International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 8, August 2018, pp. 412–421, Article ID: IJMET_09_08_045
Available online at http://www.iaeme.com/ijmet/issues.asp?JType=IJMET&VType=9&IType=8
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

ENERGY HARVESTING APPLIED TO SMART SHOES

Emanuele Frontoni, Adriano Mancini and Primo Zingaretti
Dipartimento di Ingegneria dell'Informazione (DII), Universita Politecnica delle Marche
Via Brecce Bianche, Ancona, Italy

Andrea Gatto
Dipartimento di Ingegneria Meccanica E. Ferrari, Universita di Modena e Reggio Emilia
Modena, Italy

ABSTRACT

The appeal of energy harvesting systems lies in the possibility of capturing free energy that would be dissipated and is therefore obtainable without costs. Today, advanced techniques and devices exist for capturing from the environment, storing, and managing quotas of natural energy, which are made available in the form of electrical energy. At the same time, the most recent microprocessors grant an extremely high power efficiency, which permits their operation with minimal power consumption. As a consequence, low-consuming devices can be power supplied by using energy harvesting systems. If this concept is applied to wearable electronics, the most efficient choice is that of exploiting the energy released when the users walk, by developing systems that are embedded in the shoe sole. At each step, the force exerted on the device can be transformed into a relatively high amount of electrical energy, for example by using piezoelectric elements and electromagnetic induction systems. The paper describes the design of four different solutions for smart shoes that make use of energy harvesting apparatuses for the power supply of sensors and complex monitoring systems, for example aimed at GPS localization. An initial comparative assessment of the four architectures is reported, by weighing production costs, ease of manufacture and energy harvesting performance.

Keywords: Smart shoes; Energy Harvesting; GPS localization; piezoelectric elements; electronic devices.

Cite this Article: Emanuele Frontoni, Adriano Mancini, Primo Zingaretti and Andrea Gatto, Energy Harvesting applied to Smart Shoes, International Journal of Mechanical Engineering and Technology, 9(8), 2018, pp. 412–421.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=8

1. INTRODUCTION

In the last years, thanks to the increase of efficient systems to energy recovery, and the continuous research of materials and systems able to capture and to translate different type of energy into electrical form, a high number of wearable electronic devices has been introduced and developed [1],[2]. They have been used for monitoring human activity, and they allowed not only to examine the state of body and the health of persons, but also to recover much information concerning different fields of application: human motion [3], geolocalization [4], security and many others [5].

A better solution is to generate power where it is being used, overcoming, in this way, the problem of storage and distribution. In the past years, many attempts have been made in this direction, considering different technologies [6] that go from the construction of electromechanical generators [7]–[9] to surgically positioning of piezoelectric [10] material in the animals [11], [12].

In a previous study, it has been also calculated that up to 67 Watts of power is available from heel strikes during a brisk walking (68 Kg, 2 step/sec, heel moving 5 cm) [13]. This value of power extraction from walking would surely interfere with one’s gait.

About wearable electronics devices, one of the most efficient systems for energy capturing are those that use Energy Harvesting systems [14] inserted into the shoes. These systems are installed into the soles where, during the walking and/or the running, the force is exerted. Using piezoelectric elements and electromagnetic induction systems, this force allows recovering a high quantity of electrical energy useful for sensor supply and complex monitoring systems [15]–[17]. For that, it is necessary to analyse in detail the pressure distribution along the sole of the shoes during the walking and/or the running [18], in order to optimize the positioning of the elements useful for the energy recovering.

The aim of this work is to present four different typologies of smart shoes able to recover sufficient energy to supply a geolocalization system of a person. The following solutions are different concerning the Energy Harvesting systems used and for different positioning, inside the sole, of the elements designed for the energy recovering. Preliminary comparative results of 4 different solutions are compared on the bases of costs, production feasibility and energy harvesting capabilities.

2. ENERGY HARVESTING

Energy Harvesting is the process of recovering and using free energies from the environment, as for example light, electro mechanic vibrations and small thermal gradients, capturing amounts of free energy from the surrounding environ-ment [19]–[21].

