics of battery-powered mini-UAV and rewrites master and sizing equations which are related to the airframe weight and weight portions of battery and propulsion system. Subsequently, a conceptual design flowchart of battery-powered mini-UAV is provided. Ultimately, the methodology is verified by comparing to an existing UAV (RQ-11B), and applied to size a new Mini-UAV design. Satisfying results indicate that this methodology is suitable for conceptual design of battery-powered mini-UAV.

Introduction

Conceptual design of the battery-powered mini-UAV incorporates various disciplines such as the propeller's aerodynamics, structural properties, characteristics of the battery. Ref.1 introduces a simple methodology for quickly defining and analyzing solar-powered aircraft. However, battery-powered mini-UAV has great differences in terms of airframe structure, manufacturing processes and energy system when compared with solar-powered aircraft. Consequently, the present study is developed from Ref.1 with the master and sizing equations rewritten. Simultaneously, maximum specific power of propulsion system is derived to adapt the battery-powered mini-UAV. Ultimately, the paper builds the battery discharge model and inserts it into conceptual design flowchart. All of these result in a satisfying outcome of conceptual design.

Formulation

When the design requirements, namely, payload W_{payload} , flight time t , cruise airspeed V_{cru} , climb rate V_y , load factor n , maximum airspeed V_{max} and airspeed of take-off V_{to} are given, the steps of conceptual design are shown as follows:

1. Set an initial wing area S_0 and a candidate aerodynamic configuration. Describe the significant geometric features of candidate aerodynamic configuration in sufficient details by S_0 and predict aerodynamic forces, the drag predictions are based on the equivalent skin friction coefficient method. At the same time, estimate airframe weight W_{stru} by using weight model of airframe, which will be described in the below;
2. Plot the constraint diagram of wing loading and power-to-weight ratio defined by master equations. Design points can be selected from a solution space whose boundaries is defined by master equations;
3. Solve the sizing equation for total weight W_{tot} . This equation is based on a summation of weight portions for propulsion system and battery required to design requirements. Component weight portions are estimated by average specific power of battery $S_{\text{bat.cru}}$ and maximum

specific power of propulsion system S_{pmax} . Once the W_{tot} is obtained, it can be divided by design point wing loading W_{tot}/S to determine the wing area S ;

4. The process (step (1)-step (3)) must be iterative until a converged solution S is obtained. In iteration, the relative sizes of aircraft components should stay constant. Once a converged solution S is obtained, the specific geometric parameters of candidate aerodynamic configuration can be determined, and a conceptual design which meets the design requirements is obtained.

Sizing Equation and Master Equations

The sum of the various components weights of the aircraft must equal the aircraft total weight W_{tot} :

$$W_{tot} = W_{stru} + W_{payload} + W_p + W_{bat}. \quad (1)$$

W_{stru} is weight of airframe. We assume that the payload $W_{payload}$ is fixed. Since the total weight of aircraft is constant during the flight, W_p and W_{bat} can be described by weight portions, namely f_p and f_{bat} . As to the propulsion system weight portion f_p , it depends on the maximum specific power of propulsion system S_{pmax} . For the battery weight portion f_{bat} , it depends on the average specific power of battery $S_{bat.cru}$.

$$W_p = \frac{(P/W_{tot})_{max}}{S_{pmax}} W_{tot} = f_p W_{tot} \quad (2)$$

$$W_{bat} = \frac{(P/W_{tot})_{cru}}{h_{prop} h_m h_{ESC} S_{bat.cru}} W_{tot} = f_{bat} W_{tot} \quad (3)$$

The efficiency of components of propulsion system can refer to the Ref.2. Substitution of Eq.2 and Eq.3 into equation Eq.1 gives the sizing equation. Eq.4.

$$W_{tot} = \frac{W_{stru} + W_{payload}}{1 - f_p - f_{bat}} \quad (4)$$

The power-to-weight ratio under different flight conditions, in the Eq.2 and Eq.3, is usually chosen in order to allow the aircraft to meet the design requirements. These requirements are commonly represented on constraint diagram such as Fig.1 by using master equations. Eq.5 and Eq.6 [3].

