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Possibilities to apply self-powered sensors in underground mines

The articles refers to the method of power supply to sensors for monitoring intelligent machines and buildings. Self-powered sensors, which are used more and more frequently these days, were discussed. These sensors make use of energy harvesting, particularly energy generated from such physical phenomena as: heat flow, vibrations or light. The authors presented how to implement a system of self-powered sensors in machines operating in mining areas with methane and/or coal dust explosion hazards – including automation systems and systems for diagnosing mining machines and equipment.

1. INTRODUCTION

The development of systems for monitoring and automation of mining machines and devices stipulates that a new intelligent solutions should be developed and implemented. For equipment working in areas with explosion hazards it is required to apply special structures compliant with the requirements of the ATEX directive. According to the decree by the Minister of Economy from 22 December 2005 (Journal of law No 263, item 2203), safety devices and systems used in the areas with explosion hazards have to be equipped with adequate safety measures, such as an anti-explosion structure. On the European level, this is regulated by the Directive 94/9/EC (ATEX). General requirements concerning the structure of electrical devices used in the areas with explosion hazards are dealt with by the PN-EN 60079-0 standard harmonized with the ATEX directive. Distributed control systems are more and more popular these days. They are based on industrial networks (for example those constructed based on CAN) and make it possible to reduce the number of cables. In practice, however, it is necessary to have a mains wire and a power supply one (often placed in one cable). There are also sensors which communicate by means of a wireless network, still they also need a power supply cable (optionally they can have batteries).

The systems for monitoring machines and intelligent buildings make use of self-powered sensors. These sensors have become very popular recently. They make use of energy harvesting, i.e. use energy generated during physical phenomena, such as heat flow, vibrations or solar energy. The conducted analysis of applied solutions proved that it is possible to use such sensors in the systems for automation and diagnostics of mining machines and devices. The sensors have the following application possibilities [1]:

- modernization of existing control system,
- sending measurement signals from movable elements of machines,
- portable diagnostic equipment.

2. ENERGY HARVESTING METHODS USED IN SENSORS STRUCTURES

The analysis of available literature [3, 4] and the existing solutions which have not been designed to work in areas with methane and coal dust explosion hazards [5, 8, 9, 10, 11] showed the possibilities to construct a system of self-powered sensors. As far as energy harvesting from mechanical vibrations is concerned, the solutions of electromagnetic converters and piezoelectric converters were analyzed as potential power supply sources for sensors comprised in the system [5, 7, 8, 9, 10, 11]. Additionally, the solutions concerning thermogenerators and photovoltaic converters were assessed [2].

The electromagnetic converter is based on Faraday's law which says that in the conductor placed in a time-varying electromagnetic field there is an electromotive force induced. The time-varying magnetic field is produced most frequently by moving magnets while suitably constructed coils act as conductors.

Tremont Electric applied an electromagnetic converter into a portable kinetic energy charger nPower® PEG (Fig. 1a) [10]. The charger can be used while walking (with minimal movement it generates a signal of 1 mW).

Another application of the electromagnetic converter are electromagnetic flashlights [11] which do not need batteries. The generated electrical energy is stored in the condenser. The drawback of these devices is that they need to be shaken violently for at least 2 minutes so that the condensers got charged. The accumulated energy is enough for a few minutes of light.

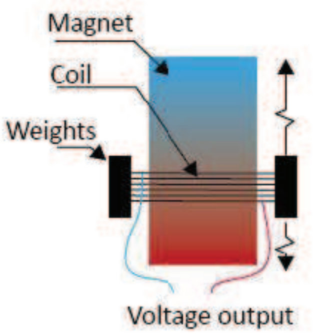
Next application is the PMG17 vibration energy harvester (Fig. 2) [9]. It uses mechanical vibrations of machines powered by alternating voltage.

a)

b)

Fig. 1. a) nPower® PEG [10], b) electromagnetic flashlight [11]

a)



b)

Fig. 2. PMG17 vibration energy harvester [9]:
a) PMG17 operating scheme; b) general view

Piezoelectric converters use the phenomenon when, as a result of mechanical stresses, electrical charge is produced on the surface of a piezoelectric material. The piezoelectric element is placed in the device in such a way that there is maximal use of the energy of mechanical phenomena which take place in the device [3, 4]. Figure 3 features piezoelectric elements used for producing energy as a result of mechanical strains, i.e. a piezo-laminate sensor for monitoring machines, detecting acoustic and over-audio emissions (i.e. detecting vibrations and shocks [3a]) as well as piezo film (3b).

