World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:16, No:8, 2022

Open Science Index, Materials and Metallurgical Engineering Vol:16, No:8, 2022 publications.waset.org/10012651.pdf

Piezoelectric Bimorph Harvester Based on Different Lead Zirconate Titanate Materials to Enhance Energy Collection

Irene Perez-Alfaro, Nieves Murillo, Carlos Bernal, Daniel Gil-Hernandez

Abstract**—**Nowadays, the increasing applicability of internet of things (IoT) systems has changed the way that the world around is perceived. The massive interconnection of systems by means of sensing, processing and communication, allows multitude of data to be at our fingertips. In this way, countless advances have been made in different fields such as personal care, predictive maintenance in industry, quality control in production processes, security, and in everything imaginable. However, all these electronic systems have in common the need to be electrically powered. In this context, batteries and wires are the most commonly used solutions, but they are not a definitive solution in some applications, because of the attainability, the serviceability, or the performance requirements. Therefore, the need arises to look for other types of solutions based on energy harvesting and long-life electronics. Energy Harvesting can be defined as the action of capturing energy from the environment and store it for an instantaneous use or later use. Among the materials capable of harvesting energy from the environment, such as thermoelectrics, electromagnetics, photovoltaics or triboelectrics, the most suitable is the piezoelectric material. The phenomenon of piezoelectricity is one of the most powerful sources for energy harvesting, ranging from a few micro wats to hundreds of wats, depending on certain factors such as material type, geometry, excitation frequency, mechanical and electrical configurations, among others. In this research work, an exhaustive study is carried out on how different types of piezoelectric materials and electrical configurations influence the maximum power that a bimorph harvester is able to extract from mechanical vibrations. A series of experiments has been carried out in which the manufactured bimorph specimens are excited under fixed inertial vibrational conditions. In addition, in order to evaluate the dependence of the maximum transferred power, different load resistors are tested. In this way, the pure active power that achieves the maximum power transfer can be approximated. In this paper, we present the design of low-cost energy harvesting solutions based on piezoelectric smart materials with tunable frequency. The results obtained show the differences in energy extraction between the PZT materials studied and their electrical configurations. The aim of this work is to gain a better understanding of the behavior of piezoelectric materials, and the design process of bimorph PZT harvesters to optimize environmental energy extraction.

Keywords**—**Bimorph harvesters, electrical impedance, energy harvesting, piezoelectric, smart material.

I. INTRODUCTION

IN recent years, the study of alternative energy sources and their applicability to the industrial sector has been promoted. The growing interest in the intelligent monitoring of manufacturing processes entails the need to supply energy to all the sensors, actuators, converters, communication nodes, etc. that are developed and deployed at different environments. In this context, problems may arise when powering devices through wired systems due to the impossibility of placing them in certain environments and applications. One option available in these cases is the use of energy storage units, such as batteries, however these have a limited lifetime [1], and sometimes maintenance work to replace the energy source cannot be carried out or is costly. This is where the concept of converting the ambient energy into electrical power, defined as energy harvesting [2], appears; being a wireless and renewable power supply solution. Furthermore, Energy Harvesting power supply systems do not have to be replaced with the time, such as unlimited energy source. On the other hand, energy harvesting systems are based on smart materials, highlighting the use of piezoelectric material especially in terms of mechanical and vibrational energy scavenging, such as industrial applications where machine tools are used. The mechanical or vibrational deformation of the piezoelectric material caused by the surrounding environment, generates a deformation on it resulting in a potential difference due to the movement of charges, phenomenon known as direct piezoelectric effect [3], [4].

Different families of piezoelectric materials can be used on energy harvesting applications depending on the operational temperature, frequency or flexibility requirements, such as PZT and polymers like polyvinylidene fluoride (PVDF), among others [5], [6]. Piezoelectric harvesters are commonly used in cantilever configuration due to the large deformation that it can be produced despite their mechanical mounting simplicity and their difficulty to be implemented in real applications [7].

Depending on whether the harvester consists of one or two beams of piezoelectric material, they are defined as unimorph or bimorph harvesters [8]. Bimorph piezoelectric ceramic harvesters are composed of two sheets of piezoelectric materials and a layer of metallic material. These multi-layer harvesters are able to harvest higher energy than those that are composed by a single piezoelectric sheet, even if they have the same total thickness [9], [10].

