A Study of Vibration-Based Energy Harvesting in Activities of Daily Living

Abstract—**Pervasive health applications are usually based on wireless sensors integrated on a personal area network. Human body sensors are intended to be wearable in order to achieve user acceptance and help their integration in patient's daily living activities. The size reduction of the employed devices, mainly limited by their batteries, is a key factor to achieve such a wearability. As a consequence, different energy harvesting sources are being studied to decrease or remove the dependence on batteries of sensors in personal wireless networks. This paper presents a study of vibration-based energy harvesting aiming to determine the power generation possibilities of human body motion during activities of daily living. A harvesting device is placed on different body parts together with an inertial unit so generated power-body motion patterns are obtained. Same activities showed different generated power depending on the device position. Activities containing high movement frequencies, accelerations and especially impacts, revealed to produce the highest power outputs. Hip and foot instep placing showed better performance and efficiency.**

Keywords-energy harvesting; human body motion; inertial sensors; activities of daily living.

I. INTRODUCTION

Most pervasive health applications including teleassistance [1], telerehabilitation [2], posture and activity analysis [3], [4] and vital constants monitoring [5] are based on sensors worn by the patient, which are integrated forming a Personal Area Network (PAN). PAN elements are normally composed by a device containing different sensors, other circuitry such as microcontrollers, radio transceivers, signal conditioners and batteries. The advances in manufacturing technologies have allowed to considerably decrease the size of a wide range of sensors, permitting the researchers and companies develop wearable devices. Device wearability is a factor of great importance since it will condition the patient acceptance to the carried device. In addition, devices must be as least invasive as possible by not interfering carrier's daily living activities.

Regardless of considerable size decrease, a dead-end has been reached since batteries represent a high percentage of the total device size and their reduction and integration evolves in a much slower way. Successive reductions of sensors will not exclusively help to reduce the final size because of battery size constraints. On the other hand, device autonomy is a key factor in PANs as many applications require a continuous monitoring of patients state. As a result, manufacturers have to trade-off size for autonomy so the device is wearable and has the proper autonomy for the aimed application. Meeting this requirement is not a trivial task and might be hard to achieve for applications needing an extended period of use, such as fall detection, analysis of Activities of Daily Living (ADL) and vital constants monitoring. The slower pace of battery development has originated many research works aiming to find alternative power sources such as energy harvesting. These works have made special emphasis in the potential of the human body as a power source and the development of vibration-based energy harvesters optimized for low frequencies. *Starner* set the grounds with a complete investigation of several human power sources, including body heat, breathing, blood pressure, limbs motion, as well as different types of harvesters including piezoelectric and rotary generators [6]. *Li et al.* developed a prototype able to harvest average power outputs of up to 4.8 W from human walking adding little extra effort to the carrier [7]; however the device cannot be classified as wearable due to its size and weight and can lead to patient's rejection as it resembles prosthesis. *Feenstra et al.* replaced the strap buckle of a backpack with a mechanically amplified piezoelectric stack actuator [8]. They were able to obtain a 0.4 mW output when the backpack was loaded with a 20 Kg load. Although the system does not add extra effort to the user, its application is limited to a scenario where a person is carrying a heavy backpack *e.g.* soldiers. *Shenck et al.* embedded a flexible piezoelectric foil stave and a piezoelectric dimorph in a shoe sole to capture heel-strike and sole-bending energy respectively [9]. They obtained an average power of 8.4 mW at a walking frequency of 1.1 Hz. *Farmer* built a system consisting of a piezoelectric vibration harvester able recharge a 7 mAh battery in a 10 minutes' walk by placing it at the hip [10]. The device was rather bulky and produced an average power of 10 μW. *von Büren et al.* used accelerometers to estimate the generated power of a kinetic harvester based on data gathered at different body points [11], [12]. An immediate extension of their work comes from the inclusion of harvesters at the same body points.

Vibration-based harvesters are very versatile since they can be embedded in the PAN devices, thus avoiding the need of wires used on many solutions where the harvester can only be placed in a specific part, such as the shoe sole or the thorax.

This paper presents a study of the power generation efficiency of different ADL, as well as different positions of the harvester. The goal is to determine the feasibility of self powered PAN devices or, in a more recent scenario, the possible battery life extension through the use of harvesters. An Inertial Measurement Unit (IMU), including a triaxial accelerometer and a biaxial gyroscope has been attached to the harvester to better understand the nature of the activities showing the highest generated output. We intend to extend the work in [11] and [12] by associating the gathered inertial data to the harvester power output.

This paper is organized as follows: the employed harvester and IMU are described in Section II, followed by the experimental setup and results which are shown in Section III.

