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SENSITIVITY ANALYSIS OF DESIGN PARAMETERS OF A SMALL SOLAR-POWERED ELECTRIC UNMANNED AERIAL VEHICLE

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Abstract

The design, fabrication, and operation costs of a solar-powered unmanned aerial vehicle (SUAV) only comprise a small fraction of the various aspects of satellite systems. Given the easy redeployment of SUAVs with a newly enhanced payload, many researchers have become interested in studying the potential of SUAVs as pseudo-satellites. However, research on the capability of a small SUAV to achieve year-round global perpetual operation remains in its infancy. The endurance of small SUAVs may be further improved by reducing system weight and power consumption. Therefore, sensitivity analyses are performed to determine the effects of payload, propulsion's weight to power ratio, and solar module's weight to area ratio on the weight and power consumption of a small SUAV. The outcome of this investigation is vital to avoid unnecessary investment on product development that may not significantly improve the performance and capabilities of SUAVs. The payload exerts the greatest effect on the maximum take-off weight of a SUAV, followed by the battery, structure, solar module, and propulsion weight. The weight to area ratio of the solar module should be prioritized in technological advancements to promote the endurance of SUAVs. In addition, small SUAVs will considerably benefit from improvements in the weight to power ratio of the propulsion.

Keywords: Battery, Electric motor, Endurance, Power Consumption, Solar, Solar-powered UAV.

1. Introduction

Unmanned aerial vehicles (UAVs) were initially developed for military applications. Since the last decade, however, UAVs have been used in commercial and large-scale applications [1-4]. This development has been mainly driven by cost and safety concerns. Cost in terms of materials and manufacturing is low when using a small platform. Rajendran and Smith [5] commented that, in addition, the safety of the pilot can be guaranteed given that he/she is not onboard but rather in the ground station. According to Babel [6], the maneuverability of an unmanned aircraft with a smaller platform is also better than that of an aircraft with a larger platform. Hence, UAVs can be used in critical missions and applications without concerns on aircraft capability and pilot safety [7-8].

Harasani et al. [9] and Fazelpour et al. [10], solar-powered UAVs (SUAVs) have recently received considerable interest from the research community because they can deliver more tasks than other types of UAV given the availability of solar energy. The utilization of renewable solar energy with near-zero emission further strengthens the benefits of using SUAVs in various applications, particularly in environmental research, surveillance, and pseudo-satellite communication. However, research on the capability of a small SUAV to achieve year-round global perpetual operation remains in its infancy [11-15].

SUAVs generally collect solar irradiance during daytime and convert solar energy into electrical energy for propulsion. The excess energy is stored in secondary batteries for flight during nighttime. Moreover, SUAVs can fly at near-space altitudes to allow them to absorb solar irradiance above the clouds, and thus, improve their endurance [12, 13, 15]. Rajendran and Smith [16] explained that reducing the weight and power consumption of SUAVs may also improve their endurance despite limited solar irradiance and daylight duration.

Therefore, this study analyzes the sensitivity in design of a small SUAV system. It investigates how maximum take-off weight, propulsion weight, solar module weight, maximum power point tracker (MPPT) weight, power consumption, and endurance vary when payload, propulsion's weight to power ratio, and solar cell's weight to area ratio change in a small SUAV.

This study also includes sensitivity analyses of the effects of payload, propulsion's weight to power ratio, and solar module's weight to area ratio on SUAV weight and power consumption. These analyses are essential to determine the effects of these parameters on SUAV design. The outcome of this investigation is vital to understand which aspects of product development should be focused on to improve the performance and capabilities of SUAVs significantly.

2. SUAV Design Methodology

Numerous SUAV components have evidently become smaller, more powerful, and more efficient than their previous counterparts. Thus, the approach for assessing the effects of technological advancements on SUAV designs is crucial. The mathematical model of a SUAV design that has been developed earlier and used in this work is illustrated in Fig. 1 [1, 3, 5, 11, 14].

This SUAV design model has seven components, namely, mass sizing, aerodynamics, performance, stability and control, mission profile, solar irradiance, and electric propulsion. The sensitivity analyses of this model will be used to identify the parts with the most significant advantage for further research to yield the best output for SUAV design.

