A Comparative Study of Different Types of Piezoelectric Interface Circuits to Perform Simultaneous Sensing and Energy Harvesting

Niharika Gogoi, *Student Member, IEEE*, Gufei Zhang, and Yuanjia Zhu,and Georg Fischer, *Senior Member, IEEE*

***Abstract*—This article is an extended work from our published article [1], with improvement in sole design and a comparison of 4 different types of rectifier circuits for piezoelectric energy harvesting. Energy is harvested from multiple piezoelectric elements embedded in an insole while simultaneously collecting gait information of the subject wearing it. The study is based on an asymmetric signal generated while walking and the harvested energy is utilized to operate a system under fixed electrical load. The influence of back-up battery and insole design optimization on accuracy of collected information is taken into consideration. A comprehensive approach for shoe insole application based on simultaneous piezoelectric sensing and energy harvesting is presented in this work.**

***Index Terms*—piezoelectric energy harvesting, wearables, smart shoe, step-counting**

I. Introduction

There is a growing interest on capturing energy from mechanical vibration in the environment, such as human movement, animal motion and vehicle movement, which are otherwise un-harvested and wasted. Although scavenging such ambient energy contribute to the levels of micro and milli Joule only, it is a promising option to operate low-power electronic devices, which is an integral part of modern livelihood. This micro or milli Joules of energy sums up to a significant value of kilo or Mega Joule if billions of people use such low-power electronic devices. Human activity has the potential to generate useful electrical energy through piezoelectric, thermoelectric, electrostatic or electromagnetic transducers, which promises self-powered and battery-less applications [2]–[5].

The Bio motion laboratory of MIT proposed parasitic power harvesting via lead based (PZT) and polymer based (PVDF) piezoelectric elements, and rotary magnetic resonator embedded in shoes. The PZT and PVDF collected peak power of 80 mW and 20 mW across load resistance of 250 kΩ, but the magnetic resonator collected peak power of 1 W. However, the magnetic generator is difficult to integrate with the shoes as compared to the piezoelectric elements [6], [7]. A preliminary study was carried out with a shoe-mounted bimorph cantilever to take advantage of heel acceleration of a human gait. Both simulation and experimental analysis were performed to understand the proposed model [8]. Screen printed piezoelectric composites on a shoe insole was proposed as a self-powered pressure mapping sensor, generating an open circuit voltage of around 2 V, when a man of average weight 70 kg walked on it [9]. An Italian group of researchers proposed 4 solutions to harvest energy to operate a GPS module. They used PVDF, buzzers and piezoelectric stacks to design the different layouts [10]. Another group of researchers designed a similar sandwich structure with arc-shaped groove between the plates. They designed two prototypes: one between two plates of engineering plastics and another between two plates of silicone rubbers. The first prototype generated more power but the second one ensured more comfort [11]. A stack of PVDF as sandwich between silicone gels was fabricated to identify human motion and used to charge a smart band [12]. A shoe pad with a piezoelectric wafer could provide a stable output power to operate an Xbee wireless module, providing 1.25 mW for transmission every 10-12 min [13]. An electrodynamic system could produce 3.1 mJ energy from each step while walking, with average power of 12.42 mW at 6 Hz and produce 20.6 mW at more mechanical vibration about 50 Hz [14], [15]. Unfortunately, this is quite a high vibration frequency to be available in the environment. In a recent study, a battery-less sensing platform with piezoelectric pads under both feet was proposed to operate a wearable system for sensing, processing and wireless communication. One foot was equipped with sensors and their information are transmitted via ambient back-scatter communication to the other foot which, after receiving the information, sends it to the user's smartphone via Bluetooth communication [16]. However, this work is restricted to only piezoelectric elements placed on shoe insole to take advantage of foot activities. The work reported in [17] also proposed a self-powered gait system with piezoelectric origami generator.

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Niharika Gogoi is pursuing her Ph.D in Institute for Electronics Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany (email: niharika.gogoi@fau.de)

Gufei Zhang is pursuing the M.S. degree in Electrical and Information Engineering from Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany (email: gufei.zhang@fau.de)

Yuanjia Zhu is pursuing the M.S. degree in Electrical and Information Engineering from Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany (email: yuanjia.zhu@fau.de)

Prof. Gerog Fischer is with Institute for Electronics Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germanyn (email: georg.fischer@fau.de).

