AN ENERGY-AUTONOMOUS WIRELESS TEMPERATURE MONITORING SYSTEM POWERED BY PIEZOELECTRIC ENERGY HARVESTING

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Abstract: Within his publication we demonstrate an energy-autonomous wireless temperature monitoring system that is powered by piezoelectric energy harvesting. An air compressor pump has been chosen as a representative target system. Two different types of piezoelectric generators, cantilever beam with a maximum power output of 37 µW and an impact-type membrane generator with a power output of 120 µW, were employed to harvest energy from vibrations at the host's case and impacts in the host's machine pedestal, respectively. A low-power wireless temperature sensor module was developed and fitted together with a specially designed energy management circuit. The realized wireless sensor system is capable of monitoring and transmitting temperature data with a sampling rate of 1 Hz. Its development has revealed a wealth of design hints for energy harvesting and power management.

Key words: energy harvesting, piezoelectric generator, power management, embedded sensor system

INTRODUCTION

Mechanical shock and vibration are ubiquitous in most technical environments, like fabrication plants, cars or airplanes, and in motions of the human body. A successful harvesting of this waste energy would open many applications for energy-autonomous wireless embedded systems. In a technical system an autonomous power supply would, for instance, allow to monitor the condition of working machinery via an embedded sensor system, without the need of power grids and batteries. An engine failure could be detected by embedded alert systems that would react on unusual vibrations. Applications in and on the human body span from sports equipment over medical implants to man-machine interfaces.

The realization of such energy-autonomous embedded systems will require a close interplay of three different functions: A mechano-electric generator has to harvest the electrical energy for, e.g., an embedded wireless sensor system. This wireless sensor system has to be optimized towards a low power consumption to operate safely in a wide range of power conditions. Finally, an electronic energy management has to ensure a safe start-up and power-down of the sensor system and a maximum energy extraction from the harvester, while working itself at a minimum power consumption.

Vibrational and shock-driven energy harvesters are among the first reported types of energy harvesters and look back onto a long research history of more than 40 years. In comparison to that, the research on electronic energy management for these generators has grown in the recent time. Only a few scientific publications on complete energy-autonomous embedded systems are found until today: An early example with all functional modules described before was presented by Kymissis et al. in 1998 [1]. They used a piezoelectric generator mounted in a shoe to power a wireless pedometer. Other prominent examples of human-powered devices are electro-mechanical wristwatches or battery-less power switches [2]. Tire pressure monitoring is one of the propagated applications of energy-autonomous embedded systems in a technical environment [3]. However, also in this area the number of detailed publications on complete systems is surprisingly small, presumably due to patent issues.

In this publication we present a functional wireless temperature monitoring system that is powered via piezoelectric energy harvesting. During the design of this system a special effort was placed on an optimal interplay of the technical environment, the energy harvesting, the power management and the system function. In the following chapters the general system concept will be presented first, followed by descriptions of all functional units. A special remark will be placed on the important role of the electronic power management for a safe system operation under a varying ambient power condition. At the end of this study similar work was found in the literature [4]. It may be interesting for a comparison of the results.

SYSTEM SET-UP

The wireless temperature monitoring system shown in Fig. 1 was designed to control the motor temperature of an electrical motor. It is powered from the waste mechanical energy of this motor that is harvested by a piezoelectric generator. Commercially

available low power devices were selected for the temperature sensor module and the RF transmitter. A power management circuit was designed as an interface between the piezogenerator and the system electronics. This unit performs the rectification of the AC current of the piezogenerator, an intermediate energy storage, the supply of all electronic modules and a defined system start-up and shut-down.
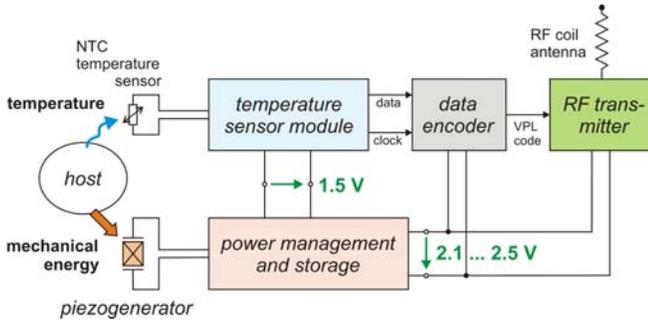

Fig. 1: System set-up of the energy-autonomous wireless temperature monitoring system.