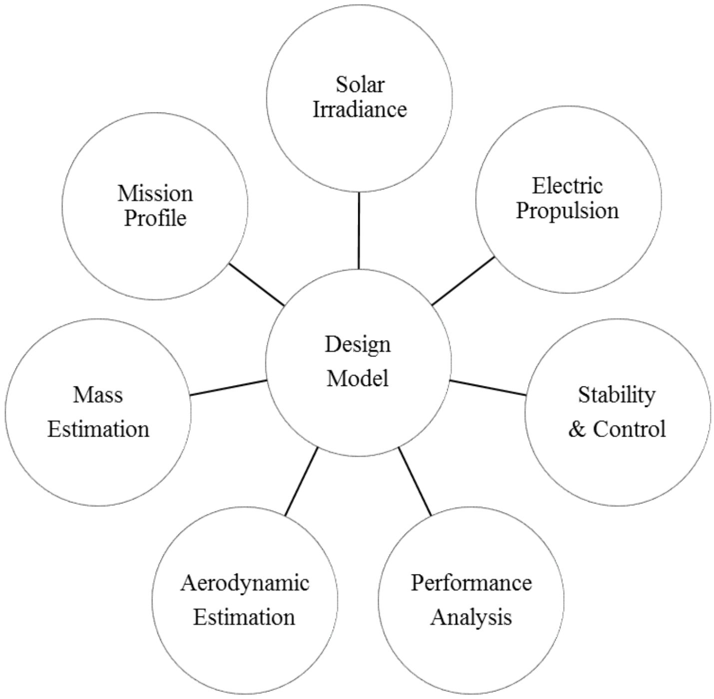

Fig. 1. Design model of a SUAV design.

3. Design Parameters

Rajendran and Smith [3] presented on series of sensitivity studies on a small SUAV developed by Cranfield University. This SUAV has been selected because its parameters are readily available. Moreover, the effects of changes on various parameters can be easily visualized in a SUAV with already five successful flights to date. A photograph taken during a scheduled flight test of this SUAV is shown in Fig. 2 [3, 11]. The initial payload of the aforementioned 3 kg SUAV weighs 0.25 kg. The propulsion's weight to power ratio is 0.0125 kg/W, and the solar module's weight to area ratio is 0.2845 kg/m^2.

Five variables of the SUAV are examined by varying the payload, propulsion's weight to power ratio, and solar module's weight to area ratio. These variables are maximum take-off weight, solar module weight, propulsion weight, power consumption, and battery-only flight endurance. The propulsion's weight to power ratio and solar module's weight to area ratio are set to within ±10% error of the specification of the studied SUAV. The payload weight is set from 0 kg to 0.5 kg to study the suitability of a wide range of payload applications.

Fig. 2. SUAV developed by Cranfield University.

3.1. Maximum take-off weight

The effects of various parameters on the maximum take-off weight of the SUAV are presented in Fig. 3. The analysis of the sensitivity of the propulsion's weight to power ratio on the maximum take-off weight of the SUAV is shown in Fig. 3(a). The findings indicate that improving the propulsion's weight to power ratio will not considerably decrease the maximum take-off weight of the SUAV.

The maximum take-off weight can be decreased by 1.87 kg when the propulsion's weight to power ratio improves by 0.1 kg/W. Overall, the maximum take-off weight is lighter by only 0.75% as a result of a 10% improvement in the propulsion's weight to power ratio.