Irene Perez-Alfaro is with Tecnalia, Basque Research and Technology Alliance (BRTA), Zaragoza, Aragon E-50018 Spain (phone: +34 667 101 075; e-mail: irene.perez@tecnalia.com).

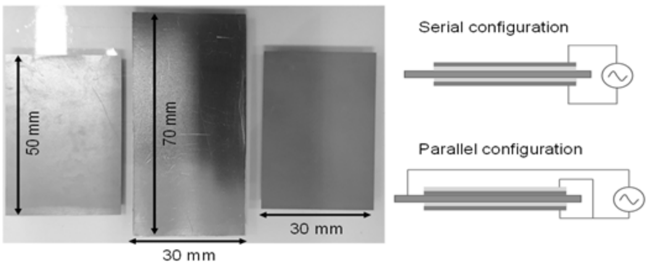
Nieves Murillo and Daniel Gil-Hernandez are with Tecnalia, BRTA, San Sebastian, Basque Country E-20009 Spain (e-mail: nieves.murillo@tecnalia.com, daniel.gil@tecnalia.com).

Carlos Bernal is with University of Zaragoza, Zaragoza, Aragon E-50009 Spain, (e-mail: cbernal@unizar.es).

There are different electrical configurations that can be realized with a bimorph harvester. One of them is the series configuration in which the piezoelectric sheets have the opposite polarization direction, on the other hand, the parallel configuration in which the sheets have the same polarization direction [11]. The state of the art also includes a lot of work focused on harvester modelling [12]-[14]. However, less effort has been invested in the real behavior of piezoelectric harvester with bimorph configuration link with its metallic interlayer. This interface layer plays an important role in the mechanical behavior of the overall harvester and, consequently, in their energy scavenging potential. We focused on bimorph piezoelectric harvester designed and manufacturing to analyze the influence of metallic interlayer rigidity on energy extraction from vibrational environment. Both electrical configurations, series and parallel, have been studied for the different metallic layer thickness. The experimental test has been carried out on homemade piezoelectric harvesters in cantilever configurations and in open circuit voltage measurements. The footprint of harvester specimens was evaluated as the electrical impedance and mechanical and electrical characteristics have been studied in order to determine the optimal piezoelectric harvester configuration to maximize the energy scavenging potential.

II. BIMORPH PIEZOELECTRIC HARVESTERS

The homemade bimorph piezoelectric harvesters are prepared based on the combination of two piezoelectric sheets with one metallic interlayer. The piezoelectric sheets are PZT Navy Type II from PI Ceramic GmbH. The metallic interlayer is a brass sheet with composition: 63% copper and 37% zinc, from Goodfellow Cambridge Limited. Two different thicknesses, 125 μm and 250 μm, have been selected to study the rigidity of the overall bimorph system and their influence into the energy collection potential. The bonding method to assemble the PZT and brass layers was the use of a conductive adhesive coating.



(a) (b)

Fig. 1 Materials for the bimorph piezoelectric harvester materials manufacture including the materials dimensions (a) and scheme of series and parallel electrical configurations (b)

The bimorph harvester dimensions are shown in Fig. 1, resulting in a complete harvester of 70 mm x 30 mm. In the same figure, two sheets of PZT Navy Type II material can be seen. On the other hand, in the same figure, the bimorph harvesters were prepared in series or parallel electrical configuration. Fig. 1 also shows the full stack electrical connection required to achieve both configurations.

Four specimens have been manufactured. Two of them with the 125 μm brass foil, references 125_2S and 125_1P, where the series configuration specimen was named *S*, and the parallel one was named *P*. Two additional specimens with the 250 μm brass foil were prepared with references 250_1S and 250_1P. All the tests carried out in the four bimorph piezoelectric harvesters have been executed in cantilever configuration for vibrational energy scavenging.

In order to analyze the footprint of the manufactured bimorph piezoelectric harvester and their differences between series and parallel as well as the influence of the different thickness used in the metallic interlayer the electrical impedance characterization has been performed with an impedance meter model E4980 AL from Keysight.

At Fig. 2, it can be seen the real, Z, and imaginary, θ, part of the four specimen impedances from 20 Hz to 1 KHz. Fig. 2 (a) represents the Z and θ of the series and parallel specimens prepared with the 125 μm brass layer and in Fig. 2 (b) those manufactured with the 250 μm brass foil.

