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Preliminary Studies on Autonomous Sensor Systems Dedicated to Air Quality Monitoring

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Abstract **– Sensor systems and smart networks devoted to environmental supervision have today assisted the analysis of primal processes and they have also provided vital hazard early warnings. At the same time the use of environmental energy is now rising up as a potential energy source dedicated to embedded and wireless computing systems where manual recharging and/or replacement of hundreds or even thousands of batteries on a regular basis is not practical. This paper presents and illustrates SENNO (SENsor NOde), a multi-parametric sensor node that intelligently manages energy transfer for perpetual operation without human intervention during air quality monitoring. The overall system design and experimental results are presented together with energy budget allocation. Preliminary results demonstrate that, after a tailored calibration process, the presented platform could effectively report and trace air quality levels in a sort of "*set and forget*" scenario.**

I. INTRODUCTION

Recently, the design and fabrication of satisfying air monitoring systems have been emphasized in reports of health diseases allied to poor atmospheric quality levels **[1-3]**. Identifying pollutants in the air and defining polluted locations and adopting air monitoring systems is paramount to the preliminary process of standard air-quality improvement techniques (e.g., improved ventilation, air cleaning and air sanitation) **[4,5]**. Advances in micro-electro-mechanical systems (MEMS), electrochemical gas transducers and wireless sensor networks technologies have permitted the development of highly-efficient, low-cost (and low-power) air quality monitoring systems (dedicated to pollutants detection and analysis) and their deployment in real environments **[6-14].** Moreover, the combination of an air monitoring system with wireless sensor networks technology is expected to reduce installation cost and thus enabling rapid and simple reshaping of the data acquisition/control arrangements. Moreover, networked monitoring systems dedicated to air pollutants ensure low-cost and continuous observation. However, remote monitoring needs rugged and reliable sensor nodes to be integrated in potentially wide, disruptive and distributed environments. Crucial issues for the deployment of these wireless nodes is that they require high levels of power-efficiency for autonomous, long and continuous operation, This is partly due to the battery replacement cost that may get too prohibitive in case of long operation time in wide deployment scenarios. This approach calls to envision a "*set and forget*" scenario. At first glance, batteries seem to guarantee an optimum source of energy for wireless sensor systems when commercial battery technologies are adopted, thus, giving aggregated, powerful energy capacity in nearly small form-factors. Today, the main trend in battery technology is towards improvements in higher energy densities. This approach has obvious advantages for portable device in which increasing the time between charges and high miniaturization of system size is paramount. In any case, energy density is not, unquestionably, the critical issue for the choice of battery technology for a wireless sensor node in a "*set and forget*" use. On the basis of this scenario, battery characteristics such as self-discharge, or lifetime, are reasonably more important than energy density or capacity and size. The adoption of a "*set and forget*" approach in this wireless sensor platform definitely results in the energy accessible to the system being bounded by the starting energy capacity of the battery together with the unforeseeable lifetime characteristics of the battery. The above mentioned effort has driven the development of methods to maximize wireless sensor systems' lifetime by minimizing energy consumption. This is achieved by adopting ultra-low power electronics (i.e. ultra-low power microcontroller with sleep current around 100 nA). The use of virtually no-power-consumption sensors (e.g. electrochemical sensors connected to signal conditioning electronics with supply current around 1uA) coupled with wireless

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communication that uses duty cycling based on long sleep times (i.e. the device remains in low power "SLEEP" mode for more than 95% of the time) helps also to realize the above goal of maximizing sensors' life time. Hence The sensorized node will be operative only for the time needed to achieve the operations of sensor warm-up, sampling, data processing and wireless data transmission or communication. This paper addresses some of the key issues related to the delivery of autonomous power for wireless sensor systems with the aim of developing a multi-parametric smart SENNO (SENsor NOde) dedicated to air quality monitoring systems.

II. THE SYSTEM CONFIGURATION

The complete designed and manufactured system named SENNO (SENsor NOde) is depicted in Figures 1 and 2 where the main blocks are indicated and well distinguishable (in green blocks related to power harvesting). In the following paragraphs a brief description of the different sections is reported.

A. Air quality sensors

The primary target of our system is to build an air quality-monitoring tool that measures the pollutants with inexpensive compact sensors. Several types of off-the-shelf chemical gas transducers can be found in the market. Each gas transducer has different operation principles, size, accuracy and power consumption varying with sensor type. With the use of electrochemical technology, this type of sensor features both a small size and a fast response time.