PERVASIVEHEALTH 2010, March 22-25, Munchen, Germany

DOI 10.4108/ICST.PERVASIVEHEALTH2010.8808

In Section IV conclusions are drawn and an outlook is given on future work.

II. HARDWARE SETUP

A. Harvesting device

A *PEH20W Volture* cantilever beam harvester from Midé Technologies [13] has been used to convert mechanical vibrational energy into alternating electrical energy which is then electronically converted to direct current. It is composed of a stack of two piezoelectrics protected by a metallic case and it is able to generate a maximum of 34 mW at 80 Hz. Since human body movements frequency will rarely be higher than 3 Hz, the output power is expected to be a few magnitudes lower. A 50 g mass is placed at the free oscillating tip of the cantilever so the harvester is sensitive to lower frequencies. A 160 KΩ load resistor is soldered at the harvester output to allow the charge and discharge of the internal 470 pF capacitor.

According to [14] cantilever beam harvesters' maximum available energy per bending can be modeled through the following expression

$$E_{\max} = \frac{9}{128} WtLS_{\max}^2 \varepsilon Y^2 g^2 \quad , \tag{1}$$

where $\varepsilon Y^2 g^2$ is a constant determined by the material properties being ε the dielectric constant, *Y* the Young's Modulus and *g* the voltage coefficient; *WtL* is the total bender volume being *W* its width, *t* its thickness and *L* its length; S_{max} is the total surface strain which can be obtained by applying

$$S_{\max} = \frac{t\Delta_{x\max}}{L^2} \quad , \tag{2}$$

defining Δ_{xmax} as the maximum deflection of the cantilever's free end. Δ_{xmax} is proportional to the applied force to the free end and, therefore, proportional to the tip mass and to the applied acceleration. The total obtained power depends on bending frequency, size and material parameters of the harvester, the applied acceleration and the tip mass. Fig. 1 shows the structure of the PEH20W harvester.

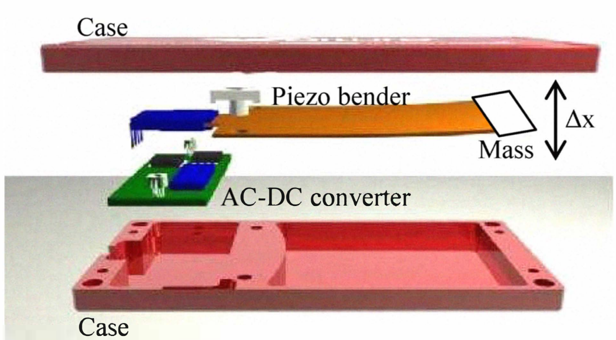

Figure 1. Internal structure of the PEH20W from Midé Technologies. A 50 g mass is glued to the bender's free end to augment its sensitivity to low frequency vibrations.

B. Inertial Measurement Unit

WAGYRO (Wireless Accelerometer and GYROscope) is an IMU developed in the Department of Computer Architecture and Technology of the University of Granada, Spain. It was originally designed to be used in Telefonica's R&D Rehabitic project. This project, currently in test at the Sant Joan de Deu Hospital in Mallorca, Spain, and the Esperança Hospital in Barcelona, Spain, allows patients to perform their rehabilitation routines at home following the instructions of a real time application that analyzes human limbs motion data. Initially, in the first phase, the IMUs are placed on thighs and shanks to obtain the knee joint angle, acceleration and angular velocity of the lower limbs.

WAGYRO includes an Analog Devices ADXL330 triaxial accelerometer with a range of ±3g and an InvenSense IDG-300 biaxial gyroscope with a theoretical range of ±500º/s. Data are sampled at a rate of 50 Hz and sent using Digi's XBee module based on IEEE 802.15.4. Figs. 2.a and 2.b show WAGYRO's internal and external appearance respectively.

C. Experimental device

The experimental device consists of the harvester and the IMU. The output voltage at the load resistor is connected to a digital input of the IMU's XBee transceptor, so the instantaneous voltage at the harvester output is sent together with the acceleration and angular velocity data gathered by the IMU's sensors. Fig. 2.c shows the final configuration.

III. EXPERIMENTAL SETUP AND RESULTS

A set of ADL was performed at the Laboratory of Semiconductors and Bus Systems of Münster University, Germany by a young healthy individual (23 years) including basic ADL presenting a repetitive nature such as walking, running, jumping and cycling as well as other more specific activities such as arm trembling simulation, arm swinging and knee rehabilitation exercises (Successive 90º knee flexions and extensions while sitting and lying on the back). The experimental device was placed at the hip, shank, foot instep and wrist depending on the activity. Table I shows the placing points, the performed activities and the average generated power for each situation.

