382 J. Eng. Technol. Sci., Vol. 50, No. 3, 2018, 382-391

Experimental Assessment of Various Batteries and Propellers for Small Solar-Powered Unmanned Aerial Vehicle

Parvathy Rajendran[1,*] & Howard Smith[2]

[1]School of Aerospace Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia
[2]Aircraft Design Group, School of Engineering, Cranfield University, MK43 0AL Cranfield, England
*E-mail: aeparvathy@usm.my

Abstract. In this study, the performance of the propulsion system of a solar-powered unmanned aerial vehicle (UAV) was investigated. Both battery and propeller variation tests were performed to evaluate their performance in relation to an electric motor. The battery was varied in the number of cells and capacity, and the propeller was varied in terms of diameter, pitch, manufacturer, and propeller type (fixed and folding propellers). For validation, the bench test result was compared with a simulation model. The bench test provided a reasonable guide for the throttle level required to obtain optimal power. A large variation existed in propeller performance between manufacturers. Sizing electric propulsion is important for UAV performance and the manufacturing factor is significant for propeller performance.

Keywords: *bench testing; electric motor; electric propulsion; LiPo battery; propeller; solar-powered unmanned aerial vehicle.*

1 Introduction

Solar-powered UAV technology has been advanced greatly by researchers Zhu, *et al.* [1], Jashnani, *et al.* [2], Rajendran and Smith [3-4], and Gao, *et al.* [5]. Solar energy has been used as power source in a large number of studies because it is renewable and environmentally friendly. However, the electric propulsion system of solar-powered UAVs should also supply the required energy throughout the night. The most common secondary power source on UAVs are rechargeable lithium polymer batteries. During the daytime, the excess energy from the solar cells that is left over after powering the flight charges the batteries. At night, the batteries supply energy to the propulsion system to sustain level flight. Nevertheless, Rajendran and Smith [6] and Lee, *et al.* [7] clarified that the efficiency of solar cells is not sufficiently high to accomplish continuous flight. Furthermore, the performance of solar cells is also affected by weather conditions, as shown by Rajendran and Smith [8]. Thus, this preliminary study intended to investigate performance optimization

Received June 30th, 2017, Revised May 28th, 2018, Accepted for publication August 20th, 2018.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2017.50.3.5

of the electric propulsion system of solar-powered UAVs. A poor combination of battery, electric motor, and propeller usage will affect the endurance and range of solar-powered UAVs directly, as discussed by Ostler, *et al*. [9], Stepaniak, *et al*. [10], Solomon [11], and Gohardani [12]. Hence, the proper selection of the propulsion system components to be used is important, as discussed by Gur and Rosen [13] and Smith and Rajendran [14].

Several manufacturers produce propellers with similar diameter-to-pitch ratios. However, component performance may vary. Therefore, the effect of the battery and the propeller on the electric motor was evaluated in the experiment conducted in this study. The performances of both battery and propeller were determined based on the power and thrust achieved by the motor. The propulsion system of the solar-powered UAV model used in this study was developed by Cranfield University researchers Rajendran and Smith [15].

2 Methodology

The electric motor model used in this study was the Hacker A30-14L, a brushless electric motor. A test rig for the electric motor bench test was constructed (see Figure 1). In addition to the standard electronic sensors attached to measure the voltage, current, rpm, and temperature of the electric motor, this rig was specifically constructed for measuring the thrust produced by using a weighing scale. A digital laser tachometer was used to record the rpm reading. Figure 2 shows a picture when the laser tachometer is beamed at the propeller tip to measure the rpm reading.