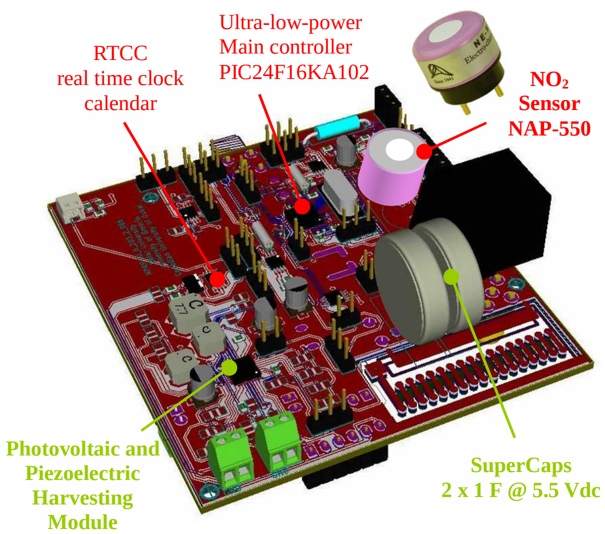


Fig. 1. 3-D of SENNO PCB with blocks (top layer) .

Moreover electrochemical sensors offer several advantages for systems that detect or measure the concentration of different toxic gases. All the sensing elements are gas tailored and show resolutions around one part per million (ppm) of gas concentration matching

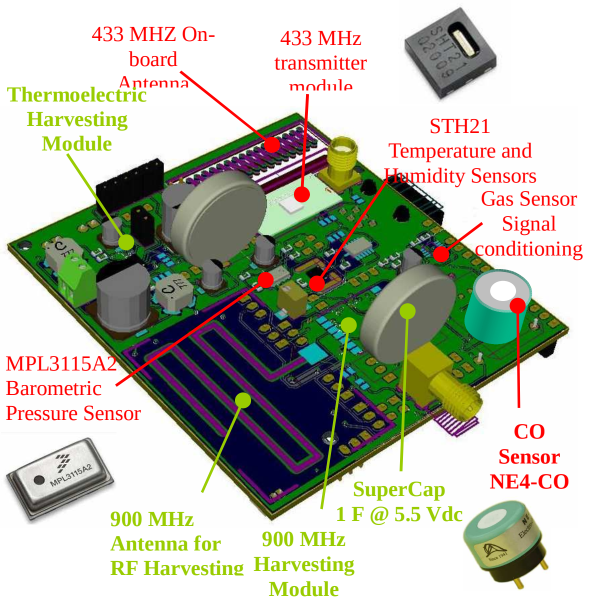


Fig. 2. 3-D of SENNO PCB with blocks (bottom layer) .

the EPA requirements. They operate with very small amounts of current, making them well-suited in self-powered wireless nodes. In our project we have adopted the following electrochemical sensors: NE4-CO Carbon monoxide, Nitrogen dioxide NE4-NO2, NE4-NO Nitrogen monoxide, NE4-H2S Hydrogen Sulphide and NE44-NH3 Ammonia from NEMOTO (examples of the sensors adopted integrated in the PCBs are reported in Figures 1 and 2). A temperature/humidity and a barometric pressure sensor (Sensirion STH21 and Freescale MPL3115A2) were also adopted in the sensor board. This is due to the fact that the sensed data of the gas transducer are susceptible to ambient temperature and humidity.

B. Power management and energy harvesting methods

The integration of numerous sensors (i.e. gas sensors, barometric pressure sensor, humidity sensor and temperature sensor) and the 433 MHz data transmission into a single sensor board led to practical problems, especially in terms of energy consumption and energy management. In order to provide an autonomous source of energy for the wireless sensor system SENNO, one can take into account scavenging energy from the environment with the aim to increase the battery energy storage (if battery is intended to be used in a rechargeable configuration) or indeed completely replace it. The sources of energy which have been identified (e.g. working together in a concurrent energy recovering functionalities) are:

i) a vibration energy harvester dedicated to the conversion of otherwise waste energy from mechanical vibrations into useable electric energy. With the aim to best accomplish this the mechanical resonator has been mounted in a tailored configuration tuning the natural frequency of the harvester to match the vibration sources. The mechanical resonator is based on PZT materials (reference number V25W Volture series from Midè Inc.). Example of the power generated for different combination of resonance frequencies/seismic masses/accelerations are given below:

- Frequency tuned to 75 Hz with acceleration = 0.5 g and 16 g seismic mass: Power extracted = 2.3 mW

- Frequency tuned to 130 Hz with acceleration = 0.5 g and 2.5 g seismic mass: Power extracted = 0.8 mW

