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Intelligent Sensor Platform with Open Architecture for Monitoring and Control of Industry 4.0 Systems

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Abstarct:

Purpose: *The work covers the development of intelligent sensors, as well as intelligent mechanisms for the assembly and control of industrial processes using modern measurement techniques, process tomography, vision systems, motion and temperature sensors.*
Design/Methodology/Approach: *Tomographic techniques and new analytical algorithms were used. Special algorithms have been developed to combine data from different types of measurements in real time to identify potential hazards or undesirable effects.*
Findings: *The use of various types of data in a single decision-making process, starting with the availability of resources, availability of staff and ending with the maintenance schedules of machines, will allow for the analysis and optimisation of the process. The use of the so-called uncertain data and data that do not have an unambiguous impact on the production process requires the use of solutions based on artificial intelligence algorithms in the decision-making process, which are able to draw conclusions relatively quickly based on such data, and then quickly affect the optimisation of the production process. The results of the conducted research indicate that a platform with an open architecture can be a useful tool in the control and steering of industrial processes.*
Practical Implications: *A measurement module that allows to unify the signal coming out of particular measurement sub-assemblies to a coherent form, thanks to which the acquisition, storage and processing of any quantity can be carried out in a similar way for each case.*
Originality/Value: *The novelty and innovation of the system is a unique technological solution (types of measurements and data processing), new algorithms for optimisation, reconstruction and data analysis, a unique multi-module device based on tomographic technologies. The project as a whole as well as each of its components is innovative on a global scale. The use of tomography for analysis, control and monitoring of technological processes is an innovative solution.*

Keywords: *Electrical capacitance tomography, cyber-physical systems, sensors, process tomography.*

JEL codes: *C61, C88, L23.*
Paper type: *Research article.*

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1. Introduction

An intelligent platform for enterprises with an open architecture and the possibility of free configuration and cooperation with external systems is the main idea of the presented solution. The system is built from several elements such as, new measurement techniques, new intelligent algorithms for optimisation and data analysis, as well as algorithms for image reconstruction and monitoring of industrial processes.

The construction of such a platform makes it possible to improve the management of the intelligent structure of a company in various aspects of its activity. It also enables optimisation of various processes such as production and logistics processes. Thanks to the extensive system, all data from intelligent sensors are transferred to the system kernel, where they can be used in the analytical system, which is used to monitor problematic processes (Musharavari, 2010).

The platform is designed in such a way as to integrate and support monitoring and measuring devices as well as IT tools (Rymarczyk *et al.*, 2021). The sensors used collect a range of data and transmit it to an analytical system. One of the most important and innovative applications is the use of tomographic techniques. As well as the use of new analytical algorithms. Special algorithms have been developed to combine data from different types of measurements in real time in order to identify potential hazards or undesirable effects. The developed methods will allow reconstruction of data in 2D and 3D dimensions (Dusek *et al.*, 2018).

The solution consists of the following elements:

- Monitoring and measuring device. A measurement device responsible for acquisition of measurement data from sensors, initial processing and sending to the server-web system. Additionally, the system will allow for remote calibration of sensors as well as monitoring and conditioning of production equipment.
- Server-web system with a mobile client. Measurement data collected on the server. The user from any place in the world can manage the collected data via a portal and external systems. The collected data can be easily visualised.
- Portal (Communication Platform). The portal will allow the user to manage the data collected on the server. The data exchange interface will enable the cooperation of the company's internal system, in which business processes are recorded, with the server-web platform.
- Algorithmic and analytical module. The expert system enables optimisation of processes in a technological sequence on the basis of a knowledge base and data from measurement sensors.

- System core. Production automation and individualization. The system on the basis of measurement data can support the production process at each of its stages (automation and optimisation).

2. Sensors

Sensors have been designed and manufactured for research purposes. The sensors were divided into several categories. The first category included temperature, humidity and pressure sensors, the second category included magnetic field strength, motion and colour sensors. As a third sensor, a sensor measuring tilt and vibration was prepared. The fourth sensor was a pressure force sensor and the fifth a fluid flow sensor (Wang, 2015). In addition to these sensors, sensors for impedance tomography and electrical capacitance tomography have been designed.

