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doi:10.15199/48.2021.03.27

An intelligent sensor platform with an open architecture for monitoring and controlling cyber-physical

***Abstract**. The work includes the process of developing intelligent sensors, intelligent mechanisms for monitoring and controlling industrial processes using modern measurement techniques, process tomography, vision systems, motion and temperature sensors, as well as advanced data processing methods.*

***Streszczenie.** Praca obejmuje proces opracowania inteligentnych czujników, inteligentnych mechanizmów monitorowania i sterowania procesami przemysłowymi z wykorzystaniem nowoczesnych technik pomiarowych, tomografii procesowej, systemów wizyjnych, czujników ruchu i temperatury, a także zaawansowanych metod przetwarzania danych. (**Inteligentna platforma sensorowa o architekturze otwartej do monitorowania i sterowania systemów cyber- fizycznych**)*

Keywords: electrical capacitance tomography, cyber-physical systems sensors, process tomography.
Słowa kluczowe: elektryczna tomografia pojemnościowa, czujniki systemów cyber-fizycznych, tomografia procesowa.

Introduction

Intelligent platforms for enterprises with open architecture with the possibility of free configuration and cooperation with external systems is the main idea of the presented solution.

The system consists of the following elements:

• New measurement techniques and construction of innovative intelligent measuring devices

• System framework with communication interface

• New unique algorithms for data optimization and analysis

• Algorithms for image reconstruction and monitoring of technological processes

The platform enables the management of an intelligent enterprise structure in terms of processes, products, simulations and products. It will enable optimization and auto-optimization of design, logistics and production processes. It will allow you to track the product cycle and ensure cooperation with external applications. The system will operate autonomously, monitoring, controlling, performing measurements and collecting their results. The collected data can be easily visualized [1]. In addition, they will be used to create a unique knowledge base and support the expert system. The essence of the solution is the development of intelligent mechanisms for monitoring and controlling industrial processes using modern measurement techniques, process tomography [2-13], vision systems, motion and temperature sensors as well as advanced methods of data and image processing, i.e. fuzzy clustering techniques and identification of parameters of system components, to determine important parameters industrial processes [14-24].

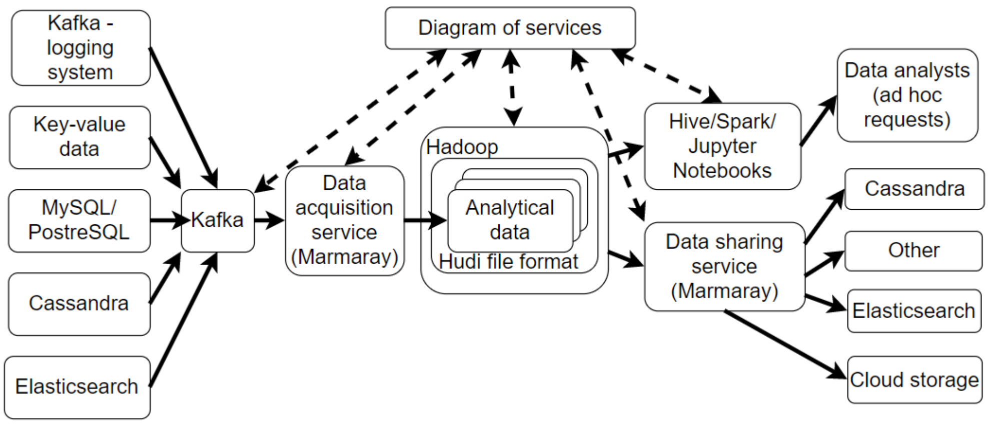

Fig. 1. Big Data platform

Measuring sensors

Intelligent sensors are a unique solution for combining traditional "measuring instruments" with microprocessor technology using modern two-way communication interfaces. In addition, the sensors have the function of auto-calibration and auto-configuration, which increases their precision and reliability. In most cases, data is collected manually or semi-automatically with little support for complex systems. To this extent, there are no open platforms offering full integration and support for the enterprise in the field of monitoring and measuring devices as well as IT tools. The solution resulting from the project implementation includes a number of measuring devices (nodes) that collect data and transfer them to an analytical system that monitors potentially problematic processes and areas.

The key innovation is the use of tomographic techniques in sensor devices and the introduction of new algorithms for analyzing data acquired by sensors. During the project, electronic circuits processing data from many types of sensors will be designed and tested. Special algorithms have been developed that combine real-time data from various types of measurements to identify potential threats or unwanted effects. The developed methods will reconstruct data in 2D and 3D dimensions.