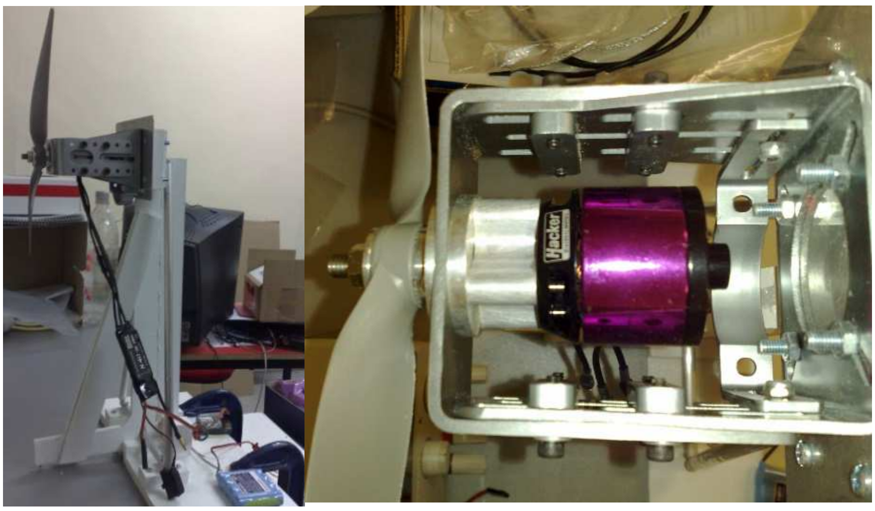

Figure 1 Bench test setup and top view of the test rig setup for electric motor (left).

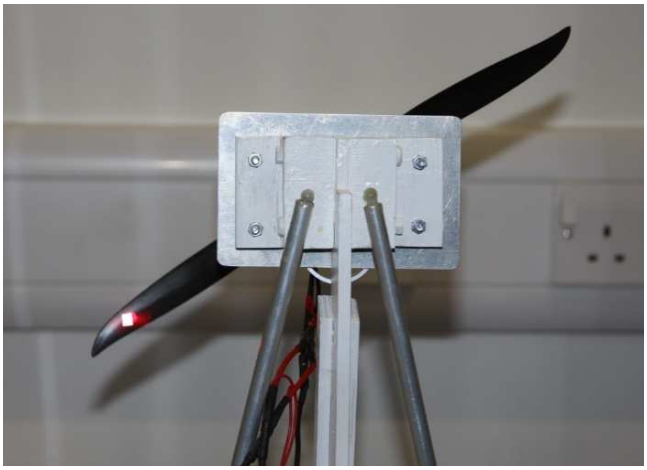

Figure 2 Laser beamed to the propeller tip.

Three battery pack variants with different cumulative currents were tested on the electric motor to investigate the power, thrust, and power-to-thrust ratio. The three battery pack variants were: 1) a customized, self-built three-cell (3S) battery pack constructed for the Cranfield University solar-powered UAV; 2) a commercially available standard 3S battery pack; 3) another commercially sold standard four-cell (4S) battery pack. The cumulative current of the customized self-built battery pack was 2.6 Ahr, while that of the 3S and 4S commercial batteries was 5 Ahr.

A total of 6 different propeller models were tested for power, thrust, and power to-thrust-ratio output at 6 throttle settings. Propeller selection was conducted on the basis of manufacturer, size, and propeller type. Table 1 provides a list of the specifications of the selected propellers. Hence, a total of 36 test data were recorded in this bench test to evaluate propeller performance.

Table 1 Propellers tested to assess performance.

Manufacturer's Name	Propeller Type	Propeller Size
E*	Fixed	13" × 8"
E*	Fixed	14" × 8"
A*	Fixed	12" × 6"
A*	Fixed	13" × 6.5"
N*	Folding	13" × 8"
G*	Folding	13" × 8"

3 Result & Discussion

3.1 Battery Variations

Figures 3 and 4 illustrate power and thrust against throttle level for the three battery packs, respectively. Generally, the optimal power and thrust values of the batteries consistently occurred at 80-90% throttle level. This is mainly due to the motor's rpm, which reduces its efficiency at throttle level lower than 80% and higher than 90%. Therefore, this bench test provides a reasonable guide for the throttle level required for obtaining optimal power. The electric motor used in the experiment achieved maximum peak power of around 650 and 500 W for the 4S and 3S battery packs respectively, similar to what is described in the specifications of the electric motor model set.