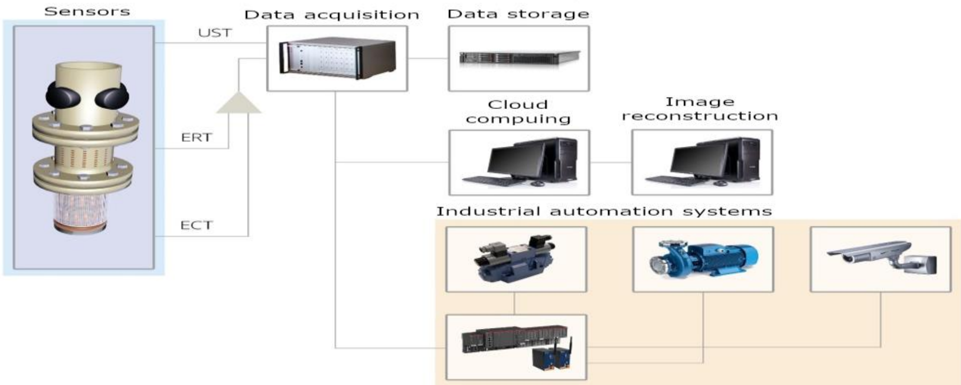
3. Concept

The system was divided into several independent components, sensors, data acquisition and exchange module, data storage module, data processing and processing module and execution module. A network of intelligent sensors using wired and wireless communication (beacons, stickers, RFID gates and tags, strain gauges, accelerometers, etc.) will allow the acquisition of data from various sources directly and indirectly related to the production process, e.g. collection of information on the location and movement of materials or products, machine vibration testing indicating its condition, or data coming directly from the production process. Sensors and measuring devices are connected to a communication interface whose task is to read the signal from a selected sensor, process it into a uniform form and then send the read and processed data to an acquisition module.

It is worth noting that sensors can return different quantities, with basic sensors returning basic electrical quantities representing physical quantities (e.g., temperature, acceleration, etc.), while more complex sensors and devices can return data in the form of dynamic analogue or digital signals (e.g., cameras, microphones) (Cichosz, 2007; Gawędzki, 2015). Prepared communication interfaces take into account the variety of possible signals coming from measuring devices, process them into the form understandable for the data acquisition module and after processing send them to the acquisition module. An important function of communication interfaces is calibration and configuration of measuring sensors. The task of the data acquisition module is to communicate with the communication interfaces connected to the sensors, send the configuration data to the communication interfaces, supervise the measurements and receive the data and then send it to the data storage module.

The acquisition module should also control the functional status and availability of the sensors, and in the event of anomalies switch the readings to backup sensors, if any, and signal an emergency situation occurring in the infrastructure. An important functional aspect of the acquisition module is also waiting for the availability of additional measuring devices, which means that the system is always ready to accept additional data occurring in the process and not measured before. This solution provides the flexibility necessary to maintain and improve the production process. Additionally, the system can read information from RFID or NFC tags.

Figure 1. *Use of tomographic techniques and sensors*



Source: *Own study.*

The task of the data processing and processing module is to draw conclusions from the collected information that can be used to modify the process or prepare the production process. In order to do so, intelligent algorithms using such solutions as expert systems, neural networks, genetic algorithms, fuzzy sets, image segmentation algorithms, data mining algorithms, as well as others based on inference, searching, planning or learning have to be created. Algorithms using neural networks, genetic algorithms or fuzzy sets are applicable in situations where the input parameters are not unambiguous or have an ambiguous impact on the course of the process, but the analysis of such ambiguous data can lead to information allowing to improve the process, resulting in an increase in efficiency, quality and therefore profitability.

The derived synthetic data in a further stage will be used in the executive module, which, using dedicated devices, will receive data from the processing module and will then introduce appropriate modifications to the process by transferring settings to controllers and devices directly controlling the production process. The changes may concern the process settings themselves as well as modifications related to optimisation, e.g. change of transport paths (Saravanan, 2006).

4. Reconstruction Accuracy and Speed

In order to verify the correctness of the algorithms for impedance tomography, a model was prepared and then measured (Sankowski and Sikora, 2010). Image reconstruction was performed. The individual cases for the models are shown in the figures below (Filipowicz and Rymarczyk, 2003).