Fig. 2. Measuring sensors designed

Sensors

Due to the different types of sensors to be used in the model, it was decided to create sensor modules that will combine several different sensors. Combining several sensors with a similar amount of generated data will allow for better use of them. Thanks to this solution, the sensors that investigate slow-moving phenomena were combined into one module. A module with sensors - temperature sensor, humidity sensor and pressure sensor - defined as type 1 was created. Type 2 of the module was designed as a set of color, zoom and magical field sensors. Module type 3 has been defined as a set of fast-changing sensors, in which data changes the fastest. Module type 3 includes sensors for acceleration, position, roll and vibration. There are two additional types of modules of one sensor each. Thus, the type 4 module has been assigned a pressure sensor, where the signals are slow-changing, and the type 5 module with slightly faster changes containing a flow sensor.

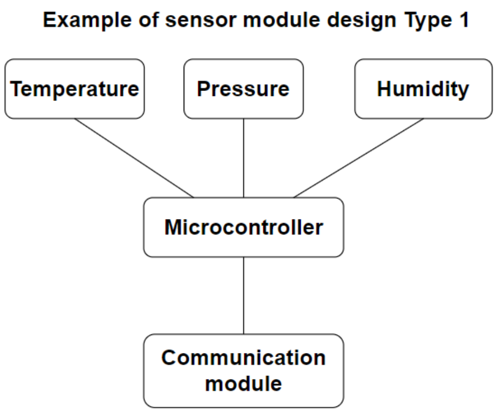

Fig. 3. Example sensor module type 1

A division was made according to the measurement location. Product measurements - refer to the measurements made on the product, semi-finished product, while the measurements of devices are the measurements of devices, machines, robot arms, etc.

Sensor modules used for measurements on devices should be such that they do not interfere with the operation of the device. The measurements on the robot's arm must be carried out with the lightest possible measurement modules and if possible wirelessly. The higher the weight of the modules, the more it can affect the operation of the robot arm, introduce additional inertia. Cable connections of such sensors may cause limitations in arm movement. Due to these limitations, the measurement modules will be built so that their weight is as low as possible and communication between the sensor module and the control panel will be wireless. Additionally, in order not to increase the weight of the device, the assembly of the sensor modules will be carried out using glue.

The sensor unit consists of five specialized wireless units. All devices are equipped with microcontrollers using Bluetooth 5 wireless communication, which allows for their installation in hard-to-reach places and remote access to data. Depending on the type of sensor, data can be sent to the microcontroller in analogue (using 12-bit ADC) or digital (using I2C or SPI communication interfaces) form. The insufficient number of communication ports of the nRF52840 wireless microcontroller can be compensated by implementing an I2C expander or using the MPU-9250 chip outputs to connect redundant sensors as Third Party Sensors. In the presented case the second variant is used. This will allow for data transmission from as many sensors as possible on one communication bus without the need for continuous switching between the modules.

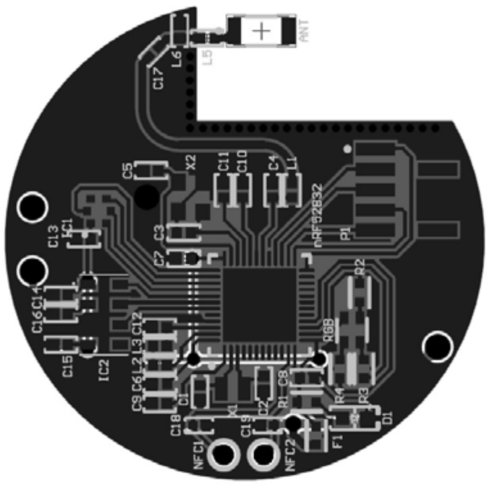

Fig. 4. Wireless temperature, absolute pressure and humidity sensor module model

The first model of the sensor is a unit that controls such parameters as temperature and humidity (HTS221 connected via SPI interface) and absolute temperature and pressure (MPL3115A2 connected via I2C interface).

The second model is a unit supporting measurements of physical parameters such as color of the registered object (BH1745NUC chip connected via I2C interface as an external or internal sensor of MPU-9250 chip) and magnetic field strength in which the device is located (MPU-9250 chip connected via I2C interface directly to GPIO microcontroller). The module is also capable of recording the presence of movement in front of the device by means of the HSDL - 9100 infrared system. It is controlled via a PWM line, and zero-one information is returned to one of the microcontroller's GPIO ports after passing through the amplification stages.