Extensive research on footwear based gait analysis [18] has triggered interest in harvesting energy from foot activities, with the aim to make the entire system self-powered and reduce dependency on battery. Although several sensors are widely investigated for the purpose of gait analysis, research in piezoelectric energy harvesting circuit through foot activities is however limited. The feasibility of such systems depends on several factors - comfortable sole design, efficiency of interface circuits, utilization of harvested energy for useful purpose, reproducebility, etc. The sensor data, acquisition and transmission unit i.e. micro-controller is the most power hungry element of the system. Therefore, it is important to optimize sensor functionalities according to the harvested power.

A. Proposed Work

The main aim of this work is to compare the performance of 4 types of rectifier circuits: full bridge standard rectifier (SEH), full-wave voltage doubler (VD), self-powered synchronous electric charge extraction (sp-SECE) and self-powered optimized synchronous charge extraction (sp-OSCE) for walking based energy harvesting applications, which are otherwise studied only for a sinusoidal signal of frequency as low as 18 Hz or higher. As human walking leads to an asymmetric signal of less than 2 Hz, it is important to compare between the circuits under such constraints to identify the differences between existing study and real applications. Each circuit has several electronic components, and impedance matching due to the total impedance present in piezoelectric element and circuit altogether determines the final output power delivered to the load. Therefore, on one hand, it might seem to be an unbalanced comparison between the circuits. On the other hand, as we keep the sensor functionalities constant, the behavior of each circuit for such constant load operation and for a non-sinusoidal signal is worth the investigation.

This work is an extension of our previously published article [1] and therefore, we would like to present the latest improvements in this article. In the previous article, 5 piezoelectric elements were embedded in square-shaped silicone molds and placed at 5 different positions under the foot. In this article, a sole layout was designed in the shape of a foot without compromising the comfort of subject. A comprehensive effort is put forward to understand the influence of sole layout optimization and back-up battery for gait based energy harvesting application. The ultimate objective of this paper is to realize the scope of a self-powered and comfortable sole layout to perform step-count and energy harvesting simultaneously.

II. System Architecture

The system architecture is shown in Fig. 1. As both sensing and energy harvesting are performed in our designed insole layout, arrows with two colors are used to differentiate between the functionalities. The highlighted red blocks - rectifier circuit and battery - are the main topic of discussion in this article.

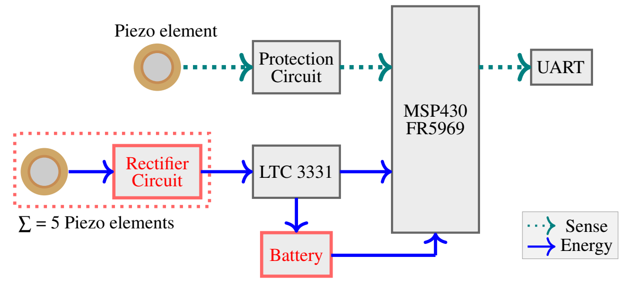
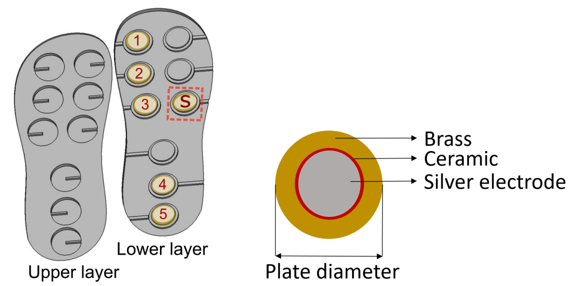