These forms of energy, once unusable, are today object of study and great interest. The always smaller request of energy by micro devices, as for example sensors, and the increasing efficiency of devices that capture energy allowed exploiting these energy sources. Many are the advantages of exploiting these solutions as, for example, to supply devices without using traditional and expensive batteries, and so ensuring energy saving and protecting the natural environment. There is also the possibility to place sensors and actuators in positions previously difficult to reach.

The energy sources usable by Energy Harvesting devices mainly are:

- mechanic: deriving from vibrations, sounds, deformations and elastic stresses;
- thermal: waste heat from furnaces, heaters, motors, and different kinds of attrition;
- light: sunlight and artificial light, with photodiodes or solar panels;
- electromagnetic: inductors, coils and transformers;

- natural: wind, tides, waves, ocean currents, solar energy;
- human body: both thermal and mechanical, generated by the normal functioning of a living organism, such as walking;
- Others: chemical energy or biological sources.

In detail, kinetic Energy Harvesting requires a transduction mechanism to generate electrical energy from motion and the generator requires a mechanical system that couples environmental displacements to the transduction mechanism [13]. The transduction mechanism generates electricity exploiting mechanical strain or relative displacement that occurs in-side the system. The strain event uses the deformation of the mechanical system, employing active materials, such as piezoelectric, piezoceramic and piezopolymer. The vibrations are actually considered the most rising source both for the discrete power density and for the abundance of resources. An Energy Harvesting device consisted of three main components: a module dedicated to the capture and to energy conversion such as a piezoelectric element that can translate energy into electrical form. The second element is a device that stores energy, as an accumulator, a condenser. Finally, there is an end application device as, for example, a sensors or an antenna. Apart from these three principal elements, there is an additional module of storage energy and/or a system of energy management.

The application fields of Energy Harvesting devices are manifold. They can be used for supplying of monitoring systems of human body vital parameters, for the localization, for verifying the correct functioning of machineries placed in inaccessible locations, for providing security and emergency devices, and finally, for reloading portable electronic devices, mobile phones or laptop, and radio devices.

3. GAIT ANALYSIS

The introduction of gait analysis [22] is important both for the choice of materials and for the optimization of the positioning inside the sole. In a study of kinematics and biomechanics of human locomotion, the gait cycle is always considered. The gait cycle is defined as the period between two successive support of the same foot to the ground. This period is divided into two distinctive phases:

- Phase of stance, during this phase, the foot is in contact with the terrain. In the normal-gait, this phase covers ap-proximately 60% of the gait cycle, reducing significantly itself during the running, and reaching the 37% during the fast running. This is the most useful phase of the walking cycle, which allows recovering a part of the mechanical energy responsible for the deformation of the sole.
- Phase of swing, in which the leg is carried forward to prepare for the support to the ground.

The point of application of the force exchanged between the foot and the terrain moves along the foot in relation to the motion of the gravity centre of the human body and to the distribution of the muscular power required to control and to produce the movement of the leg for maintaining the body balanced. The trend of the vertical component of the ground reaction forces changes with the speed of progression of the step. The map of plantar pressures allows us to know the areas of greatest load. Analysing the argument, it has been deduced that the soles discharge considerable forces, which exceed 220% of body weight during the running. Furthermore, two zones in which the pressure exerted by the foot is greater have been identified; an area that is under the heel and another one is under the front of the metatarsal zone. Figure 1 show the map of the foot zones where the pressure is the greatest. The same color identifies a zone subjected to the same pressure. The zones with the highest pressure are highlighted in red.

Figure 1 Map of the foot zones highlighting different pressures.

4. STATE OF ART

In recent years, several prototypes of energy harvesting shoes were made using different technologies. In the MIT Media Laboratory [15]–[17], three prototypes are realized. The first integrates a device consisted of a flexible plastic sheet on whose faces are glued 8 sheets of PVDF piezoelectric material with dominant polarization 31. The system recovers energy from the flexion of the sole, obtaining a mean power of 1.1mW. The second device has been produced in order to recover energy from the pressure exerted by the heel and uses a layer of PZT a layer of piezoelectric ceramic material mounted on a sheet of spring steel, generating a mean power of 1.8 mW. The last device adapts a standard rotative electromagnetic generator trough a backplate located under the heel and activated by the body weight, generating a mean power of 0.23 W.