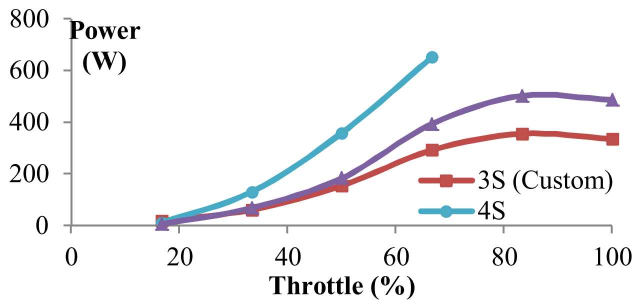

Figure 3 Power vs. throttle of 13" × 8" fixed (E*) propeller for various batteries.

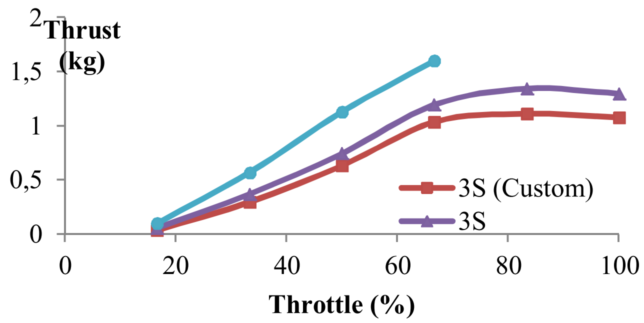

Figure 4 Thrust vs. throttle of 13" × 8" fixed (E*) propeller for various batteries by manufacturer.

Table 2 presents a detailed data analysis comparison between the three battery packs. These data were obtained by conducting the experiment at each throttle tab level, i.e. from the lowest throttle tab position to the highest (the 100% throttle setting, i.e. full power). The results were compared by setting the same power output for all batteries, i.e. 304.32 W. Therefore, the data in Table 2 only show the respective throttle settings at 304.32 W.

Table 2 Bench test result of customized and standard LiPo batteries.

Parameters	Standard 4S Battery	Standard 3S Battery	Custom 3S Battery
Capacity [Ahr]	5	5	2.6
Throttle [%]	46.486	59.777	69.703
Battery voltage [V]	19.14	11.81	10.09
Battery current [A]	15.89	25.84	30.09
Power in [W]	304.32	304.32	304.32
Propeller thrust [kg]	1.031	1.015	1.047
Power-to-thrust ratio [W/kg]	295.2	299.8	290.7

In addition, the propeller tip speed was the same for every case because of the same propeller size used. Thus, the highest power-to-thrust ratio will provide the maneuverability advantage compared to the solar-powered UAV model. Consequently, the differences in current, voltage, thrust, and power-to-thrust ratio could be distinguished between the battery packs.

Among the 3S battery packs, a higher cumulative current will deliver a lower current because of the relation between voltage level and current output. Compared with a battery pack with half of its capacity, a battery pack with full capacity is able to reach the mid voltage range while the lower-capacity battery is able to reach the lower voltage limit. Hence, when the throttle is used to provide consistent power delivery, a higher cumulative current battery will deliver lower current compared with a smaller one.

Hence, a 4S battery pack requires less current than a 3S battery because of the higher voltage to deliver the same power. The standard 3S battery pack delivered the highest power-to-thrust ratio compared with the other battery packs because of the discharge current and voltage that define the thrust and combination that gives the least thrust for the same power. Therefore, a standard 3S battery pack is more suitable than a 4S battery pack for an electric motor. Better performance can also be achieved by using a high-capacity battery pack.

Thus, the battery pack for the solar-powered UAV model was constructed by using three and seven LiPo cells in series and in parallel to deliver a cumulative current of 18.2 Ahr, respectively. As a result, the customized battery pack was capable of supplying 2130.24 W of power continuously at 70% throttle setting. Table 3 provides a performance comparison of the bench test of this customized battery pack versus the computational simulation previously published in [16]. At the same power output, the differences in battery voltage, battery current, propeller thrust, and power-to-thrust ratio were validated. The simulation error was within approximately 5%.

