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# Autonomous Sensor System with RF Link and Thermoelectric Generator for Power Harvesting

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***Abstract*** *– Autonomous sensing system is a promising approach in applications that do not allow cabled solutions and the use of battery has maintenance problems. In this paper an autonomous sensor system with low power electronics for RF communication and with an energy harvesting module is presented. The sensored system is proposed for temperature measurements, but it can be used with other sensor types to measure different quantities. When the autonomous sensor is placed on a heat source, a thermoelectric module harvests energy, powering the autonomous sensor. In this condition no external electromagnetic field is necessary, the temperature measurement is performed and the data are saved in non-volatile memory. When the readout unit is active the electromagnetic field is used to power the autonomous sensor system and to communicate the data. An experimental set-up has been arranged to compare the temperature data of the heat source collected by the autonomous sensor and a referenced thermoresistance. The experimental measurements shows good agree between the two measured temperature data. The wake-up signals demonstrate that the autonomous system works correctly for a temperature gradient of less than 9 °C, and with a readout distance of few centimeters. The presented autonomous sensor system can be efficiently used for measurements into close environment in which a temperature difference is present.*

***Keywords*** *– Autonomous sensor; power harvesting; energy scavenging; RFID sensor.*

## I. INTRODUCTION

Autonomous sensors, that can be interrogated contactless and need no batteries, are attractive for operation in applications that do not allow the use of cabled solutions, e.g. in-package [1-3] or in-body measurements [4]. In these applications the use of batteries has maintenance and replacement problems; therefore the system is often required to be powered in way that avoids batteries. In many applications reported in literature [1-5] the autonomous sensing system uses the electromagnetic field as power supply. When the readout unit interrogates the sensored system, the transmitted RF signal is used to power the passive system and so both wireless data communication and power supply are handled via an electromagnetic field and a coil antenna of the transponder interface. In this way, however, the sensor measurement can be achieved only at the time when the system is interrogated by the readout unit, because at other times the system is not powered. To allow the possibility of performing the measurement when needed, independently from the presence of the readout unit, power harvesting can be used in order to power the passive system when electromagnetic field is not applied by the readout unit.

Thermal gradients and mechanical vibrations can be used as power harvesting sources, and the energy conversion is usually performed using thermopiles and piezoelectric converters, respectively. When exposed to temperature gradients, thermopiles can generate DC output voltages of about 1 V, too low for powering commercial ICs, but current values up to one hundred milliampere [6-7]. On the other hand piezoelectric converters, if mechanically excited, can supply AC output voltages with many tens of volts of amplitude, but very low currents in the order of tens or hundreds of microampere [8-9].

In this work energy conversion is performed using commercial thermopiles, not specifically designed for power generation. In order to power autonomous systems, the converted energy must be properly handled, and in particular the thermopile output voltage value must be increased and regulated. To this purpose, integrated DC-DC converters can be used in order to boost the voltage as required.

The power converted can be time discontinuous, due to environment conditions change, so power supply from energy harvesting can not be always guaranteed. To avoid data loss it is necessary that the autonomous system be able to save the data into a non-volatile memory. The stored measurement data will then be downloaded from the system by the readout unit during RF interrogation.

In this paper an autonomous sensor system with low power electronics for RF communication and with an energy harvesting module is presented. The sensored system is proposed for temperature measurements, but it can be used with other sensor types to measure different quantities. The concept and the technology developed in the project can find application in solutions without batteries and cables. In general, it is expected that the applications that will benefit more from the project results will be those where the absolute and relative measurement timings are not critical. A possible application could be the temperature monitoring of an isolated system inside a hermetic environment using the thermopile for the power supply and storing the data. The readout unit could interrogate the autonomous sensor system for collecting data. Applications can be found for instance in [10]: industrial automation and automotive for predictive maintenance, and medical appliances field.

 

## II. EXPERIMENTAL SYSTEM

The experimental system consists of an autonomous sensor and a readout unit. The autonomous sensor system performs temperature measurements, exploiting environmental thermal gradients for its power supply. It includes a TEG (ThermoElectric Generator) module with the related electronics for the management and conversion of the power.

