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WIRELESSELY POWERED MOBILE SENSOR - ENERGY HARVESTING EXPERIMENTS

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Abstract

This paper presents an idea of wirelessly powered mobile sensors utilizing cloud management system similar to the swarm robotics. Sensors are based on the previously developed wireless passive sensors working with RFID protocol in the HF range. Preliminary research presented in this paper is related to the energy harvesting efficiency evaluation and the possibility to wirelessly power an electric motor. Performed experiments show that the magnetic field generated by the RFID reader antenna provides enough amount of energy not only to perform communication, measurements and computation, but to power the actuators as well. Achieved results state a base for further investigation in the area of wireless passive mobile sensors.

Keywords: Mobile sensor, passive, wireless, energy harvesting.

ZASILANY BEZPRZEWODOWO CZUJNIK MOBILNY - EKSPERYMENTY DOTYCZĄCE ODZYSKU

Streszczenie

W pracy zaprezentowano koncepcję zasilanego bezprzewodowo czujnika mobilnego wykorzystującego system zarządzania w chmurze, podobny do stosowanego w zarządzaniu rojem robotów. Projekt czujnika został oparty na opracowanych wcześniej bezprzewodowych czujnikach pasywnych opartych na technice RFID, pracujących w zakresie wysokich częstotliwości HF (z ang. High Frequency). Pierwsze doświadczenia, zaprezentowane w publikacji, odnoszą się do oceny efektywności możliwości pozyskiwania energii z sygnału emitowanego przez czytnik RFID oraz sprawdzenia możliwości bezprzewodowego zasilania silnika elektrycznego. Wykonane eksperymenty pokazują, że pole magnetyczne wytworzone przez antenę czytnika RFID, dostarcza wystarczającą ilość energii nie tylko do komunikacji pomiędzy czytnikiem a czujnikiem, pomiarów i obliczeń, ale również do zasilania aktuatorów. Zaprezentowane wyniki stanowią bazę dla dalszych doświadczeń w zakresie bezprzewodowych pasywnych czujników mobilnych.

Słowa kluczowe: Czujnik mobilny, pasywny, bezprzewodowy, odzysk energii.

1. INTRODUCTION

The idea of wireless sensing created new opportunities in the technical diagnostics, Structural Health Monitoring and development of plant supervisory systems. Nowadays, Wireless Sensor Networks (WSN) becomes more and more popular and slowly supersede the solution based on the wire connections [1, 2]. The new idea that allows coverage improvement using smaller number of sensing nodes is using of wireless mobile sensors [3, 4]. Even replacement of the chosen nodes with the mobile sensors could significantly increase the coverage area [5].

Another development direction in the WSN is creation of passive nodes, powered by the energy harvested from environment. Energy harvesting provides energy from different source like radio waves, temperature or vibrations. This type of technology is used for example in the smart watches [6]. The use of this technology in sensors gives possibility to fulfil requirements connected with low energy and closed spaces. These kind of sensors are based mostly on the RFID technology [7, 8].

The innovative idea is to use actuators in combination with RFID units. In the prior art, RFID harvesting modules have been used for different usage [9].

This paper presents the idea of connection of these two trends, creating wireless mobile passive sensors, without their own power source on board. Main scope of this paper is the description of investigation on mobile sensor power issues. Experiments related to the energy harvesting module based on RFID in connections with super-capacitors are presented.

This paper is organized in the four chapters. The first chapter states the introduction to the subject. The second chapter describes the idea of mobile sensing, problem of the energy harvesting and presents the actual state-of-the art, as well, as the gap in this field that is partially covered by the experiments presented further. The third chapter is devoted to the description of performed experiments and achieved results.

2. ENERGY HARVESTING

2.1 Idea of the passive mobile sensing

Proposed passive mobile sensors states the next step of the idea of wireless passive sensors based on RFID technology developed by authors Mateusz Lisowski and Przemysław Gonek. Both sensors are intended to be powered by the magnetic field generated by the typical RFID reader's antenna working in High Frequency (HF) band. The main difference is adding of the mobility feature to the sensor. This attribute significantly expands the possibility of sensors allows for using them in completely new technical diagnostic applications, what is described further.

