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Marcin KASPRZAK[1*]

DESIGN AND IMPLEMENTATION OF WIRELESS MODULE BASED ON ZiGBee FOR APPLICATIONS IN MACHINE TOOLS

This paper presents a concept of a wireless measuring system based on ZigBee modules, and the stages in its implementation. The distinctive feature of the built measuring systems is their high resistance to environmental conditions. To a large extent this was achieved through the use of induction charging. The effectiveness of this solution was determined by comparing it with conventional charging. The measuring modules built in accordance with this concept were tested in the work space of a machine tool during milling. Special attention was paid to the amount of power consumed by the tested modules during different modes of their operation. The response time of the modules during their operation in the work space of the working machine tool and in the case when the modules were completely immersed in water was tested. By comparing the measured response times the effect of the above factors on the correctness of operation of the measuring system was determined.

1. INTRODUCTION

Modern machines still need improvement and greater control of their state. Often these are large multiaxis machine tools in whose workspace (which is difficult to access because of the many assemblies moving in it) measuring modules need to be installed. In such cases, measurements involving the use of cables are often impossible. This problem is solved by the wireless transmission of signals and measurement data, which enables measurements and control at a minimum interference into the machine tool work space. Measurements can be performed on rotary and inaccessible (even from the outside) elements.

Large companies, such as Siemens or National Instruments [1], offer whole systems designed for the wireless connection of several separate networks or devices. But this does not solve all the problems arising when it is necessary to mount measuring modules on a machine tool, since such modules will be at risk of colliding with the live assemblies or be exposed to the action of the environment prevailing in the work space during machine tool operation. The typical reason why the ready-made devices available on the market cannot be used in such cases are the too large size of the measuring modules, the quite complicated measuring circuits and the lack of resistance to the conditions prevailing in the work spaces of machine tools.

[1] Wroclaw University of Technology, Department of Machine Tools and Mechanical Technologies, Wroclaw, Poland
[*] E-mail: marcin.kasprzak@pwr.edu.pl

ZigBee modules [2] were used to build the system presented in this paper. The modules are popular devices and are currently widely used in smart houses [3]. In measuring systems they usually work together with moisture, temperature and light intensity sensors. They are easy to operate, relatively inexpensive considering their capabilities, and use data encryption (which increases transmission reliability).

2. CONCEPT

The main assumption concerning the designed system was the wireless measurement of slowly-varying quantities. In the considered case, the system is based on ZigBee modules made by Telegesis. The system components should be highly resistant to the adverse impact of the environment and be small in size. An additional advantage of the modules is the possibility of their remote programming. Owing to this it will be possible (without interfering into the execution modules) to change the measuring method or the operating mode, to force a particular action and even to adapt the modules to another application. The concept of the system which has been developed is shown in Fig. 1.

