Response to comments on "Flying by the Sun only: The Solarcopter prototype", 45 (2015) 209-214

M. Hasan Shaheed*, Aly Abidali, Stephen A. Agha, Jibran Ahmed, Shakir Ahmed, Irmantas Burba, Pourshid Jan Fani, George Kwofie, Kazimierz Wojewoda, Antonio Munjiza

ABSTRACT

The Solarcopter proof of concept demonstrated the world's first purely solar-powered rotary-wing aircraft to fly, highlighting the feasibility of powering a rotary-wing unmanned aerial vehicle (UAV) exclusively by solar power. Absolutely no form of energy storage was utilised in any way. The novelties of the presented prototype include the exclusion of energy storage, utilising the central surface area of a quadrotor setup to maximise solar panel performance, and employing an ultra-lightweight, rigid, space frame structure. These key factors enabled the thrust-to-weight ratio of the presented prototype to be substantially greater than unity making the concept capable of continuous flight beyond the ground effect, provided sufficient solar energy is available. The presented concept and design was successfully validated with flight tests conducted in real-world conditions. The calculations and conclusions presented in the comments regarding the flight capability of the Solarcopter are premised on use of the Medusa 4000 rather than the Turnigy 800 motor that was implemented on the Solarcopter prototype. It is therefore unsurprising that the authors of the comments were unable to replicate the results presented for the Solarcopter.

1. Background

The original hypothesis presented in the Solarcopter article [1] was the feasibility of flying a rotary wing UAV powered by sunlight only without any additional power source. The presented Solarcopter in the original article [1] was the world's first purely solar-powered aircraft, without any form of energy storage, to fly, and hence demonstrated the validity of the hypothesis. The aircraft's development started as an undergraduate project in 2012 and was iteratively improved, which is a common design methodology; where several components are tested independently and together to assess their individual and combined real-world performance. All numerical calculations and experimental validation have shown that the thrust generated by this aircraft is substantially greater than its weight. The calculations and analysis presented in the comments are based on Medusa 4000 motors and not the Turnigy 800 motors presented within figures 3, 5, 6, 7 and 9 of the original Solarcopter article [1]. The use of Medusa 4000 motor data to favour the arguments put forward in the comments is surprising given that section H of the comments clearly states, "the motors in the photographs do not resemble Medusa motors". The specifications and performance of these two motors are significantly different.

2. Correspondence of presented figures and component description (response to section A)

Figure 1 in the PV panel section of the original article [1] clearly shows that the cells being discussed are different from SunPower cells, as there are bus bars on the top side of the cell. The 130W stated in that section does not apply to a SunPower cell, nor has SunPower, or any other solar cell manufacturer, been mentioned throughout the entirety of the article. There is no mention within the paper of solar cell manufacturers as this was not the main focus of the paper, rather, the paper outlines the proof of the original hypothesis and the design of the concept itself. The solar panel described in the PV panel section is an earlier solar panel that was used to develop the first complete prototype. A simple calculation of the cell efficiency can be derived from the parameters presented in the paper; there are 36 cells in the panel, the maximum power is stated to be 136.8W and the area per cell is 0.157m x 0.157m, therefore at 1000W/m^2 irradiance the efficiency is:

$$\left(\frac{136.8}{1000 \times 0.157 \times 0.157 \times 36}\right) \times 100 = 15.4\% \quad \textit{Solar cell efficiency} \tag{1}$$

* Corresponding author. Tel: +44 (0) 20 7882 3319.
E-mail address: m.h.shaheed@qmul.ac.uk (M.H. Shaheed)

An efficiency of 15.4% for a monocrystalline solar cell (in 2014) is not unrealistic as can be seen in Fig. I (in the appendix) provided by the National Renewable Energy Laboratory (NREL) [2]. It can be clearly seen that efficiencies of over 20% have been achieved for non-concentrator monocrystalline solar cells since the mid 80's and the lowest value recorded on the chart for a cell of this type lies between 13 and 14% efficiency dating back to the late 1970's. A variety of solar cells were tested to manufacture several solar panels, and the panel shown in both Figures 5 and 9 of the original article [1] is one of the later panels composed of SunPower solar cells as was observed in the comments, these cells are of higher efficiency, and lower overall surface area, power, and mass.