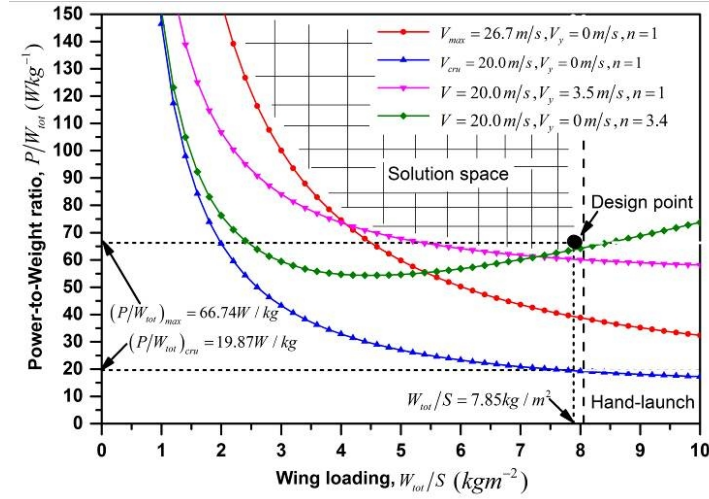


Fig. 1. Example mini UAV constraint diagram

$$\left(\frac{P}{W_{tot}}\right) = g \left\{ qV \frac{1}{g(W_{tot}/S)} \left[C_{D0} + \frac{g^2 n^2}{p A e q^2} \left(\frac{W_{tot}}{S} \right)^2 \right] + \frac{V_y V}{\sqrt{V^2 - V_y^2}} \right\} \quad (5)$$

$$\left(\frac{W_{tot}}{S}\right) \leq \frac{1}{2} r V_{to}^2 C_{Lmax} / g \quad (6)$$

From a constraint diagram, the designer selects values for wing loading and power-to-weight ratio under different flight conditions which will allow the aircraft to meet the design requirements. The best choice for UAV is typically the lower right corner of the solution space. In the case of Fig. 1, the selected values are $(P/W_{tot})_{max} = 66.74 W/kg$, $(P/W_{tot})_{cru} = 26.07 W/kg$ and $W_{tot}/S = 7.85 kg/m^2$.

Weight Model of Airframe

Presently, airframe of battery-powered mini-UAV, which is reinforced with bending beams, is predominantly manufactured by engineering plastic (such as Styrofoam, Expanded polypropylene, etc.). At the same time, shroud material is used to improve the quality of outer surfaces. The wing is designed with the scheme whose internal structure is shown in Fig. 2.

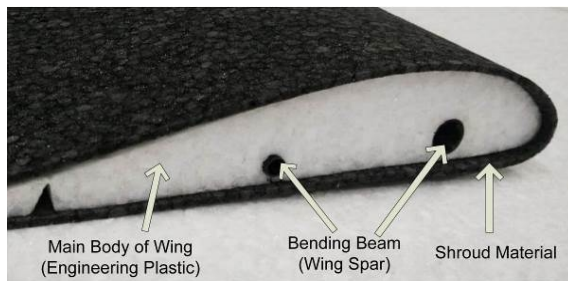


Fig. 2. Cross section of wing structure

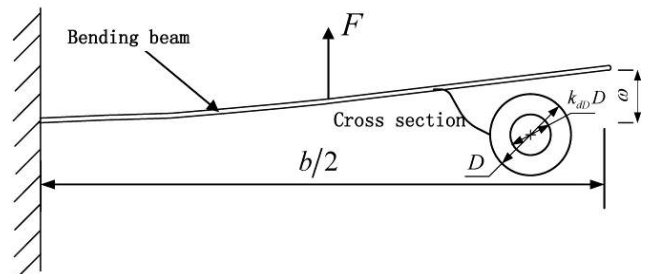


Fig. 3. Reduced mechanics model of wing

In this section, an airframe weight estimation method based on the property of structural mechanics is proposed. The airframe is divided into four main parts (wing, tail, fuselage and shroud material) to calculate their weight respectively. Wing, fuselage and tail have similar structure, their main bodies are integrally formed by engineering plastic and reinforced by bending beams which can be simplified to a cantilever beam model (shown in Fig. 3), where the resultant forces F (lift and wing gravity at the max

g case) act. Referring to structure stiffness criterion [3], the tip deformation w needs to satisfy the following requirement shown in Eq.7. Allowable tip deformation $[w]$ follows different design standards. Allowable wingtip deformation $[w]$ equals to $1/10b$.

$$w = \frac{5Fb^3}{384EI} \leq [w]/k_{beam} \quad (7)$$

Take the hollowed beam with circular section as an example, the diameter of wing spar D needs to satisfy Eq.8.

$$D \leq \sqrt[4]{\frac{5k_{beam}Fb^3}{6[w]pE[1-(k_{dD})^4]}} \quad (8)$$

Then weight of wing spar W_{S11} should be

$$W_{S11} = \frac{pD^2}{4} [1 - k_{dD}^2] b r_{beam} \quad (9)$$

Because main body of wing is integrally formed by engineering plastic. Its weight W_{S12} can be obtained from wing volume and engineering plastic density. Then the gross weight of wing W_{S1} is given by

$$W_{S1} = W_{S11} + W_{S12} \quad (10)$$

It is easy to calculate the gross weight of tail W_{S2} , gross weight of fuselage W_{S3} and the weight of shroud material W_{S4} by the similar method.