- Frequency tuned to 180 Hz with acceleration = 0.5 g and 0 g seismic mass: Power extracted = 0.6 mW;

ii) six high-performance TEGs generators with highly-efficient thermoelectric effect (reference number TG12-2.5-01L from Marlow Industries inc.). The current/voltage ratios under different temperature gradients are as reported below:

5 °C : ICC= 47 mA @ 75mV (power transferred to SENNO, due to impedance mismatching = 0.5 mW)

15 °C : ICC= 127 mA @ 200mV (power transferred to SENNO, due to impedance mismatching = 3.8 mW);

iii) one RF power source @ 900 MHz based on the Powercast P2110 harvester receiver that converts RF to DC. This module features high efficiency and ultra low power consumption

iv) One indoor thin-film amorphous silicon solar cell as energy power source with power density of 0.035uW/mm2 @ 200lux (reference number 12/096/048 from Solems S.A. France). The current/voltage ratios under different illumination levels are:

- 200 lux (artificial light): 33uA @ 4.8 Vdc

- 1000 lux (artificial light): 165uA @ 5.4 Vdc;

v) one outdoor (through window) thin-film amorphous silicon solar cell as energy power source with power density of 6 uW/mm2 @ 200W/m2 (reference number 12/096/072 from Solems S.A. France). The current/voltage ratios under different illumination levels are:

- 200 W/m2 (natural light): 7 mA @ 6 Vdc

- 1000 W/m2 (natural light): 33 mA @ 6.5 Vdc.

The highly integrated LTC 3109 AC/DC converter ideal for harvesting surplus energy from extremely low input voltage sources has been used for the TEGs section. The module is designed to use two small external step-up transformers (adopted ratio is 1:100) to create an ultralow input voltage step-up DC/DC converter and power manager that can operate from input voltages of either polarity. This capability enables energy harvesting from thermoelectric generators (TEGs) in applications where the temperature differential across the TEG may be of either (or unknown) polarity. This function covers automatically, SENNO stacked to a window, for the case where differences between external ambient temperatures and indoor room temperature can serve as a source of energy harvesting. The energy converter manages the charging and regulation of multiple outputs in a system in which the average power draw is very low, but where periodic pulses of higher load current may be required. This approch is crucial where the quiescent power draw is extremely low most of the time, except for 433 MHz transmit pulses when circuitry is powered up to make measurements and transmit data.

III. PRELIMINARY EXPERIMENTAL RESULTS

Experiments have been conducted to obtain and understand the basic characteristics of the environmentally-powered sensor node SENNO in two prototypes hardware. Each of the two complete SENNOs has been equipped with the harvesting section (thermoelectric, photovoltaic and RF all loading at the same time a 1 F SuperCap @ 5.5 Vdc) together with five sensor array based on two gas sensors (CO and NO_2), one temperature sensor, one humidity sensor (RH%) and a barometric pressure transducer. The prototypes have been tested for 5 months deployed in three dedicated studies, both in Italy and Doha (Qatar) in different conditions (of light emission, vibration levels, temperature gradients and RF radiation power). We carried out three basic studies. The first study was one week long and focused on how the five sensors array installed on the PCB board responded to temperature variations in a thermal range from +5 °C till to +50 °C in a controlled environment. The electrochemical sensors NEMOTO NE-CO (output current of 65 nA per 1 ppm of carbon monoxide) and NEMOTO NE-NO2 (output current of 690 nA per 1 ppm of nitrogen dioxide) together with the PCB board and the other sensors were placed in the PERANI UC150/70 climatic chamber (fixed location), and the atmosphere was controlled so that no substance could cause pollution.

A zero drift lower than 5 ppm has been obtained for the NEMOTO NE-CO while the NEMOTO NE-NO2 demonstrated a drift as low as 1 ppm.

The second study which consisted of the characterization of CO and NO_2 sensors is summarised in Figures 4 a) and b). Each of the studied gas sensors is separately deployed in a tailored test chamber as part of the Laboratory of Sensors at the University of Brescia (Italy). The levels of gas concentration in ppm are fixed using a mass flow controller connected to gas bottles with standard concentration (e.g., 10 ppm NO_2). Important parameters such as temperature and humidity are measured using the temperature and relative humidity sensors installed on-board of the SENNOs nodes. Fixed values of temperature and relative humidity are imposed around 25°C (± 5 °C) and 50 ±10% respectively.