Table 1. *Calculation times on the triangle grid in seconds (I object - 16 electrodes, two data frames)*

	GN-T	GN-L	TV	LSM	LARS	EN	LR	ANNs
1	0.63632	0.81620	6.94045	5.73687	0.00627	0.00321	0.64229	0.12284
2	0.64578	0.83624	7.00173	10.0086	0.00234	0.00165	0.64123	0.12246

Source: *Own study.*

Table 2. *Calculation times on the triangle grid in seconds (II object - 32 electrodes, two data frames)*

	GN-T	GN-L	TV	LSM	LARS	EN	LR	ANNs
1	0.90839	1.16106	13.612	18.802	0.00884	0.00712	0.68573	0.74876
2	0.87389	1.14458	13.675	22.348	0.00734	0.00680	0.56834	0.78485

Source: *Own study.*

Table 3. *Calculation times for algorithms on a pixel grid*

	Simple problem	Inverse problem by Kotre method	Inverse problem by Gauss-Newton method	Inverse problem by Tikhonov method	Inverse problem by Gram Schmidt method	Inverse problem by Back-Projection method
ECT	300 ms	200 ms	710 ms	5 ms	0.7 ms	1 ms
EIT	20 ms	1 ms	3 ms	4 ms	< 0.1 ms	N/A

Source: *Own study.*

Designations:
GN-T - Gauss-Newton method + Tikhonov regularization
GN-L - Gauss-Newton method + Laplace regularization
TV - total variation regularization
LSM - level set method
LARS - least angle regression
EN - elastic net
LR - logistic regression
ANNs - artificial neural networks.

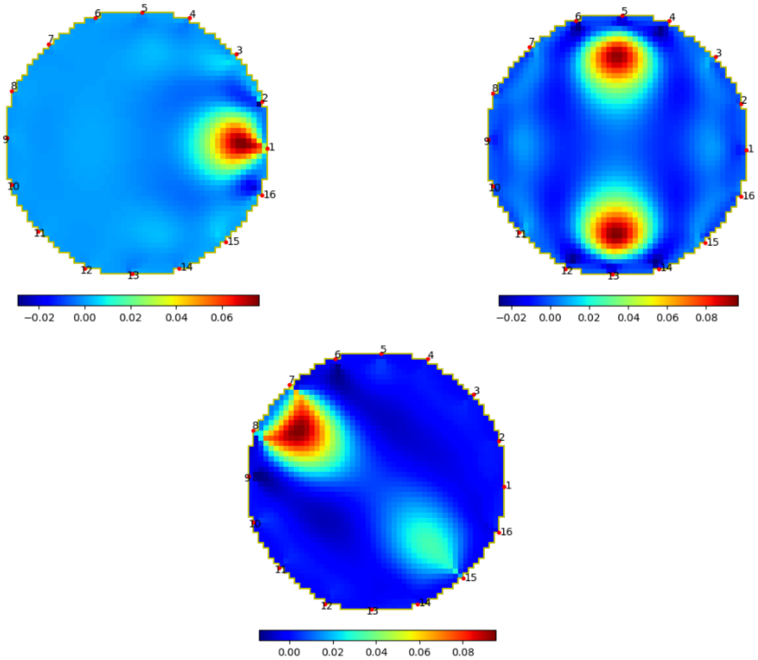
In order to verify the correct operation of the algorithms for capacitance tomography, a model was prepared and then its measurements were performed. Image reconstruction was also performed. The individual cases for the models are shown in Figure 3.

Table 4. *Finite element mesh parameters used in image reconstruction*

Number of electrodes	16
Type of electrodes	linear
Number of nodes	2218
Number of triangles	4146
Parameters for reconstruction	1878