Some Chinese researchers have tried to exploit the horizontal movement of walking instead of the vertical using a linear generator with permanent magnets [24]. The device consists of an external statoric cylinder in which windings and an internal cylindrical core on which are positioned a series of magnets have been arranged. These last translate in the external cylinder due to their inertia.

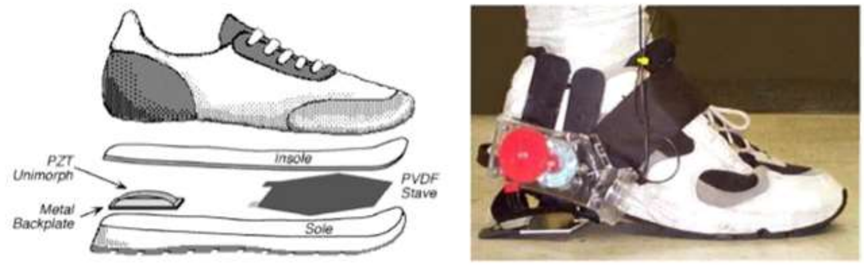

Figure 2 Representation of the three prototypes realized by the MIT Media Laboratory.

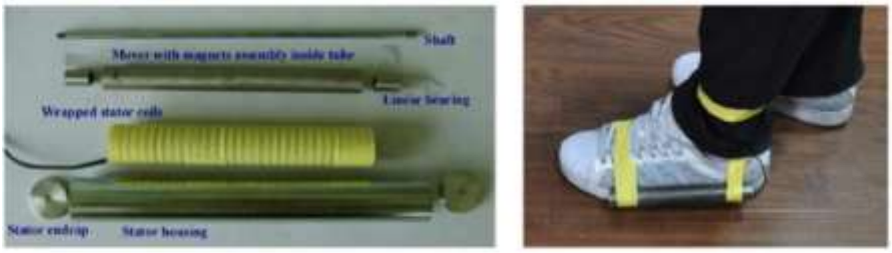

Figure 3 Representation of the prototype realized by Chinese researchers.

The SRI team, in California, realized a prototype based on an electrostatic generator located in the heel of the shoe. The energy was captured by the deformation of dielectric elastomer loaded. Researchers in Portugal have created a prototype of a sole using two PVDF piezoelectric sheets placed in zones subject to greater change of pressure [25]. In order to increase the energy, piezoelectric elements are coupled to an electrostatic generator.

Figure 4 Representation of the prototype realized by Portuguese researchers.

5. FOUR SOLUTIONS FOR AN ENERGY HARVESTING SYSTEM

In this section, four different types of smart shoes have been proposed. The soles used smart energy harvesting systems incorporating piezoelectric PVDF, buzzer and piezostack with the aim of showing four different possible solutions to recover the energy needed to supply a GPS module able to provide coordinates to a high level software [23]. Figure 5 resumes all the solutions described in the next sections, highlighting the different positioning of the sensors, and they have been labelled basing on the following description.

Figure 5 Four prototypes proposed to supply a GPS modules.

The different soles below proposed have been designed for maximizing the recovery of energy by positioning the energy harvesting devices in the points inside of the sole where there is a greater pressure exercised by the foot during walking.

The four solutions, even if different between them, efficiently allow to accumulate, at regular intervals and not continuously, the power necessary to supply a GPS module that need to run on average of about 10 - 15mW to feed.

5.1. First solution

In the first approach, a sheet of PVDF piezoelectric material has been positioned corresponding to the heel of the sole. The maximum stresses to which a sole has been subjected concern the walking phase. During its life, the shoe may be subject to considerably higher stresses that are difficult to estimate. Therefore, all piezoelectric materials characterized by brittle behaviour have been considered unsuitable and the choice has fallen on the PVDF material which presents marked characteristics of flexibility.