Synchronous electrical AC motors are advantageous hosts for mechanical energy harvesting, as they operate in phase with the constant frequency of the AC main power supply. Consequently, the mechanical vibrations generated by the electrical machinery exhibit an almost constant frequency. This allows for an easy adaptation of a resonant vibration harvester and sets a relatively constant power input for an impact-type harvester.

Within this study a small air compressor pump with a synchronous electrical AC motor was chosen as an easy-to-use host. Suitable locations for a vibration energy harvester were searched with a vibration tester (PCE-VT 2700, PCE Group) mounted at the engine case. The highest acceleration was ± 1.47 m/s² at a frequency of appr. 24 Hz. The mechanical impact forces of the elastic dampers at the engine pedestals were measured with a MEMS force sensor (Honeywell FSS 1500). A dynamic force variation of 4.4 N_{PP} was found with the same frequency.

As described in the following chapter, a vibrational cantilever beam was employed to harvest mechanical energy from the motor case, whereas an impact-type membrane generator was developed to harvest energy from the vertical impacts exerted by the machine pedestal.

PIEZOELECTRIC GENERATORS

A piezoelectric cantilever was applied for vibration energy harvesting (Fig. 2). The generator was fabricated using an established piezo-polymer composite technology, which has already been described in previous publications [5,6]. Two different

harvesters with a cantilever width of 5 mm and 11 mm, respectively, and a common cantilever length of 20 mm were realized and tested within this study. PZT sheet material (Stelco PKG 11) with a thickness of 0.15 mm was used for both devices. The thickness of the polymer layer (epoxy resin Stycast 2057) was set to a value of 0.3 mm [5]. The mechanical resonance frequency of the cantilevers was tuned to the host frequency with a seismic mass applied at the beam tip.
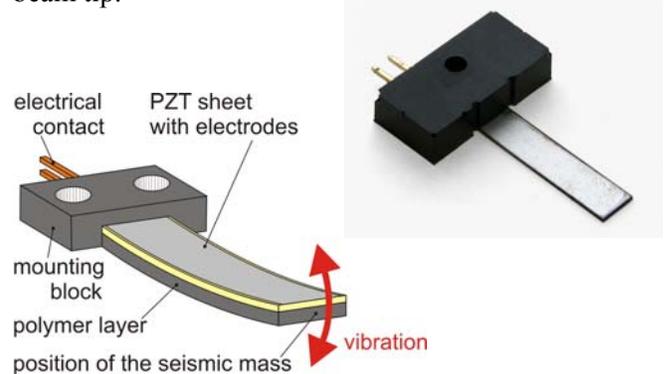

Fig. 2: Piezoelectric cantilever for vibration energy harvesting: Schematic (left) and photograph (right).

Energy from mechanical impacts in the machine pedestal was harvested with an impact-type piezoelectric membrane generator (Fig. 3). The generator was adopted from previous work [7]. It uses a circular steel substrate with a diameter of 35 mm that carries a central piezoelectric layer. The steel substrate is supported around its outer edge with a metal bearing that offers mechanical properties similar to a flexible hinge.
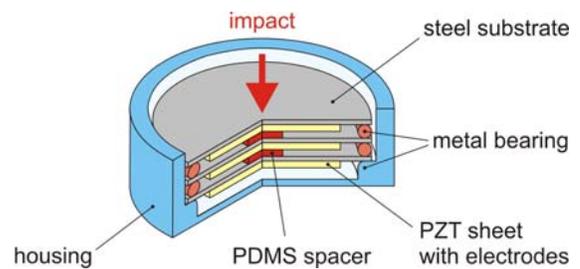

Fig. 3: Impact-type piezogenerator for energy harvesting from mechanical shock loads (schematic).

This support allows a uniform curvature of the piezo-steel disk under a central impact and thus a better uniformity of the mechanical stress in the piezoelectric material. In comparison to that, a rigid clamping would enforce a non-uniform curvature with opposite signs of the mechanical stresses and therefore opposite signs of the generated electric voltage. The result would be a lower conversion efficiency due to internal short circuits [8]. To further

increase the output power, three piezo-steel disks were stacked into an aluminium housing. The mechanical force transduction between all disks was made via elastic PDMS spacers (Fig. 3).