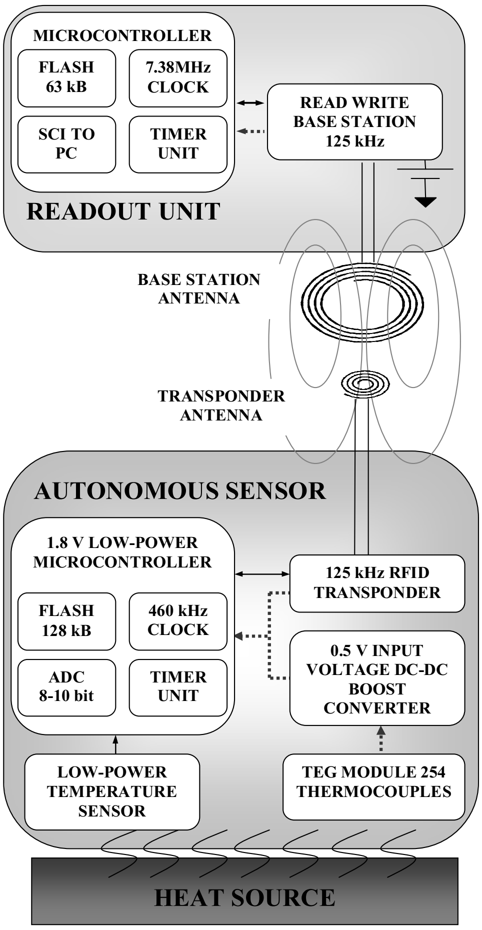


Fig. 1. Block diagram of the autonomous sensor system and the readout unit.

The system incorporates a RFID module providing signal transmission via electromagnetic coupling at 125 kHz, with operating distance in the order of few centimeters, for the communication with a readout unit. The advantage of transmitting an electromagnetic field at low frequency is the possibility to transfer data and power supply through different materials, like animal and human body tissues. The system implements strategies to reduce the power consumption: the sensor module is designed to be triggered to transmission only when required, thereby consuming less power because unnecessary transmissions are avoided.

An example of application, that is being arranged, is the possibility of using the autonomous sensor system with the aim of monitoring working parameters (i.e. temperature) of a heat exchanger for predictive maintenance. In fact the exchange efficiency of these devices decreases during the life cycle. The autonomous sensor can be fixed inside the device for all the life cycle and monitor if the efficiency decreases.

When the autonomous sensor is placed on a heat source, the TEG harvests energy, generating an output voltage. If this voltage value is high enough, the DC-DC step-up converter switches on, powering the autonomous sensor. In this operation the readout unit does not supply power by magnetic field, and the autonomous sensor system works without any external electrical power source. In this condition, the microcontroller performs the temperature measurement, saving the data in its non-volatile memory. Data can be then collected at subsequent times using the readout unit by RF communication. In the reading operation, the presence of a heat source is not strictly necessary, since the power supply is provided via electromagnetic field and the coil antenna of the transponder interface.

### *A. Autonomous sensor*

In Fig. 1 the proposed autonomous sensor system is reported. It consists of different modules integrated in a PCB board: a low-power temperature sensor, that measures the temperature of a heat source; a low-power microcontroller for the analog to digital conversion of the data, the storage into flash memory and the RF operation; a RF transponder, that transfers the data collected to readout unit; a voltage DC-DC converter in order to boost the internal voltage from the thermoelectric generator.

The low-power temperature sensor LM94022 is a precision analog output CMOS integrated-circuit temperature sensor that operates at a supply voltage as low as 1.5 V. The adjustable gain is set to obtain the lowest power, in this state the specified sensitivity is -5.5 mV/°C.

To transmit data the 125 kHz RFID transponder (U3280M) modulates the magnetic field using a damping stage; in particular the OOK modulation and the Manchester code are chosen to modulate the signal. The clock extractor pin is used to provide a field clock for the synchronization data transfer. The transponder interface can also receive data: the readout unit modulates the data with short gaps in the field and a gap-detection circuit detects these gaps and decodes the signal. Moreover the device is able to generate a power supply, which is handled via electromagnetic field and the coil antenna of the transponder interface.