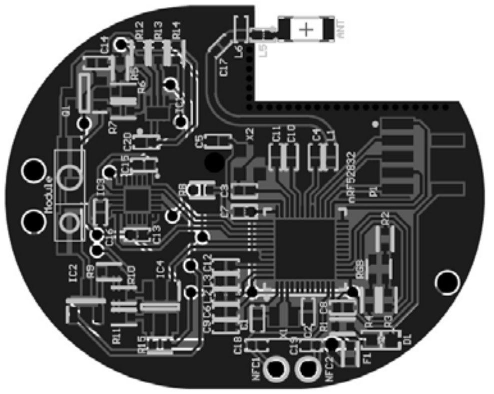

Fig. 5. Model of wireless module for color and magnetic field sensor and motion detector

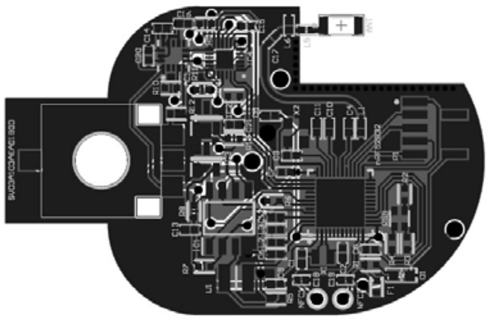

Fig. 6. Model of wireless acceleration, position, tilt and vibration sensor module

The third model is a module recording such physical parameters as acceleration (LIS3DH chip connected via the I2C interface as an external sensor of the MPU-9250 module), tilt (MPU-9250 chip connected via the I2C interface directly to the microcontroller port), vibration (MVS0608.02 chip connected to the microcontroller using a 12-bit ADC) and position (SV03A103AEA01B00 chip connected to the microcontroller using a 12-bit ADC). MVS0608.02 uses the inertia properties of a spherical object inside the housing to measure vibration. The signal coming out of the enclosure is directed to the amplification stage of the MCP6002, which also supports the amplification of the signal coming from the SV03A103AEA01B00 position sensor). In order to enable collision-free installation of the position sensor, its position has been extended beyond the outline of the main body of the device and two rectangular holes have been created for mounting purposes and one round one allowing for mechanical coupling of the sensor with the measured mechanical element, e.g. the end of an electric motor shaft or any other mechanical system. Depending on the application, it may be necessary to add a system converting one type of motion into rotary motion by means of appropriate gear units.

The fourth model is a module that records the pressure force. This is achieved by means of resistance strain gauges FSR400 or FSR402. The application of a particular element depends on the size of the surfaces acting on the measuring element. The mounting point of the strain gauge is gently moved beyond the outline of the main body of the device to facilitate the installation of the measuring part of the sensor on the tested element. Ultimately, the working part of the strain gauge is to be located completely outside the housing of the device. The analog signal, as in the previous solutions, is sampled by a 12-bit ADC after the measured signal has been previously amplified with the MCP6001 operating amplifier.

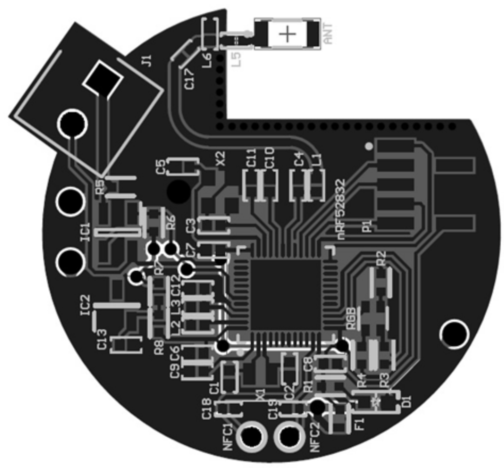

Fig. 7. Wireless pressure sensor module model

The fifth model is a module recording the flow of liquids or gases. As with previous designs, it consists of a standard control unit supporting Bluetooth technology 5. To enable the measurement of the flow of factors, the device is equipped with FS1012. It is connected to the microcontroller by means of a 12-bit ADC after previous signal amplification by means of an MCP6001 operating amplifier. The working unit of the sensor has been completely extended beyond the outline of the main body of the device (eventually the whole working part of the sensor is to be located outside the final casing of the device) to facilitate installation of the inlet and outlet valve of the measured medium. The sensor's significant extension is also intended to allow the installation of flow sets at different angles and diameters.

