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WIRELESS PASSIVE SENSING PLATFORM BASED ON RFID TECHNOLOGY FOR SHM PURPOSES

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ABSTRACT

Recently there are many attempts to use wireless communication and its capabilities in data acquisition from sensors, in SHM application. Beside typical active Wireless Sensor Networks (WSN), there are also attempts to develop sensor networks with passive nodes, using the advantages, provided by Radio Frequency Identification (RFID) technology. The main benefits of this solution are utilization of energy of the communication signal from the reader antenna for sensor circuit powering and possibility to place sensors in any places, including hard available and moving locations. Development of such sensing platform based on M24LR64E-R RFID chip working in HF band, suitable for working with different types of sensor - strain gauges, accelerometers, pressure sensors is presented. It is designed especially for monitoring helicopters rotor blades. Entire energy needed to power the microcontroller, RFID chip, sensor and other circuit elements is supplied by the reader wirelessly, by using magnetic coupling between the reader and the sensing platform antenna. The paper presents a concept of the sensing platform, its first prototypes and investigation related to communication between the platform and the reader, as well as first experimental studies related to using this platform in different applications.

KEYWORDS : *SHM, RFID sensor, passive, wireless*

1. INTRODUCTION

Growing demand for Structural Health Monitoring systems in recent years, together with the increasing number of new industrial and construction branches interested in using of them, results in the need for development of new sensing methods. One of the significant trend in the area of prototype sensing systems is using RFID technology for development of wireless sensors. Typical RFID system comprises of the reader and many transponders that in this case, could posses sensing capabilities. Reader could communicate with transponders using an antenna, via electromagnetic waves. In the case of passive system, it also delivers the energy for transponder activity. The main advantage of such devices is connected with possibility to design the system that could be passive and thus would not require maintenance. Although one could use active transponder as a base of the system, the advantages offered by using the passive one, related to long working time without need of any maintenance, possibility of placing it in hard accessible places and lack of risk connected with exhaustion of the power source, make these kind of solutions very attractive for SHM purposes.

Using RFID technology as a base for SHM sensing systems is the idea, that is being developed from the beginning of the XXI century. It is strongly connected with the evolution of RFID systems themselves. On the beginning of the century, the most popular were short-range systems based on magnetic coupling between reader and transponder and used mostly in identification and access control purposes [1]. Development of long-range systems resulted in popularization of UHF (Ultra High Frequency) RFID technology with the read range up to tens of meters. Nowadays there is a possibility to design even passive system with the efficient read range about 10 m, however, it is still problematic powering of features another than simply sending of short data string in the form of UID (Unique Identification Number) by using specified communication protocol, due to the lack of energy. This

issue could be solved by using additional powering methods, as energy harvesting modules, that could drain ambient energy from different phenomenon - temperature difference, sunlight, vibration, which is ambient mechanical energy. There is still problem with uncertainty related to interruption in the ambient power supply due to the random nature of physical phenomenon behind theme. Only the systems draining entire energy from the reader could ensure smooth operation.

Comprehensive review of wireless sensing methods used in SHM purposes is presented in [2], although the most important issues will be pointed here to create some background for investigation presented within this paper. First group of prototype sensing systems that use the impact of different physical phenomenon for communication between the reader and the transponder, which could be measured in the form of RSSI (Receive Signal Strength Indicator), is represented by RFID displacement sensor presented in [3] and RFID sensing system in the form of transponders grid reported in [4]. To this kind of solution belongs the wireless passive system for crack detection of ceramic parts presented in [5], as well as RFID based sensing system for concrete structure monitoring [6]. The second approach assumes using a RFID system as a kind of platform, which states an interface between low-power sensor and the host, e.g. some computer connected to the reader. Such platform could be equipped in any sensor that is needed for monitoring of some phenomenon. Depending on utilized RFID chip and its capabilities, such platform needs design of different elements. First investigation on such platform was presented in [7], where the standard RFID chip was not used and its role was played by low-energy microcontroller MSP430, responsible for communication and collection of sensor data issues. In this device called WISP, the small amount of data could be send taking the form of UID. Entire system was powered from the RFID reader and had the read range up to 3 m. Its interesting application, related to strain monitoring in carbon fiber plate is reported in [8]. Another force sensor system based on the HF (High Frequency) RFID range was presented in [9], although its read range is much smaller in the range of 32 mm. Development of RFID technology results in appearance of new type of IC chips, with an internal analog-digital converter and also an energy harvesting module. One of such device was a base for design of the sensing platform presented in [10]. This solution is similar to that reported in this paper, however it is described from the microwave engineering point of view and there is lack of information related to practical applications.