A plastic base allowing exploiting the curve surface formed on the upper part as a limit to the deformation of the piezoelectric sheet has been realized to anchor the piezoelectric material. In this way, the achievement of critical tensions has been avoided, allowing the PVDF material to move both for traction and for compression.

Inside the base of the device, a dedicated space for the installation of the GPS module and various electronic devices has been created. The upper part of the base holds the piezoelectric sheet, attached by two trapezoidal bars fixed on the base through captive screws which allow the material to move.

The positioning of a plantar pushes the piezoelectric in the suitably shaped surface, by deforming under the action of the foot. This curve surface has to limit the maximum elongation of the piezoelectric element, in fact, it has been dimensioned in order to reach the maximum tensions of traction about 20 MPa (the yield stress of the piezoelectric sheet is about 50 MPa). The description of the mounting of the device in the first sole has been represented in the following figure 6.

The electrical connections are made through two thin sheets of copper, in contact with two faces of the piezoelectric and kept in position by tightening of the trapezoidal bars.

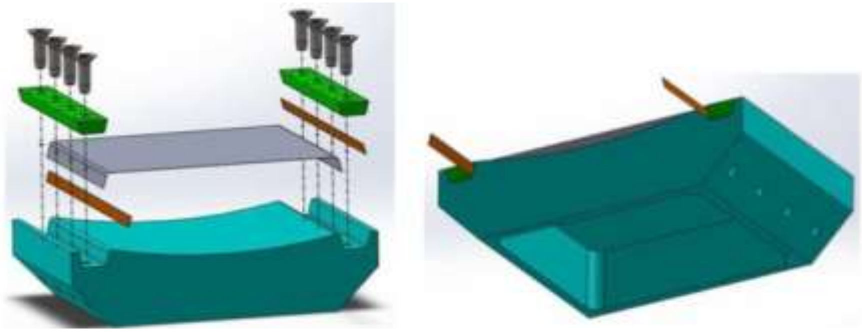

Figure 6 Description of the mounting of the device.

5.2. Second solution

The second solution uses two energy recovery systems: one placed on the rear of the sole that uses four buzzers and the second placed on the front part that uses a film of PVDF piezoelectric material. This version is certainly the most expensive and elaborate, but is the most efficient during the device operation even in emergency situations.

The uses of dual power supply system ensures the transmission of the signal even in case of failure or malfunction of one of two systems and, also, ensures the adaptation to any style of walking. As previously said, the charged areas of the foot are essentially two: the heel, with a vertical load, and the forefoot, with a vertical load and a flexion. Figure 7 shows the bottom of the sole, indicating the measures for a medium-sized foot.

The total system of Energy Harvesting allows using the energy discharged from the foot in both areas, optimizing the energy recovery process. Indeed, different styles of walking will exploit otherwise the two areas of energy harvesting: one step swiped, which uses less oscillation and hence flexion of the foot, will solicit further back area with buzzer. While the walking lighter with a more complete motion will maximize the anterior areas, with the PVDF film.

The GPS system has been positioned in the central part of the sole, where the foot download less weight.

This solution certainly complicates the production of the sole and inevitably affects the wearability and the comfort of the shoe, but it allows reaching a high level of reliability.

5.3. Third solution

In the third solution, an Energy Harvesting system based on β-PVDF material capable of producing electric current not only if stepped on, then if stressed in compression, but also if it is bent, has been effectuated. In order to exploit this feature, the piezoelectric sheet must be kept folded and for this reason it has been fixed to a bracket of a harmonic material. The harmonic steel is very flexible and perfectly adapts to the problem enduring the constant deflections which would be submitted once integrated into the system.

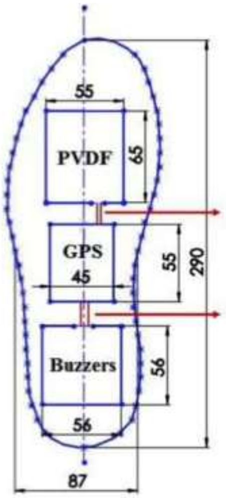

Figure 7 Representation of the bottom of the sole for the second solution.