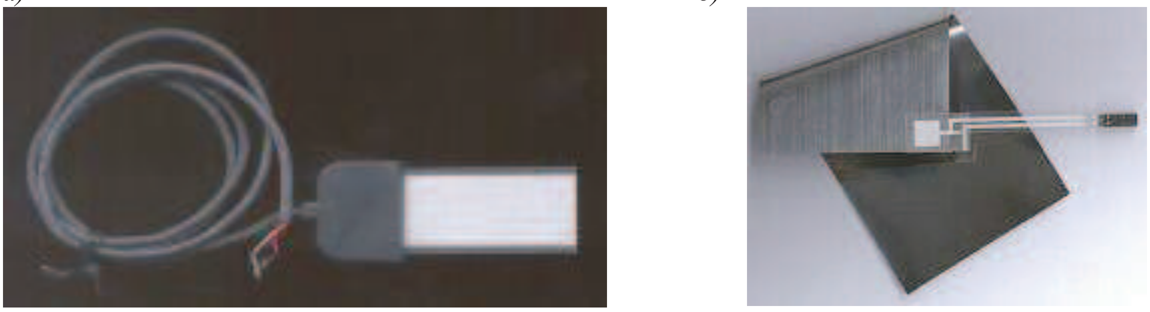


Fig. 3. Sensor for detecting vibrations and shocks:
a) piezo-laminate sensor [5]; b) piezo film [8]

An interesting and curious solution to apply piezoelectric converters is the concept of a "piezoelectric tree" which generates energy while the wind blows (Fig. 4) [7].

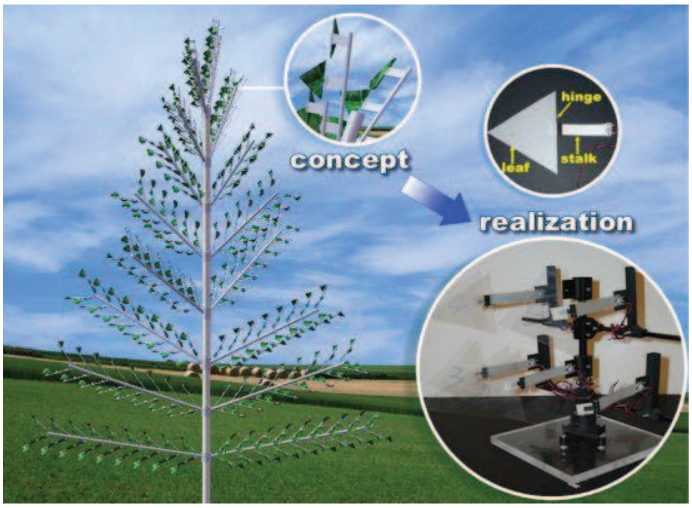


Fig. 4. Piezoelectric tree [7]

Photoelectric sensors are another group of converters that can be used in the process of building the elements of the system. Photoelectric sensors convert solar energy into electrical energy as a result of the photovoltaic effect. In this effect electric charge carriers move on the p-n junction between energy bands. The movement is caused by photons. The movement of the carriers results in a potential difference, i.e. electrical voltage.

These sensors find application in photovoltaic cells. They are used in the construction of solar batteries. The batteries are made of serial cells in the number which allows to generate current with required intensity.

Thermogeneretors – heat recovery. The phenomenon of recovery is based on the recovery of heat energy [2]. Thermogenerators are devices used to convert, for example, heat energy into electrical energy. They produce electrical energy due to temperatures difference and the resulting flow of a heat energy stream. There are two major types of thermogenerators: those based on the Seebeck effect (Peltier cells) and those using the phenomenon occurring in the Stirling engine.

Peltier cells are based on the Seebeck effect when an electromotive force (also called thermoelectric force) is generated in a loop made of two different materials whose junctions have different temperatures [2]. This phenomenon is the result of temperature dependence of contact potential difference between the materials. The contact potential difference is created as a result of diffusion of electrons from one material to another through the surface [2].

A modern Peltier cell is made of two thin tabs of a thermal conductive insulating material (aluminium oxide ceramics). Between these tabs there is a series of semiconductor elements, alternately "P" and "N" (Fig. 5). The semiconductors have a form of pillars and are made of bismuth telluride mixed with antimony and selenium. The pillars are connected in series thanks to copper paths on the outer sides of the tabs which form a ceramic shell.

