JOURNAL OF MODERN SCIENCE
SPECIAL ISSUE
3/57/2024
www.jomswsge.com

DOI: doi.org/10.13166/jms/191185

CEZARY FIGURA
WSEI University in Lublin, Poland
ORCID iD: orcid.org/0009-0008-2795-4003

KRZYSZTOF KRÓL
WSEI University in Lublin, Poland
ORCID iD: orcid.org/0000-0002-0114-2794

GRZEGORZ BARTNIK
WSEI University in Lublin, Poland
ORCID iD: orcid.org/0000-0002-1898-535X

MARIUSZ KOWALCZUK
WSEI University in Lublin, Poland
ORCID iD: orcid.org/0009-0002-8319-8843

EWA GOLEC
WSEI University in Lublin, Poland
ORCID iD: orcid.org/0009-0009-0226-9955

PIOTR CZARNECKI
Graduate School of Business - National-Louis University, Poland
ORCID iD: orcid.org/0009-0007-1041-8995

COMPLEX SYSTEM FOR ANALYSIS AND MONITORING OF TECHNOLOGICAL PROCESSES BASED ON TOMOGRAPHY

SYSTEM ZŁOŻONY DO ANALIZY I MONITORINGÓW PROCESÓW TECHNOLOGICZNYCH OPARTY NA TOMOGRAFII

Abstract

The main objective was to build a mobile impedance/capacitance tomograph for flow analysis and process optimization. The product responds to the identified needs of target customers who operate in process monitoring, control, and optimization of manufacturing processes. They need information on data processing and analysis and spatial analysis of technological processes. The designed solution's target market is the food, chemical, pharmaceutical, petrochemical, and mining industries. The paper presents the device's design and an application for data collection and visualization using tomography. Tomography is a technique for imaging a cross-section of an object based on measurements taken from the outside. Tikhonov regularisation reconstructions were used to reconstruct tomographic images. Test measurements were taken to confirm the correct operation of the completed system.

Streszczenie

Celem projektu było opracowanie złożonego systemu opartego na tomografii do analizy przepływu i usprawniania procesów. Rozwiązanie zostało zaprojektowane w celu zaspokojenia potrzeb klientów w zakresie monitorowania, kontrolowania i optymalizacji procesów produkcyjnych, zwłaszcza w przemyśle spożywczym, chemicznym, farmaceutycznym, petrochemicznym i wydobywczym. W artykule omówiono nie tylko konstrukcję tego urządzenia, ale także aplikację do gromadzenia, przetwarzania i wizualizacji danych z wykorzystaniem technik tomograficznych. Zastosowane tu metody tomograficzne umożliwiają obrazowanie wnętrza obiektu poprzez analizę zewnętrznych danych pomiarowych. W procesie rekonstrukcji obrazu wykorzystano metodę regularyzacji Tichonowa. System przeszedł również testy walidacyjne, które potwierdziły jego prawidłowe działanie.

Keywords: *tomography, production analysis, optimization, process management, process modeling, process control*

Słowa kluczowe: *tomografia, analiza produkcji, optymalizacja, zarządzanie procesami, modelowanie procesów, sterowanie procesami*

Introduction

With technological advances and increasing demands on quality and production efficiency, the need for innovative tools for monitoring and analyzing industrial processes is developing. In this context, tools based on multimodal technologies are becoming increasingly common and desirable. Multimodal systems integrate various measurement methods, enabling comprehensive data analysis and providing a more comprehensive view of the process under investigation (Król 2021, Kłosowski, 2020). This article presents a mobile multimodal system for process production analysis that uses production tomography. Advanced technology allows the precise monitoring and evaluation of various aspects of production processes, including material distribution, substance flow, and quality parameters (Kłosowski, Hoła, Rymarczyk, Wołowiec, Kowalski, 2021).

Production tomography technology enables the visualization of the material structure inside production equipment and machines, which is crucial for assessing their performance and diagnosing possible failures. It also allows the non-invasive study of flow processes and physical properties of substances in real-time, allowing a rapid response to changes in the process. Our proposal for a mobile multimodal system aims to provide a comprehensive tool for process production analysis that is flexible, easy to use and adapted to various industrial conditions (Banasiak 2014, Kłosowski, 2023; Rymarczyk, 2020). We will present the system's advantages and potential applications in various industries, including manufacturing, processing, and quality control.

