Flexible High-Efficiency Corrugated Monocrystalline Silicon Solar Cells for Application in Small Unmanned Aerial Vehicles for Payload Transportation

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In recent years, small unmanned aerial vehicles (SUAVs) have proven to be exceptionally useful. However, most of the commercially available drones are electric powered and therefore have a short endurance. Solar powered UAVs have recently received increased attention due to their ability to fly continuously for several days using solar energy. For this purpose, solar cells must show high-efficiency, lightweight and ultra-flexibility in order to be fully compliant to the drone wings/body and avoid degrading its aerodynamic characteristics. Nevertheless, previous demonstrations used rigid/semi-flexible cells. Here, corrugated ultra-flexible silicon solar cells (19% efficiency) with a smaller specific weight (645 g/m^2, encapsulated) are considered and used. A theoretical comparison between the performances of the corrugated *vs.* commercial semi-flexible cells is performed in terms of flight endurance in "AtlantikSolar" UAV. The results show that due to the ultra-lightweight of the corrugated cells and their ability to expand at higher temperatures without bowing, an enhancement in the flight time up to 19% can be achieved compared to the commercial cells which enables heavier payloads (7 lbs) transportation. Finally, the corrugated cells (12.5 cm by 4 cm) are experimentally tested on a small-sized drone under different conditions indoors and a 10% extended flight is reported.

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Recently, unmanned aerial vehicles (UAVs) have received a growing interest due to their wide potential applications ranging from military to civilian missions such as uninterrupted surveillance, remote sensing, precision agriculture, disaster relief applications and package delivery.[1-5] Currently, there are more than 11,000 UAVs in service by the United States Military for various applications. However, these drones are electric powered and therefore fall short in performance because the Li-ion battery needs to be recharged every couple of hours which requires the retraction of the drone from the field.[6] This can be dangerous especially when the drone is being used on a military or surveillance mission. Moreover, the application of drones in commercial packages delivery is emerging into a new industry. In fact, various companies are currently developing drone-based package delivery programs including Amazon, DHL, UPS and Google.[7-13] However, previous studies have shown that drones can practically cover a range of 4 km using current battery technologies.[14] This means that additional warehouses would be needed to support this application which would increase the overall cost and energy consumption compared to ground-based delivery.[9,11,14,15]

With the increasing demand for higher endurance UAVs than ever, there was a natural drive to optimize the performance and capabilities of UAVs. As a result, solar powered aerial vehicles have emerged and several successful demonstrations have been shown including, most recently, the round-the-world Solar Impulse flight using a 2,300 kg aircraft with a 72-m wingspan.[16] Thus, notable attempts have been achieved in large wingspan aircrafts with fewer demonstrations on smaller drones with long endurance such as Sky-Sailor, Sun-Sailor, SoLong and AtlantikSolar UAVs.[16-20] In fact, to date, AntlantikSolar holds the world record in flight endurance of 81 hours.[20] Nevertheless, while perpetual flights have been demonstrated in small UAVs, however, if payloads need to be transported using the drones, then lighter weight solar cells with high efficiency need to be used. Moreover, the majority of the previously demonstrated solar powered aerial vehicles used either rigid or semi-flexible solar cells as they were attached on the flat wing area only.[16-20] However, advanced small drones have curved/unconventional surfaces/bodies and foldable wings which would require flexibility and stretchability in solar cells, otherwise, the aerodynamic characteristics of the UAV would be affected. It should be noted that one of the main reasons for not previously using flexible solar cells on UAVs is their generally known lower efficiency in addition to their higher cost compared to their rigid counterpart.

Thus, the main requirements of solar cells for UAVs application include: high efficiency, low weight, high reliability and flexibility such that the cells can fully conform to the drone surfaces. In fact, while organic solar cells efficiency, flexibility and weight are constantly improving with the introduction of optimized material combinations, fabrication techniques and substrates, however, their stability and reliability are still a major concern. On the other hand, to date, silicon is still the material of choice in the PV industry due to its excellent reliability, good efficiency, low cost, non-toxicity and maturity of the manufacturing process. As a result, most of the previously reported demonstrations of solar powered drones used silicon based solar cells.[16-20] Another important point is the mismatch in the thermal coefficient of expansion between the solar cell and the encapsulation material.[21] In fact, due to this mismatch, encapsulated solar cells tend to bow at high temperatures resulting in cracks within the material. One potential technique to overcome this issue is to use an additional thermal dissipative material under the solar cells, however, this would increase the total added weight and thus reduce the extended flight time.[18,21] In this work, we show the first demonstration of sola powered small drones using ultra-flexible solar cells. We use our developed corrugation-based ultra-flexible and ultra-stretchable silicon solar cells[21-24] based on the interdigitated back contacts (IBC) technology with a high efficiency (comparable to the rigid version) and low weight to analyze the performance of the "AtlantikSolar" UAV in terms of extended flight time. It is worth to note that silicon is chosen as the material for the solar cells due to its low cost, excellent reliability, good efficiency, non-toxicity and maturity of the manufacturing process. The results are compared with the capability of the used commercial semi-flexible silicon solar cells (SunPower) to extend the flight endurance of the drone. Finally, the flight time of a small-sized Syma drone is tested experimentally indoors under different conditions using the corrugated flexible solar cells.