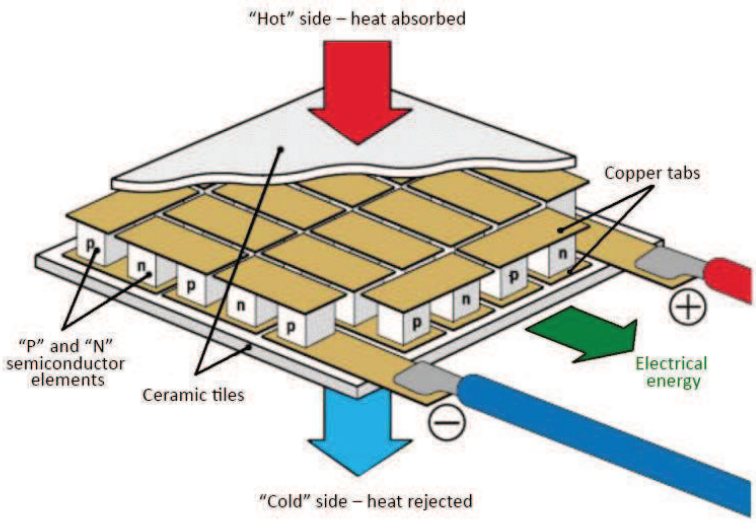


Fig. 5. Structure and operation of the Peltier cell [2]

3. USING OPERATING CONDITIONS OF MACHINES

While designing and modernizing control systems of mining machines it is necessary to work out a state-of-the-art method to conduct power and control wires, in an adequate space, with no risk of damage. Self-powered sensors can be an answer to these requirements. These sensors use, for example, the energy from rotary motion, mechanical vibrations or heat flow.

Energy can be generated from [1]:

- rotary motion of machine parts – and can be used to determine:
  – temperature of belt conveyor rollers – the energy resulting from the rotary motion of the roller is used to power a temperature sensor (a generator inside the roller); such a sensor can be a significant element of a fire protection system,
  – location of the loader of a shearer – due to restrictions related to cable routing it is possible to use an absolute encoder powered by the energy which is generated as a result of the loader rotary motion; due to a small angle of the loader movement and a big torque, it will be necessary to make a gear for multiplying the rotations,
  – location of the boom of a heading machine – similarly to the shearer loader, it is possible to use a self-powered encoder which measures the location of the boom (it is necessary to multiply the rotations),
  – location of the bucket of a loader – similarly to the above cases, it is possible to use a self-powered absolute encoder which measures the location of the bucket (it is necessary to multiply the rotations); in addition, the sensor can be equipped with a tensometric system or an element for pressure measurement – to determine the mass of mined rock in the bucket,
- mechanical vibrations and – can be used to determine:
  – temperature of selected structural joints of machines – in the case of machines it is possible to use the energy of vibrations to power temperature sensors; temperature can be measured in any place and the sensor can be moved to different places during the machine operation,
  – pressure of a hydraulic system – use of the energy generated by vibrations to power a pressure sensor,
  – vibrations (vibro-diagnostics) – possibility to construct a self-powered sensor for measuring the vibrations of the working machine for the needs of a vibro-diagnostic system,
  – stresses of the chain in a chain-and-flight conveyor – possibility to fix an element which converts the energy generated by stresses in a specially constructed measurement cell equipped with a piezoelectric system.

4. THE CONCEPT OF SELF-POWERED SENSORS SYSTEM

The concept of the self-powered sensors system, to be used in areas with methane and/or coal dust explosion hazards, was preceded by a market analysis and an analysis of technical feasibility of the project. On this basis it was decided that the following issues should be solved:

- What are the restrictions concerning the use of the proposed system in the areas with methane and/or coal dust explosion hazards?
- What are the requirements concerning the frequency of the measurement signal emitted by the sensor?
- How should the converters be installed in order to fulfill the requirements of valid regulations?
- How can the sensor be installed on a machine/device?
- How to solve the issue of radio transmission (with respect to the sensor housing)?
- How to tune a piezoelectric converter to the required operating frequencies?
- How to provide adequate temperature difference on both sides of a thermogenerator?

