3D printed packaging of photovoltaic cells for energy autonomous embedded sensors

Markellos Ntagios, Pablo Escobedo, Ravinder Dahiya*

Bendable Electronics and Sensing Technologies (BEST) Group, School of Engineering, University of Glasgow, G12 8QQ, U.K
*Correspondence to - Ravinder.Dahiya@glasgow.ac.uk

***Abstract*— Most robotic/prosthetic hands lack the ability to harvest energy, and as a result they rely on the batteries to provide the required energy for their operation. Recently solar cells have been explored to meet the energy requirements. However, most solar cells are brittle, and their chances of getting damaged during robotic operation are high. The work presented in this paper addresses this challenge through a transparent 3D printed package covering three photovoltaic cells. The package protects the cells from impact and prevents dust accumulation while ensuring minimal loss of light reaching the cells. The effect of the protective 3D printed cover on the performance of photovoltaic panel have been evaluated. This solar cell package is integrate on a 3D printed robotic hand to harvest energy from the environmental illumination and utilizes it to power the small peripheral electronic and sensing components on the hand.**

Keywords*— *energy harvesting, 3D printing, photovoltaic, robotics, rapid prototyping, additive manufacturing

I. Introduction

Recent advances in robotics, particularly in the field of sensing and actuation, have fuelled the need for energy-autonomous systems and that of energy harvesting and energy storage solutions. [1-12]. The energy storage devices such as batteries require frequent charging and they usually support robotic operation for couple of hours. To ensure that the sensing, actuating, and computing units on a robot are powered for a significant amount of time, these solutions have been complemented with the use various energy harvesting devices [13-15]. Among these, the photovoltaics emerge as most suitable due to the higher and enough energy they can generate to power various sensing/electronic components in robotics and other related applications [15-21]. Solar cells are also the optimum solution for prosthetics/robotics due to their low weight. The lightweight, fewer parts and the ease implementation of such devices are extremely attractive for robotic applications. Unfortunately, the most efficient commercial solar cells are extremely fragile to be used with robots operating in an unstructured environment. They may break or crack due to impact if the robots collide with objects around. To prevent such undesirable situations, a packaging arrangement is necessary to protect the solar cells. In this regard, 3D printed package with transparent materials has been explored here.

3D printing is a commonly used method in additive manufacturing for fabrication of arbitrary shapes. Thanks to the significant freedom in designing, 3D printing prosthetics and robotics are also on the rise [22-27]. This technology can also meet the demanding requirements for packaging of electronics, sensors, interconnects, etc., in complex and innovative ways. The latest advancements in materials and custom systems for 3D printers, have enhanced their capabilities even further. Some of the advantages can be found in 3D printed interconnects, embedded sensors, 3D printed antennas or 3D printed scaffolds, to name a few [28-32]. Lately, 3D printed technologies have been used in industries, such as automation, aeronautic, bioengineering or robotics as a prototyping method as well as to fabricate the final parts [33-35]. In this work, we extend this trend further into packaging of power generating devices such as photovoltaic to extend the autonomous operational capability of 3D printed robotic/prosthetic hands.

Herein, we present experimentation of 3D printed covers for solar cells and evaluate the effect of the printed structures on the performance of the photovoltaic device. Three 3D

Fig. 1. a) 3D printed robotic hand with three photovoltaic panels. b) 1mm thickness covers attached on the top to reduce wear and tear.

This work is supported in part by Engineering and Physical Sciences Research Council (EPSRC) through National Productivity Investment Fund project (EP/R512266/1) and Engineering Fellowship for Growth (EP/R029644/1).

printed covers were fabricated with different thicknesses and tested to see the effect of the thickness of the material on the energy generated by the solar cells. The photovoltaic cell and the cover material used in this study is commercially available. The covers were 3D printed from a transparent Polylactic acid (PLA) filament. All covers were printed with the same 3D printer and settings. From the results, we identify the trade-offs between thickness, structural integrity, and energy harvesting. The fully system can be seen in Figure 1.

This paper is organized as follows: Section II describes the solar cell and fabrication settings of the cover. Section III presents the experimentation set up of this study, the results of the measurements and their evaluation. Finally, Section IV summarizes the key outcomes of this study along with future perspectives.