The flexible solar cells are fabricated using our previously developed deep-reactive ion etching based corrugation technique which converts rigid monocrystalline silicon solar cells with IBC into flexible ones with excellent mechanical robustness and maintained efficiency (experimental section).[21-24] The solar cells are encapsulated using polydimethylsiloxane (PDMS) due to its low cost, excellent transparency, water-resistance and fast curing. The encapsulation is completed in two steps, initially, the back side of the cell is coated with a thin layer of PDMS, while the front side is kept uncovered to apply the corrugation process. After the flexing process, another thin layer of PDMS is coated onto the front side of the solar cell as depicted in Figure 1(a). As a result, encapsulated ultra-flexible solar cells are obtained which can be bent in different directions based on the corrugation pattern (e.g. linear, diamond, honeycomb, etc.). Thus, depending on the shape and curvature of the surfaces on the drones, different corrugation patterns can be realized such that the resulting flexible solar cell can fully comply with the drone surface area as shown in Figures 1(b-e). Nevertheless, the different corrugation patterns cause different losses in the silicon active area as shown in Figure 2(a), as a result, different specific weights (<736 g/m^2 *vs.* 780 g/m^2 for the initially encapsulated rigid cell) and power outputs would be obtained. Moreover, the grooves in the flexible cell due to the corrugation technique enable the encapsulated solar cells to expand when heated up without bowing as compared with the rigid version as depicted in the inset in Figure 2(a).

Solar powered UAVs use solar cells to collect solar energy and to first power the propulsion group and onboard electronics then charge the battery with the remaining energy. Solar cells are usually mounted in a specific configuration on certain areas of the wing in addition to other parts such as the body, fuselage, tail, etc. A Maximum Power Point Tracker (MPPT) is used as an interface between solar panels and the onboard electronics/battery, the MPPT is used to ensure that the maximum amount of power is drawn from the solar cells. To design a solar powered UAV, the energy and mass balances need to be first considered. In fact, more solar cells help in increasing the collected solar energy which would help in increasing the flight endurance, but at the same time, the additional weight of the solar cells increase the power consumption of the drone and thus reduce its endurance. Ideally, the energy collected during the day has to be enough to power the electrical and electronics components in addition to charge the battery so that the drone flies during the night till the next day. The consumed power during level flight can be expressed as the following:[18, 20]

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{2\,AR\,g^3}{\rho}} \frac{m^{\frac{3}{2}}}{b} \tag{1}$$

where C_D and C_L are the drag and lift forces acting on the drone during level flight, AR is the aspect ratio of the wing, m is the total mass of the drone, ρ is the air density, g is the earth acceleration and b is the wing span. It should be noted that the lift to drag ratio does not depend on the weight of the drone but its shape (aspect ratio of wings, wingspan, etc.)

For sake of simplicity and as a proof-of-concept of the benefits of the corrugated solar cells, in the following calculations, we will assume that the solar cells are mounted solely on the wing area of the “AtlantikSolar” UAV as in the actual experiment. Characteristics of the drone and the battery capacity are shown in Table 1 where the reported average power consumption during level flight is 41.6 W with the rigid cells (or 34.27 W without solar cells). In addition, the new power consumption is calculated when the different flexible solar cells are added using equation (1). It should be noted here that the comparison is made with the rigid solar cells (SunPower using IBC, efficiency of 23.7%) which were attached on the actual AtlantikSolar drone during its 81 hours flight. Moreover, in our calculations, we assume that no space is kept between the flexible cells since the corrugation enables the expansion of the cells at high temperatures without bowing as shown in Figure (2(a), inset). This would also allow a larger power output.

