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Miniaturized and low-power blood pressure telemetry system with RFID interface

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Abstract

This work deals with the development of an implantable blood pressure telemetry system, based on an active RFID tag, ISO 15693 compliant, aimed to continuously measure the average, systolic and diastolic pressure. The pressure wave undergoes embedded processing and results are stored onboard in a non-volatile memory, providing the data under interrogation by an external RFID reader. The paper presents the experimental characterization in a laboratory and preliminary in-vivo tests. The device is mainly intended for monitoring freely moving test animals for pharmaceutical research and drug safety assessment purposes, but it could have multiple uses in environmental and industrial applications.

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Keywords: Pressure; Blood; Implantable; RFID; ISO 15693; Low-power; Energy Harvesting; In-vivo; Embedded

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1. Introduction

Smart sensors and Wireless Sensor Nodes (WSN) technologies are deemed key research areas in computer science and microelectronics for achieving point-of-care and diagnostics system for personalized healthcare. In particular, implantable telemetry systems for pharmacological research applications take advantage of continuous electronic components miniaturization, diffusion of wireless data transfer technologies and power consumption reduction. In this work, a low-cost blood pressure telemetry system for small animals was developed with standard

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PCB technology and commercial components. Radio-frequency Identification (RFID) based solutions for human and animal implants are considered favorable in terms of exposure to EM fields, since in the range 1-20 MHz the electromagnetic waves are not significantly attenuated by human tissues. Moreover the power needed to establish the communication is provided by the external reader [1]. The operating distance of maximum 1 m, despite its limited range with respect to other wireless solution, permits to place the reader under the animal cage, leaving the rat to freely move in it, improving experimental capabilities. The developed system is an active RFID sensing tag, compliant with the ISO 15693 protocol, capable to measure and process the arterial blood pressure data. The device is intended to be placed in a subcutaneous region, coupled to a catheter filled with saline solution, which senses the arterial blood pressure. The main requirements (maximum volume 5 cm^3, maximum weight 9 gr, 10 days operation time, ± 3 mmHg pressure reading accuracy) were dictated by state-of-the-art telemetry systems for laboratory rats [2].

2. RFID pressure sensing system

2.1. Description and performances

The device, depicted in Fig.1b, is a two layers 34x30 mm^2 PCB assembled with commercial components; the board, once divided in two parts and vertically stacked with the battery, has a volume of 5.6 cm^3 and a weight of 8 gr. Two different temperature-compensated pressure sensors, one analog (MPX2300DT1, Freescale) and one digital (NPA-700M-005D, General Electric), have been characterized alternatively using the same PCB. The purpose of testing both sensors was to determine the optimal solution in terms of accuracy and power consumption. Both sensors feature a pressure accuracy of ±3 mmHg in the range 0-260 mmHg. Additionally to sensors, the system provides a low-power microcontroller for embedded processing (STM32L162RD, STMicroelectronics) and a dual interface non-volatile EEPROM memory for data storage and communication (M24LR64E-R, STMicroelectronics). The RFID interface of the tag is achieved by connecting the EEPROM to a double-layer PCB antenna coil, obtained with 12 trace convolutions, leading to a square with an external dimension of only 15.7 mm and a measured self-inductance of 4.6μH (4.7μH theoretical). With this configuration the achieved reader-tag communication distance is 11cm even interposing equivalent tissue material.

