Human Motion Energy Harvesting Using a Piezoelectric MFC Patch

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***Abstract*— The improvements in efficiency of electronic components and miniaturization is quickly pushing wearable devices. Kinetic human energy harvesting is a way to power these components reducing the need of batteries replacement since walking or running is how humans already expend much of their daily energy. This work explores the case of kinetic energy from bending of a piezoelectric patch. For assessing the quality of the system, a testing setup has been designed and controlled by means of knee joint recordings obtained from a large motion dataset. The promising result of the chosen patch is an output power of 2.6μW associated to a run activity.**

I. INTRODUCTION

In the past decade, we have become increasingly dependent on portable electronic devices since technology has been developing rapidly [1]. Wireless networks composed of autonomous sensor nodes will be key elements of the future intelligent environment. Such systems have already been developed for medical applications [2].

Power autonomy of the sensor nodes is essential for their success, and this requires the development of low-power electronics and of long-life energy sources. The current approach for powering them is battery, which add weight, size and inconvenience to the user. There is a need to promote alternative sustainable power sources. Smart wearable systems, endowed with autonomous sensing, actuation, processing, communication and energy harvesting and storage, are emerging as a solution to the challenges of monitoring people anywhere and at anytime in applications such as healthcare, well-being and lifestyle, protection and safety [3]. Recent advances in the field of energy harvesting have led to the development of efficient and sustainable technologies that are capable of collecting mechanical energy produced by human motion [4]. Walking, as a routine activity has great potentials for biomedical energy harvesting, namely leg motions, i.e., ankle, knee, and hip motions, heel strikes, center of mass motion, shoulder and elbow joint motions during arm swings. For example: the self-winding watch that utilizes the motion of the user's arm to accelerate a small internal mass produces $5\mu W$ [1]; the suspended-load backpack that exploit the motion of the center-of-mass relative to the ground to generate 7.4W during fast walking carrying a 38Kg load [5]; the 1.6-kg knee joint device based on negative work of the muscles [6] that generates 2.5W per knee at a walking speed of 1.5m/s; or the many researches to harvest the heel strike collision energy which is estimated to be up to hundreds of mW [7].

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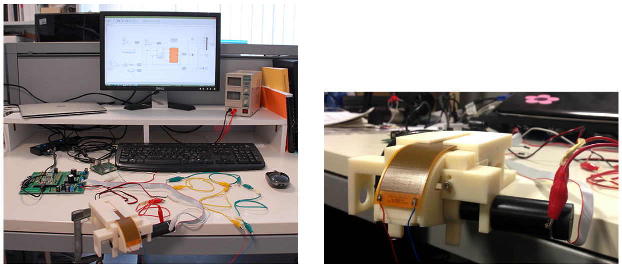
There is an impelling need of a new technology to harvest biomechanical energy that does not require the user to make specific actions to generate energy; to carry a cumbersome and heavy load that cause additional metabolic cost; to wear shoes that can cause postural problem in people who habitually go jogging and want to use their specific shoes; or for post-traumatic patients who even can't load on their legs. The development of effective, reliable and low-cost sensors for the human body with embedded power generation needs relevant innovation in optimizing the efficiency of power harvesting from ambient sources, which are generally irregular and small. Innovative transduction devices and materials need to be investigated, characterized and validated.

Recently developed composite materials allow harvesting energy from large bending motions without reliability limitations, thanks to the aid of piezoelectric fibers [8], [9], which show relevant advantages with respect to rigid and fragile traditional piezoceramic sheets [10]. This is the case of Macro-Fiber composites (MFC) tested in this work [11]. They are characterized by their flexibility on large deformation (Figure 2), which enables them to harvest energy directly from large human limb motions rather than exploit their resulting vibrations. The latter would entailed a resonant employment of the piezoelectric transducer often causing issues in developing damping systems in wearable devices.

To the authors knowledge, at the state of the art there are no studies testing the MFC power output from specific human activities under non-resonant bending conditions. In this work, we proposed a method to test the MFC power output thanks to a mechanical framework specifically designed to reproduce the kinematic of a knee joint and actuated using recorded human motion patterns. Following the introduction, a description of the energy harvesting system and a presentation of the experiments are given in Section II. The results are presented and discussed in Section III and the conclusions of the study are presented in Section IV, along with an examination of possible future work and improvements.