II. Matelias and Methods

A. Energy Harvesting Materials

In this study, a commercial photovoltaic device (193852 Monocrystalline Solar Cell, RSC-M125XL, Conrad) was used to harvest the energy from the incident solar electromagnetic waves produced from a high illumination office lamp. The light source is a 4 W LED lamp with colour temperature (CCT) of 4500 K and Color Rendering Index (CRI) higher than 80 RA according to manufacturer specifications (model LT-T15, Aglaia, California, USA). The cell has an efficiency of up to 17.8%. The panel has dimensions of 50x50 mm^2, with nominal voltage of 0.5 V, nominal current of 0.77 A, and short circuit current of 0.85 A.

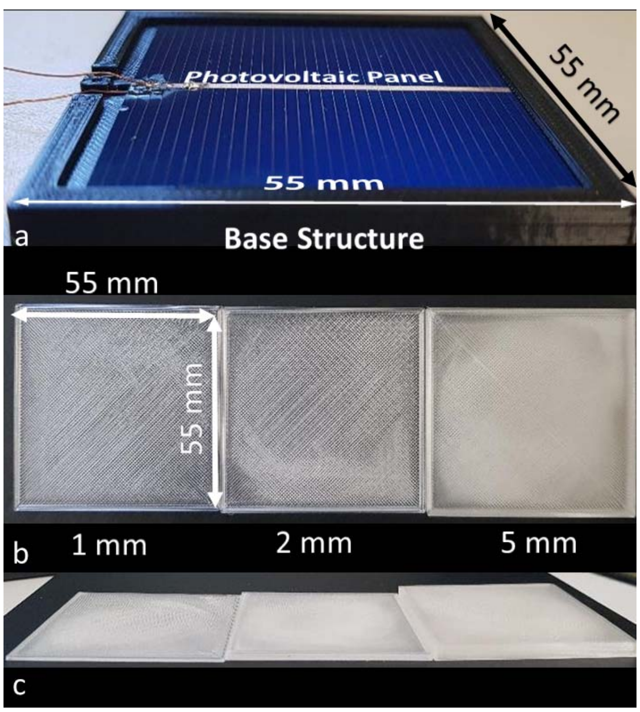

Fig. 3. a) Photovoltaic panel placed on top of the base 3D printed structure. b) Top view of the 1mm, 2mm and 5mm 3D printed transparent covers. c) side view of the 3D printed covers

B. Fabrication of the 3D printed covers

All parts used in this study were printed with Ultimaker S5 3D printer. All parts were printed with the following settings for consistency of the results. The printer had a brass nozzle with diameter of 0.4 mm. The infill was set to 100% with a line filling pattern. The layer height was set to 0.1 mm. The printed temperature was set to 200 ºC with a printing speed of 40mm/s, slightly slower than the common speed of 70mm/s. Slower printing speeds, in general, provides better adhesion between layers, which is desired for solar panel covers.

Firstly, we printed a small 3D-printed plastic part with a small cavity where the photovoltaic panel could be secured safely. This small base part was printed with a black PLA filament. This structure was necessary to keep the experimentation consistent from cover to cover. The covers were printed from a transparent PLA material. Even though the material is transparent after the printing process the parts look more translucent than transparent. After the fabrication process, the parts were placed above the base structure and