The short description of the wireless passive mobile sensors for the readers, that are not familiar with the idea of wireless passive sensors, is following. The sensor is wireless, which means that it gathers data and sends it further (to the host) wirelessly. In described case, data are sending to the HF RFID reader. It radiates the fast-changes magnetic signal that is reflected by the sensor, according to the communication scheme and this way the communication between the reader and the sensor is possible. Simultaneously, the signal emitted by the reader is used to power the sensor. Moreover, the sensor is equipped in the actuator (it could be the low-power DC-engine, but another actuators are also possible). This means that after harvesting of energy from the magnetic field generated by the reader, the sensor could move to the desired place, gather the data, and come back to the field emitted by the reader and send data wirelessly. The use of the actuators in wireless sensors requires additional effort when it comes to power issue. Mechanical actuators are the elements that consume the most energy. To combine actuators with the energy harvesting module it is necessary to store the energy and manage it reasonably.

2.2 The energy balance

The typical energy harvesting module based on RFID technology provides about few mW of energy [9], but it strongly depends on source. Energy which can be stored for example from the RFID tags readers or smart card readers. To build a smart sensor which bases on RFID technology and energy harvesting, there is no need to spend energy for data transmission because energy and data are sending in the same time through the same physical layer. Similar solution can be found in 1-wire interface. This feature makes this technology perfect for contactless sensors.

Typical smart sensor needs to have low power controller, low power sensor used to gather physical data, low power diode for basic indications, energy harvesting module, RF-module used to transmit data and some extra passive elements. In the simplest solution smart sensor consists of four active elements: energy harvesting module, data transmission module, controller and the proper sensor [10, 11]. In this case we can assume that the harvesting module and data transmission module are in the same electrical component and data transmission does not require the energy. It means that the energy gained from energy harvesting will be used by the controller and proper sensor. If smart sensor is more advanced then additional modules like diodes or small motors require most of the energy.

To power controller and proper sensor, the device requires from several dozen of microwatts to few miliwatts, what strongly depends on used technology and components. In below proposition the controller is able to dynamically work with absorption on the level of 150 µA. The sensors are able to work even on nanowatts level, but typical ultra-low power energy consumption of, for instance temperature sensor should not exceed 50µW. Taking into account additional energy loss, and energy consumption of smart sensor will not exceed 500µW. This simple calculation allows estimating the level of the current which can be used for other activities.

2.3 Energy Harvesting – Power issue

As it was mentioned earlier, excess of the energy can be used for other activities like diodes or actuators, but it is not possible to use the energy of RFID to supply actuators directly and optimally. The current produced by the module is not sufficient for continuous work of the actuator. It is possible to supply actuators directly, and this experiment has been described in this publication, but it requires using extra generator which will produce very strong magnetic field. That kind of solution is expensive and requires advanced generator and RF-amplifier that gets a lot of current from the high voltage network. Optimal solution would seem to be collecting the energy in the capacitor and using it in intervals.

In above situation work of smart sensors, which uses energy harvesting in simplest example, can be divided into few steps: gathering of the energy in super-capacitor, moving of the sensor equivalent to the discharge of the capacitor, gathering of data like temperature or pressure, gathering of the energy in super-capacitor, return to the starting point equivalent to the discharge of the capacitor once again. By using RFID technology it is possible to exchange data and gather energy in the same time. Building of power management and data exchange system that allows working with at least few smart sensors in the same time would be huge challenge for the hardware and the software. To check whether such solutions have chance on succeed some experiments has been carried out. To storage the energy super-capacitor with capacity of 0.1F has been used. It is also one of the biggest element of smart sensor. The capacitor is in the shape of a cylinder with dimensions: high equal 5mm and radius equal 4,5mm. DC motors which have been used in experiments are taken from mobile phone where it is used in vibration mechanism.

Antenna and harvesting module has been described in next chapter in this publication. The experimental results give hope that energy harvesting method is sufficient for build smart and mobile sensor which does not require any other supply source. The use of appropriate programming algorithms will allow building sensor networks operating in the swarm. Communication in that case will be provided by the cloud technology.

2.4 Possible application

Due to its innovative nature, indication of one main possible application of the mobile sensors is neither possible nor necessary. The most interesting possibility is building of the mobile sensors network, where every sensor could communicate with each other, creating the cloud of the mobile sensors. This feature allows for maximization of data acquisition possibilities - the amount of data and the surface effectively covered by sensors - due to their mobility. The possibility for using Internet of Things features in this solution expands its prospective application areas. This kind of sensors could be used in different technical diagnostic application, where exists a need for cover some surface or linear objects with a sensors and where the one sensor, due to its mobility, could gather data from more than one point. The use of data from multiple sensors may allow the exact determination of the signal source (e.g. source temperature) by carrying out intersecting line at a certain point. In that case each sensor provides one line.