II. MATERIALS AND METHODS

A novel non-resonant energy harvesting mechanism with wide operation frequency band is investigated for collecting energy from low-frequency human joint motion. The energy harvesting system (Figure 1a) is composed by the P2-type MFC piezoelectric patch [12] attached to a mechanical structure purposely-built to reproduce human joints motion approaching one degree of freedom, as elbow or knee. The structure is actuated by a DC motor thanks to an ARM microcontroller board along with the motor driver and an analog-to-digital (ADC) to acquire the MFC's power output.



(a) *MFC bending test setup*. (b) *Mechanical frame*.

Fig. 1: Test setup.

A. System Design

The Macro-Fiber Composite (MFC), recently developed at NASA Langley Research Center [13], is a planar piezo-electric device consisting of a sheet of aligned rectangular piezoceramic fibers embedded in an epoxy matrix, that inhibits crack propagation, and sandwiched between layers of interdigitated electrode pattern on polyimide film, that grant a higher electromechanical coupling coefficients. This approach improves damage tolerance and flexibility relative to monolithic ceramic. The P2-type MFC [12], which utilizes the d31 effect (Figure 2) is especially suited for energy harvesting applications and it allows to harvest energy from large bending motions without reliability limitations.

Fig. 2: Macro-Fiber Composite (MFC) piezoelectric patch

The mechanical frame (Figure 1b) has been designed in SolidWorks and printed with a 3D printer Dimension Elite P14941 (Stratasys) in ABS+P430IVR with slice thickness: 0,178 mm. Besides the main fixed frame, it is composed by a revolving frame that allows the MFC patch bending, a rail to let the patch slide into, and the motor frame.

There are two limit positions to avoid the patch to be over-bent: when the revolving frame is in vertical position the patch is straight into the rail, and moving until the max bending stop, energy is generated. We actuated and sensed the structure with a Maxon motor modular system composed of a DC brushed motor and an encoder to monitor the patch bending-angle. They are both connected to the circuit board: a STMicroelectronics board, based on an ARM microcontroller (STM32F407VGT6 Cortex-M4 32-bit RISC, 168 MHz) integrated with a Pololu motor driver (VNH5019), a fully integrated H-bridge that can be used for bidirectional speed control of the motor. The patch voltage output is acquired by the ADC chip AD7656 (Analog Devices), configured as 16 bit, 250 kSPS, $\pm 5V$, whose selection is discussed later in the paper. The DC motor position control is a Proportional-Integral-Derivative (PID) kind integrated in a dedicated interface to program the ARM microcontroller board implemented in Mathworks Simulink.

B. Assessment Design

Since every energy harvesting system combines two different sub-systems, a mechanical one and electrical one, both have to be designed very carefully. Only if both interfaces match their direct connected environment, the mechanical load conditions, as well as the charge electronics input characteristics, a high degree and efficient harvesting of kinetic human energy can be observed.

First, we performed a preliminary characterization of the energy harvesting system, since human movements cover a wide frequency and amplitude ranges and accordingly the voltage output levels can be very different. This implies the use of an external ADC with higher input voltage range besides a higher conversion resolution, in order to obtain a trustworthy output power. Then, the other issue was to determine the optimal condition to have the maximum energy transfer. Figure 3 shows the basic dipole model which is generally used to characterize electric power sources. The source with the potential Vq drives a current I through the in-series connected resistors R_{in} for the inner resistance of the power source, and R_{out} for the electrical load. Based on this model the general relations for the efficiency and power transfer can be defined. The efficiency is the power transferred into the electric load related to the total power in the source (Equation 1) as a function of the resistors.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_{out}}{R_{in} + R_{out}} \tag{1}$$

It becomes clear that by increasing the resistance of the load resistor the efficiency converges to a value of $\eta = 1$. However, real input impedances of current state-of-the-art systems for electronic charge control and collection do not meet the perfect value for a load resistor, so efficiency will be always below 1. Since the inner impedance of the piezoelectric patch is fixed, to optimize the power transfer from the power source into the electric load, we performed some tests to detect the optimal load value, as we will see better in the next section.