A number of piezoelectric sheets have been merged (16 sheets: 8 above the steel strip and 8 below this last) in order to produce enough voltage to supply the GPS device. These sheets with the bracket of harmonic materials are tightened to a chassis made of ABS to form an angle of 10 sufficient to maintain folded the piezoelectric material. The plastic support has been realized to contain inside the geolocation system. The flexion of piezoelectric element is represented in figure 8.

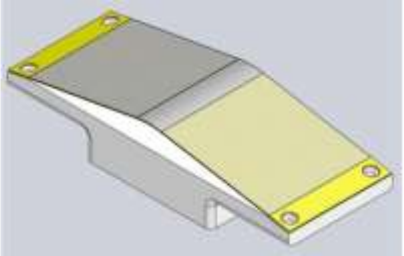

Figure 8 Representation of the device installed inside the sole

5.4. Fourth solution

Also in the fourth solution, two different systems of Energy Harvesting have been used: one positioned in the heel area and consists of 12 piezostack and the other in the forefoot area achieved using a folded sheet of piezoelectric material.

The piezostacks in the heel are placed inside a support realized through a 3D printer, which has as its main purpose to provide a rigid support base to piezostacks that otherwise would sink into the rubber of the sole dispersing large part of their deformation and thus the power generated. It was also realized an insole to provide a pressure support as uniform as possible also in the upper end of piezostacks and thus increasing the comfort of the whole system. The area of the forefoot, unlike that the heel, has a thickness available for a very modest holding of the piezoelectric, making it impossible to use piezostacks as for the heel.

In this area, a sheet of piezoelectric material folded with interposed polymeric material highly deformable between the different layers has been used, creating in this way a rectangular cell. Tests performed on piezoelectric have shown that it provides a higher voltage when subjected to flexion rather than crushing.

The implemented configuration, therefore, allows deforming efficiently the sheet of piezoelectric and in many areas by increasing the voltage further generated.

Also in this case it was necessary to achieve a rigid base in order to maximize the deformation, always using rapid prototyping. Figure 9 shows the arrangement of the various components of energy harvesting. Note how the GPS module has been allocated in the central part of the sole.

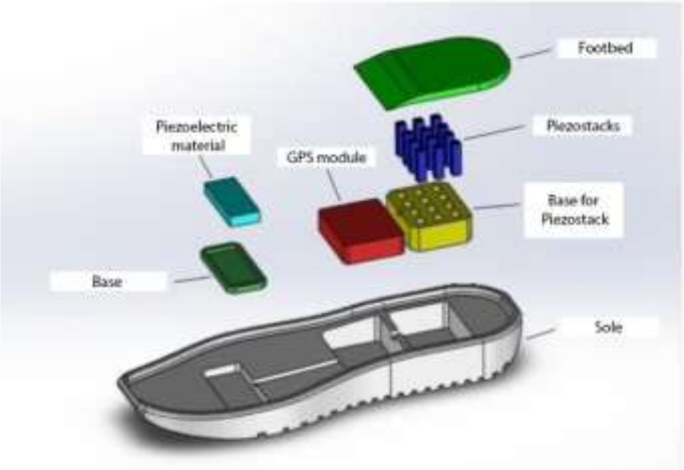

Figure 9 Disposition of the different components of energy harvesting system.

5.5. Comparative results

In this section comparative results are presented. Results, even if preliminary, are reported here following to perform a comparative analysis of the proposed techniques not only from the energy harvesting point of view but also from the industrialization perspective.

The simulation was performed to obtain a comparison between the proposed solutions from 3 different point of view:

i. level of energy harvesting measured counting the number of steps necessary to accumulate the charge needed to a position transmission (GPS localization plus GPRS message transmission); the value is measured in 10 trials and the number reported is an average

ii. ease of installation on a production line measured in a scale from 1 to 10 evaluated as the average of 3 different shoe makers opinion;

iii. solution cost per shoes normalized in a scale from 1 to 10 for a standard size shoe.

iv. comfort measured in a scale from 1 to 10

The following table reports comparative results:

Item					
ID	**Ref**	**i)**	**ii)**	**iii)**	**iv)**
1	A. First solution	13.80	8	7	8
2	B. Second solution	11.00	7	9	9
3	C. Third solution	12.50	9	8	9
4	D. Fourth solution	13.30	7	7	9

Final comparison is based on an average of the parameters reported in the table. At this step of the project we decided to give to shoe makers the possibility to define a final metric to define the better solutions. Results, even if preliminary, are a useful comparison of different Energy Harvesting system designs with a particular focus on ease installation and costs. Further investigations in that direction will follow in the progress of the current project.