Using published avergae daily solar irradiation data and peak sun hours for different cities (Tables S1 and S2),[25] the extended hours of flight of the UAV with the different solar cells are then calculated. Figure 2(b) depicts the extended hours of flight per day in Los Angeles, January, when linear corrugated solar cells are used on the AtlantikSolar drone with different payloads. The results show that using the linear corrugated cells and no payload, up to 34 hours extension in the flight time can be achieved per day due to the stored solar energy while up to 20 hours extension can be achieved with a payload of 7 lbs (assuming 7 lbs is the maximum allowed weight). It is important to note that the maximum payload weight is predetermined based on the UAV lift and gross weight limits.[26] The results also show that an extension of flight time by around 19% (5.4 hours) is possible with the flexible cells compared to the rigid ones. It should be noted that while the actual capacity of the battery used in the AtlantikSolar is limited to 733 Wh, however, the larger generated solar energy suggests that larger batteries could be more useful for additional energy storage such that perpetual flights can be maintained even with payloads. The extension in flight time per day is calculated for different cities as well without payload (Figure 2(c)) and with a 7 lbs payload (Figure 2(d)) where perpetual flights could be maintained in both cases using the different corrugated cells and across different regions throughout the year.

A small and lightweight drone (Syma X5C, 0.9 kg) is used to experimentally test the extension in flight time when corrugated flexible solar cells with an efficiency of 19% are added on its body for energy collection. For this purpose, flexible cells with a voltage output of 1.1 V and current output of >320 mA indoor (depending on the lighting conditions) are attached on the drone and connected to the battery via a power management chip (PMC) as detailed in Table S3. The total added weight on the drone is 12 g, where the solar cells and PMC were added on the center of the drone (front side and back side, respectively) as shown in Figures 3(a-b) such that the drone center of gravity is maintained for stable flight. In fact, the flight of the drone is next tested outdoors and it is found that the stability of the flight is not affected (Video S1). In order to test the extention in flight time, experimental tests are conducted indoors in order to avoid the effect of wind and to achieve a better and fairer comparison between multiple flights (with and without cells). Two different tests are conducted indoors, the first one consist of hand-holding the solar powered drone as shown in Figure 2(c) while the flight time is recorded with and without light (desk incandescent lamp). It is found that under the light, the flight time is extended by almost 7% (8 min 20 s up to 8 min 54 s, Videos S2-S3). The second test is conducted in an indoor field where mixed light is available (sunlight through the window and LED lamps in the ceiling) as shown in Figures 2(d-e) (Video S4). The initial voltage drop across the fully charged battery is 4.18 V while the speed of the drones was fixed (Figure 2(f)) during the flights indoors. It should be noted however, that the efficiency of light collection indoors drops down compared to sunlight exposed cells (measured current output from solar cells indoors under mixed light of LED and sunlight drops from to 912 mA to >320 mA, depending on lighting conditions/proximity to light source and window). Nevertheless, the results show that the battery powered drone falls down after ~8.5 min of continous flight while the solar powered drone stays flying till ~9.4 min which is a ~10% extension in flight endurance. Moreover, the measured remaining voltage drop across the battery of the battery powered drone was 2.87 V wile 3 V for the solar powered drone. This can be explained by the added weight of the cells and PMC unit which results in a higher needed power to enable the lift and flight of the drone compared with the lighter battery powered drone which was able to fly till a final 2.87 V voltage drop is reached (Figures 2(g-h)). The experiments have been repeated 5 times and comparable results were obtained. The results show the potential of solar cells in extending the flight time of small drones, the results also confirm that using higher efficiency PMC units would enable a much enhanced flight endurance.

In conclusion, the application of the corrugated flexible monocrystalline silicon solar cells is demonstrated in UAVs. The corrugation technique results in ultra-flexible cells with lower specific weight (down to 645 g/m^2, with encapsulation) and maintained efficiency compared to the original rigid cells (19%). Moreover, the grooves created in the silicon enable the encapsulated cells to expand when heated up without cracking or losing performance. Theoretical calculations are conducted on the AtlantikSolar UAV, which is the holder of the current world record of 81 hours flight. Using the different corrugated solar cells, an extension of flight time by up to 19% can be achieved compared to the rigid cells used in the actual experiment. Moreover, the results show that perpetual flights could be maintained even when payloads of 7 lbs are transported in different regions and throughout the year. Finally, experimental results on a small lightweight drone (Syma) show that an extension in flight time of ~10% can be achieved indoor when corrugated solar cells (12.5 cm by 4 cm) are attached on its body. The presented results confirm the potential of the ultra-flexible and high efficiency corrugated solar cells in the application of advanced UAVs for payload transportation.