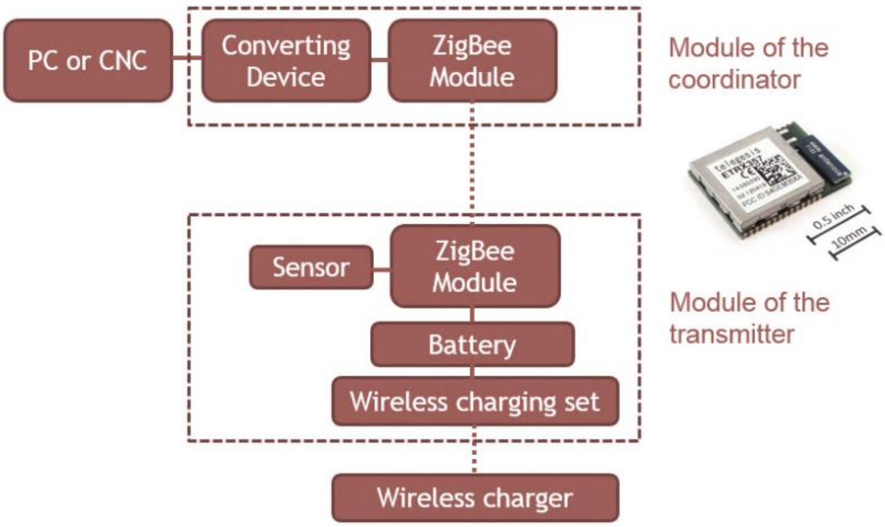

Fig. 1. Concept of wireless measuring system

Two principal modules: a coordinator and a transmitter can be distinguished in the system. The coordinator is responsible for managing the network while the transmitter handles measurements. A single coordinator module and up to 255 transmitter (a terminal device) modules are needed to run the whole network. A wireless charging set is an important component of the measurements performing device [4]. As already mentioned, a major consideration concerning the modules is their resistance to external impacts. The advantage of the proposed solution is the complete insulation of the system from the environment. At the same time the system can be charged whereby data can be continuously transmitted. Any connection other than wireless of the transmitter module to the charging set leads to some loss of its tightness and poses a risk of wrong connection [7].

3. IMPLEMENTATION

ZIG-ETRX357-PA modules with an extended range were used to build the system. Any low-voltage analogue sensors, e.g. a temperature sensor, a pressure sensor, a moisture sensor, an acceleration sensor, a distance sensor, a position sensor, can be connected to such modules. A module of this type can support up to 6 sensors mentioned above. The wireless charging circuit which the module incorporates is a standard telephone charging circuit.

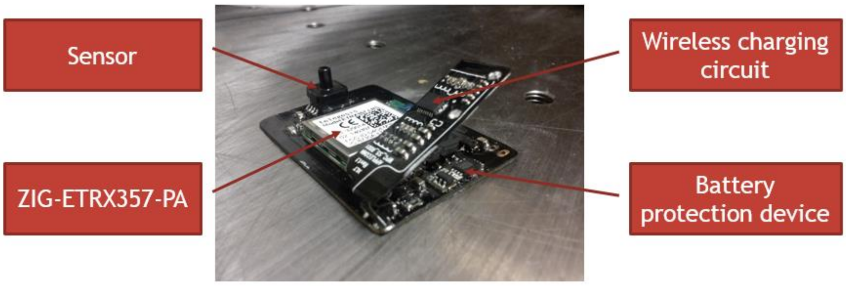

Fig. 2. Transmitter module

The transmitter system is mounted on a 50×34 mm board and its main components are: a ZIG-ETRX357-PA unit, a wireless charging circuit, a battery protection device and sensors (Fig. 2). The size of the system was to a large extent determined by the dimensions of the battery and that of the wireless charging coil. The transmitter module equipped with the battery and the charging coil, still without its case, is shown in Fig. 3. The module was placed in a milled case and sealed in resin (Fig. 4).

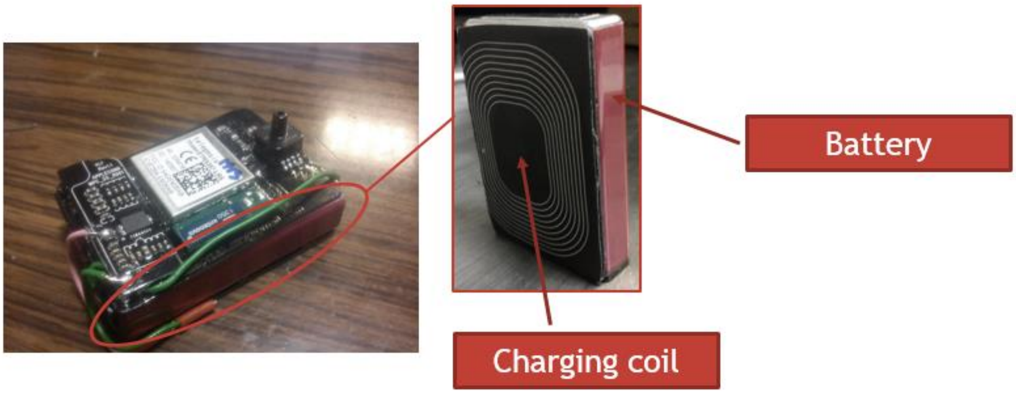

Fig. 3. Interior of transmitter module

The coordinator module is much smaller. It includes a wireless communication circuit and a converting device enabling one to connect the module (via a USB port) to a computer. The whole closed in a case has the form of a pen drive which when connected to a USB port immediately starts working (Fig. 5).