6. DISCUSSION AND FUTURE WORKS

This paper examined different devices that can be built into the shoes, where excess energy can be promptly recovered, and used for producing electrical power while walking. The project indented to design and to realize innovative and general purpose devices integrating polymer and ceramic piezomaterials achieved by injection mouldings.

Four different types of soles with energy harvesting systems for supplying a GPS module have been proposed.

On the basis of the walking cycle and the study of the distribution of the pressure exerted by the foot on the shoe through the gait analysis, the zones of the sole where to position the elements of energy harvesting in order to maximize their effectiveness have been identified. Energy recovery was achieved using piezoelectric material, buzzer and piezostacks inserted into the sole. All the elements have been integrated into the shoe creating also supports allowing the anchoring of energy harvesting devices and the integration of electronic components needed for geolocalization.

This work is in a preliminary phase, since there is only a description and comparison of performance of the systems without a strong experimental phase. In order to evaluate the ability of the systems in the energy recovering, it is necessary to compare their performances making two different tests. The first in laboratory making use of a machine for fatigue tests and performing measurements in open and closed circuit. The second test in a real application (on the road) wearing for a few days the finished prototype of the shoes in order to evaluate the energy recovered during a daily use of the shoes, the actual wearability and the comfort level.

ACKNOWLEDGMENT

The authors would like to thank 4D Engineering and Mon-tebove for the support to this project.

REFERENCES

[1] A. Khaligh, P. Zeng, and C. Zheng, “Kinetic Energy Harvesting Using Piezoelectric and Electromagnetic TechnologiesState of the Art”, IEEE Transactions on Industrial Electronics, vol. 57, no. 3, pp. 850-860, March 2010.

[2] Frontoni, E., Mancini, A., Zingaretti, P., Gatto, A. , “Energy harvesting for smart shoes: A real life application”, Proceedings of the ASME Design Engineering Technical Conference, 2013.

[3] R. Riemer, and A. Shapiro, “Biomechanical energy harvesting from human motion: theory, state of the art, design guidelines, and future directions”, Journal of NeuroEngineering and Rehabilitation, vol. 8, no. 22, 2011.

[4] A. Gutierrez,` N.I. Dopico, C. Gonzlez, S. Zazo, J. Jimnez-Leube, and I. Raos, “Cattle-Powered Node Experience in a Heterogeneous Network for Localization of Herds”, IEEE Transactions on Industrial Electronics, vol. 60, no. 8, pp. 3176-3184, August 2013.

[5] P.D. Mitcheson, E.M. Yeatman, G.K. Rao, A.S. Holmes,T.C. Green, “Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices, Proceedings of the IEEE, vol. 96, no. 9, September 2008.

[6] P. Chapman and M. Raju, “Designing power systems to meet energy harvesting needs”, TechOnline India vol. 8, no. 42, 2008.

[7] J.A. Paradiso, "Energy Scavenging for Mobile and Wireless Electron-ics", Massachusetts Institute of Technology Media Laboratory Thad Starner, Georgia Institute of Technology, GVU Center, 2008.

[8] E. Okuno, I. Caldas, C. Chow, "Conservao de Energia", In Fsica para cincias biolgicas e biomdicas, vol II, pp. 103-105. Lisboa: HARBRA, 1986.

[9] J.M. Gilbert, and F. Balouchi, "Comparison of Energy Harvesting Systems for Wireless Sensor Networks", International Journal of Au-tomation and Computing, vol. 05, no. 4, pp. 334-347, October 2008.