Source: *Own study.*

Figure 2. *Reconstruction of the ECT model for three cases*



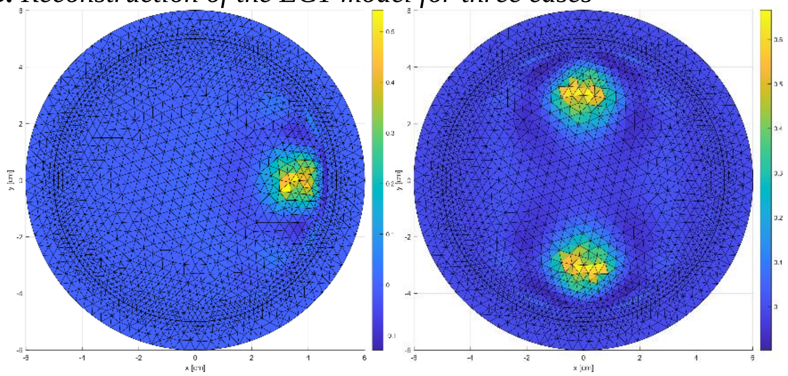
Source: *Own study.*

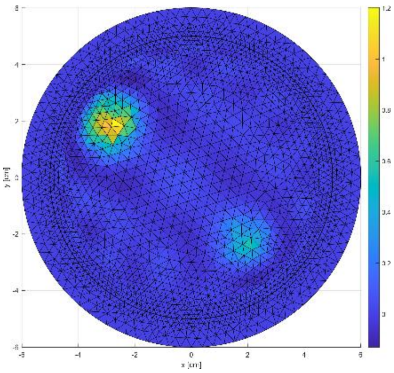
Table 5. *Summary of reconstruction parameters*

	Regularization parameter	Number of iterations	Calculation time [s]	PE	PCC
1	1.0E-7	1	0.356847	1.0137%	0.9999
2	1.0E-7	1	0.341789	1.8667%	0.9998
3	1.0E-8	1	0.355180	0.3919%	1.0000

Source: *Own study.*

Figure 3. *Reconstruction of the ECT model for three cases*



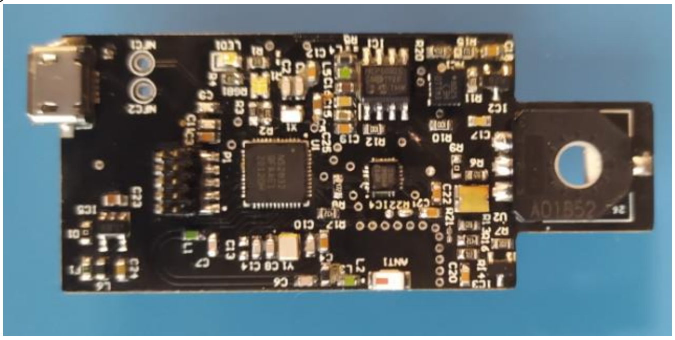


Source: *Own study.*

4.1 The Tilt Sensor and Acceleration Sensor

The tilt sensor also acted as an acceleration sensor. The sensor responsible for measuring tilt as well as acceleration was the MPU9250. The data coming from the accelerometer was in the form of data coming from the transducer located in the sensor. The resulting values were converted into typical values for the accelerometer (measuring range -4 g to 4 g) and tilt (-180° to 180°). The measuring precision for the accelerometer is 0.1g, and for the tilt the precision is 0.1°.

Figure 4. *Tilt, vibration and acceleration sensor with bluetooth transmission module*



Source: *Own study.*

The MPU9250 sensor, acting as two sensors, sent data from the 16-bit ADC on board the sensor. The sensor was able to show fluctuations of 2 - 3 degrees (tilt) and 0.2g - 0.4g (accelerometer). Measurement stability was achieved at a high level thanks to the appropriate configuration of the sensor itself (the 16-bit resolution of the ADC was chosen). The value of both roll and acceleration concerns the three axes OX, OY, OZ. The sensor is configured to take measurements at a frequency of 1kHz. This interval is configurable by entering appropriate values into the corresponding registers of the sensor. This frequency ensures continuous reading of the measurement data from the sensor and ensures possibly low current consumption by the sensor. The sensor in this operating mode consumes ~ 450 µA. In case of the MPU9250 sensor.

The data acquisition time of the MPU9250 sensor operating in accelerometer mode is analogous to that of the sensor operating in magnetometer mode. The data comes from the ADC, where the data is also stored in 3 16-bit registers. Thus, acceleration data occupies a total of 48 bits. The conversion time through the ADC should be estimated to be <90 µs. Based on the TWI bus speed in the NRD52832 microcontroller, which has been configured to 100 kHz, the total data acquisition time should be determined as < 570 µs.

The data rate is a quantity derived from the frequency of the sensor's measurements. The sensor samples the signal 1000 times per second (1 kHZ). This value is configurable. Measurements are read from the sensor every 100 ms, so the speed at which the sensor takes measurements is 1 ms, the frequency at which they are sent to the microcontroller is 100ms. The sensor did not exhibit transients and no resets or shutdowns of the sensor were also recorded.