The low-power microcontroller chosen is the Freescale 9S08QE128 which offers an 8/12-bit analog to digital converter, 128 KB Flash memory to save the data and a timer unit that permits to synchronize the data transmission. To maintain the power consumption low, the bus frequency is fixed to 460 kHz, the ADC and flash programming unit have a low-power configuration, and all the unused modules are switched off.

The power harvesting modules consists of a DC-DC converter (TPS61200) and a ThermoElectric Generator TEG. The DC-DC converter is a voltage boost (step-up) converter that switches on when the input voltage goes over 0.5 V, providing a regulated output voltage, set to 2.1 V.

The used TEG is the module TGM-254-1.0-1.3 by Kryotherm with dimension of (40x40x3.6) $mm^3$, which is composed of 254 thermocouples connected electrically in series and thermally in parallel. When a temperature difference $\Delta T$ is applied between the TEG faces, an open-circuit output voltage $V_G$ is generated according to the following equation:

$$V_G = \alpha N \Delta T \tag{1}$$

where $\alpha$ is the Seebeck coefficient of the TEG material, $N$ is the number of thermocouples and $\Delta T$ is the temperature difference applied.

### *B. Readout unit*

The readout unit consists of a read/write base station (U2270B), which is able to supply power to transponder driving the coil antenna and to demodulate the digital signal. The electronic circuit configuration used permits communication distance of about few centimeters.

The read/write base station also supplies the microcontroller 9S08AW60, that recovers and decodes the signal sent by the output pin of read/write base station. The operating voltage of microcontroller is 5 V and the frequency of the bus clock is 7.38 MHz. A timer unit is used to decode the demodulated signal and the data collected are transferred to PC using SCI.

The operating distance between reader and transponder depends on the antenna performances.

The developed antennas have a radius of 6 cm, a length of about 1 cm and 60 windings. The inductance measured with an impedance analyzer (HP4194A) is about 3.3 mH.

The antennas used are coils connected with a capacitor to form a LC parallel circuit. The resonance is fixed to about 125 kHz and the correct LC combination can be calculated using the classical resonance formula:

$$C = \frac{1}{L \cdot (2\pi \cdot f_0)^2} \tag{2}$$

where $f_0$ is 125 kHz, the operating frequency. Then the capacitance used is about 470 pF.

## III. EXPERIMENTAL RESULTS

### *A. Measuring and saving data operation*

One side of the TEG module was heated by a heater, externally powered, while a heat sink was applied on the other side, in order to maintain the temperature as low as possible. The temperatures on the two faces of the TEG were measured using two NTC thermistors, attached with termoconductive grease. The temperature difference was slowly varied from 0 °C to 13 °C while the output voltage of the TEG was measured in open circuit and loaded conditions, reported as $V_G$ and $V_L$ respectively.

Experimental results are shown in Fig. 2, which reports both the open-circuit output voltage $V_G$ of the TEG, when no load is connected and the output voltage $V_L$ across the load formed by the entire system (DC/DC converter, temperature sensor, microcontroller). These voltages are shown as a function of the temperature difference $\Delta T$. As expected from eq. (1) the open-circuit output voltage $V_G$ and the temperature difference $\Delta T$ are directly proportional.

It is visible that when the temperature difference is lower than about 3 °C, the DC-DC converter is off. In this case there isn't loading effect on TEG and the curves of $V_G$ and $V_L$ overlap. When $\Delta T$ goes beyond 4 °C, the step-up converter is switching on, requiring a current that decreases the $V_L$ voltage (intermediate phase). Hence the output voltage $V_{CC}$ of the DC-DC converter is lower than the set value of 2.1 V. In this start-up situation the boost converter has a high current absorption. When $\Delta T$ reaches a value of about 8.5 °C, the step-up converter switches on completely.

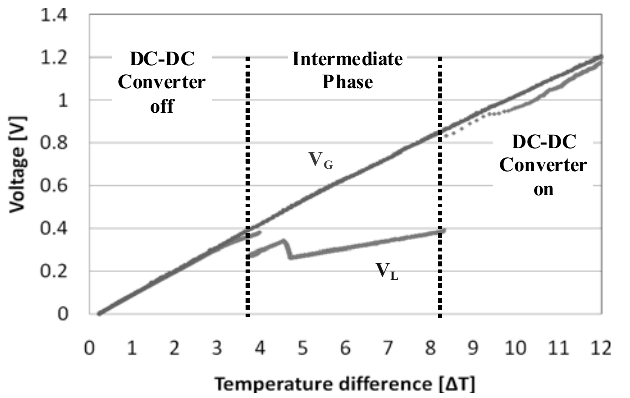


Fig. 2. Measured output voltage of TEG: $V_G$ – open circuit output voltage; $V_L$ – output voltage on loaded condition.