Fig. 1. The system architecture

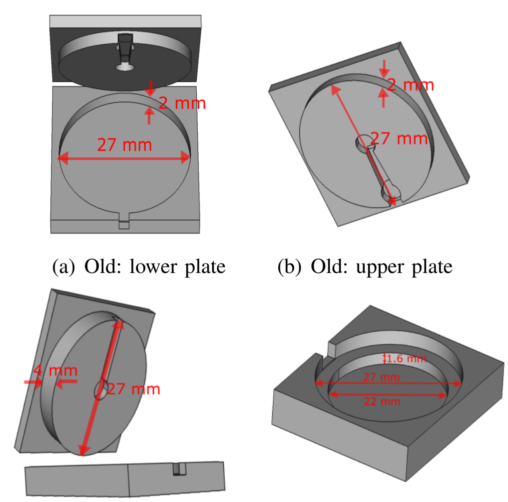
A. Sole Design



(a) (b)

Fig. 2. (a) Position of 6 piezoelectric elements on the sole layout (b)Piezo element

For protection and better electro-mechanical conversion [11], two layer of silicone rubber in shape of a sole is constructed. 5 piezoelectric elements are placed at an insole layout as shown in fig. 2(a). Another element denoted by "S" in fig. 2(a) is used for step-counting. The difference between the sole layout design in this article and previous article is already mentioned in subsection I-A. The commonly used piezoelectric element is a brass disc with a thin ceramic layer of lead zirconate titanate (PZT) on its top [19] (fig. 2(b)).



(a) Old: lower plate (b) Old: upper plate

(c) New: upper plate (d) New: lower plate

Fig. 3. Upper and lower plates of old and new sole designs

To simplify the understanding between old and new design, a square shaped part is cut from fig. 2(a). Based on the square cut, the dimension of lower and upper parts of both designs are shown in fig. 3.

B. Interface Circuit

In this subsection, we will discuss about parts of interface circuit - 4 types of rectifier circuits and DC/DC converter. As observed in fig. 1, a interface circuit is composed of a rectifier and LTC3331.

1) Rectifier circuit: The working principle of 4 types of rectifier circuits - full bridge standard rectifier (SEH), full-wave voltage doubler (VD), self-powered synchronous electric charge extraction (sp-SECE) and self-powered optimized synchronous charge extraction (sp-OSCE)- are discussed below. The prefix ”sp” is used to imply self powered technique to turn on the switch in the circuits.

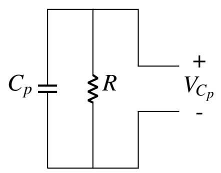
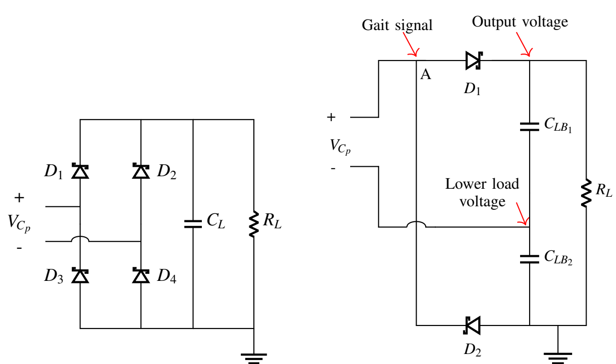


Fig. 4. Electrical equivalent of piezoelectric element

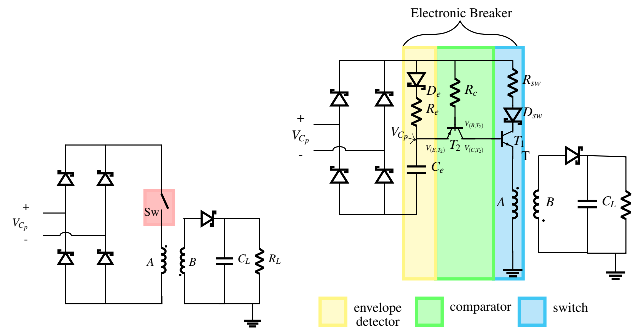
To improve the efficiency of conventional circuits, several nonlinear approaches were proposed for piezoelectric energy harvesting circuits. Before we discuss about each circuit, an equivalent electrical circuit of a piezoelectric element is shown in fig. 4 to ease the terminologies used in further discussion. A piezoelectric element is represented by a pair of capacitor and resistance.