Beside the typical technical diagnostic application, this kind of sensors could be applied in such areas, as access control. The sensor could be used as a smart lock that could react for the encrypted signal emitted by permitted smartphone. Such solution exists (e.g. “August Home” brand), but in this case the locks must be powered externally. Due to their exceptional features, the mobile sensor with the actuator could revolutionize the access control field.

3. ENERGY HARVESTING EXPERIMENTS

Experiments related to the energy harvesting contain experiments with RFID reader which generates RF field and experiments with the field generated by an external antenna which is connected to the RF amplifier and signal generator.

First case requires the reader which meets several conditions. The most important feature of reader for this experiment is supporting of ISO norm which is used in energy harvesting module. In this case it is ISO-15693 norm. There is a few norms for HF application (13,56MHz) but two most popular are ISO-14443A and ISO-15693. The main differences between those two norms are in the physical layer. Modulation, data coding and subcarrier frequency have biggest influence for both standards and are different for each of norm. Because of those differences ISO-14443A is used in application which requires high baud rates at the expense of lower distance and higher power, whereas ISO- 15693 is used in application where there are no baud rate requirements but distance and power have higher priority.

Because whole system in his assumptions had to be cheap, the reader which is a source of communication with the swarm also should be cheap, easily accessible and provides communication with USB or ethernet, what gives possibility to connect the swarm with the cloud or IoT application in the future. The above requirements are met by the family of readers produced by HID Global company. In these experiments OK5022 reader has been used. Those readers have its own antenna which dimensions are not standard but are adapted to the PCB of the reader. Distance between the reader and the energy harvesting module was about 3-4 centimeters and strength of the field generated by the reader is determined by ISO standards and was less than 5 A/m.

In the next experiment the reader has been replaced with an external antenna, RF amplifier and the signal generator. The signal generator produced the sine signal on 13, 56 MHz frequency which, according to the norm, is the carrier of signals for ISO-15693. Generated signal has been connected with the special module, which is described in ISO 10373-6. Because there was no data transfer in this case, the circuit for ISO14443 could be used.

This circuit provides possibility to achieve field, which strength exceeds value allowed by the norm in mass-produced readers. The ISO norm limits the field which is additionally decreased by the producers to limit operating range what again increases the safety of particular applications. Using of this module lets for changing the antenna, which in the reader has been implemented directly in PCB. Amplifier allows achieving strength above limits described in ISO-15693 which is below 5 A/m.

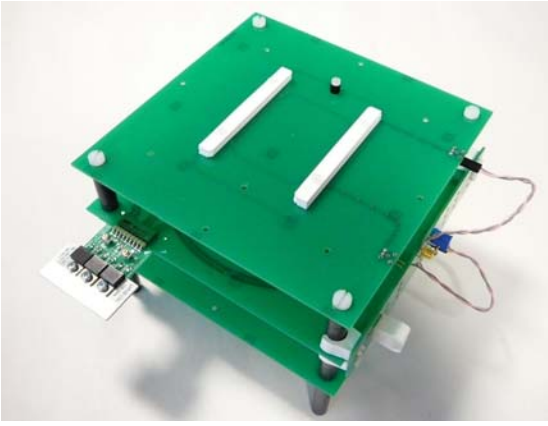

Fig. 1. ISO 10373-6 module connected to the external sine generator

In all experiments, the super-capacitor was charged wirelessly using the energy harvested from the magnetic field generated by the RFID reader's antenna. The motor was turned on and off manually, by connection and disconnection of its clamps.

3.1 Turning the motor on and off

In the first experiment, the super-capacitor was charged and then, the motor was turned on. In the Fig. 2 it is presented the timing diagram from oscilloscope, presenting the voltage measured on the capacitor. The voltage line is "thick" due to the sinusoidal signal in 13, 56 MHz frequency, generated by the RFID reader. Furthermore, the signal is distorted by the probes and cables, which collect the magnetic signal as well, causing noises.