The output voltage of the DC-DC converter switches to 2.1 V as expected, while the current absorption falls off, causing a fast increase of the voltage output $V_L$. From experimental data, when the temperature difference applied across the TEG module goes beyond 8.5 °C, the autonomous system switches on, working correctly.

Fig. 3 shows the main signals when the system wakes up due to the interrogation from the reader. The signals are: the voltage output of TEG module ($V_L$), the output voltage of the boost converter ($V_{CC}$) and the microcontroller clock.

In the first time interval ("start-up boost converter") when the voltage generated by the TEG exceeds 300 mV the DC-DC converter begins to start-up.

In the "start-up µC" interval time the boost converter output charges the capacitors connected to it and at 1.8 V switches the microcontroller on. When $V_L$ exceeds 0.4 V, the DC-DC converter turns on generating a stable output voltage of 2.1 V. From this moment, the sensor and the microcontroller are powered and the system works continuously, until the temperature gradient is maintained.

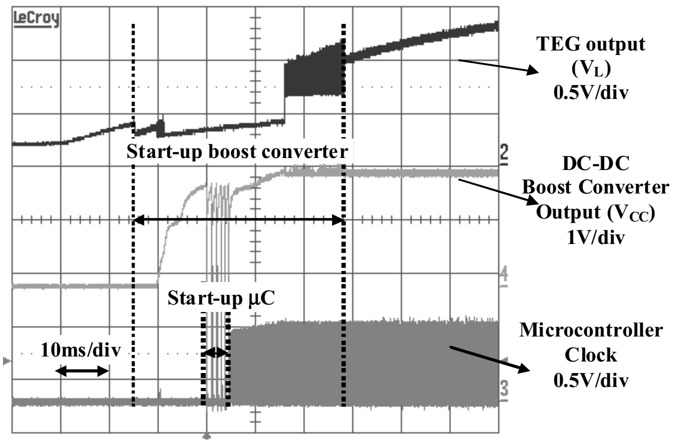


Fig. 3. Wake-up signals with the power harvesting module

In tests performed, the autonomous sensor system, powered by TEG, permits to save the measurement data into a non-volatile memory. It was verified that the collected data are correctly stored and can then be downloaded by the readout unit. In this situation the microcontroller and the temperature sensor require a power supply of about 0.9 mW, with a current consumption of about 0.4 mA and a voltage level of about 2.1 V.

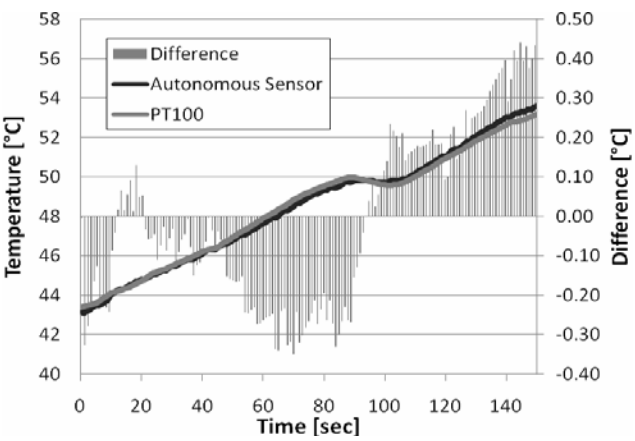


Fig. 4. Comparison between the two measured temperature data.

Fig. 4 shows the temperature of the hot side of the TEG corresponding to the data stored in the microcontroller non-volatile memory, the temperature measured by a referenced Pt100 thermoresistance and the difference between the temperature values measured by the autonomous sensor and the Pt100. The figure shows that the maximum temperature difference is about 0.5 °C.