Experimental Section

Encapsulation of the solar cells: Polydimethylsiloxane (PDMS) was prepared by mixing the silicone to its curing agent in a 10:1 ratio. The mixture is degassed in a vacuum mixer for 4 minutes. PDMS is then spin coated on the backside of the solar cell (on the back contacts) and is then cured in an oven at 60°C for 2 hours. The front side is then spin coated with a photoresist followed by the application of a hard mask (kapton). The hard mask is then patterned using a CO_2 laser while the exposed silicon areas are next completely etched in a deep reactive ion etching system. The remaining hard mask is removed using a lift off process. Finally, another thin PDMS layer is spin coated on the front side of the solar cell and cured in an oven at 60°C for 2 hours. As a result, a flexible and encapsulated solar cell is obtained.

Attachment of the solar cells on the drone: The solar cells are attached on the body on a small Syma drone using double sided tape. The power management chip is also attached using double sided tape on the back side of the drone.

Connection of the solar cell to the battery: Two solar cells (12.5 cm by 2 cm each) are connected in series using 1-mm thick wires, the output is then connected to the 3.7 V Lipo battery of the drone via a power management chip. The chip boosts the voltage output from the solar cells (1.1 V to 3.7 V) while reduces the current output from the solar cell depending on the light conditions.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

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References

[1] J. A. Berni, Z. Tejada, P. J. Suarez, E. Fereres, *IEEE Transactions on Geoscience and Remote Sensing*, **2009**, *47*, 722-738.

[2] N. J. Colella, G. S. Wenneker, *IEEE Potentials*, **1996**, *1*, 18-23

[3] J. A. Duffie, W. A. Beckman, in *Solar engineering of thermal processes*, John Wiley & Sons, Germany **2013**.

[4] M. Dunbabin, L. Marques, *IEEE Robotica & Automation Magazine*, **2012**, *19*, 24-39.

[5] M. A. Goodrich, B. S. Morse, B. S. Gerhardt, D. Cooper, J. L. Quigley, M. Adams, C. Humphrey, *Journal of Field Robotics*, **2008**, *25*, 89-110.

[6] M.R. Bhatt, *PhD dissertation*, San Jose State University, May, **2012**.

[7] D. Floreano, R.J. Wood, *Nature* **2015**, *521*, 460–466

[8] CBS News. Amazon unveils futuristic plan: delivery by drone. 60 Minutes Overtime. https://www.cbsnews.com/news/amazon-unveils-futuristic-plan-delivery-by-drone/, accessed June 2020.

[9] D. Gaitan, Drones being developed to deliver medical aid, not bombs. Bus Inside. https://www.reuters.com/article/us-medical-drones/drones-being-developed-to-deliver-medical-aid-not-bombs-idUSKBN0GF17I20140815, accessed June 2020.

[10] UPS. UPS tests residential delivery via drone launched from atop package car. United Parcel Service. https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1487687844847-162, accessed June 2020.

[11] M. Wohlsen, The next big thing you missed: Amazon's delivery drones could work—they just need trucks. Wired https://www.wired.com/2014/06/the-next-big-thing-you-missed-delivery-drones-launched-from-trucks-are-the-future-of-shipping/, accessed June 2020.

[12] M. Murphy, This is how Google wants its drones to deliver stuff to you. *Quartz*. https://qz.com/670670/this-is-how-google-wants-its-drones-to-deliver-stuff-to-you/, accessed June 2020.

[13] K.D. Atherton, Amazon patents warehouse blimps with packages delivered by drone. Popular Science. http://www.popsci.com/amazon-patents-airship-warehouses-for-delivery-by-drone, accessed June 2020.

[14] DOE. EV everywhere grand challenge progress report 2014. https://energy.gov/sites/prod/files/2014/02/f8/eveverywhere_road_to_success.pdf (U.S. Department of Energy, Washington, DC, USA, 2014).

[15] J. Stolaroff, C. Samaras, E. O'Neill, A. Lubers, A. Mitchell, D. Ceperley, *Nature Communications* **2018**, *9*, 409

[16] V.S. Dwivedi, J. Patrikar, A. Addamane, A.K. Ghosh, presented at 23rd International Conference on Methods & Models in Automation & Robotics, Poland, August, **2018**

[17] C. Goh, J. Kuan, J. Yeo, B. Teo, A. Danner, *Progress in Photovoltaics: Research and Applications* **2019**, *27*, 869-878

[18] “Zephyr: persistence and flexibility” (datasheet), airbus defence and space, Cody Technology Park, Farnborough, U.K., 2018. Available Online: https://www.airbus.com/defence/uav/zephyr.html

[19] M.C. Achtelik, J. Stumpf, D. Gurdan, K.M. Doth, presented at 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, USA, September, **2011**

[20] P. Oettershagen, A. Melzer, T. Mantel, K. Rudin, T. Stastny, B. Wawrzacz, T. Hinzmann, S. Leutenegger, K. Alexis, R. Siegwart, *Journal of Field Robotics* **2017**, *34*, 1352-1377

[21] N. El-Atab, W. Babatain, R. Bahabry, R. Alshanbari, R. Shamsuddin, M.M Hussain, *ACS Applied Materials & Interfaces* **2019**, *12*, 2269.