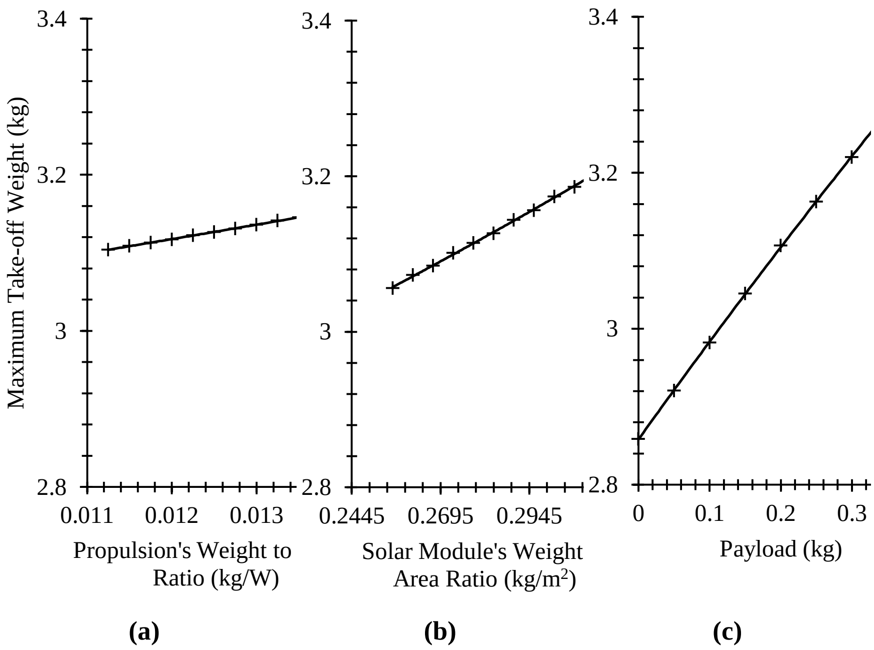

Fig. 3. (a) Propulsion's weight to power ratio, (b) solar module's weight to area ratio, and (c) payload vs. maximum take-off weight.

The maximum take-off weight of the SUAV after changing the solar module's weight to area ratio is illustrated in Fig. 3(b). The result indicates that enhancing this ratio can significantly reduce the maximum take-off weight of the SUAV. As a consequence of reducing maximum take-off weight by 0.26 kg when the solar module's weight to area ratio is decreased by 0.1 kg/m^2. Moreover, this decrease accounts for a nearly 2.4% reduction in the maximum take-off weight caused by a 10% improvement in the solar module's weight to area ratio.

The effect of the changes in payload on the maximum take-off weight of the SUAV is shown in Fig. 3(c). The analysis shows that a ±10% change in payload will not affect the maximum take-off weight of the SUAV. Moreover, the result indicates that the maximum take-off weight of the SUAV increases nonlinearly by approximately 1.137 kg for every kilogram of additional payload. This increase accounts for approximately 0.92% with a 10% payload increment.

3.2. Weight of the solar module

Figure 4 presents the results of the sensitivity analyses performed to predict the fluctuations of the weight of the solar module caused by the changes in the propulsion's weight to power ratio, the solar module's weight to area ratio, and the payload. Low propulsion's weight to power ratio improves the weight of the solar module as illustrated in Fig. 4(a).

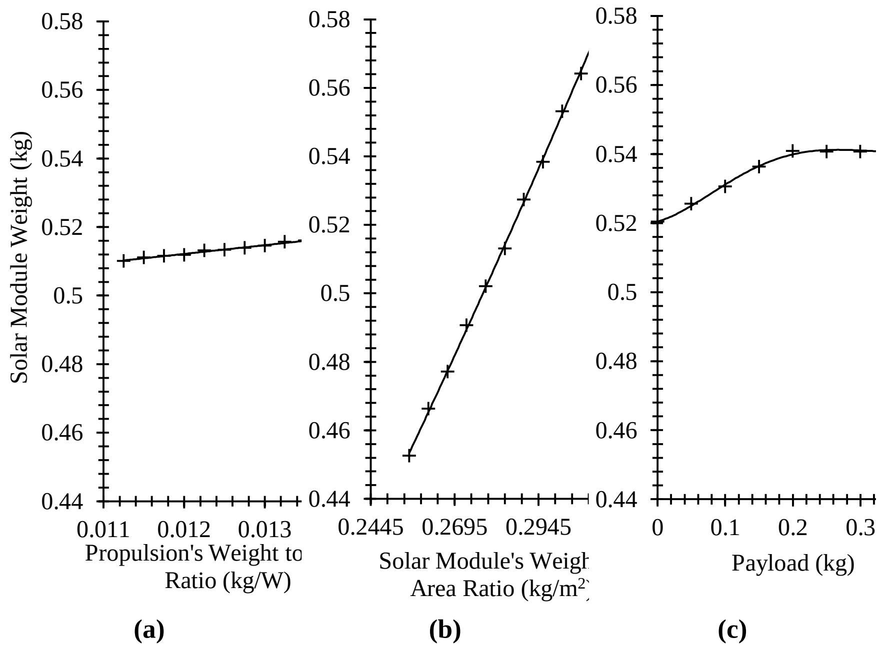

Fig. 4. (a) Propulsion's weight to power ratio, (b) solar module's weight to area ratio, and (c) payload vs. the weight of the solar module.