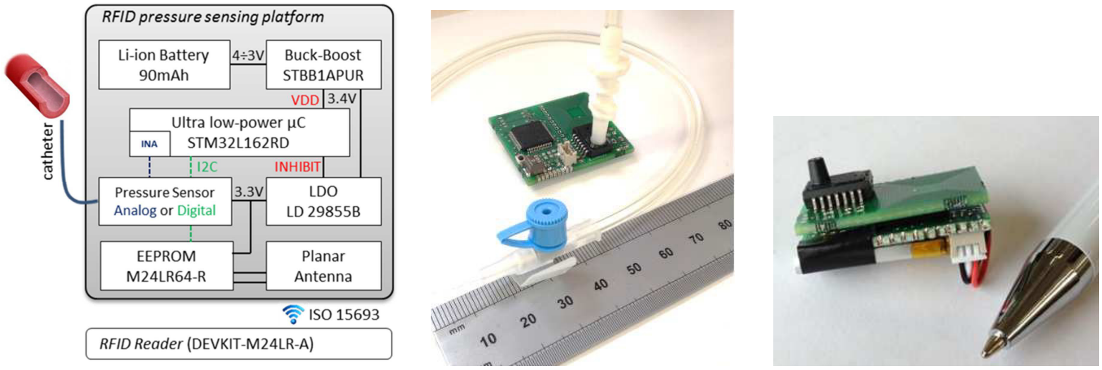


Fig. 1. (a) Device block diagram; (b) Laboratory setup for characterization; (c)Vertically stacked mechanical arrangement suitable for implant.

During laboratory characterization the platform with digital sensor exhibited a pressure resolution of 0.4 mmHgrms (5 mmHgrms with analog sensor) and maximum differences with respect to a reference sensor (Sick PBS) of ±5 mmHg (±10 mmHg for analog version) [3]. The analog pressure sensor output, based on a bridge configuration, is amplified with an instrumentation amplifier (38.5 dB, 10 kHz bandwidth) obtained by exploiting three operational amplifiers included into the microcontroller. The INA output is acquired by the microcontroller internal ADC running at 1 kS/s. The I2C interface of the digital pressure sensor permits a direct connection to the µC, with a maximum tested output data rate of 833 Hz. These reading rates are compatible with the animal maximum heart rate of 400 bpm (6.7 Hz).

The tag is programmed to process sensor data for 5 seconds, meaning few cardiac cycles; during each pressure cycle the systolic and diastolic peaks are identified with the Todd-Andrews algorithm [4] and then stored in the EEPROM. A raw pressure wave recording of maximum 20 sec, due to EEPROM memory size, has been implemented. In order to maximize the device operation time an ultra-low-power mode has been implemented for test purposes. The RFID reader (DEVKIT-M24LR-A, STMicroelectronics), intended to be placed under the cage of the animal, provides via USB interface the data to a custom software application that shows the blood pressure parameters during the experiment.

2.2. Power Consumption

The implantable device is powered with a rechargeable Li-poly battery (25x11x3.5 mm^3), with a 90 mAh capacity, having a nominal output voltage of 3.7 V. A high efficiency buck-boost regulator supplies the microcontroller with 3.4 V, while a cascaded LDO voltage regulator with enable function is used to switch-off the EEPROM and the pressure sensor during the system sleep mode. Presently the battery lifetime is approximately 70 hours for the system with digital sensor and about 63 hours with analog sensor; the difference is given by the power consumption of the µC ADC needed only for analog sensor signal acquisition (see Table 1).

Table 1. Tag supply currents for the two configurations, measured replacing battery with Agilent E3631A.

Pressure sensor mounted	**Average current provided by the battery (V=3.7 V)**		
	Irun (ΔT = 5 sec)		**Isleep**
	Isensor + EEPROM	**Itotal**	**(ΔT = 55 sec)**
Analog	3.41 mA	9.49 mA	0.7 mA
Digital	3.53 mA	8.51 mA	0.7 mA

For enhancing the device operation time the EEPROM Energy Harvesting (EH) functionality has been investigated. When EH mode is enabled by the reader and the RF field strength is sufficient, an unregulated DC voltage is provided on a pin of the EEPROM. Figure 2 show the available power and the supplied current by the EEPROM; such a current could be used to recharge the battery during the system sleep time.