The concept of the self-powered sensors system assumes the installation of any number of wireless sensors on the machine/device body (Fig. 6). The sensors send radio messages to the receiver. In the case of a stationary monitoring system, the receiver can be installed for good and connected with the telecommunications network of the mine. In the case of a mobile monitoring system, the receiver can be, for example, a palmtop with a radio communication module.

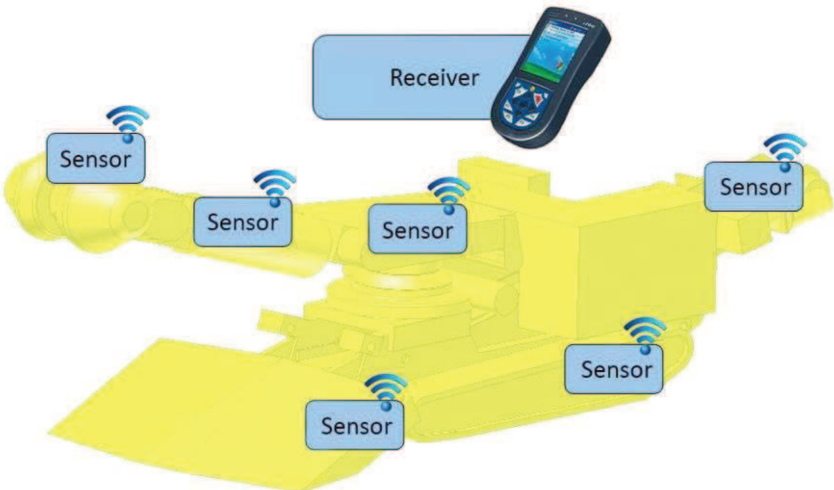


Fig. 6. Overall structure of the system

The application of self-powered sensors will enable to develop an innovative system for monitoring selected parameters of the machine/device operations. The system will be used in mines – in areas with methane and/or coal dust explosion hazards. In the case of electronic devices the best protection is their intrinsically safe structure. This structure limits the volume of electric energy in the device (including cables), which has a contact with a potentially explosive air, to such a level that the ignition is not possible – neither as a result of sparking, nor heating. The requirements concerning this type of structure are included in the PN-EN 60079-11 standard. A preliminary analysis was conducted to check the application possibilities of self-powered sensors equipped with piezoelectric converters. The EN 60079-11:2012 standard says about the necessity to carry out mechanical tests of devices with piezoelectric elements. According to this standard it is necessary to measure the capacity of the element as well as its voltage when the resistance to shocks of each part of the device available during exploitation is tested at the temperature of (20 +/-10)°C. The selected value of voltage should be the higher one obtained from two tests of the same sample. The maximal energy stored by the crystal capacity at the maximal measured voltage should not exceed the following values: in the case of **group I** devices 1500 μJ" (EN 60079-11:2012 item 10.7). If the maximal value of output energy of the given device exceeds the value determined in item 10.7 of EN 60079-11:2012, it is proposed to fix the piezoelectric element in a hermetic housing, then pour a special filling compound over and then place it in a housing resistant to mechanical impact, i.e. one which complies with the conditions of the M1 category (with the "ia" safety level – device operating in methane atmospheres all the time).

5. THE CONCEPT OF WIRELESS SENSOR POWERED BY PIEZOELECTRIC CONVERTER

The concept of a wireless sensor powered by a piezoelectric converter is presented in Fig. 7.

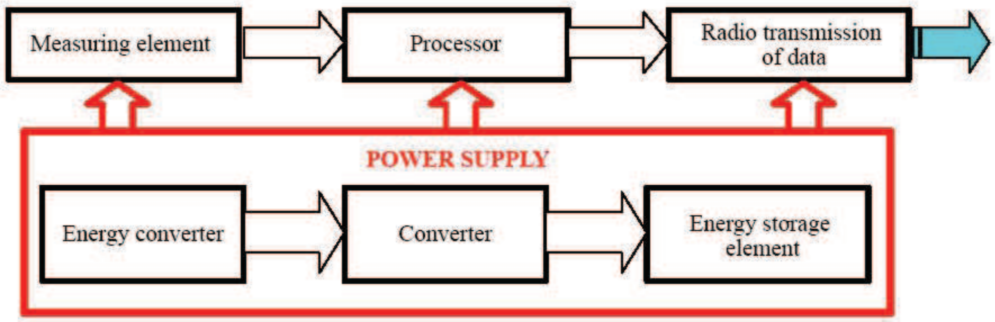


Fig. 7. Diagram of a wireless sensor [1]