Research Methodology

The designed tomograph uses EIT technology (electrical impedance tomography) to study cross-sections of closed spaces. The spatial impedance distribution can be determined, and the internal structure of the medium can be visualized by measuring voltages at electrodes immediately adjacent to the medium. Thanks to the built-in microcomputer, it is possible to take EIT measurements and view reconstructions based on them. It also has a network interface for transferring data to an external server. A modular design based on measurement cards was used to prepare the tomograph. The measurement cards were prepared to be quickly replaced or extended. Each measurement card has two measurement channels, as shown in Figure 1.

Figure 1. *Measurement card*

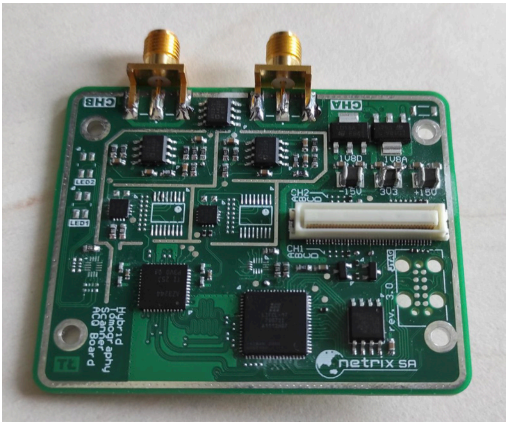
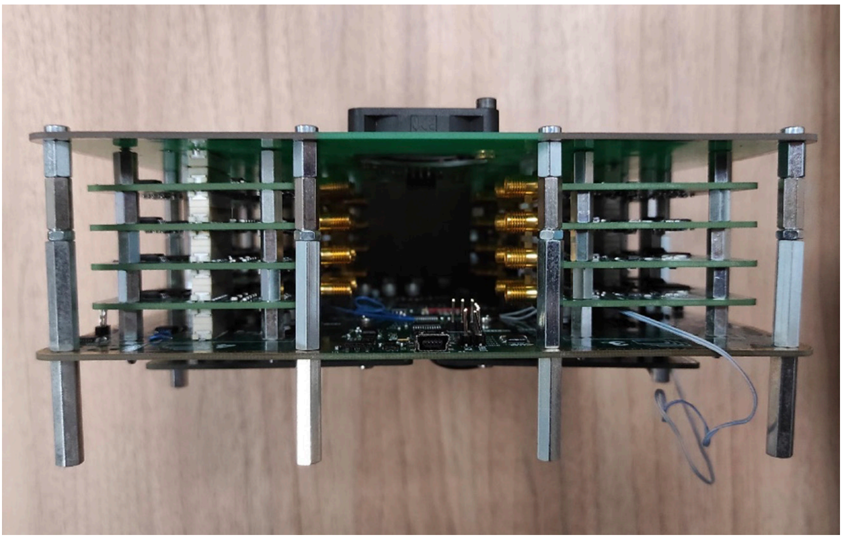
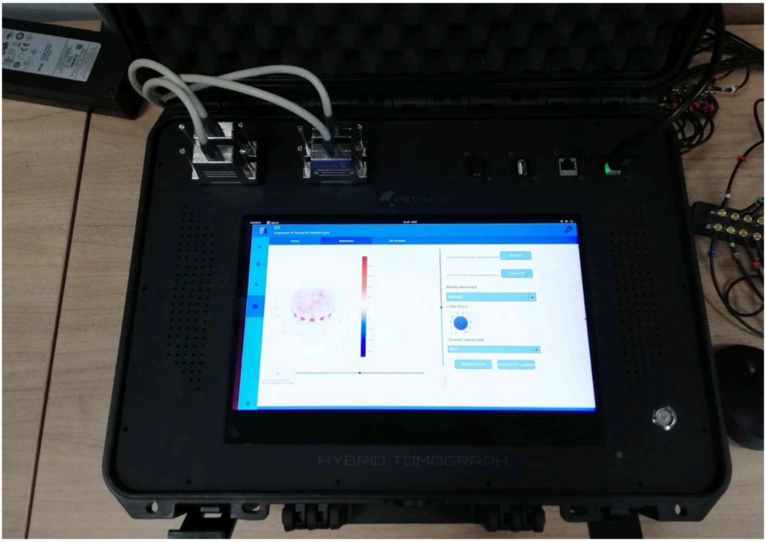