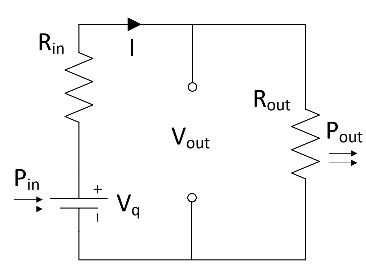


Fig. 3: Dipole model for electric power sources

After having established the overall setup, we gave thought to the motor control input. In this work no experiments with humans have been performed. We extracted human motion data from the Carnegie Mellon University (CMU) motion capture database[1], a free dataset of motions classified by subject number or motion category and recorded by means of a marker-based motion capture system. The 3D data obtained can be arranged in different ways; we used the skeleton movement one that consists in an .asf/.amc pair of files. The former element of the pair describes the skeleton and its joints: their connections, lengths, degrees of freedom, and mathematical transformations. Instead, the latter element contains the movement data. We fused and extracted the knee flexion position data (Figure 4) to control our motor[2] and simulate motions to test in term of harvestable energy. The knee is a very important joint for energy harvesting purpose due to motion amplitude, its angular range is around 120°with an extra range of 40°, to the imposed force and frequency of use, given that walking or running is how humans already expend much of their daily energy. For actuating the energy harvesting system we selected walking and running actions from the CMU motion database spanning frequencies and styles of action.

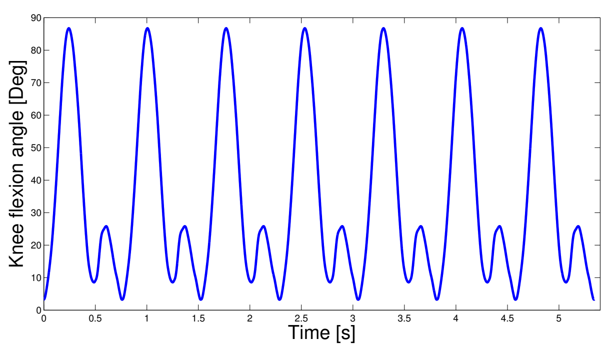


Fig. 4: Typical knee flexion-extension angle trend during walking

For the assessment we performed sixteen acquisition trials with data belonging to seven different subjects with different body geometries and, important thing for this study, with different walking or running styles, in the sense of different motion amplitude and frequency values, even between the two subjects knees in the same trial. This allowed attaining a long range of knee flexion motions, spanning from 0.8 Hz to 2 Hz and from 60°to 115°, see table I, as excitation sources for the energy harvester system.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Results

In piezoelectric transducers, the function describing the output power with reference to the applied load has an absolute maximum (Figure 5) and it is easy to choose the optimal load value (R = 470 KΩ). We tested sixteen different resistances with a run/jog activity (1.29Hz, 83.5°) system input.

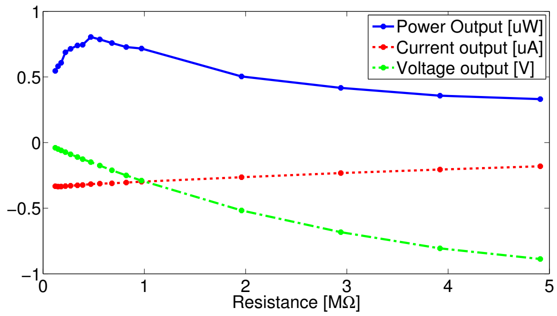


Fig. 5: Measured outputs used for selection of optimal load resistance

The output signals, voltage drop across the optimum resistance and angular position, are measured simultaneously by the ADC and by the microcontroller board acquisition system respectively, in order to correlate the output power with the angular position of the joint.

As expected, we can pleasantly point out that the main parameter influencing the energy harvesting power output is the motion amplitude (Table I). There is an almost monotonic dependency on the motion amplitude (Figure 6), the bigger it is the bigger the power output is and when the movement range is over 100° there is a power output boost of one order of magnitude. On the contrary, the frequency is not very influencing the energy harvesting power output; from the table I we can see that the higher frequencies did not generate the bigger amount of energy.

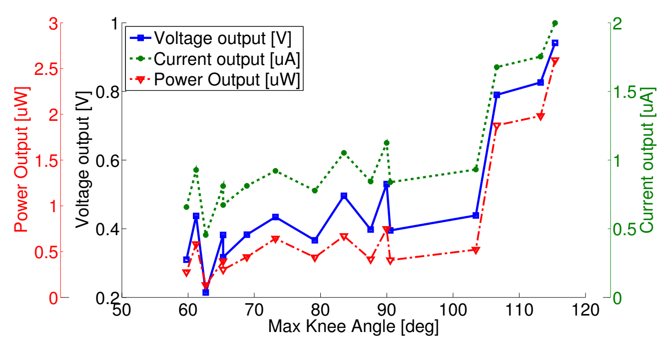


Fig. 6: Measured outputs on the chosen motion set

B. Discussion

The innovative electromechanical transducers developed allows to reach power output levels sharply over those of similar devices [14] currently at the state-of-the-art in research on piezoelectric energy harvesting systems exploiting human joints motion.