The sensor comprises four modules:

- measuring element – depending on the sensor type this can be, for example, a piezoelectric element for measuring vibrations, forces or pressure, a thermo-element for measuring temperature, etc,
- processor – a physical parameter measured by the sensor is converted from an analogue form to a digital one; thanks to that it can be radio transmitted,
- system of radio transmission of data – after the analysis of data transmission systems available on the market, it was found out that the ZigBee standard of radio exchange of data would be the most adequate for wireless sensors; the radio transmission system sends the processed digital signal to the receiver,
- power supply – in typical wireless sensors battery power supply is used; here an alternative source of power supply for all subassemblies of the sensor was proposed – the one based on piezoelectric converters.

In the case of the energy harvesting application, the power supply of the sensor is composed of three basic modules:

- energy converter (piezoelectric, induction, Peltier cell, photovoltaic),
- converter for the energy harvesting application,
- energy storage element (super condenser, battery).

5.1. Selecting piezoelectric converter

Piezoelectric converters for the energy harvesting application have, most frequently, parameters which are adapted to recovering the energy of low-frequency vibrations, from 30 to 100 Hz.

While working on the concept of the system, there were piezoelectric converters selected which can be used in power supply systems of wireless sensors. The converters were selected based on the review of literature and experiences of experts from KOMAG's Mechatronic Systems Department [1, 6]:

- **V21BL-ND** (manufactured by MIDE, Fig. 8) – the converter has a narrow range of resonance frequency and is tuned to the given resonance frequency by means of adding a tuning mass to the end of the wafer. The voltage generated by the converter is subject to change depending on the operating frequency and the converter deflection. Figure 9a features the dependence between power and voltage at the operating frequency 50 Hz. In the catalogue card of the converter the mass for loading the converter is defined, along with the deflection amplitude needed to achieve the given input voltage.

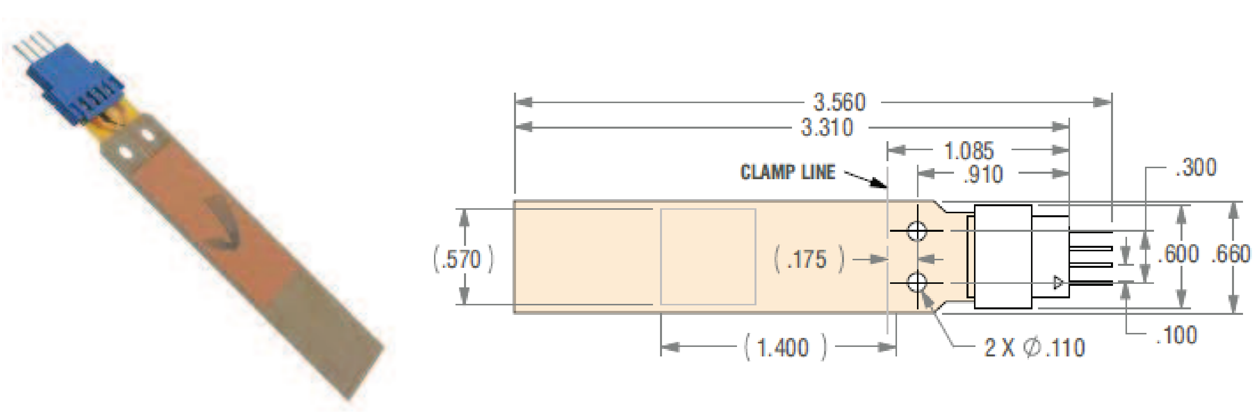


Fig. 8. V21BL-ND piezoelectric converter (dimensions in inches) [6]