(a) (b)

Fig. 5. (a) Standard circuit and (b) Voltage doubler circuit

- Full bridge standard rectifier (SEH) : The SEH circuit consists of 4 diodes arranged as Wheat-stone bridge, a filter capacitor C_L and terminal load R_L (Fig. 5(a)). It is the most commonly used rectifier circuit. For every half cycle, 2 diodes operate for rectification. For positive cycle, D_1 and D_4 conducts and for negative cycle, D_2 and D_3 conducts.
- Full-wave voltage doubler (VD) : A modified voltage doubler circuit (Fig. 5(b)) is implemented with 2 capacitors and 2 diodes. Each capacitor serve as both blocking capacitor and load capacitor. It has lower voltage drop than SEH circuit due to the presence of only 2 diodes. For positive cycle, only D_1 conducts while for negative cycle, only D_2 conducts. The VD circuit topology is more optimized and has less losss than SEH circuit.



(a) Basic SECE (b) sp-SECE

Fig. 6. sp-SECE based on electronic breaker

- Self-powered synchronous electric charge extraction (sp-SECE): The SECE circuit is known to be a load independent nonlinear technique. The electrostatic capacitance accumulated on the PZT element C_p depends on the mechanical vibration [20], [21]. When the extremum vibration is obtained, the switch Sw in Fig. 6(a) is turned on resulting in an L-C resonance between primary winding A and C_p. The instant to turn on Sw is important for accurate operation of the circuit. To make it self-powered, an electronic breaker circuit, composed of envelope detector and comparator, is used to turn on Sw (T_1 in Fig. 6(b)) [22]. The C_e in envelope detector stores the peak value ($V_{C_p,max}$) of the accumulated voltage on PZT element and compares it with the base voltage of T_2 i.e. V_{B,T_2}. The T_2 is blocked as long as stored voltage $V_{C_e} < V_{C_p}$. When ($V_{C_e} \to (V_{C_p,max} - V_{diode})) > V_{C_p}$, and $V_{C_e} - V_{C_p} > V_{Th,T_2}$, T_2 is turned on in its saturation region. Here, V_{diode} is the diode voltage drop. This turns on T_1 for charge extraction. The energy from the PZT element is transferred as magnetic energy into A, during Sw on time. As soon as Sw is turned off, the magnetic energy is transferred to the secondary winding B through the flyback transformer, charging the C_L.

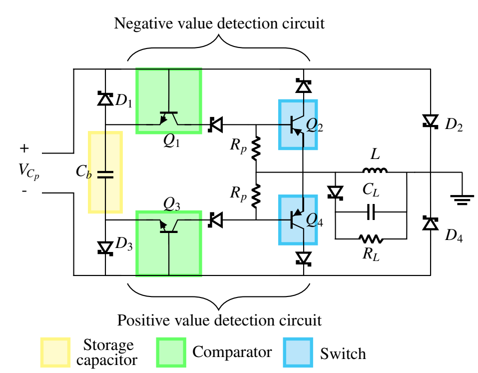
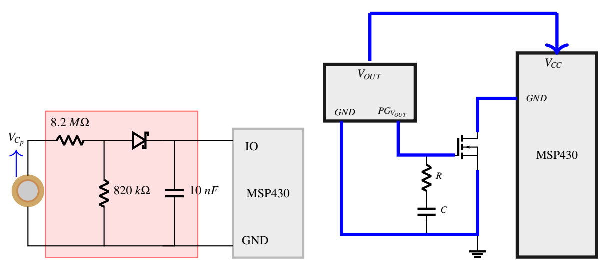


Fig. 7. Modified sp-OSCE based on electronic breaker [23]