A decrement of approximately 10% of the propulsion's weight to power ratio reduces the weight of the solar module by 10.7%, which demonstrates that the weight can be reduced by 26 g for every 0.01 kg/W improvement of the propulsion's weight to power ratio. Similarly, Fig. 4(b) shows that the weight increases as the solar module's weight to area ratio increases. The weight of the solar module decreases by 12.4% with a 10% improvement in the solar module's weight to area ratio, that is, a 0.22 kg per 0.1 kg/m2 in the solar module's weight to area ratio. Thus, the highest savings in the weight of the solar module can be obtained by improving its weight to area ratio.

The analysis of the effect of the payload on the weight of the solar module is illustrated in Fig. 4(c). The analysis shows that a ±10% change in payload will not affect the weight of the solar module. The payload affects the weight of the solar module only when it is lower than 0.25 kg. Moreover, the analysis shows that the weight of the SUAV's solar module increases nonlinearly by approximately 0.577 kg for every kilogram of additional payload, which is approximately 0.91% with a 10% payload increment. This result is obtained mainly because the weight of the solar module is limited by the amount of available wing area.

3.3. Propulsion weight

Propulsion weight is another factor that significantly affects SUAV design. Thus, sensitivity analyses have been performed (Fig. 5) on the propulsion's weight to power ratio, the solar module's weight to area ratio, and the payload.

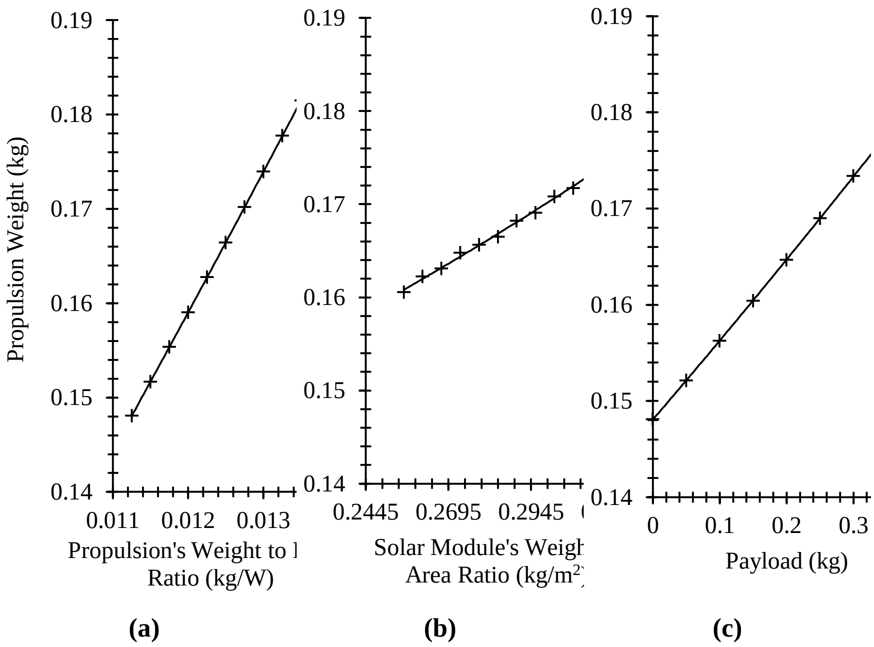

Fig. 5. (a) Propulsion's weight to power ratio, (b) solar module's weight to area ratio, and (c) payload vs. propulsion weight.

The propulsion's weight to power ratio considerably affects propulsion weight as shown in Fig. 5(a). With a 10% improvement in the propulsion's weight to power ratio, the propulsion weight of the SUAV can be reduced by 11.3%. This decrease is equivalent to 0.15 kg of propulsion weight per 0.01 kg/W of propulsion's weight to power ratio. However, the solar module's weight to area ratio only slightly affects propulsion weight.