a) *b)*

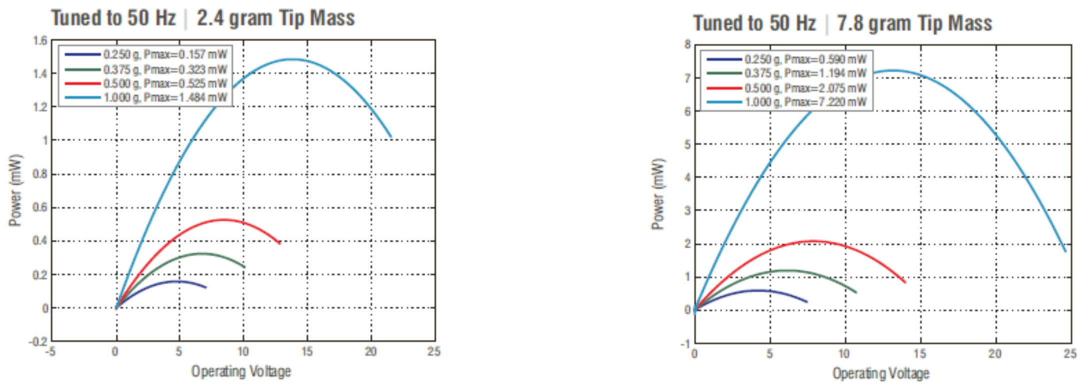


Fig. 9. Operating characteristics of piezoelectric converters at 50 Hz [6]: a) V21BL-ND; b) V25W-ND

- **V25W-ND** (manufactured by MIDE, Fig. 10) – similarly to V21BL-ND, the parameters of the converter are included in the catalogue card provided by the manufacturer. Figure 9b features the dependence between power and voltage at the frequency of 50 Hz.

Preliminary laboratory tests of the selected converters, conducted in the KOMAG Institute, confirmed that they are useful in the developed sensors systems. Due to the sizes of the converters, further works focused on the V21BL-ND converter.

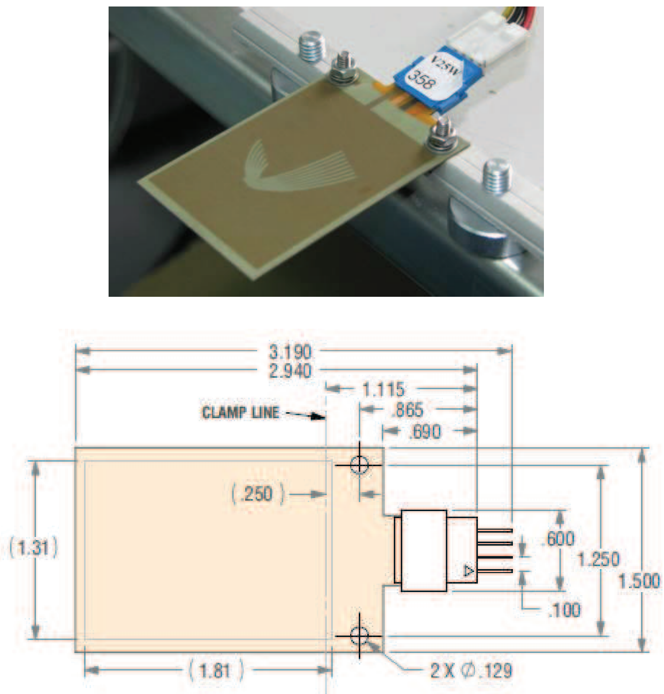


Fig. 10. V25W-ND piezoelectric converter (dimensions in inches) [1, 6]

5.2. The installation concept of piezoelectric converter

The design of the sensor housing was prepared in two versions. The first one took into account minimized dimensions of the electronic system. Figure 11a presents a 3D model of the sensor and its installation method.

The first version of the installation method is advantageous due to its easy operation. Yet the analysis of the intrinsically safe version of the sensor showed that the housing should be a complete body and should be poured over with a filling compound for electronic circuits. This way there would be no access to the electronic circuit and the piezoelectric converter. Such changes were made in the second version of the sensor (Fig. 11b):