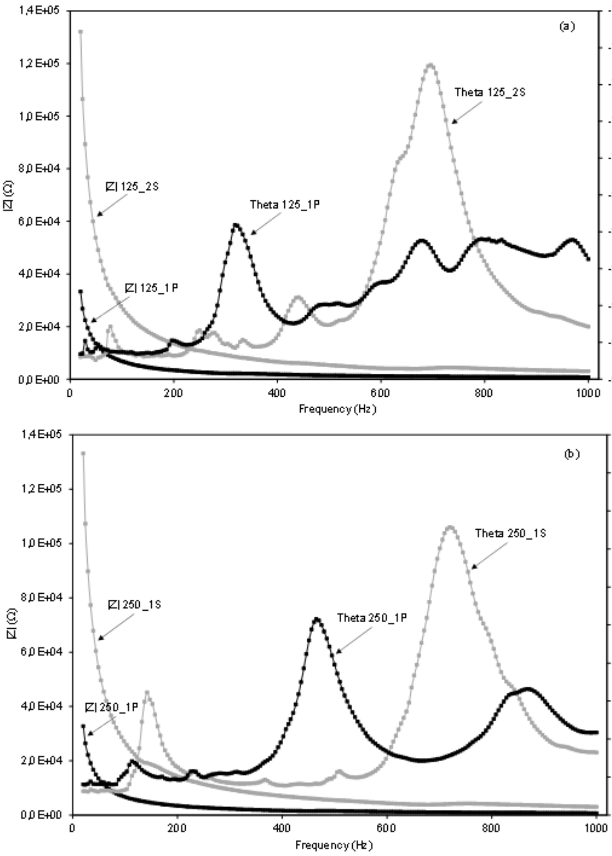


Fig. 2 Impedance analysis of the bimorph piezoelectric harvesters for the frequency range between 20 Hz and 1 KHz: (a) Specimens manufactured with the 125 μm brass, (b) specimens manufactured with the 250 μm brass

As shown in Fig. 2 the series or parallel electrical connectivity of the bimorph piezoelectric harvester has a considerable influence in the electrical impedance of the harvester in both Z and θ measurements. This behavior is observed at both thicknesses. The main peak at the imaginary phase appears at different frequencies for series and parallel configurations. The frequency of the series peak at the imaginary phase is twice higher than the parallel one. Some differences in their complex phase representation can be observed between 125 µm and 250 µm specimens. The peak of the 125_1P specimen appears at lower frequencies than the 250_1P one. This could be associated with the different thickness influence on the overall system behavior. And, as a consequence, the differences between harvesters' specimens due to its electrical and mechanical configuration, or thickness variation, could be denoted by the electrical impedance measurement.

III. VIBRATIONAL ENERGY HARVESTING TEST

In order to carry out the different experimental tests to characterize the energy harvesting properties of the four bimorphs piezoelectric harvester, an experimental testbench has been designed into cantilever configuration to excite them with vibrational forces. For this purpose, a function generator was used, model FG410 from Yokogawa Electric Corporation, that generates a sinusoidal function at the selected frequency with a maximum operation range of 30 MHz. This signal needs to be amplified before being transmitted to the shaker by a lineal power amplifier model LDS LPA 100, from Hottinger Brüel & Kjaer. Finally, the shaker equipment used for the test is an LDS vibrator model V406 from Hottinger Brüel & Kjaer.

Fig. 3 Energy Harvesting test set up equipment

The signal generated at the harvesters to stimulate the bimorph piezoelectric harvester into the vibrational selected conditions is a sinusoidal wave with an amplitude of 0.5 G and the frequency correspond to the resonance frequency of each specimen.

To control that the appropriate excitation signal is transmitted to the PZT bimorph harvester specimens, an accelerometer sensor is attached to the harvester clamping system that records the frequency and amplitude transmitted to the specimen, the sensor is an accelerometer with reference 356A15 from PCB Piezotronics. The accelerometer sensor data were acquired with a Quantum MX840B equipment from Hottinger Brüel & Kjaer, that it is connected to a personal computer to visualized and to collect the data. Finally, a multimeter 34461A, from Keysight Technologies, is connected to harvester specimens to collect their output root mean square (rms) voltages obtained during their vibrational excitation test.

IV. RESULTS

In this section, it will be discussed the results obtained at the four PZT Navy Type II bimorph harvesters, series and parallel with different thickness during the energy harvesting under 0.5 G vibrational excitation conditions. Fig. 4 shows the output RMS voltage, Voutput RMS, achieved in open circuit conditions at different excitation frequency, *f*, in a range from 10 Hz to 70 Hz. The acceleration transmitted to the bimorph piezoelectric harvester is 0.5 G RMS, by means of a sinusoidal excitation signal.