Table 3 Comparison of simulation vs. bench data for 13” × 8” fixed propeller on custom 3S battery.

Parameters	Bench Data	Simulation Data	Error (%)
Throttle [%]	69.687	-	-
Battery voltage [V]	10.09	9.81	2.8
Battery current [A]	30.09	31.03	-3.1
Power [W]	304.32	304.32	0
Propeller thrust [kg]	1.047	0.996	5.1
Power-to-thrust ratio [W/kg]	290.7	305.5	-5.1

3.2 Propeller Variation

The effect of propeller variation on the performance of the propulsion system was also investigated. Figures 5-7 display the power, thrust, and power-to-thrust ratio along the throttle levels of various types of propellers, respectively. The six propeller variants assessed in this study are shown in Table 1. The power output from the E* propellers was larger than that of the other propellers.

Both E* propellers could supply around 500 W or more when the throttle level was more than 80%. The A*, N*, and G* propellers achieved between 300 and 400 W for the same throttle level. Unexpectedly, the 12” × 6” fixed (A*) propeller only produced approximately 0.9 kg thrust, the lowest thrust compared to the other propellers.

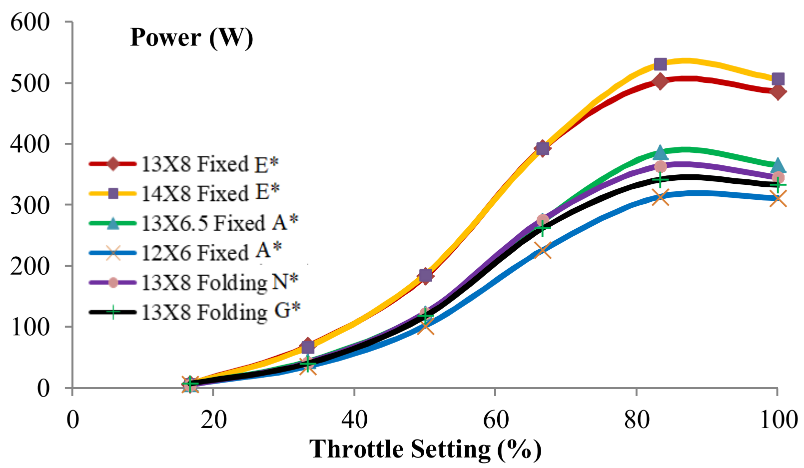

Figure 5 Power vs. throttle setting of various propellers with standard 3S LiPo battery.

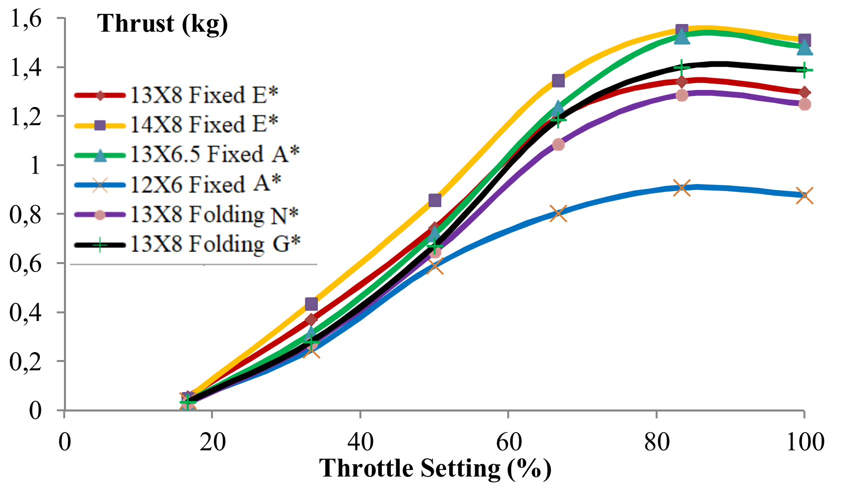

Figure 6 Thrust vs. throttle settings of various propellers at standard 3S LiPo battery.