- Self-powered optimized synchronous charge extraction(sp-OSCE): The sp-SECE based study in our previous article [1] showed that it is load dependent for gait based application. In [23], an optimized sp-OSCE was proposed, which showed that the output power is independent of load for $R_L > 50k\Omega$. Unlike sp-SECE, no transformer is used, which minimizes the electrical losses and size of the circuit. sp-OSEC is composed of 2 electronic breakers shown as positive and negative detection circuits in fig. 7. There is only 1 capacitor C_b which stores $V_{C_p,max}$ for both the cycles. The working of sp-OSEC is discussed for positive value detection. As the piezovoltage V_{C_p} increases to positive peak, C_b is charged through emitter-base junction of Q_1. The maximum charge stored in C_b is $V_{C_p,max} - V_{Th,Q1} - V_{D_3}$. As V_{C_p} decreases from its maximum positive voltage, Q_3 is blocked until $V_{C_p} - V_{C_b} > V_{Th,Q3} + V_{D_1}$. Then Q_3 is turned on which also turns on Q_4. An L-C_p oscillation is established through D_2-Q_4 and L-C_b oscillation is established through D_1-D_2-L-Q_4-Q_3. The L-C oscillation allows the inductor L to have a quick discharge of C_p and C_b leading to the freewheeling phase. The freewheeling phase lets the energy flow from L to load components. The charge extraction happens in similar way for negative cycle.

2) DC/DC converter: A buck-boost capable DC/DC converter LTC3331 with battery charger allows the harvested energy to power the micro-controller MSP430. The battery is used when harvested energy is not available or sufficient (see fig. 1). It is chosen because of its ultra low quiescent current 950 nA at no load condition. It has a low battery disconnect function to protect the battery from deep discharge [24]. The output of LTC3331 is set to 3.3 V for our analysis.

C. Sensor Data Acquisition Unit



(a) Protection circuit (b) Switching circuit for MSP430

Fig. 8. Interface circuit

5 PZT elements are used in the insole layout for energy harvesting and only 1 is used for step-count, as shown in Fig. 2(a). The low power mode 3 (LPM_3) of MSP430FR5947 Launchpad, is implemented using its IO interrupt function. The step counting is done by detecting the falling edge of piezovoltage V_{C_p} across IO port, owing to low power computation rather than performing the same by reading the entire piezovoltage. The use of ADC in the launchpad was intentionally avoided to limit the power consumption of this system. The counted steps is written into the Ferroelectric Random Access Memory (FRAM) of the MSP430. Connecting the PC and MSP430 through the data line and using the push-button in the launchpad, the stored data is transmitted to the PC through the UART port. An R-C network is designed to protect from high voltage and remove the jitters generated across the

TABLE I
LIST OF COMPONENTS

Component name	*Part number*	*Major parameters*
Piezoelectric element	7BB-27-4	Plate diameter= 27 mm Resonant frequency= 4kHz Capacitance= 16nF
Schottky diodes	B140BQ-13-F	V_F= 0.5V
NPN transistor T_1	2N3904	$V_{BE(sat)}$= 0.85V, $V_{CE(sat)}$ =0.2V at I_C= 10 mA
PNP transistor T_2	2N3906	$V_{BE(sat)}$= −0.85V, $V_{CE(sat)}$ =−0.25V at I_C= −10mA
Transformer L_1, L_2	TG05-2004NCRL	L= 20mH
Inductor L	BJ-IDT15-160	L= 20mH $R_{parasitic}$= 9.7Ω

IO port (fig. 8(a)). An N type MOSFET is used as a switch to establish a stable connection between LTC3331 and MSP430, as shown in fig. 8(b). When the output of the LTC3331 does not reach the rated voltage i.e. 3.3 V, the power good signal in $PG_{V_{OUT}}$ pin is low, and the MOSFET is in a closed state. When rated voltage is reached on V_{OUT}, $PG_{V_{OUT}}$ is set to high, the transistor is turned on, and the load is driven. The components used in this work are listed in table I.

III. Result and Discussion

A. Improvement of sole design

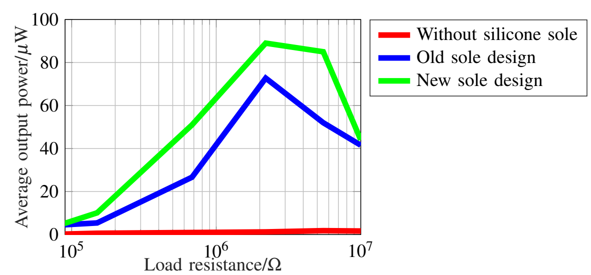


Fig. 9. Improvement of average output power with the imporvement of sole layout

The effect of sole design on the generated output power of a piezoelectric element across a resistive load is shown in fig. 9. It is to be mentioned that no other electronic circuit components are connected in this case. The silicone sole layout plays an important role to improve the electromechanical conversion and generate more output power. Without such a layout, the harvested output power is very low.