*B. RF communication*

In Fig. 5 the wake-up signals with the RF power supply are reported. The signals are: the differential voltage of the reader antenna, the voltage of the transponder antenna, the output voltage of the transponder used to power the microcontroller, and the microcontroller clock.

In the first time interval (start-up transponder) the reader is turned on and the electromagnetic field supplies the transponder charging the capacitors. In the second time interval (start-up µC) the transponder is turned on and the capacitors, connected to microcontroller, are charging.

The total wake-up time is about 100 ms. The data communication starts after 20 ms from microcontroller clock wake-up, as it is shown from transponder antenna signal.

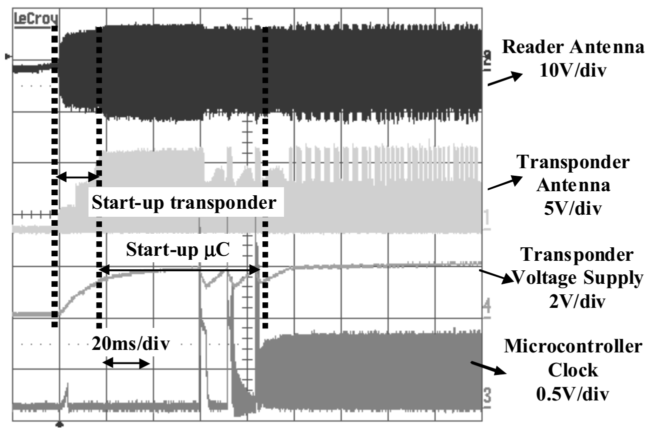


Fig. 5. Wake-up signals with the RF power supply.

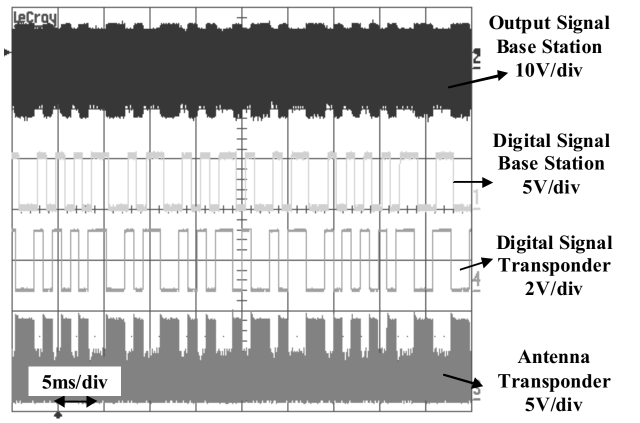


Fig. 6. Wireless transmission of the recorded temperature data.

In Fig. 6 the wireless transmission is reported. It is obtained considering a normal functioning and transmitting the measurement data collected in flash. The low-power microcontroller connected to transponder sends the digital signal for the transmission.

The tag antenna signal is reported below; it shows the OOK modulation of the digital signal. The base station receives the reflected back signal (Output Signal Base Station) and extracts the information Manchester encoded (below).

In this experimental configuration the current consumption for RF communications is about 190 µA at 2.58 V. The measurements are obtained using two multimeters (Fluke 8840A). The RF-field transfer of data is configured transmitting continuously the measurements to the base station placed at distance of about 15 mm. All the unnecessary module of the microcontroller unused is switched off, ADC and flash programming included.

The RF-field transfer at 125 kHz permits to reach a distance between the readout unit and the autonomous sensor that depends on antenna performance, transponder power and medium interposed.

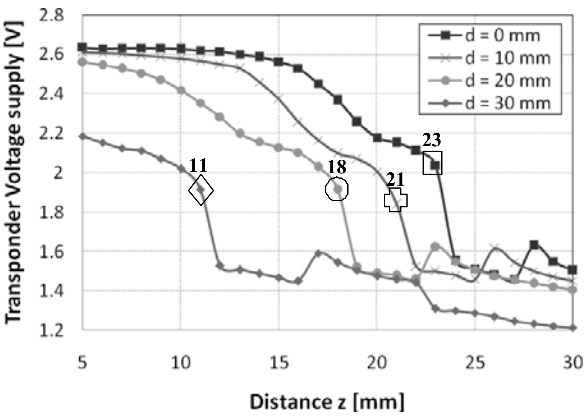


Fig. 7. Transponder Voltage Supply for different distances and in a non-axial configuration.

