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Electric Propulsion System Sizing for Small Solar-powered Electric Unmanned Aerial Vehicle

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Abstract
Propulsion system performance is one of the key factor which effects on the overall performance of an unmanned aerial vehicle (UAV). However, selection of the electric propulsion system for UAV has been a simple process for most design engineers. This is due to the standard propulsion combination (of electric motor, gearbox, ESC, propeller and battery) sets recommended by manufacturers or suppliers are based on UAV weight. Manufacturers also specify propulsion system package based on the type such as sailplane, trainer, aerobatic, and 3D aircraft. However, the recommended weight range difference between this lower and upper weight even within a particular type of UAV may vary up to 25% of the maximum take-off weight. When multiple sets are recommended, it clearly shows the wide flexibility and combinations that applicable for an unmanned aircraft. Thus, these pre-evaluated sets of electric propulsion system are obviously not the best possible options for UAV designer. Hence, a comprehensive propulsion system design for electric propulsion of both solar and non-solar UAV is done in this research. Performance comparison among various propeller sizes show that the high efficiency of electric motor with small diameter and pitch of propeller does not provide sufficient thrust output. Instead, propeller tip static speed is the parameter that should be concerned in propeller sizing; since the smaller this propeller tip static speed enables UAV to achieve higher endurance.

Keywords: UAV; drone; unmanned aerial vehicle; electric propulsion; propeller; solar-powered MAV.

INTRODUCTION
Currently, unmanned aerial vehicle (UAV) has been implemented in both military and civilian fields such as traffic monitoring, disaster monitoring, surveillance, and search and rescue [1-5]. This is undeniable that the huge potential of UAV is the reason of huge interest from scientific community [3, 6]. In addition, there is no pilot safety issue since it is no-pilot-onboard and the cost is much lower than manned aircraft [1]. Also, the unmanned aircraft has greater maneuverability and can be designed to be lighter and smaller platform [2].

Solar has been a promising power source for an electric powered UAV to increase its endurance and range in a sustainable way [7-9]. Still, the efficiency of solar cell alone is not good enough for an aircraft to sustain non-stop operation, thus require a secondary power source like batteries [8, 10, 11]. Consequently, quite a number of projects have been done to develop the solar-powered UAV technologies such as High-Altitude-Long-Endurance (HALE) project [12-15].

Performance of the propulsion system is the important on the overall performance of the electric UAV. Generally, the selection of the electric propulsion system has been a simple process for most design engineers, aero modeler and hobbyist. Manufacturers or suppliers usually recommends the standard combination of electric motor, gearbox, ESC, propeller and battery, as a sets for a stated UAV weight range. Some suppliers do specify propulsion components as a package based on the type such as sailplane, trainer, aerobatic, and 3D aircraft.

These sets recommendation is deem suitable for a stated UAV weight range that may differ up to 25% of the maximum take-off weight. Moreover, when multiple sets are recommended, it clearly shows the wide fuzziness of these combinations. Thus, these pre-evaluated sets of electric propulsion system are noticeably not the best possible options for UAV designer. Hence, the propulsion system sizing model is essential to select the most suitable combination of components of the propulsion system in order to estimate the performance of the UAV.

Thus, analysis on the electric propulsion system of the design model will be done in this study. Electric propulsion system for a UAV consists of battery, electric motor, electronic speed controller (ESC) and propeller. A complete electric propulsion system sizing model for an electric UAV will be done in this research. A case study solar-powered UAV model from Cranfield University [16] is used in this study to investigate the implication of propeller size change. Since this case study UAV may operate with and without solar, both variant has been assessed to elucidate the significant of propulsion system sizing.

METHODOLOGY

In order to obtain the best electric propulsion system combination for UAV, data such as the aircraft maximum take-off weight, operating altitude and stall speed are required. These data will be used together with the battery, electronic speed controller and electric motor's part specification to obtain the most suitable propeller size. In this section, the propulsion system sizing model are defined in 3 sub-section, which focuses the battery, electric motor and propeller.

A. Battery

The required data are battery cell's maximum voltage, maximum discharge rate, capacity, efficiency, and as well the number of cell in series and parallel and internal resistance, in the battery pack. Battery pack maximum current limit can be estimated as shown in Eq. 1.

$$\mathrm{Batt}_{\mathrm{Current-Max}} = \mathrm{Cell}_{\mathrm{Parallel}}\mathrm{Cell}_{\mathrm{Capacity}}\mathrm{Cell}_{\mathrm{C}} \quad (1)$$

This estimation on battery pack current limit is crucial to ensure the battery pack and the ESC has higher value then the electric motor maximum outburst current. This is to prevent heat dissipation, burn-out or explosion in these parts.