Figure 2. *Assembled measuring cards*



The following Figure 2 shows the assembled measuring cards. And Figure 3 shows the tomograph folded into its housing. The tomograph is equipped with a rechargeable battery, which allows it to operate autonomously, independent of a power source.

Figure 3. *Mobile CT scanner built*



Methods

The computational module is based on the Image_EIT_3D_tetra object. Based on a tetrahedral mesh, the class builds an object to solve the simple problem and the inverse problem for impedance tomography. Objects in XYZ space are considered. The objects are described by a point cloud in three-dimensional space, quadrilateral elements, triangular boundary elements, and point objects or a set of boundary elements approximating the shape and position of the electrodes. Using the finite element method for the tetrahedral components, determine the state matrix using the state_matrix method. Solving the system of linear equations for the state matrix and the stimulation pattern, we define the potential matrix using the possible method. By multiplying the potential matrix with the stimulation pattern matrix, we obtain a vector of simulated voltages using the simulation method.

Solution of the inverse problem

Several methods have been implemented:

- Reconstruction with Tikhonov regularisation (Figure 4,5).
- Iterative reconstruction with regularisation matrices (Tikhonov, Kotre, Leveberg-Marquard, Laplace.
- Reconstruction with Gramm-Shmidt regularisation.
- Iterative reconstruction with Total Variation.

Figure 4. *Visualisation with Plotly library using the display method*

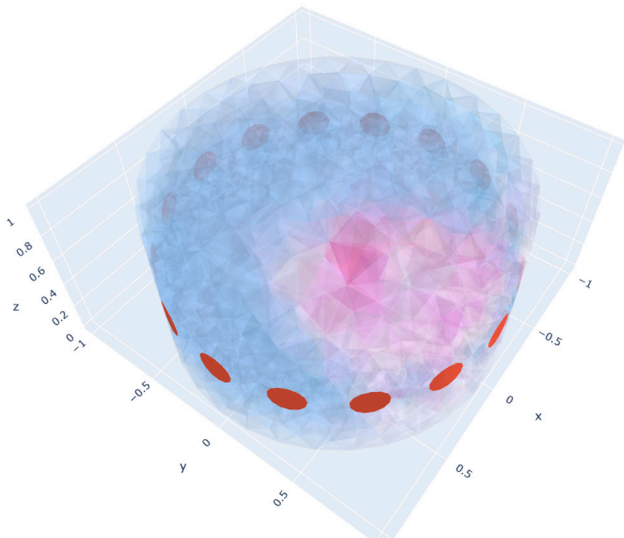


Figure 5. *Visualisation with the video library using the display tetrahedrons method*