3. Power characteristics of the Solarcopter (response to sections B & D)

Section B of the comments claim: "The open circuit voltage V_{oc} of the solar array is around 10V according to Figures 6 and 7, and certainly lower than 11V (the maximum voltage shown at any power level). This is inconsistent with Figure 8, which shows the solar panel > 12 V."

The open circuit voltage is not inconsistent as it should be obvious that it is no longer "open circuit" voltage for Figures 6 and 7 as the circuit is now "closed" as a thrust is being generated by the circuit. Therefore, it is unclear why the top end voltages have been compared in this way in the comments. The voltage in Figure 8 is higher as the voltage is indeed the open circuit voltage unlike in the other two figures. Going by the specifications given in the datasheet for the SunPower cells [3], the open circuit voltage can be as high as 0.69V per cell, therefore for 18 cells in series this can reach a voltage of 12.42V.

As already stated, there were absolutely no energy storage devices utilised in the Solarcopter: no batteries, capacitors or other storage device. The voltage drop recorded in Figure 8 of the Solarcopter article [1], after the lights are turned off, is a result of the measurement of the open circuit voltage without a load. The intent of the experiment was to show the performance degradation that accompanies cell temperature increase and not the rate of voltage decline when the cells are shaded. The data logging rate for that experiment was not high enough to capture the true rate of voltage decline. Furthermore, an energy storage device, such as a capacitor, capable of reducing the voltage drop rate by only 10 seconds in this no-load condition will provide no added benefit to the UAV system in the loaded state considering the magnitude of the UAV's power requirements.

The result plots for experiments of variation of thrust and voltage with power (Figures 6 and 7 in the original article) show the voltage at zero power to be zero. Upon review, it was found that only this data point is erroneous as it should be closer to the open circuit voltage of the solar panel at approximately 10V. As measurements were taken at 10% power intervals, this zero-voltage data point was joined to the next data point by a smooth continuous line using a plotting software. The critical aspects of Figure 6 in the article, however, are to show the take-off power percentage and the maximum thrust generated by the propulsion group, which remain valid.

Under favourable conditions, there is no reason why continuous long flights cannot be conducted. The large voltage variations seen in Figure 8 of the article are due to the large temperature changes, which are drastic and reach far above real-world conditions, and much further from standard test temperature (25°C). In reality, these temperatures will be more consistent and stable, and combined with an irradiance of 1000W/m^2 as stated within the paper, continuous flight can be achieved.

4. Solarcopter propulsion system (response to section C)

The Medusa motor was stated within the Solarcopter article as having better performance compared to the other motors tested. This was simply in the context of the thrust produced in comparison to the motor mass. The Medusa motors were initially used to complete the first iteration of the concept, hence their inclusion within the paper. The mass of 300g and 760g for preselected components, given in sections 2.2 and 2.3 of the Solarcopter article [1], are based on the Medusa motors. However, this motor was not utilised in the final iteration of the prototype as can be seen from the images (Figures 5 and 9) and data (Figure 3) presented in the Solarcopter article [1], the Turnigy motors were utilised.

This was due to improved stability and responsiveness achieved with the Turnigy 800 motors which produce a higher rotor angular velocity.

Figure 3 of the Solarcopter article [1] indicates that the Turnigy 800 motor performs more efficiently at 8V compared with 10V. That the motor presents better performance at 8V compared to the voltage for maximum power of the solar panel ($V_{mpp} \approx$ 10.4V) suggests two extreme scenario for the performance limits. Firstly, the motors operate at a lower voltage but higher efficiency and the panel is not operating at maximum power. The second possibility is maximum power is extracted from the panel but the motors are not operating at their highest efficiency. Actual operation can be anywhere between these two extremes but does not imply that the required thrust for flight is unachievable.

5. Outdoor testing conditions (response to sections E & F)

While the comments claim that the testing latitude was unfavourable, Fig. 9 of the Solarcopter article as well as the image in Fig. A either show that the Solarcopter is able to fly within this claimed "unfavourable latitude" or that the latitude was indeed sufficiently favourable for flight, in either case the aircraft has flown. It should also be considered that temperatures at this claimed "unfavourable latitude" are cooler on average relative to more temperate regions of the globe where solar cell performance can deteriorate due to higher cell temperatures as presented in the Solarcopter paper [1]. The temperature at the time and date of testing presented within the original paper (12PM on the 22/06/2014) ranged between 22–24°C [4 – 6] which is close to the standard testing temperature (25°C) [3].