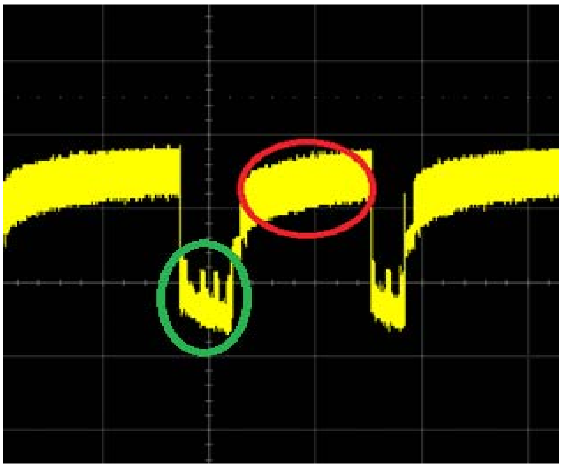

Fig. 2 Capacitor voltage signal during turning the motor on and off

There are clearly visible moments, when the capacitor is charged and voltage drops, when the motor is turned on. This significant voltage drops are caused, because a coils turned on in the motor have a low value of resistance, so the circuit is virtually shorted. After opening of clamps on the motor, the voltage rapidly turn back to the value before turning the motor. It means that the capacitor is not fully discharged. Then the period of further capacitor charging appears which is marked in the Fig. 2 with a red ellipse.

Characteristic information included on the diagram is characteristic voltage peaks, when the motor is turned on. They are marked in the Fig. 2 with the green ellipse.

Those voltage peaks are caused by the reader and its searching mechanism, which is used to detect different kind of RF tags. When the reader is searching any kind of tags in his proximity or vicinity (depends on kind of tag) then it is sending special commands in the air. Every kind of communication norm requires different kind of modulation and command. To change the physical layer (modulation, subcarrier frequency, coding) very often it is necessary to send special commands to the chip and restart it in order to achieve new values. Restart of the chip causes switching off the magnetic field what has been noticed during procedure of charging the capacitor in the Fig 2.

When the reader detects the tag, it starts the procedure which leads to detect if there is no additional tags of the same type (anti-collision) and choses one of them (activation). Last stage is called "parameter negotiation" which allows achieving better baud rate or sending more data in the frame. Those three activities do not require field restart so if the tag appears in the field then there is no voltage peaks.

According to above information we are able to tell that turning stepper motor on causes so big loaded of the chips that communication is lost for a moment. To avoid this phenomenon, the field has to be much stronger or it can be handled on higher layers where the loosing of the tag in the field is predicted by the software as a normal behaviour of the system. This experiment also confirmed the conviction that building own implementation of the reader is desirable. Implementation of the reader which support only one type of the TAG (in this case the norm ISO-15693) without permanent pooling and field restart will also protect against voltage peaks which are visible when stepper motors are turned on.

It also has to be mentioned that the capacitor will not be discharged fully because when the voltage is less than 1, 5 V, the stepper motors are not able to move even once. The controller will use the ADC to monitor the voltage and decide when and how long the stepper motors will be moving. There is some solution of stepper motors that provides better energy balance but in the swarm, which requires low costs, there is no place for high advanced motors, which price excludes them from swarm applications. In this case it is very important to achieve working prototype with low costs for future mass production.

3.2 Charging of super-capacitor

In the second experiment, it was checked charging of super-capacitor for a longer period of time. The voltage signal is presented in the Fig. 3.

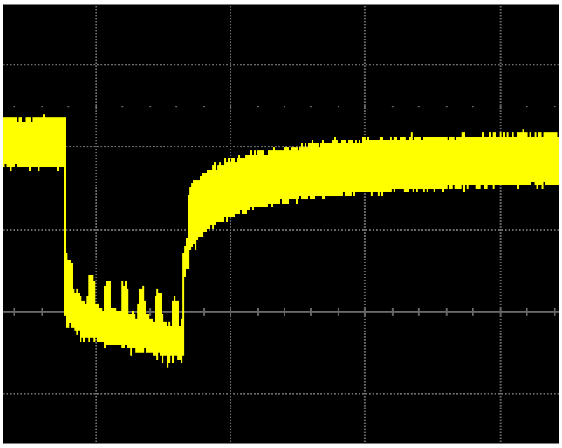

Fig. 3 Capacitor voltage signal during charging of capacitor for a longer period of time

After analysing of chart it is easily visible that the capacitor charges to about 90% of its capacity in a few seconds and then, the charging process continues, but much slower. These 90% are suitable for execution of few tens of motor rotations. This chart shows that charging for few seconds and then execution of few moves of the sensor is the optimal way to manage the sensors cloud. By measuring the voltage on the capacitor and controlling the motors, the user or the system, will be able to perform defined moves of the sensor or control the entire sensors swarm.