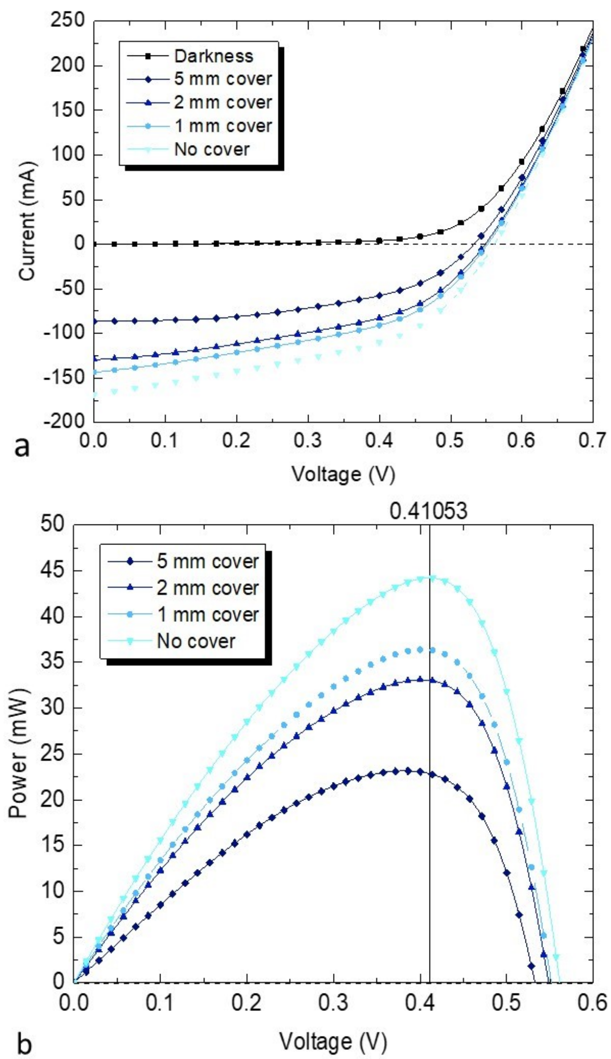

Fig. 2. a) Graph representing the current with respect to voltage recorded from the solar panel covered completely, 5mm, 2mm, 1mm and no cover. b) Power with respect to voltage for 5mm, 2mm ,1 mm and cover.

tested. PLA is a suitable material due to its non-toxicity, can sustain temperatures up to 60 ºC without alterations on its physical properties and the availability of the material and low cost.

C. *3D printed hand*

The 3D printed hand, wrist, cover and base were designed using the Computer-Aided-Design (CAD) software SolidWorks 2018 (Dessault Systems). The hand was printed on CubePro, due to its ability to fabricate structures using three different materials, and the rest of the parts on Ultimaker S5. Details for the hand and wrist can be found on our previous works [12, 26, 27]. In the robotic hand, we embedded tactile sensors and capacitance to digital converter chips. With the current work, we are targeting self-powering of the integrated circuit (IC) for the tactile sensors. The IC requires 5V input voltage and 750 μA resulting in a power consumption of around 3.75mW.

III. Results and Discussion

A. *Testing Procedure*

Firstly, the base structure with the photovoltaic panel were placed on a flat surface without any cover (Fig. 2a). A high illumination lamp was directly illuminating the structure from above at 10 cm. Then we recorded the output of the solar cell using 4-wire measurements with a Precision Source/Measure Unit (SMU) B2912A (Keysight Technologies, Santa Clara, CA, USA). The 4-wire measurement scheme eliminates the voltage error caused by the test lead residual resistance so that only the voltage drop across the device under test (DUT) is measured. The Keysight B2900A Quick I/V Measurement Software was used to automate the sweep measurements by connecting the SMU unit to a PC through USB. Afterwards, we covered the device with the 1mm thickness translucent PLA 3D printed part and recorded again the output of the device. This was followed by 2mm and 5mm thickness covers (Fig. 2b,c). Lastly, we covered the device with a thick black cloth that absorbs most of the visible light and recorded the performance of the photovoltaic panel. Figure 3a presents the recorded I-V curves of the device under no cover, 1mm, 2mm, 5mm thickness covers and completely covered. Figure 3b presents the power generation of the device under the five conditions mentioned above with respect to voltage.

B. *Results*

As expected, the thick cloth absorbed most of the light, and virtually no output was detected by the SMU. The exact opposite could be observed when there was no cover, and all other results are compared with this as the reference point. From the experimental results, a clear pattern emerges as observed from Figure 3. The thickness of the covers plays a significant role in the effectiveness of the photovoltaic panel.

In all settings, the output voltage reaches a special point as shown in Figure 3b: the maximum power voltage (V_{MPP}). The output power reaches its peak (P_{MPP}) when the output voltage is at V_{MPP}. In all cases, at V_{MPP}=0.41V, the device has the highest efficiency. From that point, we can compare different settings. When the device was uncovered, it generated a maximum power of P_{MPP}=43.8mW. Once we introduced a cover, the energy generated dropped. For the 1mm PLA cover, the energy generation dropped significantly with the P_{MPP} measured at 36.4mW. The efficiency of the device dropped even further down to P_{MPP}=33.1mW with the use of the 2mm cover. The 5mm thickness cover was found to drop the energy generation down to 23.1mW, the lowest value from all PLA covers.

TABLE I. Photovoltaic Panel Performance

Cover Type	Performance	
	Power Output	***Reduction***
No cover	43.8mW	-
1mm	36.4mW	16.9%
2mm	33.1mW	24.4%
5mm	23.1mW	47.3%

C. *Evaluation*

As expected, all 3D printed covers have reduced the effectiveness of the photovoltaic panel in terms of power generation. The 1mm cover reduced the efficiency by 16.9%, the 2mm by 24.4%, and the 5mm by 47.3%. As table I shows, the covers have a clear reduction in the efficiency. This is expected as with increasing thickness more material is absorbing the photons, resulting in a constant reduction of the energy generated. The 1 mm cover has the least effect on the power generation. Even that the 16.9% reduction on the ability of photovoltaic panel to generate power is considerable, we were able to power ten ICs consistently under the affirmation conditions. This arrangement also provided a significant protection of the device from mechanical stress, dust and other hazards.