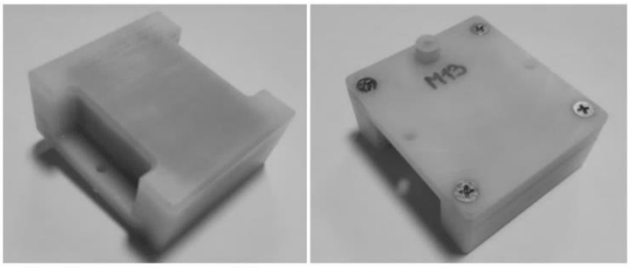

Fig. 4. Transmitter module in case

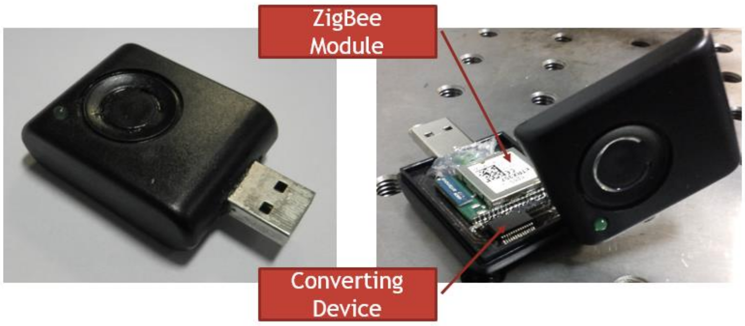

Fig. 5. Coordinator module

The principle of operation of the whole system is as follows. When connected to a computer the coordinator module automatically establishes a connection with transmitter modules within its range. Using AT commands (an international set of commands for controlling the operation of modems) one can wirelessly change the parameters of the terminal devices working in the network and query them about the actual voltage or current values describing the state of the connected sensors. A terminal device can be easily adapted to a given application even when the former must be permanently fixed to the tested element. Owing to its wirelessness and resistance to external impacts the device can be used in inaccessible or closed spaces, in hard operating conditions, on rotary elements and in places where large measuring sets cannot be introduced.

4. EXPERIMENTAL STUDIES

4.1. COMMUNICATION

The primary aim of the studies was to describe the operational state of the main component on which the presented system is based. Two basic types of this component can be distinguished, i.e. module ZIG-ETRX357 and enhanced module ZIG-ETRX357-PA (with an extended range). It was the latter module which was adopted in the system.

The experimental studies covered four major areas:

- communication,
- power consumption,
- charging,
- disturbances.

Communication in the system is based on the ZigBee protocol. The protocol comprises several layers. The lower layers perform specific services for the higher layers. The ZigBee protocol (Fig. 6) is based on the seven-layer OSI (Open System Interconnection) model [5].

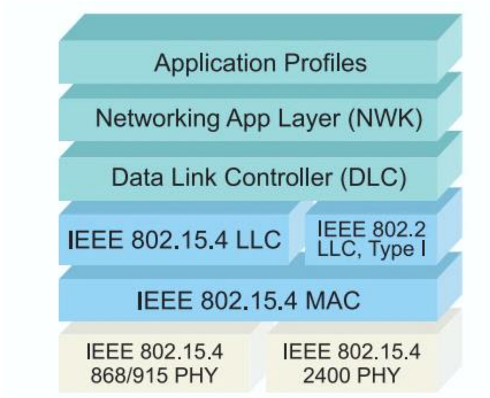

Fig. 6. ZigBee protocol layers [5]

The protocol layers are responsible for establishing a connection, responding to commands or finding and connecting new modules to the network.