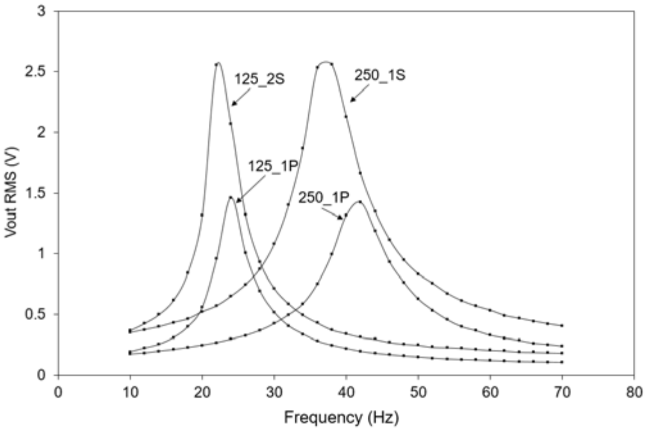


Fig. 4 V output rms, output RMS voltage versus f, frequency, for the four bimorph PZT harvester specimens, the series (125_2S) and the parallel (125_1P) specimens with 125 µm brass interlayer, and the series (250_1S) and parallel (250_1P) specimens with the 250 µm brass interlayer

The results obtained showed that the specimens with the 125 µm brass thickness have a lower resonance frequency than the specimens with the 250 µm brass thickness. On the other hand, these last samples have a greater frequential width near their resonant point. Also noteworthy is the fact that having the same thickness of brass, the series and parallel specimens experience certain differences. The series samples obtain higher voltages in open circuit than the parallel ones, although their resonance frequencies are very close to each other. Therefore, it can be said that the resonant frequency of a bimorph harvester is conditioned by its geometry, whereas the voltage amplitude obtained in an open circuit is directly affected by the electrical connection.

Other results extracted for the experiments carried out can be seen in Fig. 5. In this case, the power and voltage extracted with the different manufactured specimens have been represented versus different load resistances. The signal generated to excite the harvesters has a sinusoidal nature, an acceleration of 0.5 G

RMS, and a different excitation frequency for each harvester that coincides with its resonance, Fig. 4.

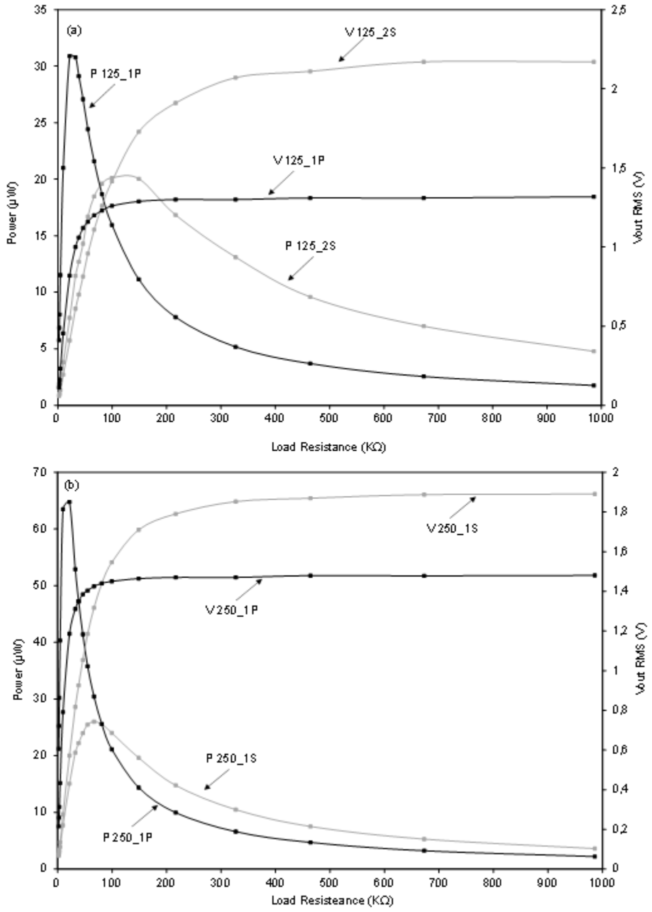


Fig. 5 Output RMS voltage and power extracted versus load resistance for the four different harvester specimens, (a) series and parallel samples manufactured with 125 µm thickness brass, (b) series and parallel samples manufactured with 250 µm thickness brass