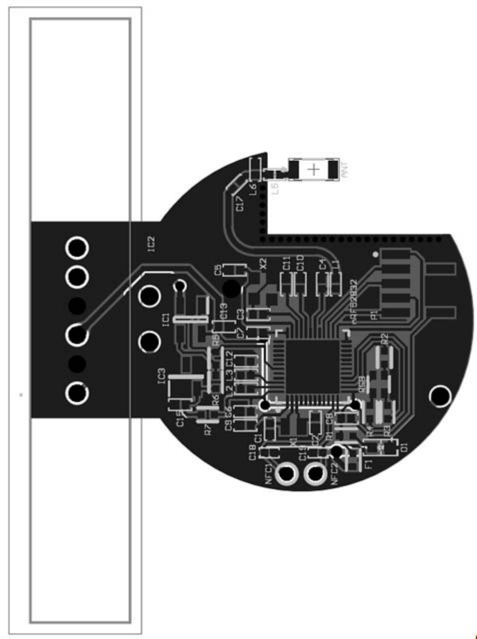

Fig. 8. Wireless flow sensor module model

ECT

The ECT test kit consists of a central unit placed in a suitcase, a set of 16 RG174 SMB-SMB coaxial cables, a CT probe and a DC 12V/1.5A power supply unit. NX smartECT is compatible with all 16-electrode probes with reciprocal electrode capacities less than 4 pF. Inside the central unit there are 3 circuits: measuring and multiplexing plate, SMB expansion plate and control and communication plate equipped with a touch screen. They are mounted directly under the front panel. Power button and sockets: DC, Ethernet and USB jack type B are connected to the electronic circuits by means of adapters mounted in the panel.

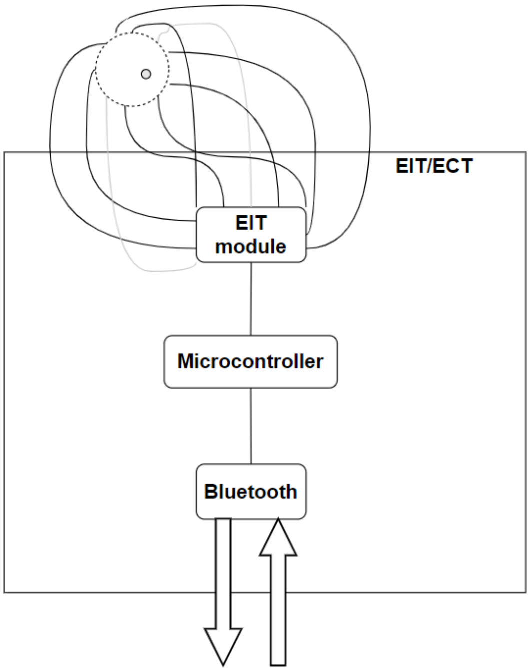

Fig. 9. ECT/EIT measurement block diagram

Control and communication system

The control and communication system is the STMicroelectronics STM32F746G-DISCO Discovery development board. Its embedded software controls the HMI (Human-Machine Interface), tomography parameter settings, shape of measurement sequences and network interface. STM32F746G-DISCO is based on the 32-bit STM32F746NGH6 microcontroller built on the ARM Cortex-M7 architecture and a 216 MHz clock. It has 1 MB of flash memory, additionally the set is equipped with 340 KB of SRAM memory. The board comes with a 4.3-inch TFT liquid crystal screen displaying 480x272 pixels in 16-bit color palette. The screen is equipped with a capacitive touch layer. In addition, the development system includes a 10/100MB network interface compliant with IEEE-802.3-2002 standard (RJ-45 socket). It is powered by 5V.

The measuring board is equipped with a specialized digital-to-analogue converter for measuring electrical capacitance Analog Devices AD7746, integrated circuits switching the extortion and measurement paths and a power section. The smartECT tomograph uses two voltage levels. The board features communication and power connectors for the control section, a power supply socket and a jumper to select the voltage level of the transmitter. In the upper part there are dowel strips for mounting the SMB extension board.