Anyway, there is no substantial recommendation on the limit differences between battery pack and electric motor for optimum performance. Nevertheless, the calculation of power available and output from battery pack is shown in Eq. 2 and 3. This calculation is to ensure there is sufficient power supply to the electric motor.

$$\mathrm{P}_{\mathrm{Batt-In}} = \mathrm{Current}_{\mathrm{Limit}}\mathrm{Cell}_{\mathrm{Series}}\mathrm{Cell}_{\mathrm{Volt-Max}} \quad 2$$

$$\mathrm{P}_{\mathrm{Batt-Out}} = \mathrm{eff}_{\mathrm{Batt}}\mathrm{P}_{\mathrm{Batt-In}} \quad 3$$

B. Electric Motor

In order to determine the performance of electric motor, additional required data are the electronic speed controller's resistance and maximum current limit, and electric motor's resistance, maximum current limit, no load current, and rpm per volt ratio. The approximation of operational voltage of battery, ESC and the electric motor is presented in Eq. 4-6.

$$\mathrm{V}_{\mathrm{batt}} = \mathrm{Cell}_{\mathrm{Series}}\mathrm{Cell}_{\mathrm{Volt-Max}} - \mathrm{I} \times \mathrm{Batt}_{\mathrm{Resistance}} \quad 4$$

$$\mathrm{V}_{\mathrm{Esc}} = \mathrm{V}_{\mathrm{Batt}} - \mathrm{I} \times \mathrm{ESC}_{\mathrm{Resistance}} \quad 5$$

$$\mathrm{V}_{\mathrm{Motor}} = \mathrm{V}_{\mathrm{ESC}} - \mathrm{I} \times \mathrm{Motor}_{\mathrm{Resistance}} \quad 6$$

Then, these electric motor's voltage values enable to determine the RPM of the motor as shown in Eq. 7.

$$\mathrm{RPM} = \mathrm{V}_{\mathrm{Motor}}\mathrm{K}_{\mathrm{V}} \quad 7$$

Then, the power input and output of the electric motor can then be calculated with RPM, voltage of ESC and RPM per volt ratio as given in Eq. 8 and 9 below.

$$\mathrm{P}_{\mathrm{Motor-In}} = \mathrm{V}_{\mathrm{ESC}} \times \mathrm{I} \quad 8$$

$$\mathrm{P}_{\mathrm{Motor-Out}} = \frac{\left(\frac{\mathrm{V}_{\mathrm{ESC}}\mathrm{RPM}}{\mathrm{K}_{\mathrm{V}}} - \left(\frac{\mathrm{RPM}}{\mathrm{K}_{\mathrm{V}}}\right)^2\right)}{\mathrm{Motor}_{\mathrm{Resistance}}} \quad 9$$

Finally, the current of the electric motor can be estimated using Eq. 10 below.

$$\mathrm{I}_{\mathrm{Motor}} = \mathrm{I} - \mathrm{I}_{\mathrm{Motor-No-Load}} \quad 10$$

C. Propeller

Subsequently, the power from the electric motor to the propeller can be estimated using Eq. 11. Meanwhile, the required power from propeller based on the simulated propeller diameter and pitch size can be evaluated as given in Eq. 12.

$$\mathrm{P}_{\mathrm{Prop-In}} = \frac{\mathrm{P}_{\mathrm{Motor-Out}}\mathrm{V}_{\mathrm{Motor}}\mathrm{I}_{\mathrm{Motor}}}{\mathrm{P}_{\mathrm{Motor-In}}} \quad 11$$

$$\mathrm{P}_{\mathrm{Prop-Req}} = \frac{0.5\rho}{\mathrm{g}}\left(\frac{\mathrm{RPM}}{60}\right)^3 (0.0254\mathrm{Diam})^4(0.0254\mathrm{Pitch}) \quad 12$$

Here, the error difference between the input and required propeller power can be determined, where within ±10% is preferred. This limits and ensures a suitable range of propeller are obtained.

Generally, a propeller with large in diameter but small in pitch will give more thrust with lower speed. Thus, the UAV will accelerate quickly but lower top speed. However, if the propeller diameter to pitch ratio is too close to 1:1, the propeller will become inefficient at low speed especially during take-off and climbing. Hence, the simulated propeller diameter to pitch ratio should be between 2:1 and 1:1.