As it can be seen in both Figs. 5 (a) and (b), the parallel configuration obtains greater electrical power than the series, while if the voltage is analyzed the relationship is reversed, the series configuration obtains a higher value. This fact has already been documented by various authors in comparative studies between different electrical configurations with bimorph harvesters [15], [16]. However, after analyzing the data obtained, further conclusions can be drawn in this regard. In the first place, if the representations of the extracted voltage (V 125_2S, V 125_1P, V 250_1S, V 250_1P) are analyzed, it is observed how from a specific value of load resistance, the output tension stabilizes at a constant voltage point. This fact is since for lower value of load resistors, the harvester must supply more current to reach a certain voltage. If the graphic representation is observed, it can be seen how there is a limitation in terms of the current that the harvester is capable of supplying, which is denoted in the voltage obtained at the smallest load resistances, and that, as can be seen, it is compensated in the higher resistances loads. In these resistances, a lower current level is requested, and therefore the voltage is stabilized at the maximum that the harvester is capable of supplying for a given level of excitation. On the other hand, in the case of the power representation (P 125_2S, P 125_1P, P 250_1S, P 250_1P), it is observed how there is a resistance value for which the transmitted power is maximum, this value is known as "impedance matching point", and does not necessarily have to coincide with the resistance value for which the highest voltage is obtained.

V. CONCLUSIONS

In this work, different experiments have been carried out with the aim of analyzing the behavior of bimorph harvesters. Four specimens have been manufactured in which some mechanical and electrical characteristics have been varied, specifically the thickness of the conductive material and the electrical connection.

The electrical voltage extracted from the harvester has been measured in open circuit output and for different load resistances too, maintaining in all cases a constant excitation signal. There are notable differences in power and voltage extraction results between two bimorph harvesters of different electrical configurations constructed from the same material. In this way, it has been possible to verify how the mechanical variables can influence the electrical behavior of the bimorph harvester.

The information obtained about how the mechanical and electrical variables of a harvester influence its behavior is very useful in the design of harvesters, allowing the optimization of energy extraction. On the other hand, this information also plays a fundamental role in the electro-mechanical modeling of harvesters that allow predicting and optimizing the conversion of vibratory mechanical energy into electrical energy.

ACKNOWLEDGMENT

The authors acknowledge the collaboration of the European Commission in this research through the grant number 869884-RECLAIM, and the Basque Government through the grant number KK-2021/00082- µ4IIoT.

REFERENCES

[1] L. Mateu and F. Moll, Review of energy harvesting techniques and applications for microelectronics, in *VLSI Circuits and Systems II*, jun. 2005, vol. 5837, pp. 359-373. doi: 10.1117/12.613046.

[2] D. Zhu and S. Beeby, Kinetic Energy Harvesting, in *Energy Harvesting Systems: Principles, Modeling and Applications*, T. J. Kaźmierski and S. Beeby, Eds. New York, NY: Springer, 2011, pp. 1-77. doi: 10.1007/978-1-4419-7566-9_1.

[3] *Advanced Piezoelectric Materials*. Elsevier, 2017. doi: 10.1016/C2015-0-01989-X.

[4] I. Perez-Alfaro, D. Gil-Hernandez, O. Muñoz-Navascues, J. Casbas-Gimenez, J. C. Sanchez-Catalan, and N. Murillo, Low- Cost Piezoelectric Sensors for Time Domain Load Monitoring of Metallic Structures During Operational and Maintenance Processes, *Sensors*, vol. 20, n.o 5, Art. n.o 5, 2020, doi: 10.3390/s20051471.

[5] D. Grzybek, D. Kata, B. Sapiński, and W. Sikora, Impact of PZT layer properties in a cantilever beam on energy harvesting performance, in *2019 20th International Carpathian Control Conference (ICCC)*, may 2019, pp. 1-5. doi: 10.1109/CarpathianCC.2019.8765954.

[6] D. Vatansever, R. L. Hadimani, T. Shah, and E. Siores, An investigation of energy harvesting from renewable sources with PVDF and PZT, *Smart*

Mater. Struct., vol. 20, n.o 5, p. 055019, may 2011, doi: 10.1088/0964-1726/20/5/055019.

[7] S. Kim, J.-H. Kim, and J. Kim, A Review of Piezoelectric Energy Harvesting Based on Vibration, *Int. J. Precis. Eng. Manuf.*, vol. 12,. 2011, doi: 10.1007/s12541-011-0151-3.