The propulsion weight decreases by 3.85% with a 10% improvement of the solar module's weight to area ratio, which is approximately 22 g per 0.1 kg/W, as illustrated in Fig. 5(b). The effect of the payload on propulsion weight is shown in Fig. 5(c). The propulsion weight of the SUAV increases by 1.28% with a 10% increment in payload weight, which is approximately 86.6 g per kilogram of payload.

3.4. Power consumption

Power consumption is a critical parameter because it affects the size and performance of a SUAV. Thus, the effect of the changes in the propulsion's weight to power ratio, the solar module's weight to area ratio, and the payload on power consumption has been analysed. The slight influence of the propulsion's weight to power ratio on power consumption is shown in Fig. 6(a). The power consumption of the SUAV decreases by 1.1% with a 10% improvement of the propulsion's weight to power ratio. This improvement is equivalent to a 1.25 W reduction per 0.01 kg/W decrement of the propulsion's weight to power ratio.

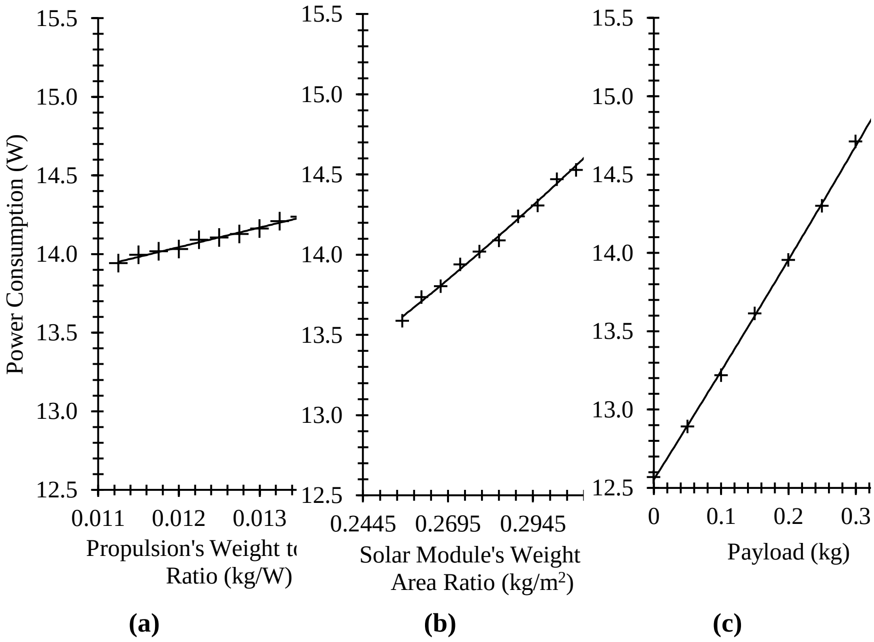

Fig. 6. (a) Propulsion's weight to power ratio, (b) solar module's weight to area ratio, and (c) payload vs. power consumption.

The effect of the solar module's weight to area ratio on the power consumption of the SUAV is slightly higher, as illustrated in Fig. 6(b). The power consumption of the SUAV is reduced by 3.93% when the solar module's weight to area ratio is improved by 10%. This finding indicates that reducing the propulsion's weight to power ratio or the solar module's weight to area ratio is ineffective in decreasing power consumption. A change in payload slightly affects the power consumption of the SUAV as shown in Fig. 6(c). Power consumption increases by less than 1.5%

for the SUAV with a 10% increment in payload. This translates into a 7.3 W increase in power consumption for every kg of payload added to the SUAV.

3.5. Endurance of battery-operated flight

Figure 7 illustrates the effects of the propulsion's weight to power ratio, the solar module's weight to area ratio, and the payload on the endurance of a battery-operated flight. The influence of the propulsion's weight to power ratio on the endurance of the battery-operated flight of the SUAV is illustrated in Fig. 7(a). The flight duration of the SUAV increases by 0.83% with a 10% reduction in the propulsion's weight to power ratio. This increase is roughly 1.1 h per 0.01 kg/W of the propulsion's weight to power ratio.

