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Wireless Readout of Resistive Sensors

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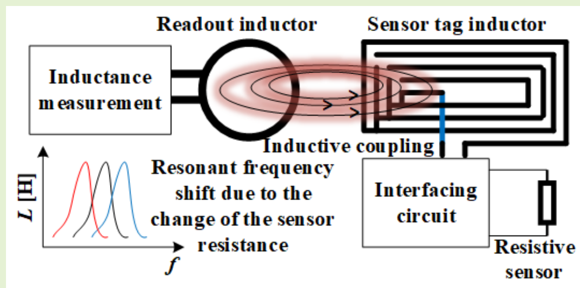
***Abstract*— In this paper we present a method for wireless readout of resistive sensors. Our approach is based on the topology where resistive sensor and reference resistor form a voltage divider network, with reference resistor connected in parallel with a varactor diode. Variation of the sensor resistance causes voltage changes over the varactor, and consequently capacitance of the varactor. Varactor is placed in the LC circuit, thus a change of resonant frequency occurs due to the change of the sensor resistance. Resonant frequency can be detected with external readout inductor connected to the inductance measurement device. The proposed method is theoretically analyzed and experimentally verified with discrete resistors and resistive force sensor. Main advantages of our approach are: (1) it keeps simplicity of the voltage divider network interface with resistive sensors, (2) energy autonomy of sensor tag is extended as energy needed for readout is provided by an external reader, (3) proposed method can be easily adopted for various dynamic range of resistive sensors, and (4) two methods for power supply (battery and energy harvesting with inductive coupling) were analyzed.**



***Index Terms*— Wireless readout, inductive coupling, resonant frequency, resistive sensors, wireless power transmission.**

I. Introduction

Resistive sensors are very important for various applications, from soft robotics [1,2], gas sensors [3-5], humidity sensors [6] to pressure sensors in biomedical applications [7, 8]. In addition to the above mentioned resistive sensors, a Metal Oxide Semiconductor (MOS) type of sensors are also very important class, as they are very common in gas sensing applications [9]-[12]. Sensing principle of MOS sensors is based on the change of the resistance of the sensing material when it is exposed to some specific gas or gasses [9].

Readout of resistive sensors can be very simple using voltage divider network. Voltage over resistive sensor is then usually measured with analog to digital converter and microcontroller. For some type of sensors (for example, MOS) presence of the voltage supply is necessary as they must be pre-heated over several hours to reach stable operating temperature. Moreover, gas sensing is usually performed in harsh environments which triggers need for remote access to the measured values. Therefore, communication modules for data transmissions or displays are also necessary. However, communication modules and displays are components that require power supply resources that are not negligible. They also increase overall size and price. In addition to that, some applications require just periodical readout of the sensed variable. For example, height increase over time with Force Sensing Resistor (FSRs) or with micro force resonant sensor [13]. For such kind of sensors, it is convenient to save energy by putting sensor node to sleep or standby while measurements are not performed, or to provide wireless energy transfer required for short time operation.

Wireless readout of resistive sensors is important in applications where sensor nodes are placed in inaccessible place with limited energy resources. Typical readout system includes impedance analyzer, primary inductor connected to the impedance analyzer and secondary inductor connected to the sensor. With analytical modelling, it is possible to establish expression for secondary components brought to primary side, and to obtain phase minimum and corresponding frequency as functions of the sensor resistance, as it was shown in [14]. However, use of impedance analyzers is not very practical outside the laboratory environment because of the size, weight and need for grid power supply. Very interesting approach is to convert the resistance of the resistive sensor to the resonant frequency of the LC circuit, because readout methods used for wireless interface with the passive LC sensors can be used with resistive sensor nodes as well. There are several methods presented in the literature with aim to replace commercial impedance analyzer in the interface with passive LC sensors [15]-[21]. For example, one approach is that the readout inductor is a part of the voltage controlled oscillator with frequency dependence on the inductance of the readout inductor, while inductance changes because of the mutual

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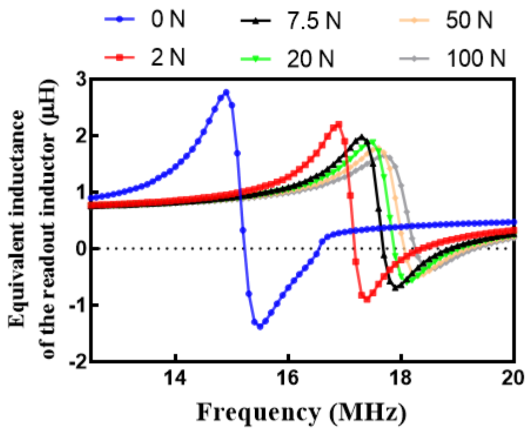

Fig. 23. Inductance plots of the readout inductor for different values of load applied to the FRS 402 sensor.