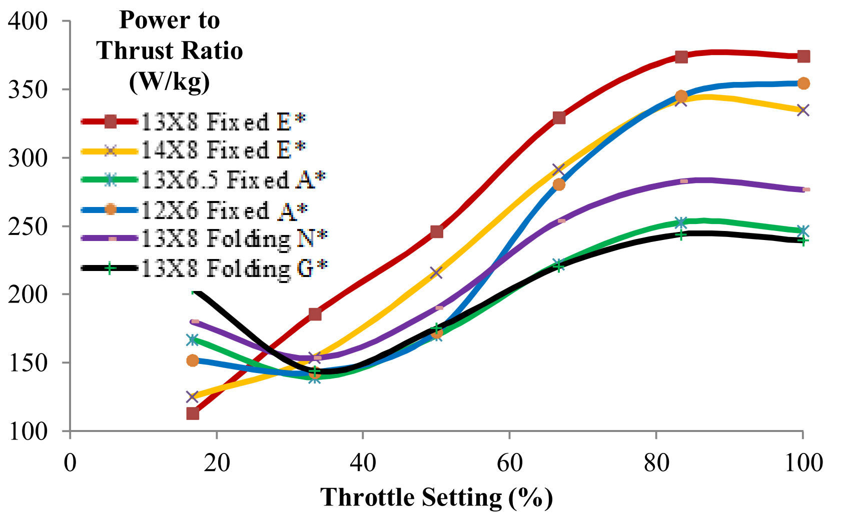

Figure 7 Power to thrust ratio vs. throttle setting of various propellers with standard 3S LiPo battery.

Furthermore, a lower propeller diameter-to-pitch ratio tended to have smaller thrust for the same throttle level. Generally, a lower propeller diameter-to-pitch ratio also had a better power-to-thrust ratio (Figure 7). This value is consistent with the propeller tip static speed, which is dependent on the propeller diameter. A lower propeller diameter leads to a lower propeller tip static speed. The 13” ×

8” fixed (E*) propeller outperformed the other fixed propellers by having high power and low thrust.

Table 1 shows a performance comparison of the 13” × 8” propellers of E*, G*, and N*. With the testing conducted on the same power output, the throttle level for the E* propellers was smaller while their power-to-thrust ratio was the highest, i.e. 299.8 W/kg. This value was higher than that of the N* propellers by 15%. This result indicates that fixed propellers have better performance than folding propellers. Nevertheless, the 13” × 8” folding propeller manufactured by N* outperformed the G* propeller by almost 13%. This large variation in propeller performance between manufacturers indicates that the manufacturing factor cannot be ignored.

Table 4 Comparison between various 13” × 8” propellers using standard 3S lithium polymer battery.

Parameters	Folding (G*)	Folding (N*)	Fixed (E*)
Throttle [%]	74.273	71.630	59.777
Battery voltage [V]	11.89	11.90	11.81
Battery current [A]	25.59	25.57	25.84
Power [W]	304.32	304.32	304.32
Propeller thrust [kg]	1.311	1.164	1.015
Power-to-thrust ratio [W/kg]	232.1	261.4	299.8

4 Conclusion

In summary, the optimal power and thrust values of the batteries for the studied solar-powered UAV occurred at around 70% throttle level. Thus, this bench test provides a reasonable guide for the throttle level required for obtaining optimal power. A lower propeller diameter-to-pitch ratio tends to have smaller thrust for the same throttle level. Generally, a lower propeller diameter-to-pitch ratio also has better power-to-thrust ratio. The fixed propellers outperformed the folding propeller consistently. Notably, a large variation existed in propeller performance between manufacturers, which indicates that the manufacturing factor cannot be ignored. Nevertheless, the developed electric propulsion simulation data managed to make predictions within a 5% error compared with the actual bench test performance. Thus, the size of the electric propulsion system is important in maximizing the performance of UAVs and the manufacturing factor has a significant influence on propeller performance.

Acknowledgement

This publication was supported by a Short Term Grant of the Universiti Sains Malaysia with no. 304/PAERO/60315002.