A major communication parameter is range, i.e. the maximum allowable distance between the coordinator and the transmitters. According to the specifications of the modules, the range in open space reaches 100 m. Taking into account the peculiar operating environment of the target system, the modules were tested in appropriate conditions.

In the case of the first configuration, based on the ZIG-ETRX357 module, the range amounted to 8 m when there were obstacles (a computer, cabinets and a wall) on the path of communication. The range of the second configuration (with module ZIG-ETRX357-PA) in the same conditions amounted to about 25 m, but the system consumed three times more energy. In the case of battery power supply this can be a major consideration due to the shortening of the time interval between successive battery chargings.

4.2. POWER CONSUMPTION

The amount of consumed power is a prime consideration in each device whose source of energy is a battery [6]. Power consumption depends on many factors. The proposed configuration is characterized by an extended range whereby it consumes much more energy than the basic configuration. Thus the amounts of power consumed by the two configurations are different, but in both cases they do not depend on the distance between the coordinator and the transmitters. This means that power consumption remains at a constant level in the whole operating area of each of the configurations, which differ in only their operating range diameter and amount of consumed energy.

A major parameter having a bearing on power consumption is the current state of the module. Two such states are distinguished:

- online operation,
- off-line operation.

Online operation is the state when the coordinator is connected to the power supply and the transmitter is within its operating range. In such a case, the coordinator and the transmitter operate within one network and they can “see” each other. Off-line operation occurs when the coordinator is not connected to the power supply or it is connected to the latter, but the transmitter is not within its range.

Then as a device permanently connected to the battery the transmitter still attempts to connect to the network. Figure 7 shows power consumption by the transmitter in the online operation state for a time interval of 60 s.

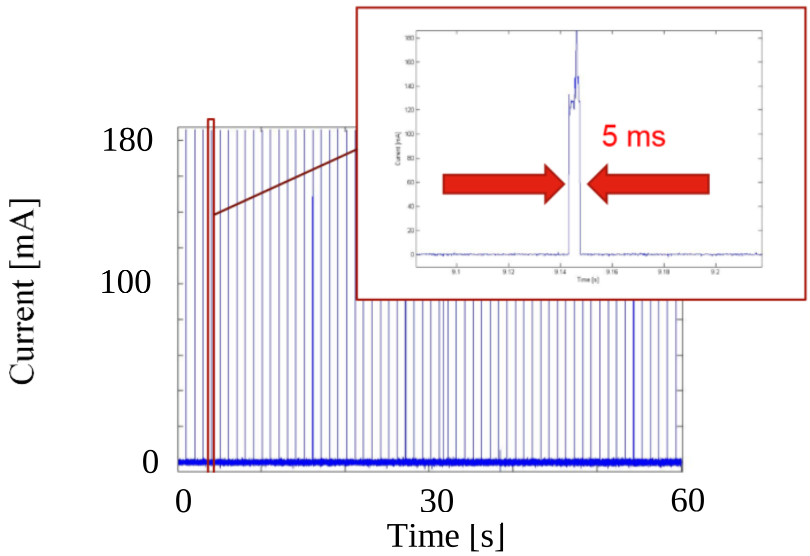

Fig. 7. Current drawn by transmitter operating online

This diagram shows a cycle of 60 peaks of 140 mA, each lasting for 5 ms, illustrating the communication with the coordinator and the checking of the state of commands. The frequency of the peaks can be adjusted from 4 Hz upwards. For the same parameters the diagram of power consumption by the transmitter working off-line looks as shown below.

Also in this case there are 60 peaks, but their character is heterogeneous. At the very end of the period a peak appears which lasts considerably longer (for about 2200 ms) than the other peaks. This is the time when the model activates itself, informing about its presence and searching for an active network within its range.