B. Analysis of each circuit for only 1 piezoelectric element

Only 1 PZT element is placed on position 3 (Check Fig. 2(a)) to choose the optimal values of resistors and capacitors in the rectifier circuits of VD, sp-SECE and sp-OSCE. The results discussed here are only from the rectifier circuit, without connecting to LTC3331.

- VD: As C_{LB_1} and C_{LB_2} are in series, the stored voltage depends on their equivalent capacitance, $C_{eq}=\frac{C_{LB_1}C_{LB_2}}{C_{LB_1}+C_{LB_2}}$, where $C_{eq} < C_{LB_1}$ and $C_{eq} < C_{LB_2}$. Low C_{eq} implies quick charging and quick discharging and high C_{eq} shows the opposite. The dotted graph in fig. 10 has unstable voltage. Although stability is obtained for high values of C_{LB_1} and

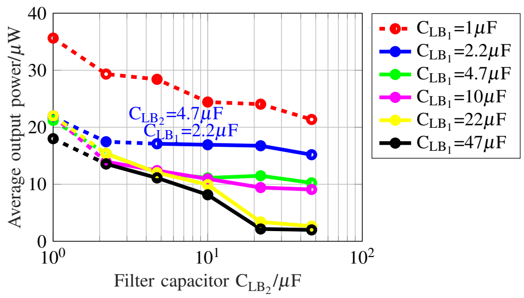


Fig. 10. **VD**: Average output power as a variation of C_{LB_1} and C_{LB_2} for $R_L = 5.5\,\mathrm{M\Omega}$

C_{LB_2}, the harvested output power is very low. The stable voltage is obtained only for

$$2.2\,\mu\mathrm{F} < (C_{LB_1} and C_{LB_2}) < 10\,\mu\mathrm{F} \tag{1}$$

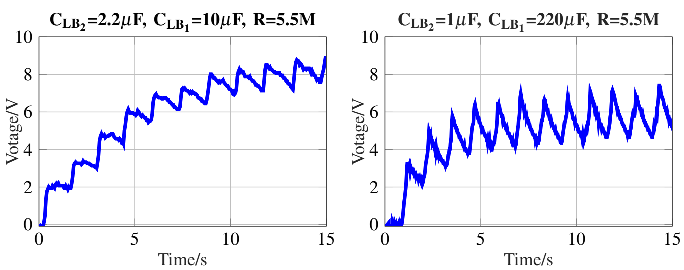


Fig. 11. **VD**: Voltage stability

If one of the capacitance values is less than $2.2\,\mu$F, e.g. if $C_{LB_1} = 1\,\mu$F, regardless of what C_{LB_2} is, the C_{eq} is less than $1\,\mu$F , which leads to fast discharge. Each C_{LB_1} and C_{LB_2} should be lesser than $10\,\mu$F, otherwise leads to slow charging. The role of C_{LB_1} and C_{LB_2} in output voltage stabilization is shown in fig. 11.

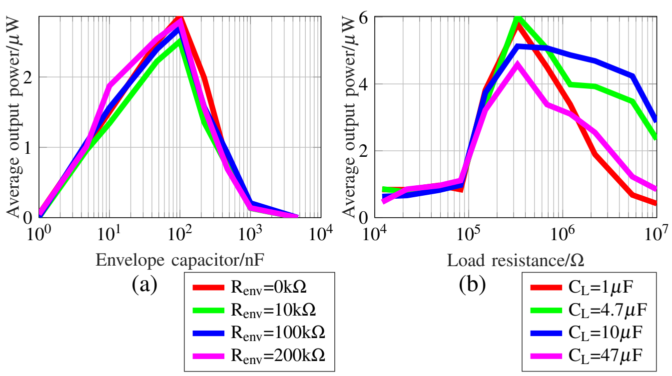


Fig. 12. **sp-SECE**: Average output power as a variation of (a) envelope components ($R_L = 10M\Omega$ and $C_L = 10\mu F$) and (b) load components ($R_{env} = 0\Omega$ and $C_{env} = 100nF$)