IV. Conclusion

This paper presents a novel study of 3D printed transparent materials as protective cover for photovoltaic panels and their effect on the energy harvesting capabilities of such devices. The study presents the use and advantages of 3D printed protective covers for fragile photovoltaic cells. We observed that the 1mm thickness cover provides significant durability to the energy harvesting device with a small reduction on the performance of 16.9%. The device with this cover generates 36.4 mW. With this amount of power generated it is possible to power around 10 ultra-lower power ICs. This will alleviate some of the high demand energy requirements of robotics/prosthetics. The excess generated from the device can be further stored and use in a later time. Also, this device can be used as a sensor for ambient light and/or time of the day. Moving forwards, more samples are needed to be explored and experimentation of the 3D printing parameters, such as ironing, and different materials, in order to obtain a better performance on the solar panel. Experimentation with post-processes approaches, like vapor or thermal annealing, could result in an increase performance of the covers. Integration with the rest of the robotic hand and testing other 3D printed materials are some of the future works.

REFERENCES

[1] R. Dahiya, “E-Skin: From humanoids to humans,” *Proceedings of the IEEE,* vol. 107, no. 2, pp. 247-252, 2019.

[2] M. Soni, and R. Dahiya, “Soft eSkin: distributed touch sensing with harmonized energy and computing,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 378, no. 2164, pp. 20190156, 2020.

[3] S. Luo, J. Bimbo, R. Dahiya *et al.*, “Robotic tactile perception of object properties: A review,” *Mechatronics,* vol. 48, pp. 54-67, 2017.

[4] B. Siciliano, and O. Khatib, *Springer handbook of robotics*: Springer, 2016.

[5] Z. Kappassov, J.-A. Corrales, and V. Perdereau, “Tactile sensing in dexterous robot hands — Review,” *Robotics and Autonomous Systems,* vol. 74, pp. 195-220, 2015/12/01/, 2015.

[6] Y. Bahramzadeh, and M. Shahinpoor, “A review of ionic polymeric soft actuators and sensors,” *Soft Robotics,* vol. 1, no. 1, pp. 38-52, 2014.

[7] S. Viteckova, P. Kutilek, and M. Jirina, “Wearable lower limb robotics: A review,” *Biocybernetics and biomedical engineering,* vol. 33, no. 2, pp. 96-105, 2013.

[8] B. Vanderborght, A. Albu-Schäffer, A. Bicchi *et al.*, “Variable impedance actuators: A review,” *Robotics and autonomous systems,* vol. 61, no. 12, pp. 1601-1614, 2013.

[9] D. F. Häufle, M. Taylor, S. Schmitt *et al.*, "A clutched parallel elastic actuator concept: Towards energy efficient powered legs in prosthetics and robotics." *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob),* pp. 1614-1619, 2012.

[10] R. S. Dahiya, and M. Valle, *Robotic tactile sensing: technologies and system*: Springer Science & Business Media, 2012.

[11] R. S. Dahiya, G. Metta, M. Valle *et al.*, “Tactile sensing—from humans to humanoids,” *IEEE transactions on robotics,* vol. 26, no. 1, pp. 1-20, 2009.

[12] W. Navaraj, and R. Dahiya, “Fingerprint-Enhanced Capacitive-Piezoelectric Flexible Sensing Skin to Discriminate Static and Dynamic Tactile Stimuli,” *Advanced Intelligent Systems,* vol. 1, no. 7, pp. 1900051, 2019.

[13] D. B. Licea, S. A. R. Zaidi, D. McLernon *et al.*, “Improving radio energy harvesting in robots using mobility diversity,” *IEEE Transactions on Signal Processing,* vol. 64, no. 8, pp. 2065-2077, 2016.

[14] D. Meike, and L. Ribickis, "Energy efficient use of robotics in the automobile industry." *15th International Conference on Advanced Robotics (ICAR),* pp. 507-511.

[15] C. G. Núñez, W. T. Navaraj, E. O. Polat *et al.*, “Energy-Autonomous, Flexible, and Transparent Tactile Skin,” *Advanced Functional Materials,* vol. 27, no. 18, pp. 1606287, 2017.