In addition, the ideal performance occurs when the pitching velocity of the propeller should be within 2.5 and 3 times of the aircraft stall speed and the calculation of pitching velocity of propeller is using Eq. 13 below:

$$\mathrm{V}_{\mathrm{Prop-Pitch}} = \frac{\mathrm{RPM}}{60}(0.0254\mathrm{Pitch}) \quad 13$$

Also, the thrust of propeller must at be least 25% more than the maximum take-off weight of the UAV to have reasonable climb and acceleration capabilities. This can be estimated by using Eq. 14 below.

$$\mathrm{Thrust}_{\mathrm{Prop}} = \frac{\mathrm{P}_{\mathrm{Prop-Req}}}{\mathrm{gV}_{\mathrm{Prop-Pitch}}} \quad 14$$

Regardless, the thrust of propeller is recommended to be no more than the maximum take-off weight by 50% to minimize unnecessary thrust and save relevant weight which can be used to strengthen structure and increase endurance. Lastly, the efficiency and power to thrust ratio of electric propulsion system, power to weight ratio and propeller tip static velocity can be determined by using Eq. 15-18.

$$\mathrm{eff_{Electric}} = \frac{\mathrm{P_{Prop-out}}}{\mathrm{P_{Motor-In}}} \times 100 \tag{15}$$

$$\mathrm{P_{Ratio}} = \frac{\mathrm{P_{Motor-In}}}{\mathrm{gW_{TOmax}}} \tag{16}$$

$$\mathrm{PT_{Ratio}} = \frac{\mathrm{P_{Motor-In}}}{\mathrm{gThrust_{Prop}}} \tag{17}$$

$$\mathrm{V_{Prop-Tip-Static}} = \pi \frac{\mathrm{RPM}}{60} (0.0254\mathrm{Diam}) \tag{18}$$

Only then a list of simulated propeller's diameter and pitch size combination can be produced when all the criteria mention above are met. Finally, the propeller size which has the least of either propeller tip static velocity can be chosen. This gives the most optimum propeller size combination which will lead to better performance especially high endurance and long range for a UAV. Nevertheless, there is a power to weight ratio guide for various flying capabilities as shown in Table 1.

Table 1 : UAV Power to Weight Ratio Guide

Flying Capabilities	**Power to Weight Ratio (W/lbs.)**
Electric Glider, Park Flyer & Slow Flyer	30-60
Trainers & Basic Scale Flying	60-75
Sport Flying & Improved Climbing	75-100
Limited 3D, Pattern & Racing	100-150
Full Power 3D & Pattern Aerobatics	150-220

A sailplane is known to have wider wing span, large wing area and requires minimum maneuverability, thus requiring less power compare to other unmanned aircraft. A trainer is similar to sailplane in maneuverability but has average wing span and area. An aerobatic plane is the higher maneuverable version of a trainer. As for the 3D airplanes, they perform the highest maneuverability with the ability to hover easily.

RESULT & DISCUSSION

Propeller sizing model for both solar and non-solar UAV has been simulated to show the impact of this sizing configuration on overall performance of UAV design. Table 2 illustrate the without solar and with solar UAV propeller sizing chart respectively.

Results shows when a propeller diameter and pitch are lower, the efficiency of the electric motor is higher. The propeller size of 11X5.5 inches for non-solar UAV and 12X6.5 inches can achieve up to 82.10% and 80.27% of motor efficiency correspondingly. Yet, the propeller size with the highest efficiency of electric motor does not produce the highest propeller thrust output. Both these propellers can only thrust of 0.76 kg and 0.91 kg respectively.

In propeller sizing, the propeller size with the lowest value of propeller tip static speed is chosen. This is because of the least propeller's tip static speed will give the longest endurance flight and this is essential for 24 hours continuous flight. Therefore, propeller size of 14X8 and 13X8.5 inches is the most suitable size for the without solar and with solar UAV respectively.

Normally, the propeller thrust output increases as the propeller diameter and pitch is higher. Hence, the optimum size of propeller for UAV with solar at 13.5X8 and without solar at 14X8 inches. These propeller are capable to produce propeller thrust of 0.96 and 1.14 kg and produces power of 230.32W and 241.57 W in respective order.

This is definitely in contrast to the idea of choosing a propeller size that gives the most efficient electric motor or the highest power to weight ratio.