References

[1] Zhu, X.F., Guo, Z. & Hou, Z.X., *Solar-Powered Airplanes: A Historical Perspective and Future Challenges*, Progress in Aerospace Sciences, **71**, pp. 36-53, 2014.

[2] Jashnani, S., Nada, T.R., Ishfaq, M., Khamker, A. & Shaholia, P., *Sizing and Preliminary Hardware Testing of Solar Powered UAV*, The Egyptian Journal of Remote Sensing and Space Sciences, **16**(2), pp. 189-198, 2015.

[3] Rajendran, P. & Smith, H., *Future Trend Analysis on the Design and Performance of Solar-Powered Electric Unmanned Aerial Vehicles*, Advanced Materials Research, **1125**, pp. 635-640, 2015.

[4] Rajendran, P. & Smith, H., *Review of Solar and Battery Power System Development for Solar-Powered Electric Unmanned Aerial Vehicles*, Advanced Materials Research, **1125**, pp. 641-647, 2015.

[5] Gao, X.Z., Hou, Z.X., Guo, Z., Zhu, X.F., Liu, J.X. & Chen, X.Q., *Parameters Determination for Concept Design of Solar-Powered, High-Altitude Long-Endurance UAV*, Aircraft Engineering And Aerospace Technology, **85**(4), pp. 293-303, 2013.

[6] Rajendran, P. & Smith, H., *Implications of Longitude and Latitude on the Size of Solar-Powered UAV*, Energy Conversion Management, **98**, pp. 107-114, 2015.

[7] Lee, B., Park, P., Kim, L. & Kwon, S., *The Flight Test and Power Simulations of an UAV Powered By Solar Cells, A Fuel Cell and Batteries*, Journal Of Mechanical Science And Technology, **28**(1), pp. 399-405, 2014.

[8] Rajendran, P., Smith, H. & Masral, M.H., *Modeling and Simulation of Solar Irradiance and Daylight Duration for a High-Power-Output Solar Module System*, Applied Mechanics and Materials, **629**, pp. 475-480, 2014.

[9] Ostler, J.N., Bowman, W.J., Snyder, D.O. & McLain, T.W., *Performance Flight Testing of Small, Electric Powered Unmanned Aerial Vehicles*, International Journal Of Micro Air Vehicles, **1**(3), pp. 155-171, 2009.

[10] Stepaniak, M.J., van Graas, F. & de Haag, M.U., *Design of an Electric Propulsion System for a Quadrotor Unmanned Aerial Vehicle*, Journal of Aircraft, **46**(3), pp. 1050-1058, 2009.

[11] Solomon, O., *Model Reference Adaptive Control of a Permanent Magnet Brushless DC Motor For UAV Electric Propulsion System*, 33rd Annual Conference of the IEEE Industrial Electronics Society, **1-3**, pp. 1186-1191, 2007.

[12] Gohardani, A.S., *A Synergistic Glance at The Prospects of Distributed Propulsion Technology and the Electric Aircraft Concept for Future Unmanned Air Vehicles and Commercial/Military Aviation*, Progress in Aerospace Sciences, **57**, pp. 25-70, 2013.

[13] Gur, O. & Rosen, A., *Optimizing Electric Propulsion Systems for Unmanned Aerial Vehicles*, Journal Of Aircraft, **46**(4), pp. 1340-1353, 2009.
[14] Smith, H. & Rajendran, P., *Review of The Elementary Aspect of Small Solar-Powered Electric Unmanned Aerial Vehicles*, Aust. J. Basic & Appl. Sci, **8**(15), pp. 252-259, 2014.
[15] Rajendran, P. & Smith, H., *The development of a Small Solar Powered Electric Unmanned Aerial Vehicle Systems*, Applied Mechanics and Materials, **465-466**, pp. 345-351, 2014.
[16] Rajendran, P. & Smith, H., *Development of Design Methodology for a Small Solar-Powered Unmanned Aerial Vehicle*, International Journal of Aerospace Engineering, **2018**, Article ID 2820717, 2018.