[16] A. Kaplan, N. Kingry, P. Uhing *et al.*, “Time-optimal path planning with power schedules for a solar-powered ground robot,” *IEEE Transactions on Automation Science and Engineering,* vol. 14, no. 2, pp. 1235-1244, 2016.

[17] D. Brunelli, C. Moser, L. Thiele *et al.*, “Design of a solar-harvesting circuit for batteryless embedded systems,” *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 56, no. 11, pp. 2519-2528, 2009.

[18] L. E. Ray, J. H. Lever, A. D. Streeter *et al.*, “Design and power management of a solar‐powered “cool robot” for polar instrument networks,” *Journal of Field Robotics,* vol. 24, no. 7, pp. 581-599, 2007.

[19] V. Raghunathan, A. Kansal, J. Hsu *et al.*, "Design considerations for solar energy harvesting wireless embedded systems." *International Symposium on Information Processing in Sensor Networks,* pp. 457-462, 2005

[20] C. G. Núñez, L. Manjakkal, and R. Dahiya, “Energy autonomous electronic skin,” *npj Flexible Electronics,* vol. 3, no. 1, pp. 1-24, 2019.

[21] P. Escobedo, M. Ntagios D. Sjakthivel *et al.*, "Energy Generating Electronic Skin with Intrinsic Tactile Sensing without Touch Sensors" *IEEE Transactions on Robotics (T-RO)*, (accepted), 2020.

[22] K. V. Wong, and A. Hernandez, “A review of additive manufacturing,” *International scholarly research notices,* vol. 2012, 2012.

[23] R. R. Ma, L. U. Odhner, and A. M. Dollar, "A modular, open-source 3D printed underactuated hand." *IEEE International Conference on Robotics and Automation (ICRA),* pp. 2737-2743, 2013.

[24] I. Llop-Harillo, and A. Pérez-González, “System for the experimental evaluation of anthropomorphic hands. Application to a new 3D-printed prosthetic hand prototype,” *International Biomechanics,* vol. 4, no. 2, pp. 50-59, 2017.

[25] J. Ten Kate, G. Smit, and P. Breedveld, “3D-printed upper limb prostheses: a review,” *Disability and Rehabilitation: Assistive Technology,* vol. 12, no. 3, pp. 300-314, 2017.

[26] M. Ntagios, H. Nassar, A. Pullanchiyodan *et al.*, “Robotic Hands with Intrinsic Tactile Sensing via 3D Printed Soft Pressure Sensors,” *Advanced Intelligent Systems,* vol. 2, no. 6, pp. 1900080, 2020.

[27] M. Soni, M. Bhattacharjee, M. Ntagios *et al.*, “Printed Temperature Sensor Based on PEDOT: PSS-Graphene Oxide Composite,” *IEEE Sensors Journal,* vol. 20, no. 14, pp. 7525-7531, 2020.

[28] H. Nassar, A. Pullanchiyodan, M. Bhattacharjee *et al.*, "3D Printed Interconnects on Bendable Substrates for 3D Circuits." *IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS),* pp. 1-3, 2019

[29] M. Ntagios, W. T. Navaraj, and R. Dahiya, "3D Printed Phalanx Packaged with Embedded Pressure Sensor." *IEEE SENSORS,* pp. 1-4, 2018

[30] H. Nassar, M. Ntagios, W. T. Navaraj *et al.*, "Multi-Material 3D Printed Bendable Smart Sensing Structures." *IEEE SENSORS,* pp. 1-4, 2018

[31] B. Zhang, Z. Zhan, Y. Cao *et al.*, “Metallic 3-D Printed Antennas for Millimeter- and Submillimeter Wave Applications,” *IEEE Transactions on Terahertz Science and Technology,* vol. 6, no. 4, pp. 592-600, 2016.

[32] H. N. Chia, and B. M. Wu, “Recent advances in 3D printing of biomaterials,” *Journal of biological engineering,* vol. 9, no. 1, pp. 1-14, 2015.

[33] K. Rong, D. Patton, and W. Chen, “Business models dynamics and business ecosystems in the emerging 3D printing industry,” *Technological Forecasting and Social Change,* vol. 134, pp. 234-245, 2018.

[34] Y. W. D. Tay, B. Panda, S. C. Paul *et al.*, “3D printing trends in building and construction industry: a review,” *Virtual and Physical Prototyping,* vol. 12, no. 3, pp. 261-276, 2017.

[35] S. Park, “3D printing industry trends,” *International Journal of Advanced Culture Technology,* vol. 2, no. 1, pp. 30-32, 2014.