2. SENSING PLATFORM DESCRIPTION

The sensing platform presented in this paper is based on the HF RFID technology and is foreseen for using in different SHM applications, especially for continuous monitoring of the state of helicopter rotor blades during operation. The core of the first design states the M24LR64 dual interface EEPROM chip, which is responsible for data storage and wireless communication with reader. In the second prototype it was replaced with M24LR64E version, which allowed to avoid designing of energy harvesting part. The second main device states the MSP430 low-energy microcontroller, that converts sensing data from the analog to the digital form and supervises activity of the entire platform. The sensing platform is intended to work with typical HF read range up to 0,8 m, depending on utilized reader, what determines its application possibilities. Below are stated basic information related to physical principles of platform operation, schematic diagram that presents idea and particular section of platform and description of possible applications.

2.1 Physical principles

Each RFID system in HF range bases on similar physical phenomenon. In this chapter will be presented only the fundamental relationships, there are important form the point of view of conducted experiments. For more comprehensive knowledge related to the operating principles of different RFID systems, one should refer to the [1].

First important equation describes the resonance frequency f of the LC circuit, which is formed from the planar coil antenna (inductance L) and internal capacitor in RFID chip (capacitance C):

$$f = \frac{1}{2\pi\sqrt{LC}}[\text{Hz}] \qquad (1)$$

Because the operation of the HF system, namely power transfer and communication between the reader and the transponder, is based on the magnetic coupling between their antennas, the resonance peak should occur in 13,56 MHz in order to achieve the best performance.

Another important phenomenon for the read range of entire system is related to the magnetic field strength generated by the reader antenna. It could be described by particular equation:

$$H = \frac{INa^2}{2r^3}[\text{A/m}] \qquad (2)$$

where I is the current of the antenna, being simultaneously the resultant of the reader power, N is the number of antenna windings, a is the radius of planar coil antenna and r is the distance from antenna to the point, where the quantity is measured - in our case it means the point where the transponder is located. From this formula one could receive many useful information. First one is the impact of the antenna dimension for the read distance. The best performance will be achieved for bigger antennas, but the limitation are related to needs of particular application. The important information are also related to the attenuation of magnetic field strength according to the inverse cube of distance from the source (antenna). One could conclude, that for the same voltage supply, achieving of twice bigger read distance needs using of eight times bigger reader power, which is however limited by particular norms. This relationship causes, that typical range for HF systems is given as tens of centimeters.

2.2 Idea of sensing platform

The sensing platform should serve as a wireless interface between the reader connected to some data storage host (i.e. controlling computer or PLC) and any low-power sensor connected to it. Simultaneously it should power the sensor, draining the energy needed for this purpose from the magnetic field generated by the reader. In the Figure 1 there are presented schematic diagram of main activities and sections of the sensing platform.

2.3 Application possibilities

According to the low-energy type of sensor connected to the platform, it could be applied for different SHM purposes. It was designed primarily for the measurement of rotor blades monitoring in helicopters. Other variables, such as acceleration, strain and stress could also be measured. Foreseen read range and data rate, as well as small dimensions makes it well fitted for this issue. Another possible application is related to placing sensor in hard accessible or even not visible places, from where the data could be stored remotely. Possibility of placing the sensor on moving parts makes it attractive for automotive and airplane industry. The platform is also suitable for measurement of environmental conditions, such a temperature, humidity or pressure. The only requirement stated to the connected sensor is related to its low energy consumption.