[8] A. Ertuk and D. J. Inman, An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations, *Smart Mater. Struct.*, vol. 18. 2009, doi: https://doi.org/10.1088/0964-1726/18/2/025009.

[9] D. Zhu, A. Almusallam, S. Beeby, J. Tudor, and N. Harris, A Bimorph Multi-layer Piezoelectric Vibration Energy Harvester, presented in PowerMEMS 2010. 2010.

[10] Q. Lu, L. Liu, F. Scarpa, J. Leng, and Y. Liu, A novel composite multi-layer piezoelectric energy harvester, *Compos. Struct.*, vol. 201, pp. 121-130, oct. 2018, doi: 10.1016/j.compstruct.2018.06.024.

[11] J. Park, S. Lee, and B. M. Kwak, Design optimization of piezoelectric energy harvester subject to tip excitation, *J. Mech. Sci. Technol.*, vol. 26, n.o 1, pp. 137-143, 2012, doi: 10.1007/s12206-011-0910-1.

[12] M. F. Lumentut and I. M. Howard, Electromechanical Piezoelectric Power Harvester Frequency Response Modeling Using Closed-Form Boundary Value Methods, *IEEEASME Trans. Mechatron.*, vol. 19, n.o 1, pp. 32-44, feb. 2014, doi: 10.1109/TMECH.2012.2219066.

[13] S. K., K. Shankar, and C. Sujatha, A Lumped Electromechanical Model for Output Power from Partially Covered Piezoelectric Energy Harvester, in *2019 IEEE 2nd International Conference on Power and Energy Applications (ICPEA)*, abr. 2019, pp. 94-98. doi: 10.1109/ICPEA.2019.8818525.

[14] R. Kashyap, T. R. Lenka, and S. Baishya, Study of doubly clamped piezoelectric beam energy harvesters with non-traditional geometries, in *2016 7th India International*

[15] H. Fazilah Hassan, S. Idris Syed Hassan, R. Abd Rahim, Acoustic energy harvesting using piezoelectric generator for low frequency sound waves energy conversion, in International Journal of Engineering and Technology (IJET), 2015.

[16] X. Xu, D. Cao, H. Yang, M.He, Application of piezoelectric transducer in energy harvesting in pavement, in International Journal of Pavement Research and Technology vol. 11, 388-395, 2018

Open Science Index, Materials and Metallurgical Engineering Vol:16, No:8, 2022 publications.waset.org/10012651.pdf

Irene Pérez-Alfaro received her MEng in Electronics Engineering from University of Zaragoza (Spain) in 2020. Since 2018 she has been worked in Tecnalia as researcher with special interest in sensor and actuator development based on smart materials. Actually, she is developing her PhD in the University of Zaragoza electronics and communications Engineering department focused in the development of advanced techniques for energy conversion using piezoelectric harvesters applied to self-powered IoT systems.

Nieves Murillo received her PhD in Physical of Material at the University of the Basque Country (Spain) in 1997. Awarded for his PhD. During his thesis she was awarded with Mari Curie Fellowship at the IMEM-CNR Institute in Parma (Italy) and develops part of his research activities in the CSIC Madrid (Spain). She has held post-doctoral position at the Max-Planck Institute in Stuttgart (Germany). Since then, she was awarded with a Ramon y Cajal Fellow at Cidetec with successfully assessment of I3 evaluation. Her research fields are focused in two main areas: sensor and actuator development based on smart materials, including optical, piezoelectric, magnetic and superconducting, including the materials design, fabrication, and applications development. She has participated over 40 international and national projects, she is co-author of over 50 scientific publications, including a book chapter. Her citation level is over 280. She has been member of organizing committees of three international conferences. She has imparted more than 10 invited talks at international events.

Carlos Bernal (M'08) received the M.Sc. and Ph.D. degrees in electrical engineering from the University of Zaragoza, Spain, in 2000 and 2012, respectively. Since 2001, he has been an Associate Professor, with special interest in power and mixed-signal electronics, with the University of Zaragoza. His research interest is focused on high-efficiency resonant switch-mode converters and their control.

Daniel Gil-Hernandez received his MEng in Mechanical Systems Engineering from University of Zaragoza (Spain) in 2014. Since 2011 he has been worked in Tecnalia as researcher with special interest in sensor and actuator development based on smart materials. He is co-author of over 5 scientific publications.