[22] N. El- Atab, N. Qaiser, R. Bahabry, M.M. Hussain, *Advanced Energy Materials* 2019, *9*,

[23] N. El-Atab, R. Shamsuddin, R. Bahabry, M.M. Hussain presented at the 46th IEEE Photovoltaic Specialists Conference (PVSC), Chicago, **2019**

[24] R. Bahabry, A. Kutbee, S. Khan, A. Sepulveda, I. Wicaksono, M. Nour, N. Wehbe, A. Almislem, M. Ghoneim, G. Torres Sevilla, A. Syed, S. Shaikh, M. Hussain, *Advanced Energy Materials* **2018**, *8*, 1702221.

[25] Solar Electricity Handbook, http://www.solarelectricityhandbook.com/solar-irradiance.html, accessed April 2020

[26] K. Valavanis, G. Vachtsevanos, *Handbook Of Unmanned Aerial Vehicles*, Springer International Publishing, Cham, **2020**.

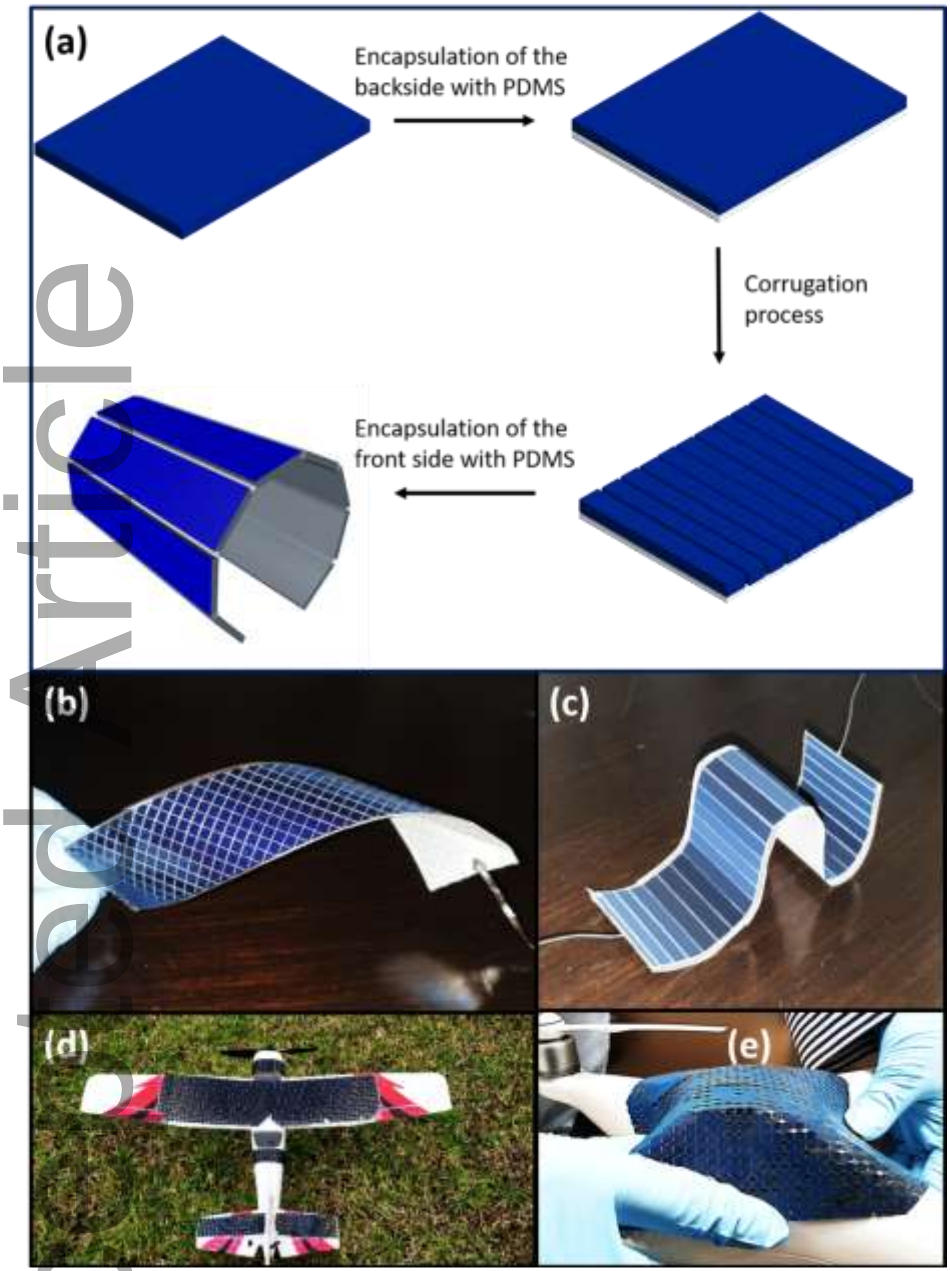

Figure 1. (a) Development process flow of the encapsulated and corrugated flexible solar cells (b) Flexible linear corrugated silicon solar cells. (c) Flexible linear corrugated silicon solar