We measured resonant frequencies for 3 loads in the range from 0 N to 10 N, as it is shown in Table VII.

TABLE VII
RESONANT FREQUENCIES FOR DIFFERENT LOADS.

Load (N)	Resonant frequency (MHz)
2	16.9
5	17.2
10	17.4

Applying non-linear regression (second order polynomial), we defined calibration curve of the sensor:

$$y = 0.8897x^2 - 14.95x \quad (21)$$

where y is load in N, and x is the resonant frequency in MHz.

With R^2=0.9386, and the standard deviation of the residuals *Sy.x*=1.417, it can be concluded that the presented system exhibits excellent correlation between applied loads and measured resonant frequency. After calibration, we performed measurement with 7.5 N load and measured resonant frequency was 17.3 MHz. Estimated load with Eq. (21) is 7.643 N. Therefore, relative error is 1.9%.

In addition to the performed analysis of the developed readout system and the FSR sensor, an important fact was observed. The utilized force sensor was enclosed into a protective plastic sheath, both to prevent the sensing element from being damaged and from coming in contact with potentially conductive surfaces. However, this has created a “sandwich” effect, adding two more layers on each side of the sensor. Given that these layers are plastic, they are relatively elastic, and thus, they can act as an absorber of some of the applied force, since they will partially deform as an effect of it. Therefore, some irregularities are to be expected in calibrating the sensor, due to either some of the applied force being absorbed by the casing or the force being unevenly applied throughout the whole sensing area of the sensor.

C. Figures of merit

After provided comprehensive and detailed analysis regarding the technical aspects of our proposed method, before conclusion we will provide a figure of merit and to characterize the performance relative to its alternatives. Readouts of resistive sensors based on two methods were usually reported: (1) voltamperometric (VA) based on conversion of resistance to a voltage or current [36, 37], and (2) current/resistance to time conversion (RTC) [38]-[41]. Since the compared solutions are quite different in terms of architecture and implementation, comparison of different typologies, readout time, power consumption and cost is given in Table VIII. A possible implementation with discrete component readout board from [16] has been considered for the evaluation of the cost of readout system for our sensor tag topology.

TABLE VIII
FIGURES OF MERIT: COMPARISON OF THE PROPOSED SYSTEM WITH OTHER SIMILAR SOLUTIONS IN THE LITERATURE.

Ref.	Topology	Wireless readout	Readout time	Power	Cost
[36]	VA	No	100 ms	5 mW @3.3 V	~50 USD
[37]	VA with logarithmic amplifier	No	<1 ms	50 mW @3.3 V	~30 USD
[38]	RTC based on pulse-width modulation	No	<1 ms	40 μW @1 V	~10 USD
[39]	RTC with voltage-mode oscillator	No	<15 s	4 mW @3.3 V	~10 USD
[40]	RTC with current mode oscillator	No	<15 ms	700 μW @0.75 V	~10 USD
[41]	RTC based on moving threshold oscillator with reset	No	<30 ms	25 mW @3.3 V	~10 USD
This work	Resonant frequency shift due to the change of the sensor resistance	Yes	<1 s	3.15 mW @9 V	~75 USD

IV. CONCLUSION

In this work, we presented a method for wireless readout of resistive sensors based on the topology where change in resistance of the sensor is detected with external readout inductor. Readout inductor and sensor tag are inductively coupled, thus sensor tag does not consume additional energy for data delivery and display. Such approach increases energy autonomy of the sensor tag, and therefore its operational period.

Obtained results reveled that proposed approach is reliable method for interface with resistive sensors as voltage drop on the varactor caused by the resistance change of the sensor, resulted in resonant frequency shift. We also showed that change in coupling factor does not affects readout functionality. Results with battery powered sensors tags, as well as with energy harvesting were also presented.

Our future work is directed towards interface of the proposed method with in-house developed sensors, especially on textile and flexible substrates. Moreover, our focus will be on the development of the portable device for impedance/inductance measurement and data acquisition.

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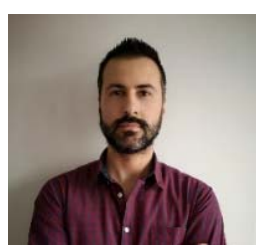

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