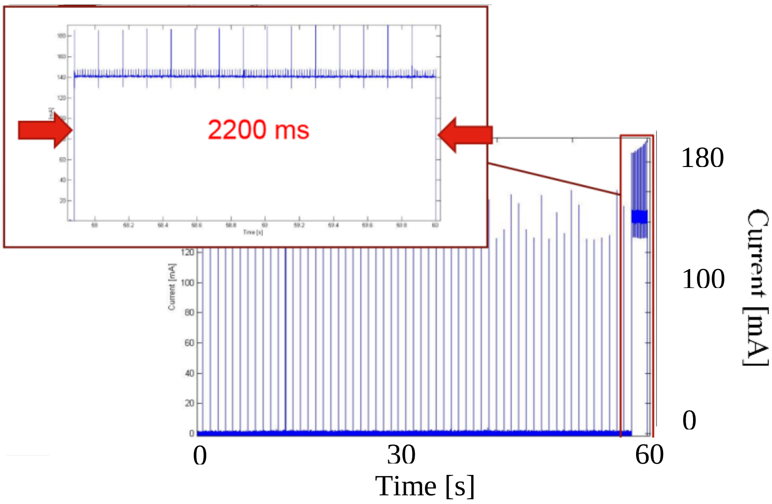

Fig. 8. Current drawn by transmitter operating off-line

The total power consumption during sixty-second operation is compared for the two cases in Fig. 9. It is surprising that the system being off-line consumes seven times more power than when being online.

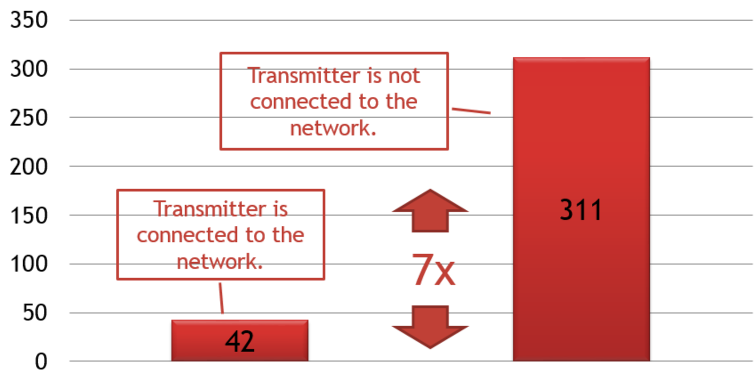

Fig. 9. Power consumed by transmitter being: 1 – online, 2 – off-line

The amount of power consumed also depends on the length of the information being transmitted, i.e. on the data packet transmission time, increasing proportionally to the increase in the number of commands sent and received by the module.

4.3. CHARGING

Because of its low power consumption the presented transmitter can be classified as low-power device, which means that it does not need much power in order to work and so its energy source can be small. A small power source has its limitation in the form of the allowable charging current. A 3.7 V battery with a capacity of 2 Ah was used in the developed transmitter module. The rated charging current of the battery is 1 A. Because of the small dimensions of the device a small battery charging unit with a maximum capacity of 500 mA was employed. For these specifications wireless charging should be as efficient as wire charging. This is confirmed by the results of transmitter module battery charging voltage measurements for respectively wire and wireless charging (Fig. 10).