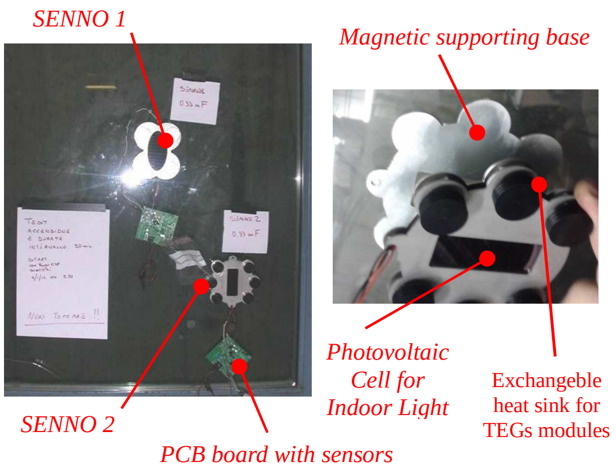
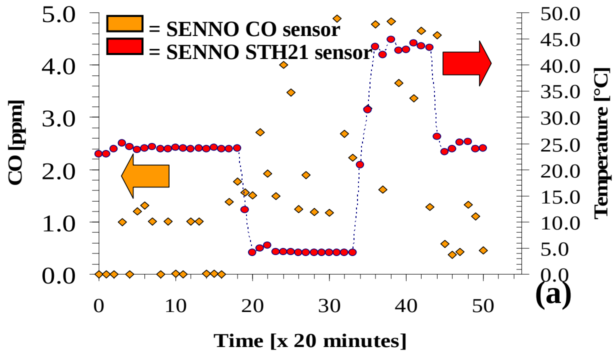


Fig. 3. SENNO 1 and SENNO 2 during the test .

The voltages obtained from SENNOs sensors' channels are received via 433 MHz wireless line in a receiving node and stored in the main processing and control unit (desk PC) that performs the data processing and data logging. The data have been also published through a LabVIEW Web server which collects an historical evolution of the air quality in the monitored gas chamber areas and to evaluate air quality trends.

The third study was dedicated to a first evaluation of the SENNO power consumption vs perpetual functionality in an indoor application where the harvesting sections were fixed to a window as reported in Table 1 (see Figure 3). The Total energy harvested from the environment exceeded the total energy required by SENNO by almost a factor of four if we only consider internal artificial light, RF and thermoelectric effect (while the factor moves to 50 considering external light) and thus envisioning a perpetual operation without human intervention for battery replacement. A system operating cycle of once in every 20 min is considered.



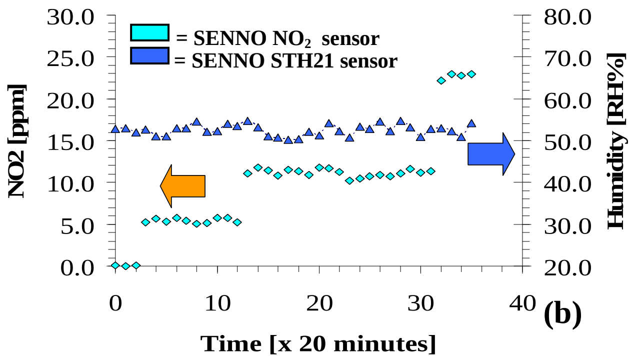


Fig. 4.(a) Temperature zero drift for the CO gas sensor (b) Gas sensor response to NO_2

Table 1. *Energy allocation per day under different conditions*

Operation	Energy per day (J)
Sensors Warm-up (60 seconds every 20 minutes)	0.4
Sensor Measurement (2 seconds every 20 minutes)	1.15
Data Processing and Storage (1.0 seconds every 20 minutes)	0.01
Data Transmission (0.6 seconds every 20 minutes)	0.69
Sleep Mode (19 minutes every 20 minutes)	0.5
Total System Energy Budget Required by SENNO prototype per day	**≅ 2.75**
Total Energy Recovered per Day Under the Following Conditions:	**≅ 137.3**
1- Energy from External Low Sunlight (average: 4 hrs 100 W/m², 3 hrs 50 W/m², 10 hrs night 0 W/m²)	125
2- Energy from Internal Artificial Light (office average: 8 hrs 200 lux)	4.3
3- Energy from Temperature Difference Throught the Window : 10 hrs with 5 °C and 14 Hrs with 0°C (non-operative)	6.2
4- RF Energy @ 900 MHz: 3 W EIRP (trasmitted) with SENNO positioned at 5 m (24 hrs operative)	1.8
5- Energy from Vibrations: none	0

IV. ACKNOWLEDGMENTS

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V. CONCLUSIONS

In the present paper we have presented SENNO (SENsor NOde), a multi-parametric sensor node that intelligently manages energy transfer for perpetual operation without human intervention during air quality monitoring in indoor applications. The overall system and first experimental results have been presented together with energy budget allocation. Preliminary results demonstrated that, after a tailored calibration process, the presented platform could effectively reveals and follow the air quality levels in a "*set and forget*" scenario.

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