In Fig. 7 the transponder voltage supply is measured with a multimeter (Fluke 8840A) when the autonomous sensor system is transferring data. The distance *z* between the antennae of the Base Station and the autonomous sensor is changed from 5 mm to 30 mm using a micrometer screw, while *d* represents the shift from the coincident axial position of the two antennas. For every diagram the highlighted values represent the maximum distance for the correct transfer data.

## IV. CONCLUSIONS

In this paper an autonomous sensor system with wireless RF communication and with a thermoelectric module is presented.

The device measures the temperature of a heat source, saves data into a non-volatile memory and transfers measured data by a RF link. The system consists of a low-power analog temperature sensor, a low-power microcontroller for the analog to digital conversion of the data, for storage into flash memory and for RF operation, providing signal transmission via electromagnetic coupling at 125 kHz, for the communication with an external readout unit.

During measuring and saving operation the autonomous sensor system harvests power from heat source by thermoelectric module connected to a voltage DC-DC converter in order to boost the internal voltage from the thermoelectric generator and doesn't require the power from the external readout unit.

The data can be collected using the external readout unit by RF communication. When the readout unit interrogates the system the power of the autonomous sensor is supplied by the electromagnetic field generated by the external readout unit.

The experimental results show the functioning of the system in the operations of measuring, saving and transferring: the system works correctly for a temperature gradient of about 8 °C and a maximum readout distance of about 23 mm, when the two coils are coaxial.

## REFERENCES

[1] E. L. Tan, W. N. Ng, R. Shao, B. D. Pereles, K. G. Ong, A wireless, passive sensor for quantifying packaged food quality, Sensors 2007,7 (2007),1747-1756.

[2] A. Vergara, E. Llobet, J.L. Ramırez, P. Ivanova, L. Fonseca, S. Zampolli, A. Scorzoni, T. Becker, S. Marco, J. Wollenstein, An RFID reader with onboard sensing capability for monitoring fruit quality, Sensors and Actuators B 127 (2007) 143–149.

[3] E. Abada, S. Zampolli, S. Marco, A. Scorzoni, B. Mazzolai, A. Juarros, D. Gomeza, I. Elmi, G. C. Cardinali, J. M. Gomez, F. Palacio, M. Cicioni, A. Mondini, T. Becker, I. Sayhan, Flexible tag microlab development: Gas sensors integration in RFID flexible tags for food logistic, Sensors and Actuators B 127 (2007) 2–7.

[4] A. M. Sodagar, G. E. Perlin, Y. Yao, K. D. Wise, K. Najafi, An Implantable Microsystem for Wireless Multi-Channel Cortical Recording, Proceedings of Transducers '07, Lion France (2007), 69-72.

[5] S. Yeh, K. Chang, C. Wu, H. Chu, J. Y. Hsu, GETA sandals: a footstep location tracking system, Pers Ubiquit Comput (2007) 11, 451–463.

[6] M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli, A. Taroni, Characterization of Thermoelectric Modules for Powering Autonomous Sensors, Proceedings of IMTC 2007 Instrumentation and Measurement Technology Conference, (2007).

[7] M. Strasser, R. Aigner, C. Lauterbach, T.F. Sturm, M. Franosch, G. Wachutka, Micromachined CMOS thermoelectric generators as on-chip power supply, Sensors and Actuators A 114 (2004), 362–370.

[8] M. Ferrari, V. Ferrari, D. Marioli, A. Taroni, Autonomous Sensor Module with Piezoelectric Power Harvesting and RF Transmission of Measurement Signals, Proceedings of IMTC 2006 Instrumentation and Measurement Technology Conference, Sorrento Italy (2006).

[9] S. Priya, Advances in energy harvesting using low profile piezoelectric transducers, J Electroceram (2007) 19, 165–182.

[10] H. Ramamurthy, B.S. Prabhu, R. Gadh, A.M. Madni, Wireless Industrial Monitoring and Control Using a Smart Sensor Platform, Sensors Journal, IEEE Volume 7, Issue 5, May 2007, 611 – 618.