AD7746 is a 24-bit Analog Devices capacity-digital converter. The chip is built in delta-sigma architecture. It is characterized by 4 aF resolution, ±4 pF range, 0.01% linearity and sampling rate up to 91 Hz. It has a built-in temperature sensor and serial interface compatible with I2C. It works in both 3.3 V and 5 V logic. It is factory set to work at lower voltage, it can be changed by jumper on the bottom of the PCB. Its real resolution is about 2 fF, so it provides very accurate readings of electrical capacity. Unfortunately, it is bought by the low speed of the converter. The transducer measures the tested capacities directly, without any additional signal conditioning systems. Between it and the tested capacity there are only keys on the extortion and measurement tracks.

Switching of the force-and-measurement paths is realized by a system of 32 analog keys CMOS Vishay DG-413 controlled binary by 2 16-channel Texas Instruments CD74HC154M decoders. They are connected to each other in the H-bridge system in such a way that all the lines that do not take part in the measurement at a given moment are connected to the mass. The extortion signal tracks are locked with separate keys than the measurement tracks.

The DC section on the measuring and multiplexing board is responsible for powering the whole device. It supplies 3.3 V and 5 V.

SMB expansion board

The SMB expansion board is equipped with 16 SMB sockets for connecting cables connecting the device to the capacitive probe. Line activity is indicated by light-emitting diodes in red for the extortion line and green for the measurement line. The plate is structurally necessary to raise the sockets to the screen level. This solution additionally gives the possibility to change the type of connectors from SMB to other in case of such a need without the need to redesign and install a more complex measuring plate.

The CT scanner measures capacity by switching channels according to a user-selected sequence: classic or alternative.

The first one consists in giving an excitation signal in the first stage of the cycle to the electrode which acts as a forcing electrode and then making sequential readings by switching the remaining measuring electrodes using a multiplexing system. After the first stage of the cycle is completed, the capacitances between the electrode serving as the forcing electrode and each other serving as the measuring electrode are known. In the next stage, the role of the forcing electrode is taken over by another electrode and a series of switching and measurement is carried out in a similar way, with the difference that each electrode which previously served as the forcing electrode does not take part in any subsequent stage of the cycle. Each subsequent stage is therefore one measurement shorter than the previous one. The method of measurement results from the use of a single capacity-digital converter. It is the most frequently used switching technique, as a result of which the obtained data are saved in the form of a triangular matrix. Due to the symmetrical nature of the object being tested, the measurements are made for half of the inter-electrode capacity. These results are sufficient to obtain the remaining ones, as the inter-electrode conductance is independent of the polarity during the measurement. On the basis of the collected data a square array without diagonals is built (measurement of the second with the second or the fifth with the fifth is impossible). The microcontroller of the control system does not perform this operation, it only sends numerical data to the server. Before receiving each sample from the CDC transducer, the control system of the CT scanner checks its status and measurement records. Thanks to this protection, the device does not transmit incorrect or repeated data to the server. In case of an error, the program retrieves the sample again. Standard measurement time is at least 0.8 seconds for one full measurement sequence.