Generator type	P_{max}	R_{opt}	U_B at R_{opt}
Vibrating beam (11 mm)	37 µW	157 kΩ	2.42 V
Impact-type	120 µW	30 kΩ	2.15 V

Table 1: Maximum output power P_{max}, optimum load resistance R_{opt} and optimum load voltage U_B of both piezogenerators (after full-wave rectification acc. to Fig. 5)

Table 1 summarizes typical results for both types of generators. All data were generated with minimal host vibrations as a worst-case condition. The vibrating beam delivers significantly less power than the impact-type generator. It would be feasible to increase the size of the beam or to use several beams for a higher output power. However, such a large generator would not fit well to the size of the host.
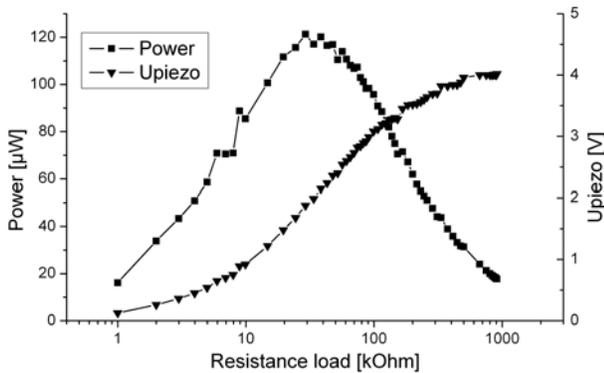

Fig. 4: Load curve of the impact-type piezogenerator when operated with an input force of 4.4 N_{PP} at 24 Hz. The data are taken after full-wave rectification acc. to Fig. 5.

In comparison to that the impact-type harvester offers several benefits: A multiple stack of piezo disks is easily integrated without a significant increase of the device size. Moreover, this generator harvests in the machine pedestal of the host and at a frequency far below its mechanical resonance. In consequence, it will further assist in damping the undesired engine vibrations without any resonance effects. Due to these advantages the impact-type harvester was chosen.

Fig. 4 shows the output DC voltage and output power of the impact-type harvester as a function of the load resistance. For this measurement all three piezo disks were connected in parallel to a single full-wave Shottky rectifier and a 220 µF storage capacitor (Fig. 5). This configuration delivers a maximum output power of 120 µW at an optimum DC load voltage U_B of 2.15 V. In a range of ±0.2 V around this set-point the output power falls slightly to 110 µW.

SYSTEM ELECTRONICS AND POWER MANAGEMENT

For temperature recording a commercial temperature sensor module was chosen due to its low power consumption of 12.75 µW at a supply voltage of 1.5 V. A synchronous serial interface at the sensor module delivers the measured temperature data. A CMOC logic circuit was designed to encode these data into a variable pulse length (VPL) format. Wireless transmission was done in the 433 MHz ISM band using a low-power radio module (AM-RT4-433, RF Solutions Inc.). This module does not draw standby power between data transmissions. With a sampling rate of one temperature reading per second it consumes approximately 60 µW of average power at its minimum supply voltage of 2 V.

As a drawback the temperature sensor module showed a significant increase of its power consumption at sub-threshold supply voltages. This problem is common for many CMOS devices [4] and may lead to a deadlock when an energy harvesting system starts from a zero power state. During start-up the generator is loaded near short circuit, as the voltage at the storage capacitor is still small. The generator may therefore not be capable to deliver enough power to charge the storage capacitor and to overcome faulty sub-threshold current drains.
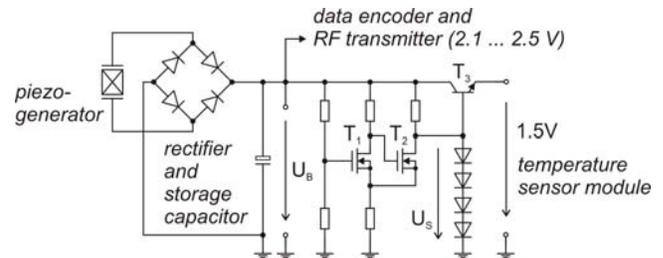

Fig. 5: Electronic power management, composed from a rectifier, an energy storage capacitor and a low-power voltage regulator with Schmitt-trigger characteristics.