cell. (d) Flexible corrugated solar cells attached on a UAV with fixed wings. (e) Flexible silicon solar cell attached on the drone with unconventional surface.

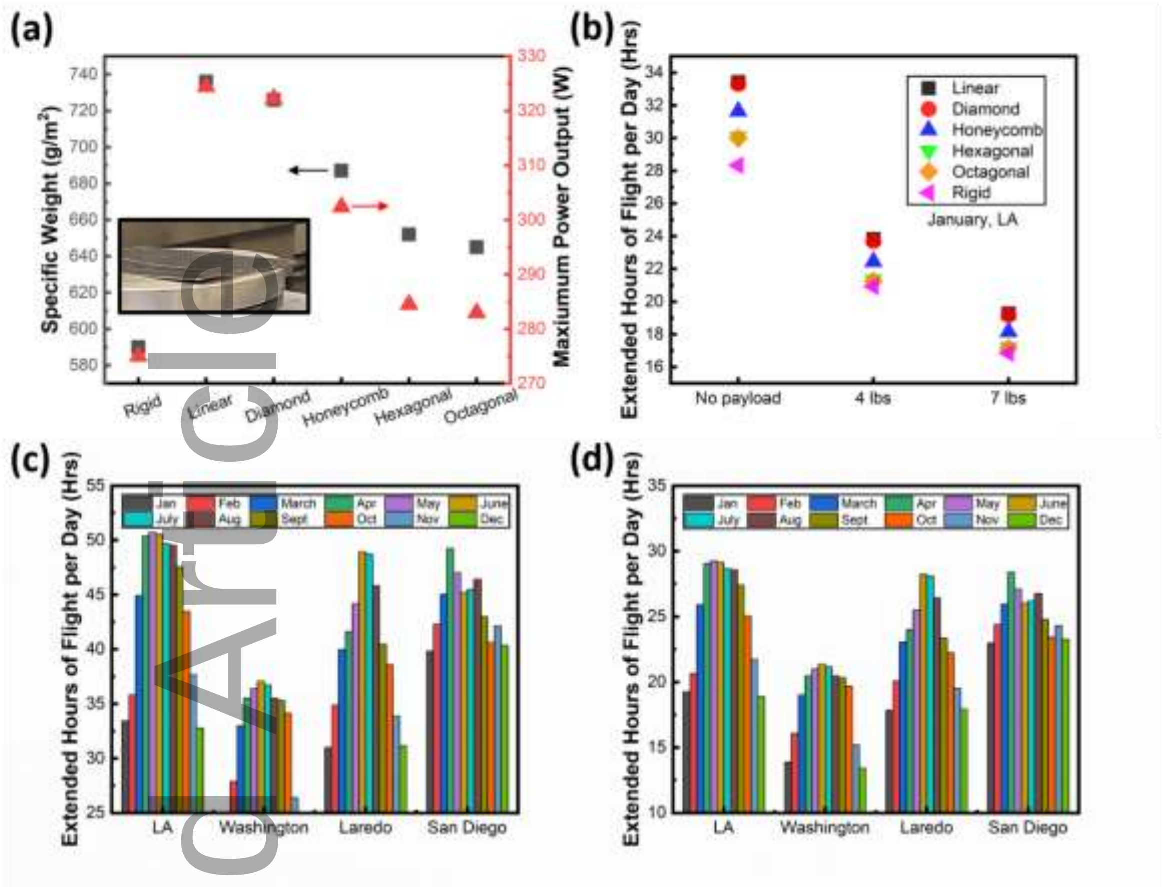

Figure 2. (a) Calculated specific weight and maximum power output from the different corrugated flexible (encapsulated) and rigid (un-encapsulated and spaced) solar cells considered. Inset shows a rigid and a corrugated solar cells placed on a hot plate. The rigid cell bends upward at high temperatures. (b) Extended flight time of the AtlantikSolar UAV per day in LA, in January, using the different corrugated and rigid solar cells at different payloads. (c) Calculated extended hours of flight per day in different cities using the linear corrugated solar cell technology with no payload. (d) Calculated extended hours of flight per day in different cities using the linear corrugated solar cell technology with a 7 lbs payload.