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REFERENCES

[1] Charpentier P., Véjar A., From Spatio-Temporal Data to Manufacturing System Model, J Control Autom Electr Syst, vol. 25, no. 5, pp. 557–565, 2014
[2] Romanowski, A. Contextual Processing of Electrical Capacitance Tomography Measurement Data for Temporal Modeling of Pneumatic Conveying Process. In Proceedings of the 2018 Federated Conference on Computer Science and Information Systems (FedCSIS), Poznan, Poland, 9–12 September 2018; 283–286
[3] Grudzien, K.; Chaniecki, Z.; Romanowski, A.; Sankowski, D.; Nowakowski, J.; Niedostatkiewicz, M. Application of twin-plane ECT sensor for identification of the internal imperfections inside concrete beams. In Proceedings of the 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Taipei, Taiwan, 23–26 May 2016; 1–6
[4] Romanowski, A. Big Data-Driven Contextual Processing Methods for Electrical Capacitance Tomography. IEEE Trans. Ind. Informatics, 15 (2019), 1609–1618
[5] Kryszyn J., Smolik W., Toolbox for 3d modelling and image reconstruction in electrical capacitance tomography, Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska (IAPGOŚ), 2017, (1), 137-145
[6] Dušek J., Hladký D., Mikulka J., Electrical Impedance Tomography Methods and Algorithms Processed with a GPU, In PIERS Proceedings, 2017, 1710-1714
[7] Rymarczyk T., Characterization of the shape of unknown objects by inverse numerical methods, Przegląd Elektrotechniczny, 88 (2012), No. 7b, 138-140
[8] Rymarczyk T., Kłosowski G., Tchórzewski P., Cieplak T., Kozłowski E.: Area monitoring using the ERT method with multisensor electrodes, Przegląd Elektrotechniczny, 95 (2019), No. 1, 153-156
[9] Rymarczyk T., Nita P., Vejar A., Woś M., Stefaniak B., Adamkiewicz P.: Wearable mobile measuring device based on electrical tomography, Przegląd Elektrotechniczny, 95 (219), No. 4, 211-214
[10] Kłosowski G., Rymarczyk T., Kania K., Świć A., Cieplak T., Maintenance of industrial reactors based on deep learning driven ultrasound tomography, Eksploatacja i Niezawodnosc – Maintenance and Reliability; 22 (2020), No 1, 138–147
[11] Kłosowski G., Rymarczyk T., Wójcik D., Skowron S., Adamkiewicz P., The Use of Time-Frequency Moments as Inputs of LSTM Network for ECG Signal Classification, Electronics, 9 (2020), No. 9, 1452
[12] Kłosowski G., Rymarczyk T., Cieplak T., Niderla K., Skowron Ł., Quality Assessment of the Neural Algorithms on the Example of EIT-UST Hybrid Tomography, Sensors, 20 (2020), No. 11, 3324
[13] Koulountzios P., Rymarczyk T., Soleimani M., A quantitative ultrasonic travel-time tomography system for investigation of liquid compounds elaborations in industrial processes, Sensors, 19 (2019), No. 23, 5117
[14] Korzeniewska, E., Sekulska-Nalewajko, J., Gocawski, J., Droż Dż, T., Kiebasa, P., Analysis of changes in fruit tissue after the pulsed electric field treatment using optical coherence tomography, EPJ Applied Physics, 91 (2020), No.3, 30902
[15] Sekulska-Nalewajko, J., Gocławski, J., Korzeniewska, E., A method for the assessment of textile pilling tendency using optical coherence tomography, Sensors (Switzerland), 20 (2020), No.13, 1-19, 3687
[16] Pawłowski, S., Plewako, J., Korzeniewska, E., Field modeling the impact of cracks on the electroconductivity of thin-film textronic structures, Electronics (Switzerland), 9 (2020), No.3, 402
[17] Kosinski, T.; Obaid, M.; Wozniak, P.W.; Fjeld, M.; Kucharski, J. A fuzzy data-based model for Human-Robot Proxemics. In Proceedings of the 2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), New York, NY, USA, 26–31 August 2016; 335–340
[18] Fraczyk, A.; Kucharski, J. Surface temperature control of a rotating cylinder heated by moving inductors. Appl. Therm. Eng., 125 (2017), 767–779
[19] Goetzke-Pala A., Hoła A., Sadowski Ł., A non-destructive method of the evaluation of the moisture in saline brick walls using artificial neural networks. Archives of Civil and Mechanical Engineering, 18 (2018), No. 4, 1729-1742
[20] Kozłowski E., Mazurkiewicz D., Żabiński T., Prucnal S., Sęp J., Assessment model of cutting tool condition for real-time supervision system, Eksploatacja i Niezawodnosc – Maintenance and Reliability, 21 (2019), No. 4, 679–685
[21] Kozłowski E., Mazurkiewicz D., Żabiński T., Prucnal S., Sęp J., Machining sensor data management for operation-level predictive model. Expert Systems with Applications 159 (2020), 1-22
[22] Kozłowski E., Kowalska B., Kowalski D., Mazurkiewicz D., Survival Function in the Analysis of the Factors Influencing the Reliability of Water Wells Operation. Water Resources Management 33 (2019), No. 14, 4909-4921
[23] Daniewski K., Kosicka E., Mazurkiewicz D., Analysis of the correctness of determination of the effectiveness of maintenance service actions. Management and Production Engineering Review 9 (2018); No. 2, 20-25.
[24] Kozłowski E., Mazurkiewcz D., Kowalska B., Kowalski D. – Application of multidimensional scaling method to identify the factors influencing on reliability of deep wells. In: Burduk A., Chlebus E., Nowakowski T., Tubis A. (eds) Intelligent Systems in Production Engineering and Maintenance. ISPEM 2018. Advances in Intelligent Systems and Computing, 835 (2018), 56-65