3. DOWNSCALING ISSUES IN SUBSEQUENT PROTOTYPES

Based on the idea of sensing platform presented above, there were developed subsequent prototypes of sensing platform consisting of different parts. Main intentions behind designing the first prototype was testing of different power supply section, testing of data storage and communication algorithms and checking of possibility to using data buffer elements. It consists of few sections - power supply,
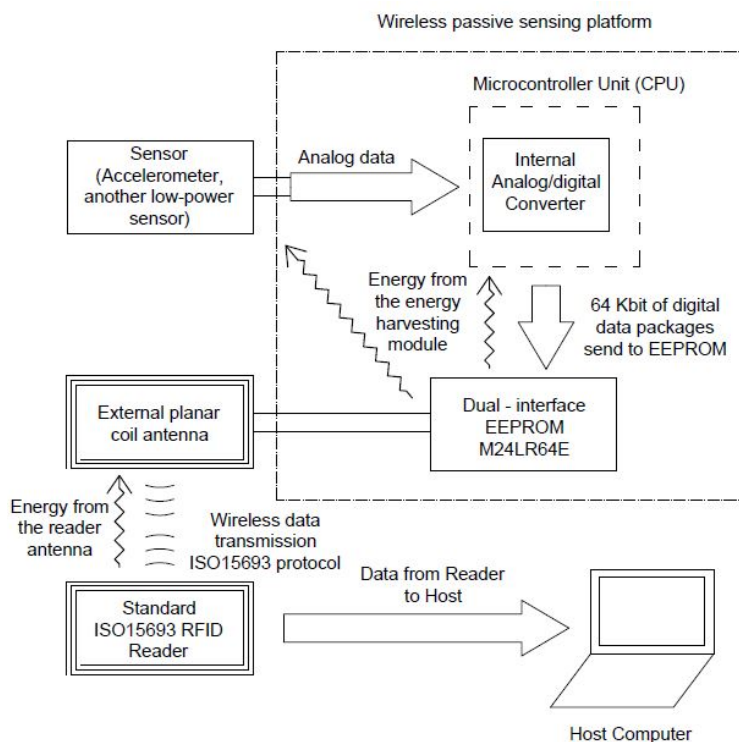
Figure 1 : Schmeatic of the sensing platform

supervision, sensor data storage and communication. Algorithm of data management is presented in [2] and it will not be described here comprehensively. Its main activity is related to store digitized data from the sensor and send it wirelessly to the reader. Entire process of data storage and buffering is supervised by microcontroller. Main parts of this two sections state low-energy microcontroller STM32F051, two interface EEPROM M24LR64, responsible for the wireless communication with reader and buffering flash memory AT45DB. It was attached also IC for communication via RS232 and USB interfaces, for testing purposes only. The power supply module consists of voltage regulator and DC/DC converters, which should regulate signal from planar coil antenna, rectified by typical Graetz bridge arrangement with additional preconditioning capacitance. The first prototype allowed to assess the data rate and possible sampling frequency and energy conditions that should meet the final design, but due to the lot of sections included only for testing purposes, that were unnecessary in the working prototype, it had large dimension of 85 x 105 mm.