Fig. A. Outdoor flight testing of the Solarcopter multirotor UAV

From the exact date (22/06/2014), time (12:00 hours) stated for flight tests in the Solarcopter article (Figure 9 [2]) and the outdoor test location (51.525°N, 0.0318°W), the corresponding solar elevation is 59.48°. This corresponds to an incidence angle of 30.51°. While a specific time is stated for the flight test, the flight test window lasted till 13:30 hours. The incidence angle therefore varied between 30.51° at 12:00 hours, 28.09° at 13:00 hours and 28.60° at 13:30 hours. The solar elevation angle of 30.51° is therefore the worst case scenario and is utilised in the calculations presented in Section 6 of this response.

Fig. B is a plot of solar irradiance and temperature measurements reported for Westminster, London, (51.500°N, 0.12802°W) which is geographically proximal (6.28 km) to the location for the Solarcopter outdoor test flights. Based on the assertions in the comments, the solar irradiance should not rise above 1000*cos (30.51°) W/m^2, or 861.5 W/m^2 at any point in this timeframe. The solar irradiance for this location, date and time combination clearly rises above the 861.5 W/m^2 limit that would apply if the elevation angle effect on irradiance is as presented in the comments. The incident angles (complement of the solar elevation angle) during the time period of the presented plot and the Solarcopter test date are similar (within 0.1%) for corresponding times. Also evident from the plot is the relatively low (and favourable) temperature for this location compared to more tropical climates.

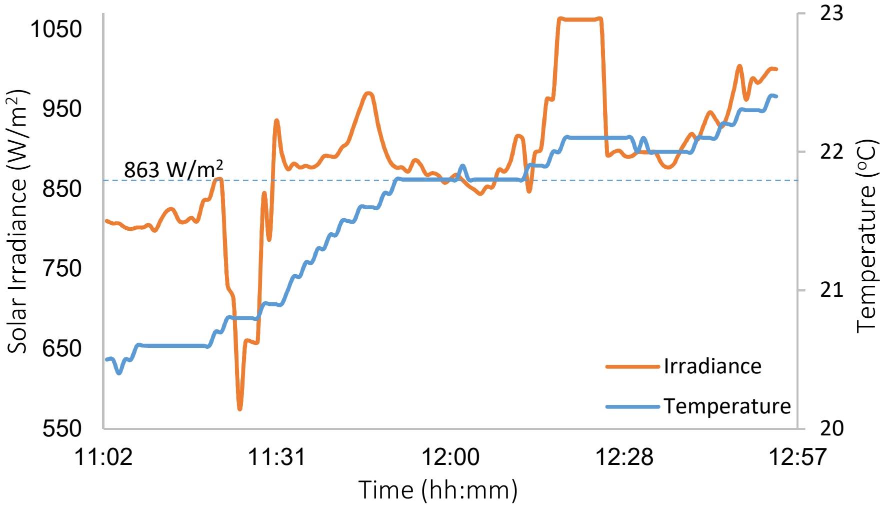

Fig. B. Solar irradiance and temperature for Westminster, London. 17 June 2019 [7]

The comments cite the work of Kingry et al [8] to assert that a power output of 2.3 W per cell as realistic for a SunPower cell operating in the outdoor environment. This claim, however, does not state the operating conditions in which these measurements are made. Therefore, it cannot be ascertained if these cells are exposed to optimal temperature and maximum irradiance conditions or if the panel is operating at the maximum power point. Furthermore, based on the flight time of one hour stated by Kingry et al [8] the average power output of the solar panel can be computed using the following equation:

$$T_{flight} = \frac{[Batt \times 60]}{[P_{draw} - P_{solar}]} \tag{2}$$

Where, T_{flight} is the flight time in minutes, stated as one hour. $Batt$ is the battery capacity expressed in Wh, (6600mAh*22.2V) Wh. P_{draw} is the power drawn by the motors, and P_{solar} is the average power generated by the solar panel. Based on the stated total mass of the system, 8.175kg, the power required by each motor at hover is about 131.5W (using the thrust data presented in their paper). This flight time will only be achieved with a power per solar cell well above 3.5W. This formula is based on the assumption of 100% battery power recovery and an average solar panel power output. Given that ambient conditions will vary over time; one will expect the power output to be less than this average value and greater than this at other times.