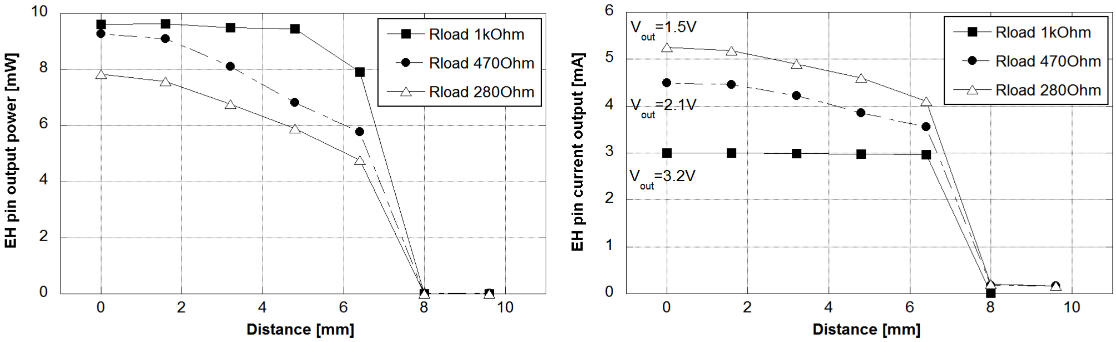
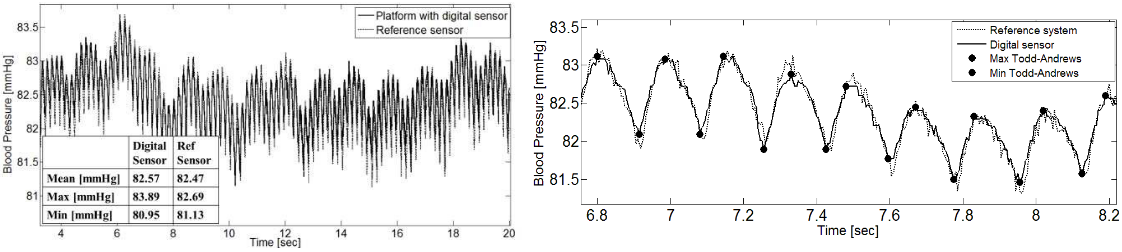


Fig. 2. EEPROM energy harvesting characterization as a function of the distance from the reader; power can be extracted up to 6.5 mm distance.

3. Experimental Results

An adult male Sprague-Dawley rat (Charles River Laboratories International Inc., Wilmington, MA) weighing 400-500 g was used for the in-vivo tests of the developed system. After anesthesia with isoflurane, the left femoral artery was isolated and cannulated with a PE50 catether. Animal care and treatment were conducted in conformity with the institutional guidelines, in compliance with national (DL n. 116/1992, Circ. 8/1994) and international (EEC Dir. 86/609, OJL 358, Dec 1987; NIH Guide for the Care and Use of Laboratory Animals, US NRC, 1996) laws and policies. The catheter end was split and connected both to the device, placed aside the animal and to a reference pressure sensor (Deltran II, Utah Medical Products). The synchronous acquisitions are in accordance within 1mmHg, as depicted in Fig. 3. The blood pressure wave, having an average frequency of 5.76 Hz (346 bpm) was modulated at 0.83 Hz by the breath. The same in-vivo test has been performed with the RFID device analog pressure sensor mounted, which was able to follow the average blood pressure but not to detect the peaks, due to its lower resolution with respect to the digital sensor.



	Digital Sensor	Ref Sensor
Mean [mmHg]	82.57	82.47
Max [mmHg]	83.89	82.69
Min [mmHg]	80.95	81.13

Fig. 3. (a) Synchronous recording (~20 s) of the femoral artery blood pressure with the device mounting the digital sensor and a reference measurement system; (b) systolic and diastolic peak detection, independent to baseline wondering.

4. Conclusion

This paper presented the development and in-vivo tests of a miniaturized pressure sensing platform with an RFID interface. The system is suitable for implantable blood pressure telemetry, featuring on-board data processing with an outstanding performance in terms of power consumption. Two different configurations were characterized, one using a digital pressure sensor and one with an analog type. The solution with digital sensor provided best performances in terms of power consumption (1.34 mA average current, 3.7 V supply) and resolution (0.4 mmHgrms); the in-vivo measurement results were in accordance within 1mmHg with those obtained with a reference sensor. The work is presently focusing on further tag miniaturization, achievable by choosing smaller packages for the electronics components, and on the biocompatible device encapsulation. It is worth emphasizing that the developed pressure sensing system is suitable for many applications, such as environmental or structural monitoring.

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