- sp-SECE: Fig. 12 shows the average output power of a single circuit, dependent on envelope and load components. Unlike the sine wave input discussed in literature, the average output voltage of sp-SECE when harvested from walking is load-dependent. The harvested power is maximum for R_{env}=0 kΩ and C_{env}=100 nF, and these values are considered for further experiments.

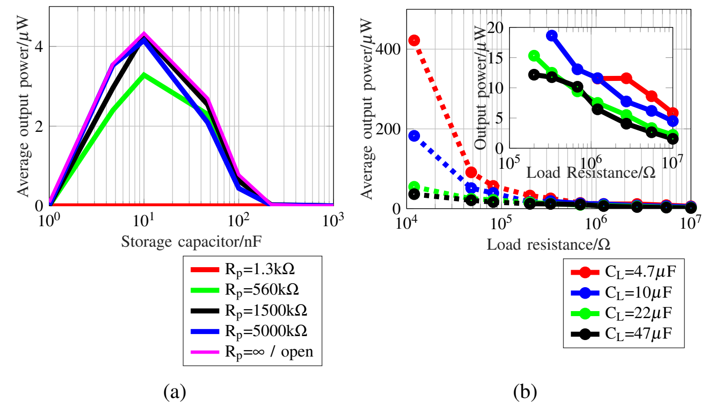


Fig. 13. **sp-OSCE**: Average output power as a variation of (a) pull down resistors R_p and storage capacitor C_b ($R_L = 10M\Omega$ and $C_L = 10\mu F$) and (b) load components ($R_p = \infty$ and $C_b = 10nF$). An inset plot is added in (b) to show stable output power harvested at high load resistance.

- sp-OSCE: Fig. 13(a) shows the results of an sp-OSCE circuit, where maximum average output power is obtained for without pull down resistor R_p and storage capacitor $C_b = 10\,$nF. The dotted plots show unstable power obtained at low load resistance due to high amplitude ripples. The inset fig. 13(b) shows that stable output power is harvested for $R_L > 10^5\Omega$.

C. Output of LTC3331: role of battery

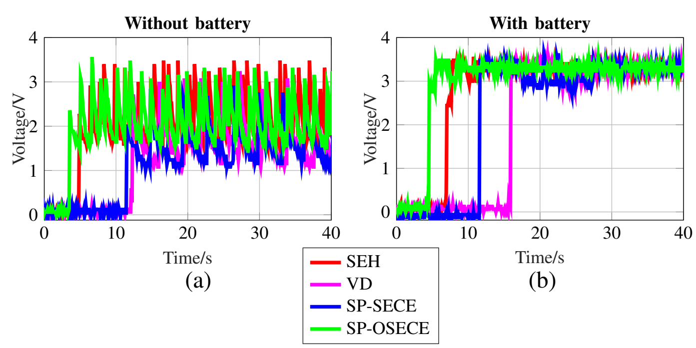


Fig. 14. Role of battery in output of LTC3331

Based on optimal values decided from previous subsection III-B, rectified output of 5 PZT elements are connected in parallel and then total output power is used to operate MSP430 performing step-count. Fig. 14 shows comparison of 4 types of rectifier circuits, each connected to a LTC3331 DC/DC converter while walking. It is observed that a battery stabilizes the output of LTC3331. The efficiency of a rectifier circuit is interpreted from the number of steps required to turn on the buck regulator and achieve stable battery voltage. The average charging current per step also informs about the performance of circuit.

The working of the 4 rectifier circuits, with battery, is summarized in table II. It shows that sp-OSCE has an optimal performance considering the number of steps required to achieve the desired voltage and average charging current per step.