Fig. 3 shows a graphical representation of the data in Table I. It is easy to determine at a glance, that activities containing higher frequencies, higher amplitudes and specially impacts produce the highest power outputs.

Figure 2. WAGYRO's internal (a) and external (b) appearance. Experimental device (c).

Digital Object Identifier: 10.4108/ICST.PERVASIVEHEALTH2010.8808
http://dx.doi.org/10.4108/ICST.PERVASIVEHEALTH2010.8808

As seen in equations (1) and (2), the applied force over the cantilever is directly proportional to the generated power, so activities containing impacts such as walking, running and jumping will be more efficient than activities with no impacts having the same frequency and similar amplitude such as cycling and arm swinging.

A reaction force is suffered by the body when it impacts with the floor. This reaction force, which is proportional to the acceleration of the impact and to the human body mass, will produce a high displacement of the bender's free end. Therefore, impacts are the main factor determining the power generating efficiency of an activity. The inertial data confirm this fact since, as we can observe in Figs. 4 and 5, where impacts produce abrupt changes in acceleration leading to acceleration peaks matching up with generated power peaks. The more impacts the activity has, the most acceleration peaks are produced, and thus, the most power is generated. On the other hand knee rehab activities show poor efficiency since there are no impacts, frequency is low, and soft movements lead to low accelerations.

TABLE I. AVERAGE GENERATED POWER FOR DIFFERENT ADL AND PLACING POINTS.

Activity	Placing point	Average power (µW)
Walking	Hip	1.40
	Shank	10.30
	Foot instep	11.52
	Wrist	0.04
Slow running	Hip	9.65
Fast running	Hip	22.89
	Shank	28.74
	Foot instep	28.44
	Wrist	4.36
Jumping	Hip	22.70
Cycling	Shank	0.36
	Foot Instep	1.34
Knee rehab (sitting)	Shank	0.02
	Foot Instep	0.39
Knee rehab (lying)	Shank	0.36
	Foot Instep	0.44
Arm swinging	Wrist	3.08
Arm trembling simulation	Wrist	0.62

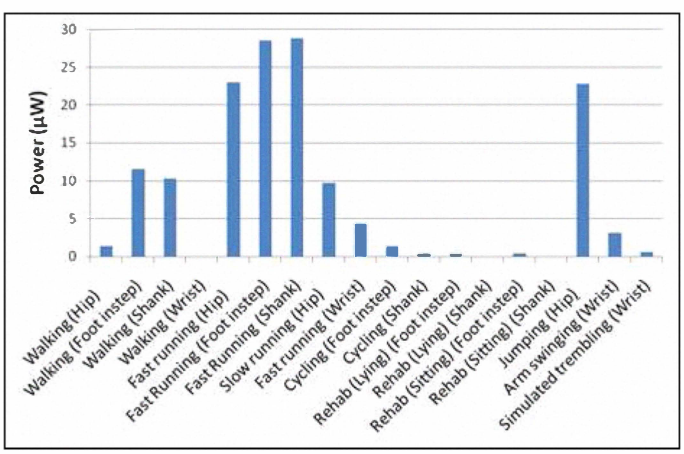

Figure 3. Average generated power for different ADL and placing points.

As depicted in Fig. 6, wrist and knee rehab activities show poor efficiency since there are no impact and frequency is low. The orientation of bender horizontal plane with respect to the impact plane is also an important factor affecting the efficiency as experiments showed that a perpendicular orientation produced a higher displacement in opposition to little displacement when both planes are parallel.

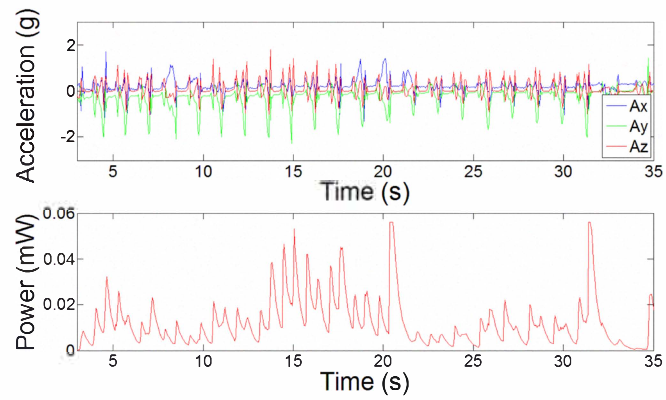

Figure 4. Measured accelerations and generated power during walking. Experimental device is placed on the foot instep.