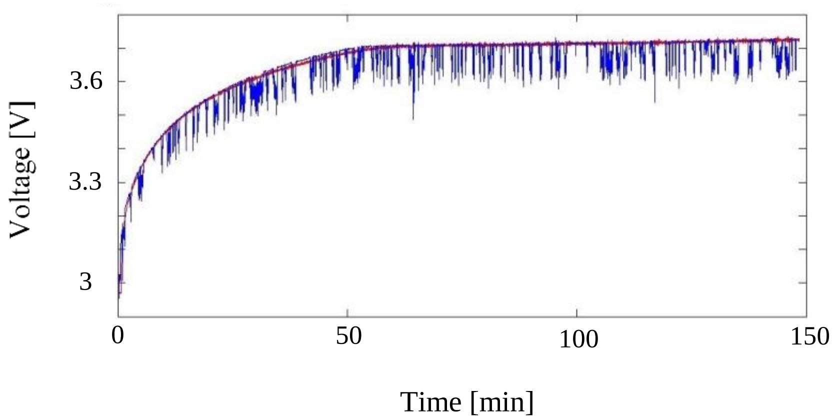

Fig. 10. Comparison of wire and wireless charging of transmitter module battery

The wire charging characteristic and the wireless charging characteristic are in agreement as regards both the voltage value and the time constants. Moreover, frequent voltage drops are visible during wire charging (the blue line). Wireless charging (the red line) is characterized by greater stability in this case. The adopted wireless charging system can charge the battery to 80% in 120 minutes and to 100% in 480 minutes.

4.4. DISTURBANCES

Disturbances can affect the operation of the wireless measuring system modules. It is a major problem the solution of which can ensure the correct operation of the modules. A number of tests were carried out in order to verify the suitability of the designed system for operation in the work space of the machine tool. Several factors connected with the operation of the machine tool occur in its work space. They include variable magnetic fields (originating from the drives), moving assemblies, chips displacing in the work space, the cooling fluid, etc. All of this can adversely affect the operation of the modules.

Because of the digital form of the transmitted data, in which a correct signal and its absence are distinguished, the modules were tested with regard to their response time. The network coordinator at equal intervals would send a message to the measuring device. After receiving the message the device would perform the measurement and send back the value of the measured physical quantity. The time which elapsed between sending a message and receiving the correct message from the terminal device (the transmitter) was registered. The testing included checking the behaviour of the transmitter module in the following three different operating conditions:

- the module placed in the space of an idle machine tool,
- the module placed in the space of the working machine tool,
- the module completely immersed in water.

The tested machine tool was a HAAS MINIMILL milling machine. The diagram below (Fig. 11) shows the response time of the module during its operation in the different conditions.