Weight Model of Airframe. we define a structure correction coefficient k_{stru} to improve accuracy of estimation when manufacturing errors and other auxiliary structures are considered. Then the weight of airframe W_{stru} can be acquired from the following Eq.11. k_{stru} ranges from 1.2 to 1.4.

$$W_{stru} = k_{stru} (W_{S1} + W_{S2} + W_{S3} + W_{S4}) \quad (11)$$

Specific Power

Maximum Specific Power of Propulsion System. Propulsion system weight portion f_{bat} (also see in Eq.2) is mainly relevant to the maximum specific power of propulsion system s_{pmax} .

$$s_{pmax} = \frac{P_{pmax}}{W_p} \quad (12)$$

As to brushless DC motor, there is a direct proportion relationship between its weight W_m and the maximum output power P_{mmax} [4]. Namely

$$W_m = \frac{P_{mmax}}{S_{mmax}} \quad (13)$$

S_{mmax} varies between the following limits: $110W/kg \leq S_{mmax} \leq 800W/kg$ commonly. We define a weight correction coefficient k_p to calculate the weight of the propulsion system, which ranges from 1.5 to 2.0 according to statistical data. Then the expression for the weight of propulsion system can be written as

$$W_p = k_p W_m \quad (14)$$

Substitution of Eq.13 and Eq.14 into equation Eq.12 gives the maximum specific power of propulsion system S_{pmax} .

$$S_{pmax} = \frac{h_{prop}}{k_p} S_{mmax} \quad (15)$$

Average Specific Power of Battery. Battery weight portion f_{bat} (also see in Eq.3) is mainly related to average specific power of battery $S_{bat.cru}$, which under the flight time t (or discharge time, which approximately equals to the flight time), $S_{bat.cru}$ is defined as the Eq.16.

$$S_{bat.cru} = \frac{E_{act}}{W_{bat}t} \quad (16)$$

Nowadays, most battery-powered mini-UAVs are driven by lithium polymer battery [5]. But this kind of battery displays distinct energy density and average specific power under different discharge power, which is called Peukert phenomenon [6, 7]. It is hard to apply statistical relationship between discharge energy E_{act} and battery weight W_{bat} to calculate the average specific power of battery directly. The parameter sensitivity analysis shows that the energy density of the battery has a significant influence on the performance of the battery-powered mini-UAV [4], so the Peukert phenomenon can't be ignored in the conceptual design, The functional relationship between discharge time t , constant discharge power P_{req} and rated capacity C_{rate} can be obtained by multilevel Peukert equation. See Eq.17.

$$t = f(P_{req}, C_{rate}) \quad (17)$$

Then actual discharge energy of battery E_{act} can be obtained from Eq. 18.

$$E_{act} = p_{req} t \quad (18)$$

Because the rated capacity C_{rate} is not affected by the discharge power under the same manufacturer in same batch, it is reasonable to utilize statistical relationship between battery weight W_{bat} and the rated capacity C_{rate} to calculate average specific power of battery $S_{bat.cru}$. For an instance, when the rated capacity is under 8.0 ampere-hour (Ah), battery weight can be calculated from the Eq.19 which is obtained by statistical data. Consequently, average specific power can be solved from Eq.16 to Eq.19. Take the 3 series batteries as an example, Fig. 4 shows average specific power in different discharge time with different rated capacities.

$$W_{bat} = 0.0693C_{rate} + 0.0179 \quad (19)$$

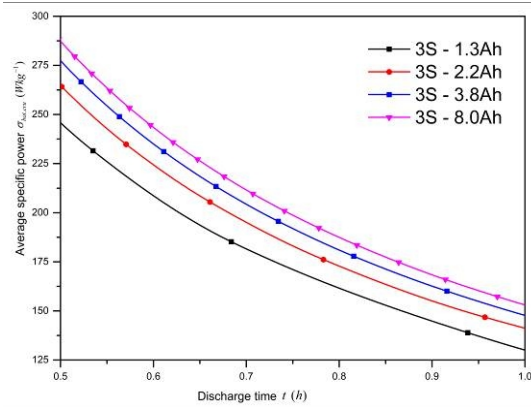


Fig. 4. Relationship between discharge time and average specific power about lithium polymer battery with 3 series

