Piezoelectric Glove Design and Test for Future Wearable Devices

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Abstract. We present the first results of experimental measurements performed to estimate the available energy derived from the movement of the fingers of one hand. The proposed system consists of a mechanical hand made with a 3D printer, on which 5 piezoelectric strips are applied, electrically connected in series or in parallel. Measurements have shown that the series configuration produces the best result. In this configuration, in fact, the open circuit peak-to-peak voltage reaches 39.6V.

1. Introduction

In recent years, together with an increased attention towards low-power portable electronic devices, particular interest in the energy harvesting has grown considerably. The spread of implantable and wearable devices and the consequent development of applications dedicated to them have pushed research and industry to evaluate energy harvesting as a valid alternative way to increase the lifespan of these devices.

In fact, the battery constitutes a great limit for the user both in terms of duration and of periodic maintenance. The environment is rich in different types of energy sources that can be collected, transformed and accumulated, so to extend the battery life in portable devices.

The variety of energy sources in the environment and in the human body has been the subject of many studies that have deepened the suitable techniques for energy harvesting [1-8] for low voltage and low power applications [9-16]. In some cases, in addition to the extension of the battery life, efforts have been made to make the devices completely autonomous [17-29].

The human body offers many sources of energy, as shown in fig. 1, which have been extensively studied, sometimes quantifying the power generated by breathing, by moving the upper and lower limbs and by walking. Often, however, the information about the amount of energy collected by the harvester is omitted.

This work focuses on the amount of energy recovered in the natural movement of the fingers of one hand, through the use of piezoelectric transducers, aimed at supporting the power supply of mobile and wearable devices. This approach has numerous advantages related to the permanent life of the device and to the reduction of its weight given the uselessness of the battery, particularly interesting in areas where the electrical network is not very developed.
Piezoelectric materials constitute a consolidate technique for converting the mechanical energy of living subjects into electrical energy. Some works have dealt with piezoelectric energy harvesting, using different types of materials. In this context, interdisciplinarity is fundamental to join the progress of electrical circuits and that of materials technology towards an improved conversion efficiency. In order to make harvesting more efficient in biomedical applications, piezoelectric sensors with a flexible structure, high bandwidth at high frequencies and low resonance frequency must be employed. For these reasons, for applications on the human body, considering the two PZT macro-categories, piezopolymers (PZTp) are preferred to piezoceramics (PZTc). In fact, the PZTp as well as being cheap, are also less fragile and therefore easily integrated on wearable devices. Their disadvantage, on the other hand, consists of the smaller coupling coefficients between the mechanical and electrical variables with consequent lower energy conversion efficiency. On the other side, the PZTc having a high electromechanical transformation efficiency and a wide range of shapes obtainable are too fragile to follow the movements of the human body.

In the past, many articles have dealt with bio-vital energy harvesting, also considering the simultaneous presence of different types of harvesters. In particular, in some works, a model of piezoelectric harvester exploiting the movement of a single finger and maximizing the energy collected in correspondence of a load resistance matched with the impedance of the piezoelectric material was presented. Our work shows the experimental results of a system consisting of a mechanical hand on which PZTp piezoelectric strips are applied. We tested a mechanical hand made with a 3D printer, on which 5 piezoelectric strips are applied, electrically connected in series or in parallel.

![Figure 1: Human body energy sources and related power](image)
2. Design, Implementation and test

We have carried out measurements using an architecture consisting of a 3D printed mechanical hand (see Figure 2a) in which each finger is operated by a servomotor by means of a microcontroller. The presence of fittings on each finger allows to reproduce the natural movement of opening and closing of hand intent on grasping objects. A glove was then realized (see Figure 2b) that allowed to place a piezoelectric strip on each finger, so to evaluate the single contribution of energy recovered. We have chosen a rather inexpensive PZT TE Connectivity [30] commercial strip, whose picture is reported in Figure 3.

![Figure 2: a) the implemented 3D hand, b) the realized glove](image)

The acquisition of the measurements, through a digital oscilloscope, was carried out under conditions of variable resistive load and by connecting the strips both in parallel and in series as shown in Figure 4. In accordance with the theory, the analysis of the measurements obtained shows that the RMS power collected is maximum in the series configuration and at high resistive loads, comparable to the equivalent internal impedance of the piezoelectric material. In order to characterize the system in voltage and current and to be able to calculate the power generated by the system, we connected a variable resistive load. Measured results are reported in Table 1.

![Figure 3: PZT strip from TE Connectivity [30]](image)

From Table 1 it can be seen that the parallel configuration gives better performance being both generated voltages, delivered current and available power higher than in the series configuration.