6. Solarcopter thrust-to-weight ratio (response to sections F, G, H & I)

The thrust test for the Turnigy 800 brushless DC motor has been reproduced using a thrust measurement stand with direct data logging. Measurement tolerance as stated by the manufacture is 0.5% for both thrust and torque, and has a data logging rate of 8Hz [9]. The measuring equipment was calibrated immediately prior to performing these experiments to ensure the accuracy of these measurements. Given the calibration of the measuring equipment and the unobstructed path for airflow, the measurements obtained therefore reflect the motor performance outside the ground effect.

The stated final mass of 925g for the Solarcopter is based on the Turnigy motors and the solar panel presented in the first section of the article. The mass of the system with the SunPower panel and Turnigy motors will be slightly lower than the 788.2g presented in the comments due to the balsa supports weighting slightly less than the mentioned 0.8g per cell or 28.7g in total for the initial panel due to the smaller size of these cells, however, the mass of 788.2g proffered in the comments will be utilised in subsequent calculations.

The presented thrust-to-weight ratio of 1.36:1 is based on the components presented within the original paper [1]. The solar panel power was stated as 136.8W, therefore the maximum power per motor would be 136.8W/4 = 34.2W. The paper [1] states a total thrust of 1250g, which gives a thrust of 1250g/4 = 312.5g per motor. The highlighted point in the thrust plot of Fig. C (a reproduction of Figure 3 in the Solarcopter article [1]) shows the measurement point closest to the stated operating power point. This figure confirms the thrust data of the Turnigy 800 motor presented in Figures 3 and 6 of the original Solarcopter article [1].

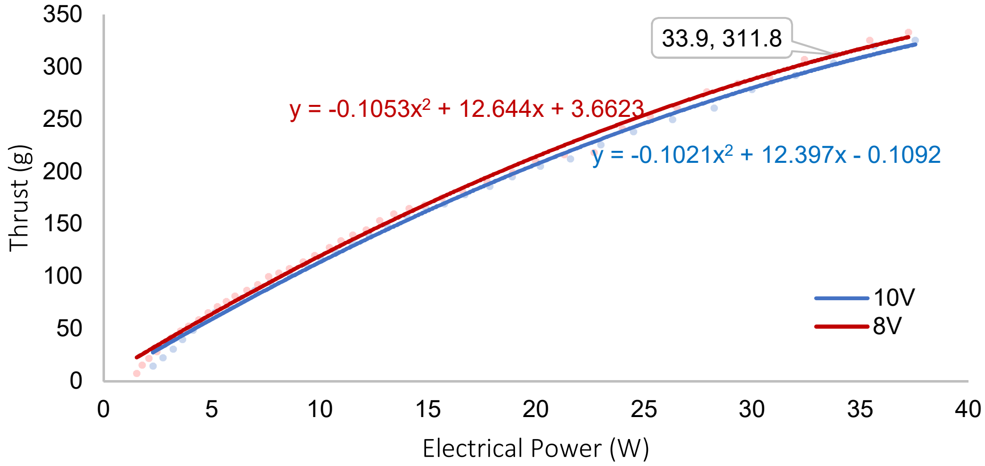

Fig. C. Thrust curves for the Turnigy 800 brushless DC motor with 12 inch propeller utilised

From the corresponding thrust value for this power point, the stated thrust-to-weight ratio cannot be described as unrealistic. Furthermore, if this is considered for the SunPower cells then the total power would be 3.42W x 36 = 123.12W. This implies 123.12/4 = 30.78W per motor. From the data in Fig. C the total thrust can then be approximated using the equations of the lines of best fit. The thrust-to-weight ratio calculations for different scenarios are presented in the appendix and summarised in Table A. These include the original panel with the Turnigy motors, the SunPower panel with the Turnigy motors, and taking into consideration efficiency losses and the incidence angle for the sake of completeness. Three calculations are made for each motor voltage. The first case (A) divides the thrust directly with the mass, the second case (B) considers a 3% efficiency loss to the system and the third case (C) considers the 3% efficiency loss in combination with the incidence angle. These calculations are presented for the less efficient, 10V, motor operating line. In all cases, the thrust-to-weight ratio is significantly greater than unity.