The experimental results on the dedicated test bench reported in the previous section can be used to estimate the power harvested from specific human activities. For instance, by considering the flexion-extension motion of the

[1] http://mocap.cs.cmu.edu/
[2] https://github.com/eruffaldi/paper_zp_embc15

CMU_name	Action	Amax (deg)	f (Hz)	Vpp (V)	Vavg (V)	Pavg (uW)	Iavg (uA)
35_01_Left	Fast Walk	59.7	1.79	1.358	0.3099	0.2766	0.6579
08_01_Right	Fast Walk	61.2	1.96	2.428	0.4373	0.5823	0.9282
06_01_Left	Walk	62.7	0.82	1.318	0.2143	0.1354	0.4549
16_36_Left	Run	65.3	1.29	1.472	0.3819	0.3954	0.8107
35_01_Right	Fast Walk	65.3	1.79	1.435	0.3172	0.3024	0.6732
06_01_Right	Walk	68.9	0.83	2.187	0.3827	0.4416	0.8124
08_01_Left	Fast Walk	73.2	1.99	3.212	0.4342	0.6436	0.9218
16_36_Right	Run	79.14	1.26	1.919	0.3665	0.4376	0.7779
02_03_Right	Run/Jog	83.5	1.29	1.983	0.4960	0.6713	1.0528
02_03_Left	Run/Jog	87.6	1.41	1.451	0.3977	0.4170	0.8443
35_26_Left	Run/Jog	89.9	1.41	2.293	0.5301	0.7482	1.1253
35_26_Right	Run/Jog	90.5	1.41	1.460	0.3952	0.4066	0.8388
09_02_Right	Walk/Wonder	103.4	1.29	1.744	0.4387	0.5215	0.9313
09_02_Left	Walk/Wonder	106.6	1.35	3.408	0.7901	1.8794	1.6772
09_06_Right	Run	113.2	1.35	3.448	0.8262	1.9822	1.7538
09_06_Left	Run	115.4	1.35	4.150	0.9414	2.5921	1.9984

TABLE I: Experimental test results

ninth subject knees associated to the run activity at 1.35Hz frequency with 115° motion amplitude, we obtained about 2 and 2.6μW; and by employing two MFC flexible patches per knee, one in the front and one on the back of the joints, it results about 10.4μW output power. Seen the remarkable progress in science and technologies over the past decades direct to develop even more low power microelectronics and power management approaches to minimize the energy consumption while meeting required performance constraints, it will be possible to integrate our energy harvester in wearable wireless devices. For instance, a low power sensing system for human motion detection can be composed of the Nordic Semiconductor nRF51822 RF system-on-chip with an ARM Cortex-M0 32 bit processor integrated, and the Bosch BMI160, 6-axis inertial measurement unit that provides precise acceleration and angular rate measurement. The power consumed by the RF system-on-chip is 1.8μW in stand-by mode, and 31.5mW when transmission is on. Instead, the sensors maximum power consumption is 2.7mW when all the three low power integrated sensors are active. For such configuration the energy generated by the harvester will be temporarily accumulated in a storage battery, which works as reservoir and levels the power supply to the load when needs.

IV. CONCLUSION AND FUTURE WORK

The new energy harvesting system described is a valid starting point to grow a zero-power wearable device for monitoring people anywhere. Collecting mechanical energy produced by human joint motion with such thin piezoelectric patch will allow everybody to extract his power otherwise discarded without having to deal with current biomechanical energy harvesting system constraints as the need to wear specific shoes or to walk at all. Indeed, the main innovation of this work is the non-resonant employment of the piezoelectric transducer. The subject wearing the device is not bound to walk or jog at a specific frequency or as fast as he can, and even post-traumatic patients can produce energy during their rehabilitation therapy. Future developments will focus on the wearable assessment in order to evaluate harvestable energy from different human activities along with the development of an ultra-low-power sensing system for human motion detection.

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