To evaluate the system under real conditions, the glove with PZT strips was transferred to a human hand. The measurements made in the new situation confirmed the results obtained previously. In
particular, the possibility of using the piezoelectric glove thus designed to support the power supply of low voltage and low power devices is confirmed. Measurements have shown that the series configuration produces an open circuit peak-to-peak voltage reaches 39.6V. The proposed work fully stated that piezoelectric glove can be used for recharging low power devices with wearable devices.

**Figure 4:** Setup conditions

**Table 1:** Measured results

| CONFIGURATION | LOAD          | VOLTAGE RMS | CURRENT RMS | POWER RMS |
|---------------|---------------|-------------|-------------|-----------|
| SERIES        | OPEN CIRCUIT  | 7.66 V      | -           | -         |
| SERIES        | 10 kΩ         | 36 mV       | 3.6 μA      | 0.13 μW   |
| SERIES        | 1 kΩ          | 3.5 mV      | 3.5 μA      | 0.01 μW   |
| PARALLEL      | OPEN CIRCUIT  | 5.13 V      | -           | -         |
| PARALLEL      | 10 kΩ         | 89 mV       | 8.9 μA      | 0.80 μW   |
| PARALLEL      | 1 kΩ          | 9 mV        | 9 μA        | 0.08 μW   |
3. Conclusions
We have here proposed measurement results on an energy harvesting glove. The harvested energy is obtained by piezoelectric strips applied on the hand by means of a dedicated homemade glove. Preliminary results have confirmed that the proposed glove can be used in practical wearable applications.