There could be used two movement strategies in this case. The sensor could moves a few centimeters, perform the measurement of desired variable (pressure, temperature, etc.) and then measure the voltage on the capacitor - if there lefts sufficient amount of energy, the sensor will execute another moves, if the amount is too small, it must turn back and charge the capacitor. Based on this algorithm, one could notice that the sensor does not move continuously, rather by leaps and bounds with interruptions for the capacitor charging. 3.3 Capacitor discharging.

3.3 Capacitor discharging

The situation, when the capacitor is completely discharged is presented in the Fig. 4. In the tested case, the capacitor has discharged to the level, on which the motor activity was not possible, after 3 seconds of motor working.

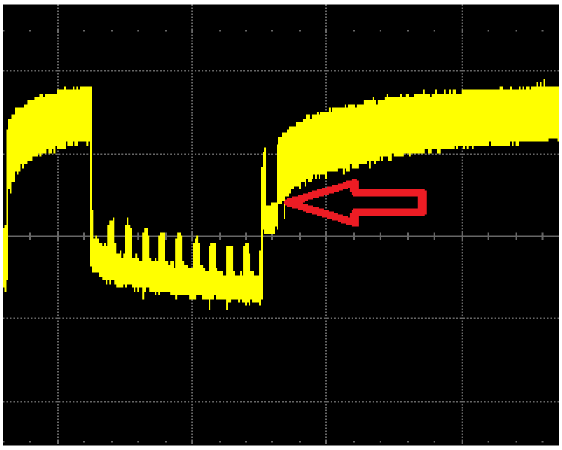

Fig. 4 Capacitor voltage signal after full discharge

It could be seen that in the first (the fastest) moment of capacitor charging, after the full discharge, the current consumption of the capacitor is significant, what causes the pooling process in the RFID reader (marked in the Fig. 4 with the red arrow). This first period of charging excludes the possibility of communication between the reader and the sensor. This phenomenon could be avoided, by the continuous monitoring of capacitor voltage and automatic disconnection of the load by the low voltage level, preventing the same a full discharge of the capacitor.

3.4 Using of different antennas

Another antenna connected to the RFID reader was also tested. Using of smaller antenna causes the longer time of capacitor charging and lower voltage in the whole system. This causes smaller amount of rotations that could be executed on the motor and the lower value of motor's power. Using of antenna from the lowest class (six) does not allow for charging of capacitor enough, what causes problems in finding of transponder chip in the field of the reader. This pooling problem is presented in the Fig. 5.

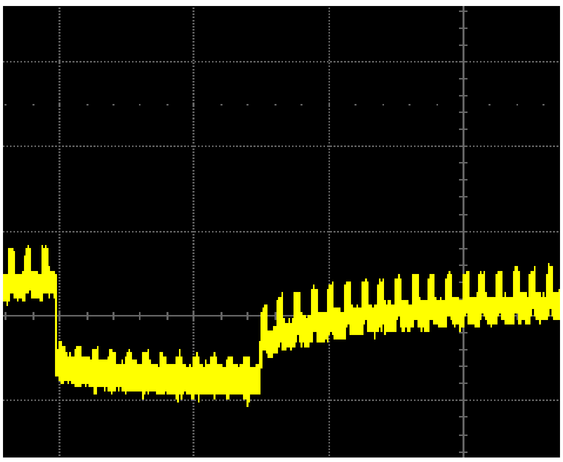

Fig. 5. Charging of capacitor in the field generated by the lowest-class antenna. The pooling problem is visible.

By checking the possibility to use smaller antennas, it was checked also the ability to use device equipped in the Near Field Communication (NFC) protocol as a reader. The NFC is the popular protocol embedded in the everyday use electronics, as smartphones and tablets, based on the HF RFID communication principles. The possibility was checked using the (Galaxy Core Prime SM-G361F). Unfortunately, the generated field was too weak to ensure the sufficient voltage level and fully charge the capacitor.