The second prototype is much smaller, than the first one with dimension of 40 x 20 mm, what is caused by many factors. The most important difference is the change of the EEPROM chip for the similar one M24LR64E, with additional feature related to energy harvesting system being the part of the IC. This ability allows for resignation from the external power supply section, except the usage of ultra low dropout voltage regulator NCP583, which regulates the voltage on the level of 1,8 V. The EEPROM chip offers four levels of energy harvested current, from 300 μA, up to 7 mA and more information about this feature is given in next chapter. Another difference is related to resigning from additional communication interfaces, USB and RS232, because the parts responsible for this ability unnecessarily drew energy. The changes also concern the resignation from the additional flash memory buffer, caused by lack of such devices with sufficiently low level of energy drain. The last important change was related to the replacement of previously utilized microcontroller with the ultra low energy MSP430F2132, having the low energy drain on the level of 90 μA, by operation with 100 kHz frequency (250 μA for 1 MHz), additional low-power mode handling and possibility to work with

Table 1 : Main difference between two prototypes

Part	Prototype 1	Prototype 2
Microcontroller	STM32F051, 32 bit MCU, min. supply voltage 2 V, average current over 1 mA	MSP430F2132, 8 bit MCU, min. voltage 1,8 V, average current 100 μA
RFID chip	M24LR64, I2C, ISO15693 RFID communication, 64 KBits EEPROM	M24LR64E, I2C, ISO15693 RFID communication, 64 KBits EEPROM, additional energy harvesting module (up to 7 μA)
Energy harvesting	Graetz bridge, voltage regulator, DC/DC converter	Internal part of EEPROM, additional low-power voltage regulator NCP583
Communication interfaces	RS232, USB, I2C	I2C
Dimension	85 x 105 mm	40 x 20 mm

ultra low voltage level - 1,8 V. Entire design is supplemented by exemplary low-power sensors, which is LM94021 temperature sensor and ADXL335 accelerometer. The Table 1 summarizes primary differences between two prototypes with information about features assured by particular devices. Both prototype boards are also presented on the Figure 2.
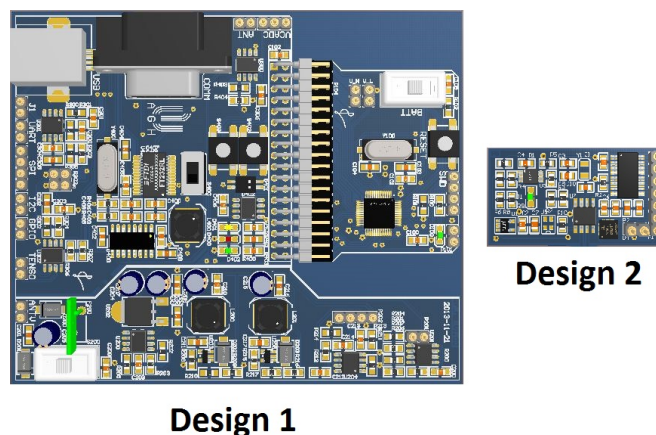

Design 2

Design 1

Figure 2 : Comparison of PCB design of two prototypes (without planar coil antennas connected)

4. PERFORMED INVESTIGATION

Design and evaluation of wireless passive sensing system based on RFID technology needs many different researches. Part of them are related to microwave technology and are connected mostly with the assessment of energy and communication efficiency between reader and transponder. The most important investigation in this area is connected with the design of the planar coil antenna, that must meet requirements related to the value of inductance according to the equation 1 and the quality factor Q, what has an impact on the energy transmission efficiency. Although this researches are important for the features and activity of the entire system, they are not essential from the point of view of this paper, due to its microwave nature. Suffice it to say, the planar coil was calculated and designed with help of the ST antenna calculator and the ready system was measured by the help of HP4395A network analyzer. The best performance was achieved for the planar coil with dimension 60 x 60 mm and inductance of 4,92 μH, by the internal capacitance of RFID chip of 27,5 pF, which values give the theoretical resonance frequency peak in 13,68 MHz, according to the Equation (1) .