To overcome this problem, a voltage regulator with Schmitt-trigger characteristics was designed as a simple, but efficient power management circuit (Fig. 5). The Schmitt-trigger circuit is made from two ultra-low-power MOSFETs T_1 and T_2. Its output voltage U_S defines the driving current for a voltage regulator composed from transistor T_3 and four silicon diodes. When the voltage U_B at the storage capacitor goes above a pre-set value of 2.2 V, transistor T_2 in the Schmitt-trigger is switched off to enable a current flow into the base of transistor T_3 and the clamping diodes. The regulator turns on and delivers a supply voltage of 1.5 V to the temperature sensor module. At a supply voltage U_B of 1.9 V the regulator is shut down again by the Schmitt-trigger via a turn-on of T_2.
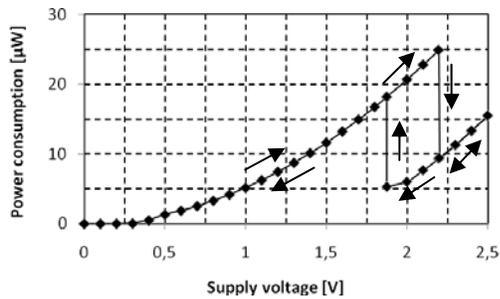
Fig. 6: Calculated power consumption of the Schmitt-trigger voltage regulator versus its supply voltage U_B.

The power management starts operation at a supply voltage of 0.4 V and requires a maximum power of 25 µW (Fig. 6). Due to the discrete circuit design all threshold voltages can be set as desired. This allows a reliable operation in a wide voltage range and avoids an overload of the energy harvester. Also, a significant reduction of power consumption is feasible, but has not been implemented here. In sum, this simple circuit fulfills two important tasks for the energy management: The piezogenerator is operated close to its optimum load point at 2.15 V and a faulty cold start of the system electronics is prevented.

SYSTEM PERFORMANCE

The complete system is shown in Fig. 7. With a diameter of 48 mm and a height of 9 mm the piezogenerator fits under one machine pedestal of the host. The electronic system was integrated into a module with dimensions of 79 mm x 45 mm x 27 mm. After turn-on of the host and a 20 sec harvesting period the wireless temperature sensor system and its internal display start to operate. With a worst-case power supply occurring from minimal host vibrations the DC voltage at the storage capacitor is about 2.3 V. This gives a margin of 0.4 V to the power-down level.

DISCUSSION AND CONCLUSIONS

An energy-autonomous embedded sensor system has been realized as a test bed for system design. Two types of piezoelectric generators were compared to find the best suitable concept. As result, an impact-type piezogenerator was designed that is easily fitted at the host and delivers 120 µW of electrical power. Commercial electronic devices with low-voltage and low-power capabilities were selected for sensor signal processing and RF transmission. A specific power management was designed for a safe system start-up and an optimal energy transfer from the harvester.

It turns out that an optimal system design, i.e. the best interplay of energy harvesting, power management and system function, is crucial for energy-autonomous embedded systems. This demands a more
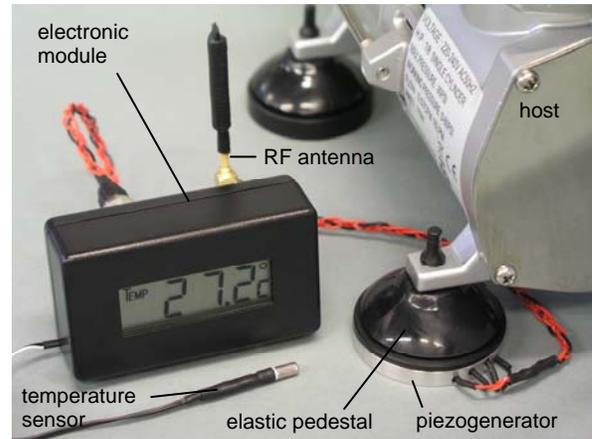

Fig. 7: Photograph of the energy-autonomous wireless temperature monitoring system together with the impact-type piezogenerator, taken during operation at the host.

system-oriented approach, especially for the research on energy harvesters and power management concepts. Also, power management circuits with a low transistor count may be a good choice for energy harvesting applications due to their potentially low power drain and predictable behavior under variable power supply.

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