Table A

The calculated thrust-to-weight ratios summarised

	Original (136.8W / 925g)	Pictured (123.1W / 788g)
10v (no loss)	1.32:1	1.49:1
10v + 3% loss	1.29:1	1.42:1
10v +3% loss + Incidence angle	1.17:1	1.28:1

The arguments for insufficient thrust made in the comments are based on system efficiency and power loss due to “unfavourable conditions” but have not acknowledged that in achievable real-world conditions, the UAV’s thrust-to-weight ratio would be adequate to fly beyond ground effect. In large part, this wrong conclusion is reached because the calculations were premised on thrust data for the wrong motor (Medusa 4000 rather than Turnigy 800).

The motor thrust experiments are performed with no obstructions in front or behind the airflow diameter as seen in Fig. II in the appendix (ensuring that no external effects such as the ground effect will skew the thrust data). Given that the solar panel of the UAV is capable of producing sufficient power to generate adequate thrust to lift its mass, it is valid to conclude based on these results and previous data that the Solarcopter is more than capable of flight beyond the ground effect.
Furthermore, with regards to efficiencies, the thrust data provides the actual power required to achieve a certain thrust and therefore this power value captures any inefficiencies of the propulsion system. With regards to the solar panel, if optimal conditions are met then the expected power per cell that can be achieved for the SunPower cell is in the region of 3.42W. The true test was to see if the aircraft could fly in these outdoor conditions, which it successfully accomplished.

7. Concluding remarks

The original Solarcopter paper introduced the hypothesis of flying by Sun only and the proof of concept through a prototype design and testing. The prototype demonstrated that our original hypothesis was correct. The same hypothesis was later independently confirmed by Goh et al [10] using a similar design. A confirmatory thrust experiment was performed on the presented motor and propeller in the original paper and it has been shown that the thrust data presented within the original paper of this propulsion system is consistent with the data presented here. The thrust-to-weight ratio has been shown to be greater than unity in all cases by showing the approach followed in the computation.

We hope that this clarification and elaboration will be of help to all those working in the field.

References

[1] M.H. Shaheed, A. Abidali, J. Ahmed, S. Ahmed, I. Burba, P.J. Fani, G. Kwofie, K. Wojewoda, A. Munjiza, Flying by the Sun only: The Solarcopter prototype, Aerosp. Sci. Technol. 45 (2015) 209–214.

[2] NREL, Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL, Best Res. Effic. Chart | Photovolt. Res. | NREL. (2019) https://www.nrel.gov/pv/cell-efficiency.html. https://www.nrel.gov/pv/cell-efficiency.html (accessed December 8, 2019).

[3] SunPower Corp, C60 Solar Cell Mono Crystalline Silicon, Sunpower Corp. (2010) 3–4. www.sunpowercorp.com. (accessed June 7, 2019).

[4] Timeanddate.com, Weather in June 2014 in London, England, United Kingdom, (n.d.). https://www.timeanddate.com/weather/uk/london/historic?month=6&year=2014 (accessed December 14, 2019).

[5] www.worldweatheronline.com, London, City of London, Greater London, United Kingdom Historical Weather Almanac, (n.d.). https://www.worldweatheronline.com/london-weather-history/city-of-london-greater-london/gb.aspx (accessed December 14, 2019).

[6] www.wunderground.com, London, United Kingdom Weather History | Weather Underground, (n.d.).https://www.wunderground.com/history/daily/gb/london/EGLC/date/2014-6-22 (accessed December 14, 2019).

[7] London grid for learning, Weather Monitoring System, (2019). https://weather.lgfl.org.uk/qtables.aspx?sid=70&pid=19&day=1 (accessed June 28, 2019).