More practical investigation are connected with the assessment of possible read range of the sensing platform, energy consumption of the core elements of platform and the amount of energy available for external sensors, possible data rate and data storage abilities. Researches related to the read range of entire system were conducted on the simple test stand by using ID ISC.MR101-USB FEIG reader, with maximal power 1W, connected to external antenna ID ISC.ANT340/240. The sensing platform, together with planar coil antenna connected to it, was placed in the symmetry axis of the reader antenna. The maximal read range was measured by postponement of the platform from the reader antenna and checking the maximal range, where the reader could receive transponder UID. Resulting from the nature of energy harvesting module being integrated part of the RFID chip, the maximal range for the energy collection from the reader signal should be assessed separately. It is caused by the fact, that this module is equipped in four energy harvesting modes with different level of maximal current it could provide (7 mA, 3 mA, 1 mA and 300 μA). It works in a way that particular mode turns on only when it is possible to provide the maximal current. This in turn is dependent on the value of magnetic field strength H (according to equation 2), generated by the reader antenna. Referring to the investigation reported in [10], the maximal field strength provided by the similar reader antenna is on the level of 2A/m. This results in availability to use of only two harvesting modes with maximal current of 1 mA and 300 μA respectively, because the other two modes need the value of magnetic field strength on the level of 2,4 A/m and more. The effective energy harvesting range was then measured by implementation of simple code with blinking LED to the microcontroller. Data rate and storage possibilities, what could be defined as data management process, were improved by development of particular microcontroller code and then tested by using emulated sensing signal from external microcontroller attached to the platform instead of sensor, as well as by testing signal collected from internal temperature sensor. Achieved results are described in the chapter below.

5. RESULTS AND DISCUSSION

The main results from investigation are related to the second prototype of the sensing platform and outcomes described in this chapter refers to it. The most important result is connected with the read range of the platform, which is equal to 40 cm by using 1 W reader. In the case of using of 8 W, so-called "long range HF reader", according to the Equation (2) , this value could be twice bigger up to 80 cm. Further improvement of the read distance could be achieved by using the reader antenna with bigger dimensions. The read range was achieved for the transponder planar coil antenna described in previous chapter, stating that the theoretical resonance frequency correspond well to the real one, measured by the network analyzer. It should be mentioned, that in the case of HF systems, there is always a trade-off between miniaturization of the system and the possible read range, according to the rule, that the bigger antenna, the larger range. In our case achieved dimensions of the sensing platform alone (40 x 20 mm) are such small, that the dimensions of entire system are determined mostly by the

size of the planar coil antenna.

The second group of importance outcomes is related to sensing possibilities of the platform. Significant feature is the power consumption of additional external sensor. It is possible to supply the power to and read the data from the sensors with the average operational power on the level of 15 mW, with additional assumption of possibility to working with supply voltage of 1,8 V. The energy harvesting is then possible on the distance of 10 cm from reader, although the read distance is still 40 cm. It could result in application with differential reader position for the powering and read data purposes. Exemplary sensors used in researches were the LM94021 temperature sensor with the current consumption of 9 μA and the ADXL335 accelerometer with the current consumption of 350 μA. For the testing purposes of the data management segment, emulated data was also collected from the external microcontroller. In the testing conditions, by using internal clock with the frequency of 1 MHz, it is possible to achieve the data rate on the level of 200 Hz, whose value is limited by the EEPROM data rate and collect up to 64 KBits of data which could be send wirelessly to the reader. Presented results and features of the sensing platform are concluded and summarized in the next chapter.

6. CONCLUSION AND FUTURE WORKS

Described features of the platform, connected with achieved read range and data storage capabilities make it attractive for specific SHM purposes and after implementation of particular changes (i.e. the usage of long range version of the HF reader) it should be also applicable for the main assumed application, which is the monitoring of rotor blades in helicopter. The platform is well suited for the purposes of collecting data packages in specific moments and sending it to the reader later. Although its read range is the biggest limitation, performed design and evaluation works give a wide experience for the researcher, which could be used for the design of similar system working in UHF, with the read range on the level of few meters. Further development and investigation on this platform is also planned, in order to conduct a series of different application experiments, development of custom commands for the RFID reader for the handling of data storage purposes and using advanced algorithms related to energy management process. Works presented within this paper state significant contribution in the subject of development of new sensing possibilities in SHM applications.

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