References

1. Y. Tan and S. Panda, “Optimized Wind Energy Harvesting System Using Resistance Emulator and Active Rectifier for Wireless Sensor Nodes,” IEEE Transactions on Power Electronics, vol. 26, no. 99, p. 1, 2011.
2. M. Renaud, P. Fiorini, R. van Schaik and C. van Hoof, "Corrigendum: Harvesting energy from the motion of human limbs: the design and analysis of an impact-based piezoelectric generator", Smart Materials and Structures, vol. 21, no. 4, p. 049501, 2012. Doi: 10.1088/0964-1726/21/4/049501.
3. L. Pantoli, A. Leoni, V. Stornelli and G. Ferri, "Energy harvester for remote sensors systems," 2016 International Multidisciplinary Conference on Computer and Energy Science (SplitTech), Split, 2016, pp. 1-3.
4. A. Leoni, L. Pantoli, V. Stornelli, G. Ferri, M. Russo and P. Soric, "99/900 MHz IC architecture for autonomous systems," 2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SplitTech), Split, 2017, pp. 1-8.
5. A. Delnavez and J. Voix, "Flexible piezoelectric energy harvesting from jaw movements", Smart Materials and Structures, vol. 23, no. 10, p. 105020, 2014. Doi: 10.1088/0964-1726/23/10/105020.
6. A. Proto, M. Penhaker, D. Bibbo, D. Vala, S. Conforto and M. Schmid, "Measurements of Generated Energy/Electrical Quantities from Locomotion Activities Using Piezoelectric Wearable Sensors for Body Motion Energy Harvesting", Sensors, vol. 16, no. 4, p. 524, 2016. Doi: 10.3390/s16040524.
7. R. Fedele, M. Merenda and F. Giammario, "Energy harvesting for IoT road monitoring systems", Instrumentation Mesure Métrologie, vol. 18, no. 4, pp. 605-623, 2018. Doi: 10.3166/2im.17.605-623.
8. F. Pratič, F. Della and M. Merenda, "Self-powered sensors for road pavements", The 4th Chinese–European Workshop on Functional Pavement Design, CEW 2016. Doi: 10.1201/9781315643274-151.
9. P. Di Marco, A. Leoni, L. Pantoli, V. Stornelli and G. Ferri, "Remote sensor networks with efficient energy harvesting architecture," 2016 12th Conference on Ph.D. Research in Microelectronics and Electronics, Lisbon, 2016, pp. 1-4.
10. S. Shahab, M. Gray and A. Erturk, "Ultrasonic power transfer from a spherical acoustic wave source to a free-free piezoelectric receiver: Modeling and experiment", Journal of Applied Physics, vol. 117, no. 10, p. 104903, 2015. Available: 10.1063/1.4914130.
11. V. Stornelli, M. Gray and A. Erturk, "Low voltage low power fully differential buffer", Journal of Circuits, Systems and Computers, vol. 18, no. 3, pp. 497-502, 2009.
12. L. Pantoli, V. Stornelli, G. Leuzzi, "A low voltage low-power 0.25 μm integrated single transistor active inductor-based filter", Analog Integrated Circuits and Signal Processing, vol. 87, no. 3, pp. 463-469, 2016.
13. V. Stornelli, L. Pantoli, G. Leuzzi, G. Ferri, "Fully differential DDA-based fifth and seventh order Bessel low pass filters and buffers for DCR radio systems", Analog Integrated Circuits and Signal Processing, vol. 75, no. 2, pp. 305-310, 2013.
14. R. Caliò et al., "Piezoelectric Energy Harvesting Solutions", Sensors, vol. 14, no. 3, pp. 4755-4790, 2014. Doi: 10.3390/s140304755.
15. H. Kim, J. Kim and J. Kim, "A review of piezoelectric energy harvesting based on vibration", International Journal of Precision Engineering and Manufacturing, vol. 12, no. 6, pp. 1129-1141, 2011. Doi: 10.1007/s12541-011-0151-3.
16. H. Sodano, D. Inman and G. Park, "Comparison of Piezoelectric Energy Harvesting Devices for Recharging Batteries", Journal of Intelligent Material Systems and Structures, vol. 16, no. 10, pp. 799-807, 2005. doi: 10.1177/1045389x05056681.
17. A. Erturk and D. Inman, "Piezoelectric energy harvesting", Chichester: Wiley, 2011.
18. A. Erturk and D. Inman, "An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations", Smart Materials and Structures, vol. 18, no. 2, p. 025009, 2009. Doi: 10.1088/0964-1726/18/2/025009.
19. R. Pancirolli and M. Porfiri, "Hydroelastic impact of piezoelectric structures", International Journal of Impact Engineering, vol. 66, pp. 18-27, 2014. Available: 10.1016/j.ijimpeng.2013.12.007.
20. D. Vatansever, R. Hadimani, T. Shah and E. Siores, "An investigation of energy harvesting from renewable sources with PVDF and PZT", Smart Materials and Structures, vol. 20, no. 5, p. 055019, 2011. Doi: 10.1088/0964-1726/20/5/055019.
21. Y. Cha, W. Chae, H. Kim, H. Walcott, S. Peterson and M. Porfiri, "Energy harvesting from a piezoelectric biomimetic fish tail", Renewable Energy, vol. 86, pp. 449-458, 2016. Doi: 10.1016/j.renene.2015.07.077.
22. Barile, G., Leoni, A., Pantoli, L & Stornelli, V., "Real-time autonomous system for structural and environmental monitoring of dynamic events", Electronics (Switzerland), vol. 7, no. 12, 2018.
23. A. Doria, G. Fanti, G. Filippi and F. Moro, "Development of a Novel Piezoelectric Harvester Excited by Raindrops", Sensors, vol. 19, no. 17, p. 3653, 2019. Doi: 10.3390/s19173653.
24. P. Gao, J. Song, J. Liu and Z. Wang, "Nanowire Piezoelectric Nanogenerators on Plastic Substrates as Flexible Power Sources for Nanodevices", Advanced Materials, vol. 19, no. 1, pp. 67-72, 2007. Doi: 10.1002/adma.200601162.
25. X. Zhang et al., "An Arc-shaped Piezoelectric Bistable Vibration Energy Harvester: Modeling and Experiments", Sensors, vol. 18, no. 12, p. 4472, 2018. Doi: 10.3390/s18124472.
26. A. Leoni, I. Ulisse, V. Stornelli, G. Ferri, "Flexible Piezoelectric Harvester for Human Fingers: Measurements and Applications", FLEPS 2019 - IEEE International Conference on Flexible and Printable Sensors and Systems, Proceedings, DOI: 10.1109/FLEPS.2019.8792280, 2019.

27. G. De Pasquale, S. Kim, D. De Pasquale, "GoldFinger: Wireless Human-Machine Interface with Dedicated Software and Biomechanical Energy Harvesting System", IEEE/ASME Transactions on Mechatronics, 21 (1), art. no. 7105378, pp. 565-575, 2016

28. C. Maurini, M. Porfiri and J. Pouget, "Numerical methods for modal analysis of stepped piezoelectric beams", Journal of Sound and Vibration, vol. 298, no. 4-5, pp. 918-933, 2006. Doi: 10.1016/j.jsv.2006.05.041.

29. Y. Cha, J. Hong, J. Lee, J. Park and K. Kim, "Flexible Piezoelectric Energy Harvesting from Mouse Click Motions", Sensors, vol. 16, no. 7, p. 1945, 2016. Doi: 10.3390/s16071945.

30. "TE Connectivity piezoelectric strip 1-1002405-0 datasheet", Mouser.it, 2020. [Online]. Available: https://www.mouser.it/datasheet/2/418/NG_DS_LDT_with_Riveted_Leads_A1-1135524.pdf. [Accessed: 01- Mar- 2020].