Table 2 : Case Study UAV Propeller Sizing Chart

	Propeller Diameter	Propeller Pitch	Current (A)	Voltage (V)	Power In (W)	Motor Efficiency (%)	Required Propeller Power (W)	Propeller (kRPM)	Propeller Thrust (kg)	Propeller Pitch Speed (m/s)	Propeller Tip Static Speed (m/s)	Power to Weight Ratio (W/kg)
UAV (Without Solar)	11	5.5	14.44	10.56	144.58	82.10	146.66	8.45	0.76	19.67	123.59	31.17
	11	6	15.43	10.43	152.06	82.04	154.34	8.35	0.74	21.20	122.11	32.82
	11	6.5	16.39	10.31	159.02	81.86	161.40	8.25	0.73	22.70	120.68	34.40
	12	6	21.50	10.67	229.30	80.77	184.76	7.89	0.94	20.05	125.95	88.19
	12	6.5	22.64	10.56	239.13	80.27	191.46	7.78	0.91	21.40	124.10	91.97
	12	7	23.72	10.47	248.23	79.81	197.57	7.67	0.89	22.72	122.35	95.47
	13	6.5	27.56	10.12	278.90	77.70	215.99	7.28	1.10	20.02	125.79	107.27
	13	7	28.77	10.01	288.01	77.00	220.99	7.15	1.06	21.19	123.66	110.77
	13	7.5	29.93	9.91	296.50	76.25	225.24	7.03	1.03	22.33	121.62	114.04
	14	7	33.90	9.55	323.71	73.46	236.79	6.63	1.23	19.65	123.45	124.50
	14	7.5	35.14	9.44	331.63	72.54	239.50	6.50	1.18	20.65	121.10	127.55
	14	8	36.32	9.33	338.91	71.61	241.57	6.38	1.14	21.62	118.87	130.35
UAV (With Solar)	12	6.5	22.64	10.56	239.13	80.27	191.46	7.78	0.91	21.40	124.10	79.71
	12	7	23.72	10.47	248.23	79.81	197.57	7.67	0.89	22.72	122.35	82.74
	12	7.5	24.76	10.37	256.80	79.29	203.04	7.56	0.86	24.00	120.66	85.60
	13	7	28.77	10.01	288.01	77.00	220.99	7.15	1.06	21.19	123.66	96.00
	13	7.5	29.93	9.91	296.50	76.25	225.24	7.03	1.03	22.33	121.62	98.83
	13	8	31.03	9.81	304.32	75.53	228.97	6.92	1.00	23.44	119.68	101.44
	13	8.5	32.26	9.70	312.81	73.93	230.32	6.80	0.96	24.46	117.52	104.27
	14	7.5	35.14	9.44	331.63	72.54	239.50	6.50	1.18	20.65	121.10	110.54
	14	8	36.32	9.33	338.91	71.61	241.57	6.38	1.14	21.62	118.87	112.97

CONCLUSION

This modelling and simulation will deepen the capability of an electric UAV design configuration sizing into a whole new aspect since there is a vast difference to conventional fossil-fueled aircraft in propeller sizing. The efficiency of electric motor increases with lower propeller diameter and pitch. Still, high efficiency of electric motor does not deliver high thrust output. Although the efficiency of electric motor decreases with larger diameter and pitch, the propeller thrust and power to weight ratio is higher. Therefore, the propeller tip static speed is to be chosen as the key parameter for propeller sizing instead of power to weight ratio. This is due to longer endurance flight can be achieved with lower propeller tip static speed. In addition, high power to weight ratio also means high power consumption.

LIST OF ABBREVIATIONS

$\mathrm{Cell_C}$	Battery Cell's Maximum Discharge Rate (A/Ahr.)
$\mathrm{P_{Batt-In}}$	Power Available in the Battery Pack (W)
$\mathrm{P_{Batt-Out}}$	Power Output in the Battery Pack (W)
$\mathrm{Current_{Limit}}$	The Smallest among the Maximum Current Limit of Battery, ESC & Electric Motor (A)
$\mathrm{V_{Batt}}$	Battery's Operational Voltage (V)
I	Current (A)
$\mathrm{Batt_{Resistance}}$	Battery Pack's Internal Resistance (Ohms)
$\mathrm{V_{ESC}}$	Electronic Speed Controller's Operational Voltage (V)
$\mathrm{ESC_{Resistance}}$	Electronic Speed Controller's Internal Resistance (Ohms)
$\mathrm{V_{Motor}}$	Electric Motor's Operational Voltage (V)
$\mathrm{Motor_{Resistance}}$	Electric Motor's Internal Resistance (Ohms)
RPM	Electric Motor's Shaft Rotation per Minute (rpm)
$\mathrm{K_V}$	Electric Motor's RPM per Volt Ratio (rpm/V)
$\mathrm{P_{Motor-In}}$	Power Input in the Electric Motor (W)
$\mathrm{P_{Motor-Out}}$	Power Output in the Electric Motor (W)
$\mathrm{I_{Motor}}$	Electric Motor's Current (A)
$\mathrm{I_{Motor-No-Load}}$	Electric Motor's No Load Current (A)
$\mathrm{P_{Prop-In}}$	Power Input to the Propeller (W)
$\mathrm{P_{Prop-Req}}$	Power Required from the Propeller (W)
g	Gravitational Force at the chosen Altitude (g/m^2)
Diam	Propeller's Diameter (in)
Pitch	Propeller's Pitch (in)
$\mathrm{eff_{Electric}}$	Electric Propulsion Systems' Efficiency (%)
$\mathrm{P_{Ratio}}$	Aircraft Power to Weight Ratio (W/N)
$\mathrm{PT_{Ratio}}$	Electric Propulsion Systems' Power to Thrust Ratio (W/N)
$\mathrm{V_{Prop-Tip-Static}}$	Propeller Tip Static Velocity (m/s)

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