The effect of the solar module's weight to area ratio on the endurance of the battery-operated flight of the SUAV is illustrated in Fig. 7(b). A 10% improvement in the solar module's weight to area ratio increases flight endurance by 4%, which is roughly 1.7 h of extra time per 0.1 kg/W of the solar module's weight to area ratio. However, the endurance of the SUAV exhibits a steady loss with an increase in payload. It decreases by approximately 1.14% with a 10% increment in payload, which is 7.9 h per kilogram of payload.

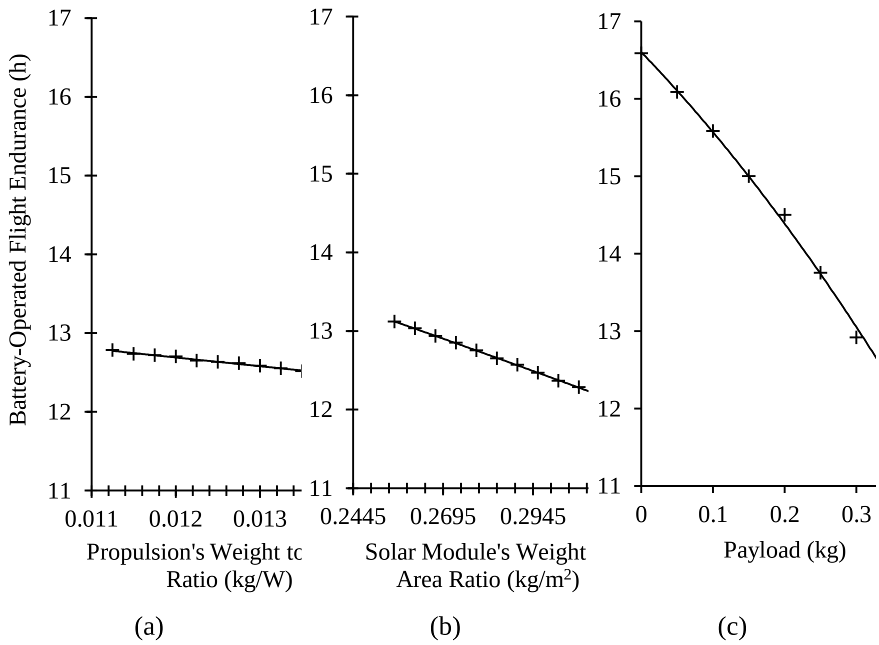

Fig. 7. (a) Propulsion's weight to power ratio, (b) solar module's weight to area ratio, and (c) payload vs. the endurance of the battery-operated flight.

4. Discussion

Table 1 shows that a 10% change in payload can improve the maximum take-off weight, solar weight, MPPT weight, propulsion weight, power, and endurance of the SUAV by up to 1.5% only. The propulsion's weight to power ratio exerts similar improvements on the maximum take-off weight, power, and endurance. However, the same propulsion's weight to power ratio can significantly improve the solar, MPPT, and propulsion system weights of the SUAV by up to 11.3%. Moreover, the solar module's weight to area ratio may improve its weight by up to 12.4% when this ratio is increased by 10%. A 10% reduction in the solar module's weight to area ratio also considerably influences the maximum take-off weight, power consumption, and endurance by 2%-4%. Thus, the solar module's weight to area ratio should be prioritized in technological improvements to improve SUAV design.

Table 1. Summary of the sensitivity analysis of the SUAV design.

Parameters	Improvement (%)		
	Propulsion's Weight to Power Ratio	Solar Module's Weight to Area Ratio	Payload
Maximum Take-off Weight	0.75	2.4	0.92
Solar Module Weight	10.7	12.4	0.91
Propulsion Weight	11.3	3.85	1.28
Power Consumption	1.1	3.93	1.5
Battery-Operated Flight Endurance	0.83	4	1.14

5. Conclusion

The sensitivity analysis of the system shows that a ±10% improvement in the payload of the SUAV is not encouraging because this change only leads to a slight improvement in the overall performance of the SUAV. The improvement resulting from the changes in the propulsion's weight to power ratio is similar to the trend of the payload. However, a 10% decrement in the propulsion's weight to power ratio reduces propulsion and solar module weight by up to 11.3%. By contrast, the decrease in the solar module's weight to area ratio significantly influences SUAV performance. Thus, the solar module's weight to area ratio should be prioritized in technological advancements to improve the characteristics and specifications of SUAVs.

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