- the dimensions of the electronic circuit were increased,

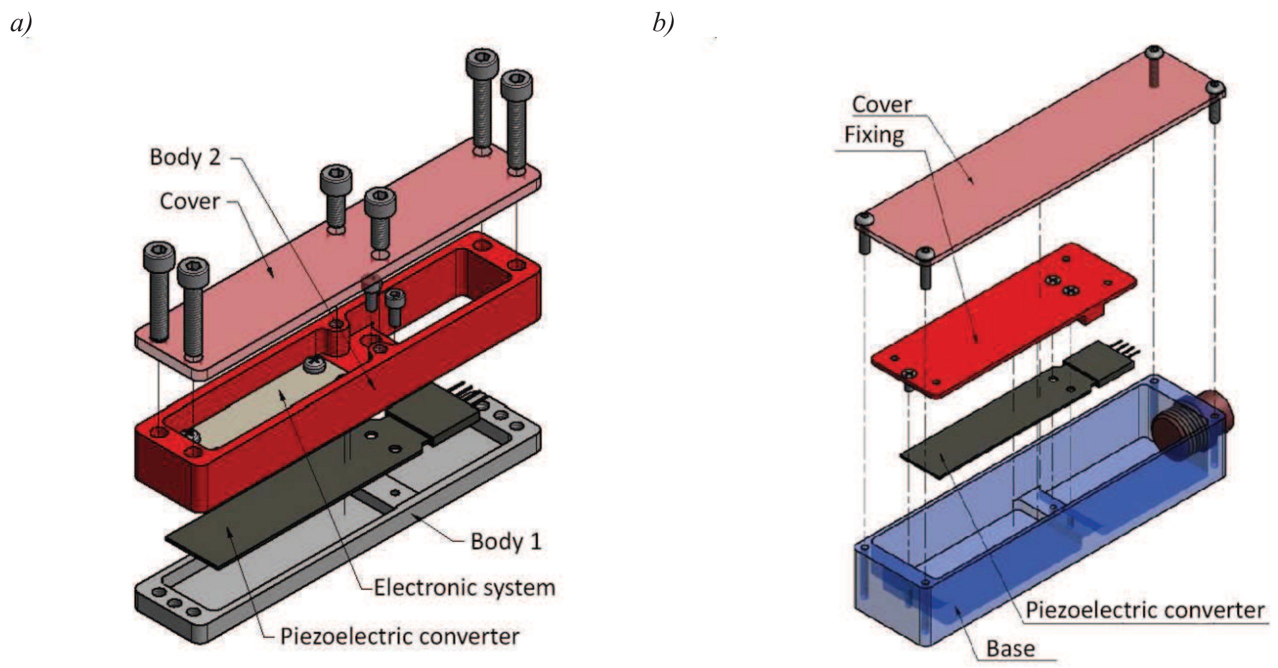


Fig. 11. 3D model of a wireless sensor [1]:
a) version 1, b) version 2

- the housing was made as one element (it is possible to pour a resin filling over the housing),
- the chamber of the piezoelectric converter was separated,
- the housing can be made of plastic which will enable the operation of the radio system.

6. CONCLUSIONS

Designing intelligent systems to control mining machines requires that the issue should be solved of routing power supply and control wires in a proper space with no risk of damage. The issue can be solved by applying self-powered sensors which make use of energy generated as a result of rotary motion, mechanical vibrations or heat flow.

The article features the possibilities to use a system of self-powered sensors with respect to machines operating in areas with methane and/or coal dust explosion hazards. The presented concept of the self-powered sensors system and the sensor powered by a piezoelectric converter takes into account the requirements related to the system operations in these areas, i.e. the criteria of the M1 category are fulfilled. As a result of the concept implementation it will be possible to monitor the parameters which have not been measured so far due to technical difficulties and which are significant from the point of view of occupational safety. Measuring the temperature of the rollers of a belt conveyor can be an example of such a process.

References

1. Jasiulek D. et. al.: *Alternatywne źródło zasilania czujników stosowanych w górnictwie*, ITG KOMAG, Gliwice 2012, not published.
2. Woszczyński M., Stankiewicz K.: *Perspektywy rozwoju systemów rekuperacji i konwersji energii cieplnej w maszynach górniczych napędzanych silnikami spalinowymi*, KOMTECH 2009, Monograph of ITG KOMAG, Gliwice 2009.
3. Xu-rui Chen, Tong-qing Yang, Wei Wang, Xi Yao: *Vibration energy harvesting with a clamped piezoelectric circular diaphragm*, Ceramics International 38S (2012), pp. 271-274, Available online 5 May 2011.
4. Hui Shena, Jinhao Qiu, Marco Balsi: *Vibration damping as a result of piezoelectric energy harvesting*, Sensors and Actuators A 169 (2011), pp. 178-186.
5. Catalogue card of a piezoelectric converter - Measurement Specialties LDT0-028K.
6. Catalogue card of piezoelectric converters - MIDE Volture.
7. http://www.environmentteam.com/2010/02/06/ piezoelectric-tree-to-produce-electricity-from-wind-energy/.
8. http://www.powerauditing.com/piezolaminaty/czujniki/.
9. PERPETUUM: http://www.perpetuum.com.
10. Power PEG: http://www.npowerpeg.com.
11. NightStarCanada: http://www.nightstarcanada.com/.

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