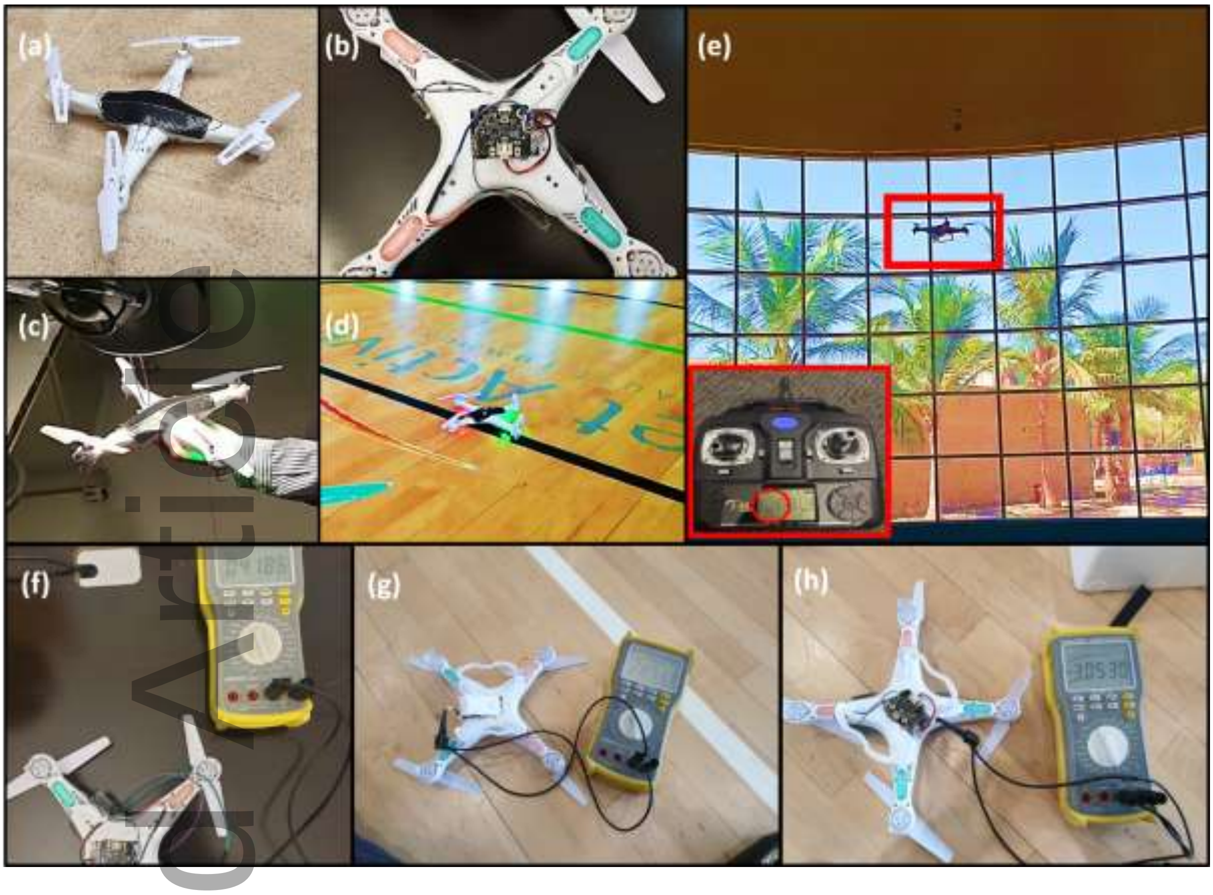

Figure 3. (a) Attached flexible solar cells on the Syma drone. (b) Added power management circuitry interfacing between the solar cells and the battery. (c) Experimental testing of the solar powered drone indoor under incandescent light using a desk lamp. (d-e) Experimental testing of the solar powered drone indoor under mixed lighting (indoor sunlight and LED). Inset in Figure (e) showing the remote controller of the drone with the used fixed speed during the flight. (f) Voltage drop across the fully charged battery. (g) Final voltage drop across the battery of the drone without solar cells. (h) Final voltage drop across the battery of the solar powered drone.