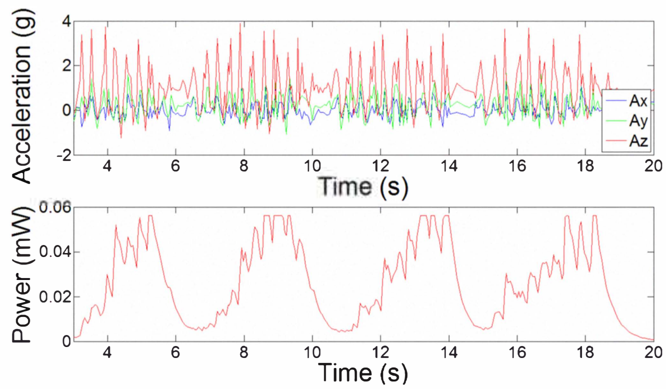

Figure 5. Measured accelerations and generated power during 4 series of running. Experimental device is placed on the hip.

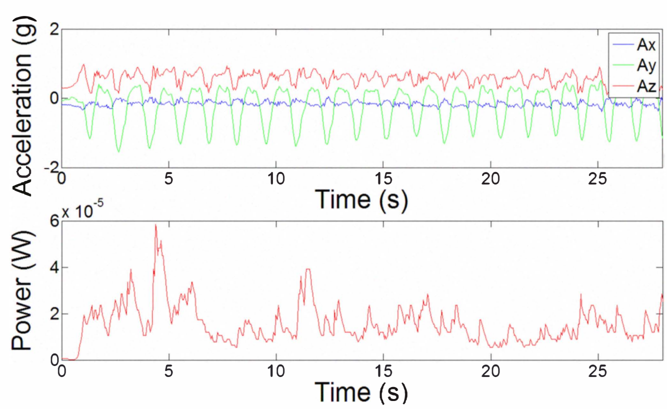

Figure 6. Measured accelerations and generated power during knee rehabilitation (lying). Experimental device is placed on the shank.

Digital Object Identifier: 10.4108/ICST.PERVASIVEHEALTH2010.8808
http://dx.doi.org/10.4108/ICST.PERVASIVEHEALTH2010.8808

Table II shows WAGYRO's power consumption for different sampling frequencies and the extra battery time gained for an average generated power of 29 μW (fast running, device located in the shank) using a 1100 mAh battery. A maximum of 10.5 minutes of extra time is obtained for a 9.5 Hz sampling frequency and a minimum of 3 minutes for a 55 Hz sampling frequency. However not all PAN devices continually measure and send data; devices in a sleep mode or transmitting less frequently could obtain a higher extra battery time.

IV. Conclusions And Future Work

The performed experiments have shown that different ADL and placing points lead to different power generation efficiencies. This different behavior is caused mainly by three factors: movement frequency, movement amplitude and the presence of impacts. Intense activities such as running, which present high amplitudes, high frequencies and impacts are able to produce an average power of 28.74 μW. Other less intense activities, yet more common, such as walking, which present lower frequencies and amplitudes and include impacts, are able to produce an average power of 11.52 μW. On the other hand, activities not presenting impacts and having low frequencies and amplitudes produce an almost negligible power output. The orientation of the harvester is a key factor to increase the efficiency; the bender has to be oriented along the perpendicular plane to the plane where the vibrations are being produced, usually the acceleration gravity plane.

The study has shown that the hip is the most optimal point to place the device for both generation efficiency and wearability. Moreover, several works where individuals have carried inertial units have concluded that the hip is an optimal spot to detect falls and analyze activities [15], [16]. As a conclusion, it has been observed that, with actual technology, the generated power is clearly insufficient to suppress batteries from PAN devices. However, harvesting could be very useful for telecare applications where transmissions are less frequent and device is usually asleep. Furthermore, future PAN devices, including WAGYRO, will have their power consumption reduced by employing new low consumption sensors and radio transceivers and by applying low consumption communication protocols.

TABLE II. Extra Battery Time Gained Applying Harvesting to WAGYRO

Sampling Frequency (Hz)	Power consumption (mA)	Extra battery time (min)
55	26.9	2.6
36	21.2	4.2
26	18.4	5.6
21	16.8	6.7
17	15.5	7.9
9.5	13.4	10.5

This fact, together with the use of harvesters optimized for low frequencies, could increase the feasibility of including a harvester in a PAN device.

Future works will be focused on using harvesters having a better low frequency optimization, using other PAN devices such as panic buttons as well as extending the experiments data base by including more individuals in a wider age range, so harvested energy can also be used as a classification parameter in an ADL recognition system.

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Digital Object Identifier: 10.4108/ICST.PERVASIVEHEALTH2010.8808
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