3.5 Using the RF amplifier

In the last experiment, the antenna was connected to the RF amplifier (Frankonia FLL-75). It was fed with the sinusoidal signal in the 13,56MHz and the power on the level of much higher than 7.5 A/m, which is the upper limit according to ISO norms. This set generates the magnetic field with a strength that was sufficient to power the motor working continuously. It allows for the conclusion that it is possible building of the system, where the mobile sensor could drain the energy and storage it in a super-capacitor or directly use it as a mechanical energy. This kind of system needs development of its own field generator. Important limitation related to this problem is government legislation related to the maximal power of electromagnetic fields generated.

4. CONCLUSION AND FUTURE WORKS

4.1 Achieved results

The magnetic field generated by the OK5022 reader used in experiments was sufficient to charged super-capacitor and run stepper motor in a periodic time intervals but it was not enough for continuous motion of the motors. It should be mentioned that antennas which were used for energy harvesting have been taken from ISO norm (tests included classes from 1 to 6) whilst reader's antenna was not standardized, what gives additional room for maneuver in order to improve reliability and interoperability of energy harvesting in future.

The use of the amplifier and the external antenna, which was fitted to the antenna of energy harvesting module, made it possible to achieve energy transfer for continuous motor movements without charging and discharging super-capacitor.

These tests confirmed that increasing of field strength, and using fitted antenna is sufficient for remote energy transfer high enough for continuously motor movement. It shows that in future it will be desirable to focus on building own reader to energy harvesting and data transfer.

4.2 Conclusion

Investigation presented in this paper was mainly related to the powering problem of the wireless passive mobile sensor, which idea and main features were also described.

Performed investigation shows that construction of such proposed sensor is feasible in today's state of the art, using standard communication devices, as HF RFID reader and antenna in the system. The amount of energy harvested from the magnetic field generated by the reader allows sensor to move by leaps and bounds with interruptions for the capacitor charging. The continuous movement needs bigger power, which could be delivered, by the development of dedicated power generator, according to the existing restrictions. The powering of the wireless mobile sensor by using NFC equipped devices is impossible at that moment.

Moreover, the last experiment with the RF amplifier shows that the energy harvesting, from the generated magnetic field, could be used not only in the measurement systems, with a low level of power consumption, but also in mechanical and control systems, where the amount of consumed power could is generally higher.

4.3 Possible use in the diagnosis

Mobile wireless sensors can be applied in every place where access is very limited. Additionally there are some places which are closed on the stage of production and there is no way to get into them without destroying structure. There are three applications where that kind of sensors seems to be needed. First one is SHM (structure health monitoring). Wireless sensor can be sunk in the asphalt and allows measurements every time when it is needed. Thanks to wireless energy transmission there will be no need to install battery or external contact in the structure. Similar application can be find in automotive industry. One of very known problems is wasting of bulbs in lamps. Wireless sensor gives possibility to check the state of the bulbs inside of the glass without need to apply connectors or batteries. By monitoring temperature it will be possible to warn drivers that bulbs are in suspect state and it is advisable to replace them. It has been checked that there are no distortions during data communication in high frequency (13.56 Mhz) RFID data transmission when RFID sensor is closed in glass cover.

Second application is implantable biomedical sensors based on RFID[2]. Mobile sensor with wireless data and energy transmission allows to avoid all issues connected with hygiene and infections. In solutions where connectors are implemented within the human body there are problems connected with installation and invasiveness of such method. Developed sensor does not have such problems because of its wireless nature.

Third application is to use the swarm of sensors to detect faster and more precise deformations or disorders in structures. Every mobile device may have a temperature sensor or accelerometer and is sending information to the cloud. By approximation with the lines and gathering data in a cloud, group of sensors is able to precise determine the source of disorders faster than normal manual detection with one device.

4.4 Future works

During presented investigation the first prototype of the wireless passive mobile sensor was developed. The next steps will be the development of the measurement system, performance of first mobile measurements in lab and then development of the pilot installation. Application of such system in the measurements of vibration, temperature, pressure or other variables will be checked. Part of the works on the development of entire system could be shortened using experience from previous works of the authors, related to data management process and wireless measurement performance. Using of this knowledge base should facilitate performance of next investigation. Simultaneously, the ideas for possible applications of proposed system are searched.

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