TABLE II
SUMMARY OF THE LTC3331 RESULTS

Circuit	Steps to activate buck	Steps to achieve battery voltage	Average charging current to battery per step
SEH	4	6	150 - 170 µA
VD	10	16	45 - 60 µA
sp-SECE	6	16	20 - 30 µA
sp-OSCE	3	5	170 - 190 µA

D. Accuracy of step counting

TABLE III
ACCURACY OF STEP-COUNT WITH SP-OSCE CIRCUIT (WITH BATTERY)

Steps performed	Steps received via UART	Accuracy
10	7	70%
15	13	86.7%
20	17	85%
25	22	88%
30	28	93.3%
40	36	90%
50	45	90%
100	97	97%

Although simultaneous step-count and energy harvest is succesfully achieved, it is important to verify the accuracy of step-count. The accuracy test is summed up in table III, whose average is 87.5%. It is observed that few steps are missed by the UART port.

IV. CONCLUSION

The overall performance of a shoe application depends on its sensor functionalities and its accuracy, electronic circuits and comfort. The design of such an application, popularly known as smart shoe, requires multidisciplinary knowledge and expertise to realize its best results.

In this work, an attempt to simultaneous sensing and energy harvesting from multiple piezoelectric elements is achieved. It opens up possibilities of ambient mechanical vibration to power a human gait acquisition system. The proposed shoe design ensures comfort and fulfills our technical goals. The sp-OSCE outperforms the other circuits. The stable output voltage is obtained only when the battery is connected to it. It is important to mention that the values obtained in tables II and III might vary slightly from one individual to another individual, based on their walking pattern, weight and health conditions. For further improvement, an integrated circuit is a possible technology to assemble and miniaturize electronic components used in the system.

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Niharika Gogoi (Graduate Student Member, IEEE) was born and brought up in Assam, India. She received her degrees in Bachelor of Technology in Electronics and Communication Engineering from Tezpur University in 2015 and Masters in Energy from Indian Institute of Technology, Guwahati in 2019. Currently, she is a third-year doctoral student in Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. Her research interest includes wearable and biomedical device, and energy harvesting circuits.

Gufei Zhang was born in Rugao, Jiangsu, China in 1997. In 2020, he received double B.S. degrees in Electrical and Information Engineering from Changshu Institute of Technology and Mittweida University of Applied Sciences. Now he is studying for M.S. degree in Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. His research interest includes Energy harvesting circuits and Embedded system design.

Yuanjia Zhu was born in Nanjing, Jiangsu, China in 1997. In 2020 he received the B.S. degrees in Electrical and Information Engineering in field Automation Technology from the Changshu Institute of Technology and the University of Applied Sciences Mittweida. He is currently pursuing the M.S. degree in Electrical and Information Engineering from Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. His research interest includes Energy harvesting and Embedded system design.

Georg Fischer (Senior Member, IEEE) was born in 1965 at Lower Rhine region. From 1986 to 1992 he studied electrical engineering with RWTH Aachen University, Aachen, Germany, from with special focus on communications, microwave/RF and electro-dynamics. He received the Dipl.Ing. (TH) degreein electrical engineering in 1992, and the Dr.-Ing.degree (summa cum laude) from the University ofPaderborn, Paderborn, Germany, in 1997 for a the-sis on a polarisation agile antenna array system forsatellite communication. From 1993 to 1996, he wasa Research Assistant with the University of Paderborn. In 1996, he joined theBell Labs Research of Lucent Technologies in Germany focusing on base station RF technology. In 2000 he was promoted Bell Labs DMTS (Distinguished Member of Technical Staff), in 2001 Bell Labs CMTS (Consulting Member of Technical Staff) and in 2007 he was nominated for Bell Labs Fellow. In2008 he was appointed a Full Professor for electronics engineering with FAU Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. His scientific research focuses on analogue-digital balance of electronic systems. In Medical, he researches new detection schemes, new circuit designs and digital assisted signal processing approaches for biosignal acquisition and molecular communication. Starting from a microelectronics viewpoint, he is looking forsynergies between wearables and professional medical equipment in order to allow for assessment of biosignal during daily life, routine activities and sports.He is a Member of EUMA, VDE and named inventor on more than 50 patents