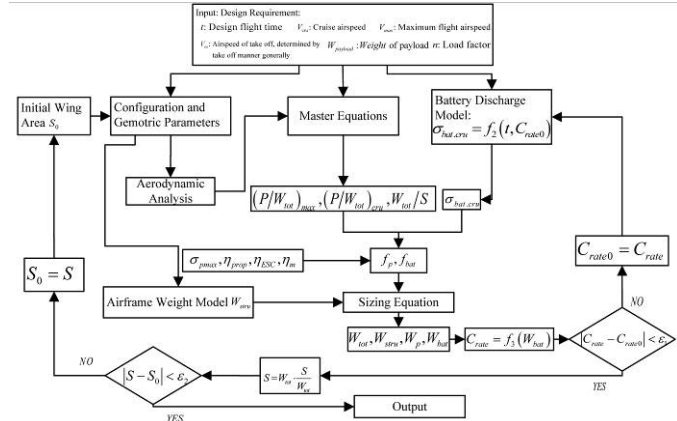


Fig. 5. A conceptual design iterative flowchart of battery-powered mini-UAV

Test Cases and Analysis

Verification on an Existed UAV. Take the hand-launched RQ-11B Raven UAV produced by United States AeroVironment Corporation as an example.

Table 1. Parameters of RQ-11B Raven UAV's performance and configuration [13]

Parameter	V_{cru}	V_{max}	V_{to}	n	V_y	AR	$W_{payload}$	t
	$[ms^{-1}]$	$[ms^{-1}]$	$[ms^{-1}]$		$[ms^{-1}]$		$[kg]$	$[h]$
	17.70	26.70	8.00[9]	2.40	6.10	7.60	0.20	1.50

Using the flowchart shown in Fig. 5 to determine the overall parameters. Compare the data with the real one in the following aspects shown in the Table 2.

Table 2. Comparisons between real and theoretical parameters on RQ-11B Raven UAV

Parameter	W_{tot}	S	W_{tot}/S	$(P/W_{tot})_{cru}$	$(P/W_{tot})_{max}$	b	L	C_{mac}	C_{rate}
	$[kg]$	$[m^2]$	$[kgm^{-2}]$	$[Wkg^{-1}]$	$[Wkg^{-1}]$	$[m]$	$[m]$	$[m]$	$[Ah]$
Reality	1.90	0.27	7.00	---	---	1.37	0.91	0.20	---
calculation	1.56	0.27	5.76	22.00	46.87	1.38	0.92	0.20	6.80(3S)

Wing loading is smaller than real one since the wing loading is constrained by take-off airspeed V_{to} in this case. Although some parameters of the RQ-11B Raven UAV are inexact, such as airfoil, the parameters obtained from the methodology fit nicely with the real ones.

New UAV Design. Utilize the flowchart shown in Fig. 5 to design a new battery-powered mini-UAV by the following specific design requirements listed in Table 3.

Table 3. Design requirements

Parameter	V_{cru} [ms^{-1}]	V_{max} [ms^{-1}]	V_{to} [ms^{-1}]	n	V_y [ms^{-1}]	$W_{Payload}$ [kg]	t [h]
	13.00	18.00	10.00	2.40	1.50	1.00	1.00

This UAV adopts tri-surfaces configuration and taxiing take-off strategy for differ from case 1. After the UAV was built, the actual parameters of the UAV were measured. Part of the overall parameters is listed in Table 4.

Table 4. Part of the conceptual design parameters comparison between calculation and reality.

Parameter	W_{tot} [kg]	S [m^2]	W_{tot}/S [kgm^{-2}]	$(P/W_{tot})_{cru}$ [Wkg^{-1}]	$(P/W_{tot})_{max}$ [Wkg^{-1}]	b [m]	L [m]	C_{mac} [m]	C_{rate} [Ah]
Reality	3.26	0.57	6.81	28.80	66.98	2.40	1.23	0.24	8.00(3S)
Calculation	3.15	0.53	5.97	26.40	63.38	2.20	1.21	0.24	7.60(3S)

Table 4 indicates that the calculated results is slightly smaller than actual values, this may be related to the manufacturing process and some aspects of methodology, which is beyond the consideration. Generally speaking, the calculated results are acceptable.

Fig. 6(a) and (b) show the 3-Dimension and flight test figures of the UAV designed by this proposed methodology.



Fig. 6. The devised UAV's 3-Dimension (a) and flight test (b) figures

Conclusion

A methodology has been described and demonstrated that provides a simple means for defining, evaluating, and sizing conceptual designs for battery-powered mini-UAV. Airframe weight model, which is based on the structural mechanics, is built with the consideration of the specialty of airframe. At the same time, the paper focuses on the maximum specific power of propulsion system and average specific power of battery, which are related to the weight portions. The methodology presented has been shown to be a quick tool in the conceptual design. The satisfying results of the various analyses suggest that the developed methodology is suitable for conceptual design of battery-powered mini-UAV.

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