Designing Electric Propulsion Systems for UAVs

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1 Introduction

Due to the advantages of electric motors and electric batteries, the electric propulsion systems are widely used in UAVs [1,2]. The UAV's performance and endurance, the payload capacity and the flight time of the vehicle are affected highly by the structure and design of the electric propulsion system. In this paper, a new systematic design methodology for electric propulsion system (propeller, electric motor and battery pack) is proposed based on the design specifications given in terms of the required thrust, permissible propulsion system's weight and required flight time.

For design, a mathematical model of the propeller is considered to quantify the generated thrust and the corresponding mechanical power. Using the momentum theory [3] with certain assumptions, the static thrust T developed by a propeller and the mechanical power P needed to generate this thrust are given respectively as $T = \frac{\rho}{128\pi} N^2 d^2 {k_1}^2 \omega^2 R^2 ((1 + \frac{64\pi R}{3Ndk_1}\theta)^{0.5} - 1)^2$ and $P = \frac{\rho}{2048\pi^2} N^3 d^3 k_1^3 \omega^3 R^2 ((1 + \frac{64\pi R}{3Ndk_1}\theta)^{0.5} - 1)^3$, where ρ, N and d are respectively the air density, the number of blades and the chord length of the blade of the propeller. k_1 is known as the two-dimensional lift slope factor and is considered as $k_1 = 5.7$ [4]. R, θ and ω are respectively the radius, the pitch angle, and the rotational speed of the propeller.

2 Design Methodology

Inputs to the design algorithm: (i) the maximum allowable radius of the propeller R_{max}, (ii) the total mass requirement of the UAV M_{total} and the allowance for the propulsion system mass M_p, and (iii) the required minimum flight time t_f.

Step 1: Set the required thrust $T_h = \alpha g M_{total}$, where $\alpha > 1$ is a safety factor to be chosen by the designer (e.g. $\alpha = 1.2$).

Step 2: Selecting a set of propellers: **2a)** Choose a set of commercially available propellers $\mathbb{Y}$ whose radii are $R_y \leq R_{max}$ $\forall$ $y \in \mathbb{Y}$. **2b)** For each propeller $y \in \mathbb{Y}$, calculate the minimum rotational speed ω_y and the corresponding minimum mechanical power P_y (using the expression given in Section 1) necessary to generate the required given thrust T_h. A propeller y is infeasible for the design if $\omega_y > \omega_{max_y}$, where ω_{max_y} is the maximum allowed rotational speed of the propeller y (specified by the manufacturer) and hence the propeller y must be excluded from the design process. Let $\overline{\mathbb{Y}}$ the set of all feasible propellers. 2c) Over

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all propellers $y \in \overline{\mathbb{Y}}$, find the minimum rotational speed and minimum mechanical power necessary to generate the required thrust; i.e., $\omega_{min} = \min_{y\in\overline{\mathbb{Y}}}(\omega_y)$ and $P_{min} = \min_{y\in\overline{\mathbb{Y}}}(P_y)$.

Step 3: Selecting a set of motors: **3a)** Select a set of commercially available BLDC motors $\mathbb{Z}$ such that $\forall\ z \in \mathbb{Z}$ the following conditions are fulfilled: $P_{max_z} \geq P_{min}$, $\omega_{max_z} \geq \omega_{min}$ and $M_z < M_p$ where P_{max_z}, ω_{max_z} and M_z are respectively the power rate, the maximum rotational speed and the mass of the motor z. **3b)** Construct motor-propellers groups $G_j, j = 1, 2, .., n(\mathbb{Z})$, where $n(\mathbb{Z})$ denotes the number of the motors in the set $\mathbb{Z}$. The jth group G_j contains a motor $z_j \in \mathbb{Z}$ and a subset of propellers $\mathbb{I}_j \subseteq \overline{\mathbb{Y}}$, where $\mathbb{I}_j := \{y \in \overline{\mathbb{Y}} : \omega_y \leq \omega_{max_{z_j}}, P_y \leq P_{max_{z_j}}\}$. **3c)** For the jth group G_j, calculate V_y^j and I_y^j $\forall\ y \in \mathbb{I}_j$, where $V_y^j = \frac{\omega_y}{k_{v_{z_j}}}$ and I_y^j is obtained from the operational chart of the motor z_j. V_y^j and I_y^j are respectively the required voltage and current for the motor z_j to rotate the propeller y at the minimum speed ω_y necessary to generate the required thrust. In group G_j, the pair $(z_j\ , y)$, where $y \in \mathbb{I}_j$, is feasible for the design if $I_y^j \leq I_{max_{z_j}}$, where $I_{max_{z_j}}$ is the maximum allowed continuous current of the motor z_j (specified by the manufacturer). Select all feasible pairs in $G_j\ , j = 1, 2, ..., n(\mathbb{Z})$.

Step 4: Selecting a set of batteries: **4a)** For each feasible pair $(z_j\ , y) \in G_j$, select a set of commercially available battery packs $\mathbb{B}_y^j$ such that $\forall\ b \in \mathbb{B}_y^j$ the following conditions are fulfilled: $V_b \geq V_y^j$, $I_{max_b} \geq I_y^j$ and $M_b \leq M_p - M_{z_j}$, where V_b and I_{max_b} are respectively the effective voltage and maximum continuous discharging current of the battery $b \in \mathbb{B}_y^j$, and M_b is the mass of the corresponding battery pack. **4b)** $\forall\ b \in \mathbb{B}_y^j$, calculate the mass of the propulsion system $(z_j\ , y\ , b)$ and the full load (i.e. minimum) flight time as: $M_{z_j,y,b} = M_{z_j} + M_b$ and $t_{z_j,y,b} = \frac{I_{0_b}}{I_y^j}$, where $(z_j\ , y) \in G_j$ is a feasible pair and I_{0_b} is the current rate ($\mathtt{A.h}$) of the battery $b \in \mathbb{B}_y^j$. If $t_{z_j,y,b} < t_f$, the battery pack b cannot provide the required flight time when used with the pair $(z_j\ , y)$ and must be excluded from $\mathbb{B}_y^j$. **4c)** Calculate $M_{z_j,y,b}$ and $t_{z_j,y,b}$ for all feasible pairs $(z_j\ , y) \in G_j$, $j = 1, 2, ..., n(\mathbb{Z})$.

Step 5: Based on the values of $M_{z_j,y,b}$ and $t_{z_j,y,b}$ for all feasible pairs, we can choose the best design to achieve maximum flight time $(z_t\ , y_t\ , b_t)$ or minimum propulsion system weight $(z_w\ , y_w\ , b_w)$ or a design that satisfy a trade off between the two factors.

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