[8] N. Kingry, L. Towers, Y. Liu, Y. Zu, Y. Wang, B. Staheli, Y. Katagiri, S. Cook, R. Dai, Design , Modeling and Control of a Solar-Powered Quadcopter, in: ICRA, 2018: p. 8.

[9] RCbenchmark (2019) Series 1580 Dynamometer Datasheet. Document ID: R33YF1. Available at: https://docs.rcbenchmark.com/en/dynamometer/series-1580/datasheet.html.

[10] C.S. Goh, J.R. Kuan, J.H. Yeo, B.S. Teo, A. Danner, A fully solar-powered quadcopter able to achieve controlled flight out of the ground effect, Prog. Photovoltaics Res. Appl. (2019) 1–10.

Appendix

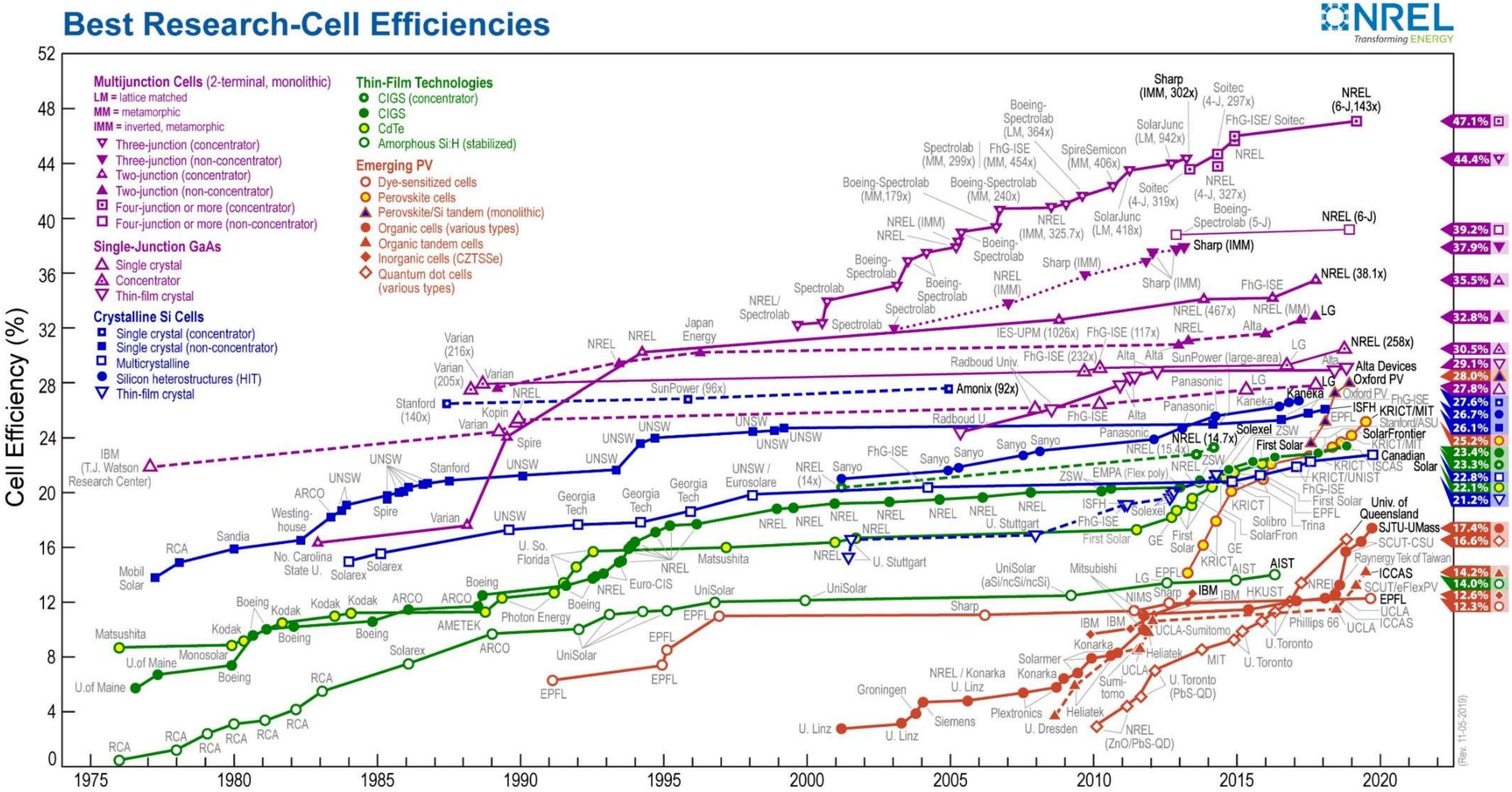

Fig. I. Various solar cell efficiencies recorded over time [2]