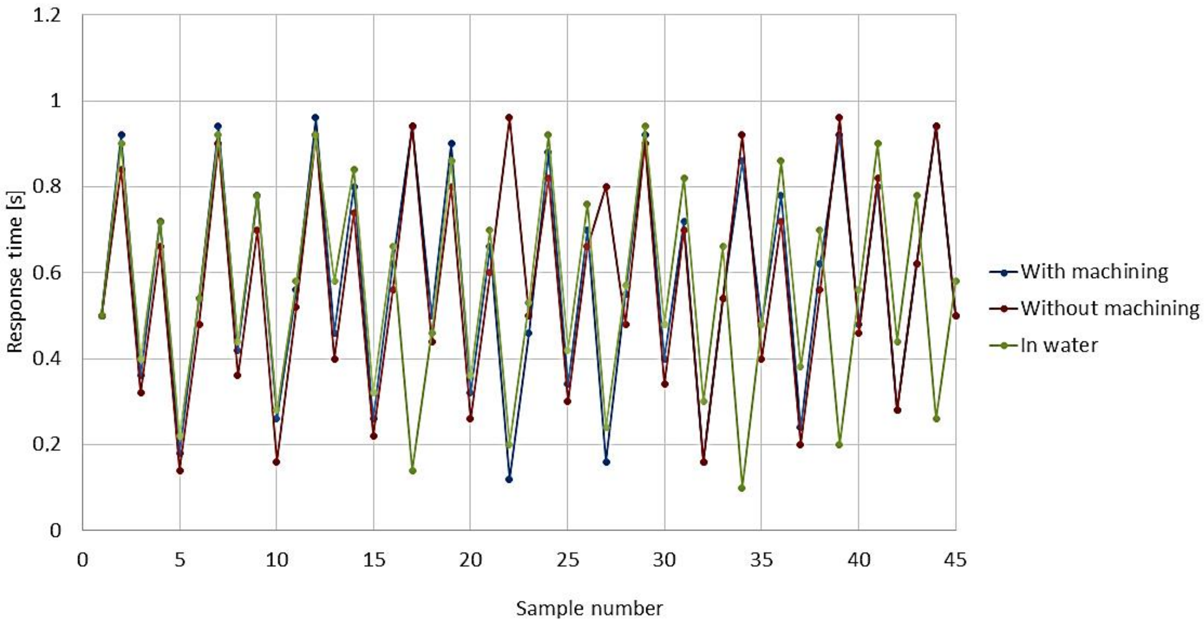

Fig. 11. Module response time in different operating conditions

Several indicators were calculated in order to compare the three graphs. The first indicator was the arithmetic mean of all the samples:

$$\tilde{x}_1 = 0.57933, \qquad \tilde{x}_2 = 0.577778, \qquad \tilde{x}_3 = 0.56000$$

where:

$\tilde{x}$ – an arithmetic mean

$$1,2,3 \ \text{– a number defining the operating conditions} \ \begin{pmatrix} 1 - \text{with machining}, 2 - \text{without machining}, \\ 3 - \text{in water} \end{pmatrix}$$

The next indicator was the arithmetic mean of the function minima and maxima:

$$\tilde{x}_{1min} = 0{,}37792, \qquad \tilde{x}_{2min} = 0{,}37833, \qquad \tilde{x}_{3min} = 0{,}35870$$
$$\tilde{x}_{1max} = 0.80952, \qquad \tilde{x}_{2max} = 0.80571, \qquad \tilde{x}_{3max} = 0.77076$$

The last indicator, enabling the best comparison the tested values, was a convergence coefficient.

$$V_1 = 0.43786, \qquad V_2 = 0.43356, \qquad V_3 = 0.43792$$

The convergence coefficient values indicate that water environment (*V3*) and machining (*V1*) have a similar, but very small (in the order of 1%) effect on the quality of communication.

5. CONCLUSION

The aim of this research was to design and built wireless measuring systems able to work in industrial conditions, i.e. in the machine tool work space. The devices are based on popular ZigBee modules widely used in various measuring systems, also in industry.

The experimental studies showed the capabilities of the developed system. A small (55×50×28 mm) device, hermetically closed in a case completely insulating the device from the outer environment, has been built. Owing to this the device is watertight even if completely submerged. The device has no moving parts and is solid and compact, thanks in part to the use of wireless charging (not used in such systems before). Measurements showed that the effectiveness of the wireless charging does not differ from conventional wire charging (the charging time is the same).

Interesting observations concerning the system’s power consumption during its online and off-line (idle) operation were made. It was found that when the module is not online, i.e. is not connected to the coordinator, it consumes 7 times more energy. This occurs when the power supply is disconnected from the network forming device. Then the wireless module battery operating time is considerably shorter. As a result, as power consumption periodically increases, the charging time is longer. Another interesting observation emerges from the comparison of the module’s online operation (measurements performed every second) and off-line operation (no measurements performed): in the former case, power consumption in nearly three times lower.

It is also interesting to note the range of the device equipped with the basic ZigBee module or the enhanced ZigBee module. The tests showed that the communication range of the latter module is three times longer, which entails about three times higher energy consumption. This fact should be taken into account in the design of wireless measuring systems.

In order to verify the suitability of the designed system for operation in work spaces in which various disturbances occur, the time from the instant of sending a command to the instant of receiving the response (the measurement result) was measured. Tests were carried out for three different states: 1) the work space without machining, 2) the work space with machining and 3) complete immersion in water. The tests showed that the machining process and complete immersion in water affected the quality of communication to merely one per cent.

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Wroclaw University of Technology

Narodowe Centrum Badań i Rozwoju

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