[10] A.J. Pointon, C. Eng, "Piezoelectric Devices, IEEE Proc. vol.129, pp. 285- 307, 1982.

[11] D. Morton, "Human Locomotion and Body Form", The Williams & Wilkins Co., Science Education vol. 36, no. 312, 1952.

[12] S. Suzuki, T. Katane, H. Saotome, and O. Saito, "A Proposal of Electric Power Generating System for Implanted Medical Devices", IEEE transactions on magnetic, vol. 35, no. 5, pp. 21-23, 1999.

[13] J. Kymissis, C. Kendall, J.A. Paradiso, and N. Gershenfeld, "Parasitic power harvesting in shoes", Second International Symposium on Wear-able Computers, 1998. Digest of Papers, vol. 24, pp. 132-139, 19-20 Oct. 1998.

[14] S. Chalasani, and J.M. Conrad, "A Survey of Energy Harvesting Sources for Embedded Systems", Southeastcon, 2008. IEEE, pp. 442-447, 3-6 April 2008.

[15] N.S. Shenck and J.A. Paradiso, "Energy Scavenging with Shoe-Mounted Piezo-Electrics", IEEE Micro, vol. 21, no. 3, pp. 3041, 2001.

[16] J. Hayashida, "Unobtrusive Integration of Magnetic Generator Systems into Common Footwear", BS thesis, Dept. of Electrical Engineering and MIT Media Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., 2000.

[17] C.J. Kendall, "Parasitic Power Collection in Shoe-Mounted Devices, BS thesis, Dept. of Physics and MIT Media Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., June 1998.

[18] C. Dal Zovo, Valutazione sperimentale delle distribuzioni delle pres-sioni plantari, Tesi 2010

[19] R. Amirtharajah, J. Collier, J. Siebert, B. Zhou, and A. Chandrakasan, "DSPs for Energy Harvesting Sensors: Applications and Architec-tures"; Intel & Massachusetts Institute of Technology, IEEE 1536, pp. 72-74, 2005.

[20] H. Hosaka, "Personal electric power generation technology for portable information equipmention", Micro Mechatronics - Journal of the Horo-logical Institute of Japan vol. 47, no. 3, pp. 38-46, 2003.

[21] Y. Kagetsu, Y. Osaki, H. Hosaka, K. Sasaki, and K. Itao, "Research on automatic power generator using self-exciting rotation", Micro Mechatronics - Journal of the Horological Institute of Japan, vol. 48, no. 4, pp. 22-33, 2004.

[22] W. Tao, T. Liu, R. Zheng, and H. Feng "Gait Analysis Using Wearable Sensors", Sensors, vol. 12, pp. 2255-2283, 2012.

[23] Luchetti, G., Servici, G., Frontoni, E., Mancini, A., Zingaretti, P. "Design and test of a precise mobile GPS tracker", 21st Mediterranean Conference on Control and Automation, MED 2013 - Conference Proceedings, 2013.

[24] C.-F. Wang, D.-M. Miao, P.C.-K. Luk, J.-X. Shen, C. Xu, and D. Shi, "A Shoe-Equipped Linear Generator for Energy Harvesting, IEEE International Conference on Sustainable Energy Technologies (ICSET), pp. 1-6, 6-9 Dec. 2010.

[25] J.G. Rocha, L.M. Goncalves, P.F. Rocha, M.P. Silva, and S. Lanceros-Mendez, "Energy Harvesting From Piezoelectric Materials Fully Inte-grated in Footwear, IEEE Transactions on Industrial Electronics, vol. 57, no. 3, pp. 813-819, March 2010.

[26] Ruchi Sharma and Dr. S. Balaji, Investigating Techniques And Research Trends In Rf Energy Harvesting, International Journal of Computer Engineering and Technology (IJCET), Volume 5, Issue 7, July (2014), pp. 157-169.

[27] K. Ajith, T. Praveen Kumar, V. Ramaiah and Sai Teja, High Efficient Bridgeless Boost Rectifier For Low Voltage Energy Harvesting Applications. International Journal of Electrical Engineering & Technology, 7(3), 2016, pp. 93–105.