Thrust-to-weight ratio calculations for different scenario

Earlier iteration (Panel power of 136.8W & 925g system mass) Thrust-to-weight ratios

A – Direct calculation, B – Addition of a 3% efficiency loss, C – 3% loss + Incidence angle of 30.51

*Worst-case thrust-to-weight ratio is **1.17:1***

A = -0.1021*(136.8/4)^2 + 12.397*(136.8/4) - 0.1092 = 304.4g x 4 motors = 1217.7g / 925g = **1.32:1**

B = -0.1021*((136.8*0.97)/4)^2 + 12.397*((136.8*0.97)/4) - 0.1092 = 298.8g x 4 motors = 1195.1g / 925g = **1.29:1**

C = -0.1021*((136.8*0.97*cos(30.51))/4)^2 + 12.397*((136.8*0.97*cos(30.51))/4) - 0.1092 = 270.8g x 4 motors = 1083.2g / 925g = **1.17:1**

Figure 8 system (Panel power of 123.1W and 788g system mass) Thrust-to-weight ratios

A – Direct calculation, B – Addition of 3% efficiency loss, C – 3% loss + Incidence angle of 30.51

*Worst-case thrust-to-weight ratio is **1.28:1***

A = -0.1021*(123.1/4)^2 + 12.397*(123.1/4) - 0.1092 = 284.7g x 4 motors = 1138.8g / 788g = **1.49:1**

B = -0.1021*((123.1*0.97)/4)^2 + 12.397*((123.1*0.97)/4) - 0.1092 = 279.0g x 4 motors = 1115.9g / 788g = **1.42:1**

C = -0.1021*((123.1*0.97*cos(30.51))/4)^2 + 12.397*((123.1*0.97*cos(30.51))/4) - 0.1092 = 251.2g x 4 motors = 1004.8g / 788g = **1.28:1**

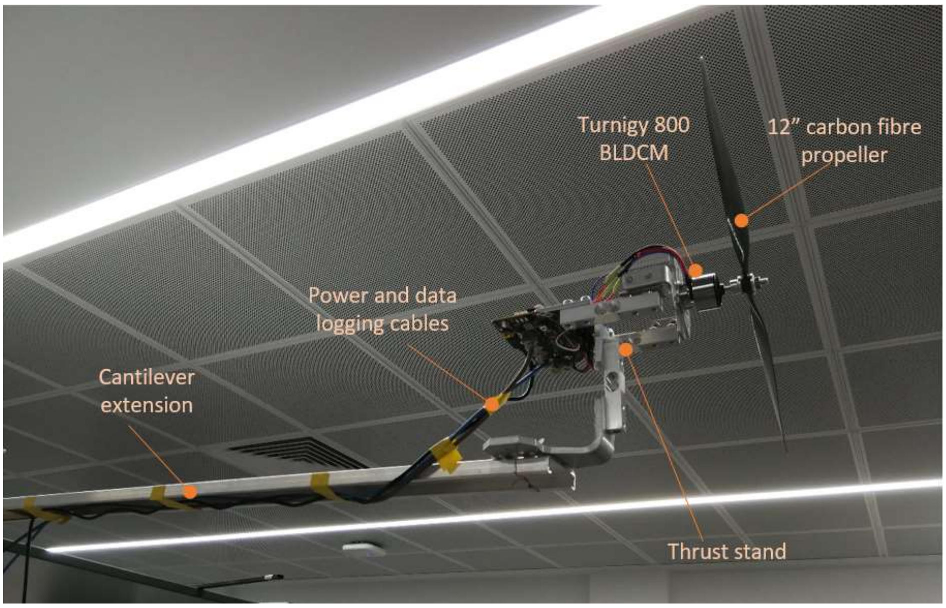

Fig. II. Thrust measurement setup