4.2 Vibration Sensor

The MVS0608.02 analogue micro-vibration sensor worked on the principle of a resistive voltage divider. This sensor was a passive sensor. The data from the measurement of the analogue vibration value was sent to the receiver, on whose side the algorithm for its interpretation should be developed. The sensor used an ADC converter with which the microcontroller was equipped. The converter was configured in 10-bit resolution mode, hence the measurement precision is one unit per 1023 possible values of the converter.

The MVS0608.02 sensor showed no major fluctuations during operation. During the sensor's measurements, the measurements did not show large measurement fluctuations. It was observed that when a constant vibration source was applied to the sensor (or no vibration excitation was applied at all). The measurement stability with the ADC configured in this way was determined by testing to be between 2 and 4 values (which is ~ 0.2 % - 0.4). No rescaling of the obtained values was performed in the microcontroller.

The measurement frequency of the ADC in the microcontroller was determined to be 10 Hz. Thus, the ADC samples the received voltage signal 10 times per second. The average current consumption while the ADC is converting the analogue signal to digital is <30µs. The sensor operates in resistive voltage divider mode and is passive, hence does not need an individual power source, hence does not consume current. Measurement sensitivity was observed to be high, with the sensor responding to even the smallest microvibration stimuli. The sensitivity of this sensor can be influenced by selecting additional elements for the voltage divider in its circuit. External factors such as temperature, air humidity, dust or strong electromagnetic fields did not affect the operation of the sensor.

The data acquisition time was defined as the time needed for the analogue-to-digital converter to perform the measurement. This is the only time needed for the processor to receive the measurement made by the transmitter. According to the catalogue note, this time consists of conversion and acquisition time. The conversion time is constant and is <2 µs, while the acquisition time is between 3 µs and 40 µs depending on the configuration. In this device, the data acquisition time is tack + tconv = 5 µS in total. The data rate for the sensor under development is to be understood as the frequency at which the microprocessor transducer samples the received voltage signal. The transducer measures 50 samples per second.

During several days of operation, the sensor, being a passive sensor, did not exhibit behaviors such as unexpected shutdowns or resets. The voltage signal sent was always dependent on the vibration source.

5. Conclusions

The system in its essence uses completely new solutions not very widely described in such terms in the scientific literature. Ultimately, the techniques and algorithms developed as part of the project interact in feedback loops, and their implementation in a parallel architecture will ensure that the diagnostic and control system will operate in real time mode.

The end result of the proposed project is an intelligent diagnostic and control system capable of performing a comprehensive assessment and characterisation of the process and able to analyse a variety of signals, maintaining the process in the set state. Measurements were carried out under laboratory conditions. The measurements are aimed at experimental confirmation of the correct operation of all functional elements of the system. The paper presents measurement results and image reconstructions from EIT and ECT measurements. As well as tests of vibration and acceleration sensors.

References:

Cichosz, P. 2007. Systemy uczące się. Warszawa: Wydawnictwa Naukowo-Techniczne.

Dusek, J., Vejar, A., Rymarczyk, T., Mikulka, J. 2018. Convergence error exploration for electrical impedance tomography problems with open and closed domains. In 2018 International Interdisciplinary PhD Workshop (IIPhDW), 39-44.

Filipowicz, S.F., Rymarczyk, T. 2003. Tomografia impedancyjna, pomiary, konstrukcje i metody tworzenia obrazu. Warszawa: BEL Studio.

Gawędzki, W. 2015. Pomiary elektryczne wielkości nieelektrycznych. Kraków: Wydawnictwa AGH.

Musharavati, F. 2010. Process Planning Optimization in Reconfigurable Manufacturing Systems. Universal-Publishers.

Rymarczyk, T., Król, K., Zawadzki, A., Oleszek, M., Kłosowski, G. 2021. An intelligent sensor platform with an open architecture for monitoring and controlling cyber-physical. Przegląd Elektrotechniczny, 97(3), 141-145. https://doi.org/10.15199/48.2021.03.2.

Sankowski, D., Sikora, J. 2010. Electrical capacitance tomography: Theoretical basis and applications. Warszawa: Wydawnictwo Książkowe Instytutu Elektrotechniki.

Saravanan, R. 2006. Manufacturing Optimization through Intelligent Techniques. CRC Press.

Wang, M. 2015. Industrial Tomography: Systems and Applications. Elsevier.