Table 1. Characteristics of SoLong UAV and the used solar cells

	AtlantikSolar Aircraft				
Total weight with no load	6.09 kg				
Wingspan	5.69 m				
Wing area	1.45 m^2				
Power consumption	34.27 W (with no solar cells load)				
Battery capacity	733 Wh				
Solar Cells	**Linear**	**Diamond**	**Honeycomb**	**Hexagonal**	**Octagonal**
Specific weight (kg/m^2)	0.736	0.726	0.687	0.652	0.645
Active area loss (%)	5.6	6.25	12	17.2	17.64
Flexibility	Unidirectional	Multidirectional	Multidirectional	Multidirectional	Multidirectional
Minimum bending radius (mm)	5	5	6	6	15
Maximum power output (W)	324.4	322.2	302.4	284.5	283

The application of corrugated ultra-flexible silicon solar cells with high efficiency (19%) and ultra-lightweight (<0.73 kg/m^2) on small UAVs is demonstrated. The ultra-flexible cells can be attached onto the drone's wings or body with full compliance and can enable perpetual flights with added payloads. Experimental results show that >10% extended flight time could be achieved indoor.

Keyword Flexible solar cells, UAV, monocrystalline silicon

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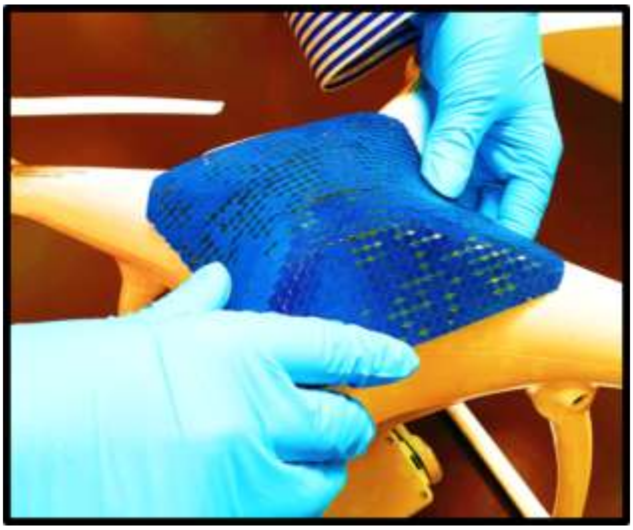
Ultra-flexible monocrystalline silicon solar cells for Application in Unmanned Aerial Vehicles



Supporting Information

Flexible High-Efficiency Monocrystalline Silicon Solar Cells for Small Unmanned Aerial System Application

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Table S1. Average daily solar irradiation in different cities throughout the year.

Irradiation per day in ($Wh/m^2/day$)	**LA**	**Washington**	**Laredo**	**San Diego**
January	4500	3240	4170	5360
February	4820	3750	4690	5690
March	6050	4440	5380	6060
April	6780	4780	5600	6630
May	6830	4900	5950	6330
June	6800	4990	6590	6080
July	6690	4940	6560	6120
August	6670	4780	6170	6250
September	6400	4750	5450	5790
October	5850	4590	5190	5470
November	5070	3550	4560	5670
December	4410	3140	4190	5430

Table S2. Average daily peak sun hours in different cities throughout the year.

Peak sun hours per day (hrs)	LA	Washington	Laredo	San Diego
January	4.5	3.24	4.17	5.36
February	4.82	3.75	4.69	5.69
March	6.05	4.44	5.38	6.06
April	6.78	4.78	5.6	6.63
May	6.83	4.9	5.95	6.33
June	6.8	4.99	6.59	6.08
July	6.69	4.94	6.56	6.12
August	6.67	4.78	6.17	6.25
September	6.4	4.75	5.45	5.79
October	5.85	4.59	5.19	5.47

November	5.07	3.55	4.56	5.67
December	4.41	3.14	4.19	5.43

Table S3. Solar powered drone parameters.

Solar Powered Drone Parameters	
Solar cells dimensions	2 cm by 12.5 cm
Solar cell efficiency	19%
Solar cell output indoor	>320 mA
Power management chip (PMC)	DFRobot
PMC voltage output (battery charging)	3.7 V
Syma drone initial weight	910 g
Total added weight (encapsulated solar cells, wires and PMC)	12 g

Video S1. Testing the stability of the drone flight outdoors with added weight of solar cells and power management chip.

Video S2. Testing the solar powered drone flight time when hand-held and under no light.

Video S3. Testing the solar powered drone flight time when hand-held and under an incandescent lamp.

Video S4. Testing the solar powered drone flight time indoors under mixed lighting (LED and sunlight).