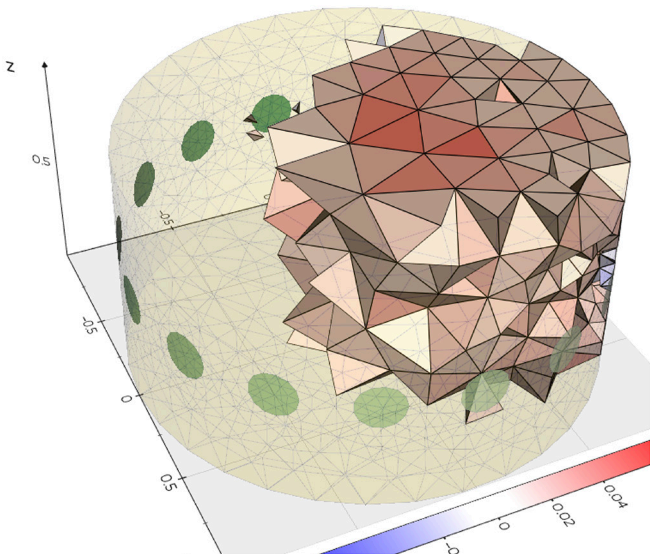
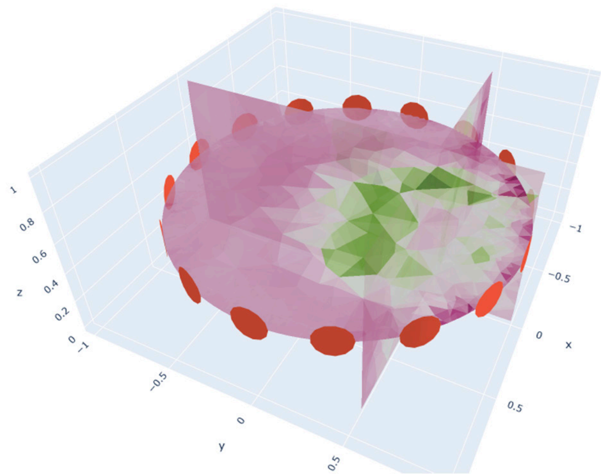
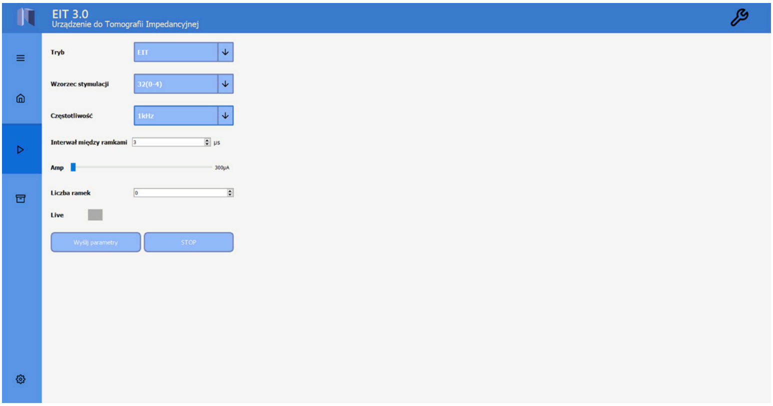


Figure 6. *Visualisation with the video library using the display slices method*



Three methods are used, which are the responsibility of the two Python libraries plotly and video, the display, display_slices, and display_tetrahedrons methods, respectively. The first method generates an interactive HTML file with the possibility of rotations (Figure 4), the second displays the corresponding user-defined cross-sections (Figure 5), and the third opens an interactive window with the possibility of rotations (Figure 4).

Figure 7. *The tab responsible for communication*



The monitoring module is the part of the application responsible for communication with the measuring device.

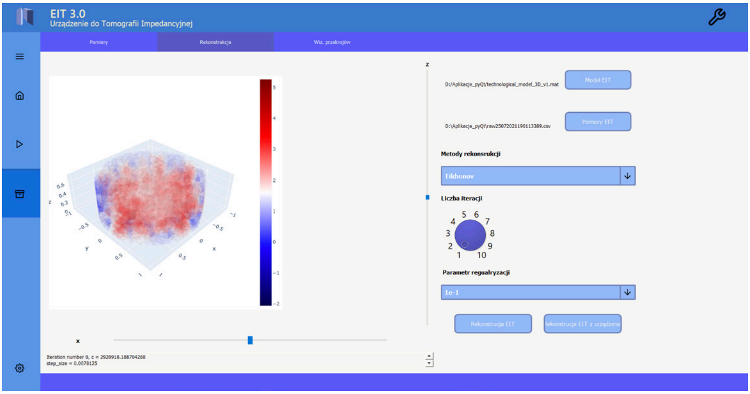
- communication takes place over TCP,
- modes to choose from [‚EIT’, ‚ECT’, ‚EIT + ECT’],
- stimulation pattern of the electrodes to be selected from the set [‚32(0-4)’, ‚32(0-8)’, ‚32(0-16)’, ‚32 3D’],
- selectable frequency from a set [‚1kHz’, ‚10kHz’, ‚100kHz’, ‚200kHz’],
- data frame interval in µs,
- current in µA,
- whether we want to do reconstruction in continuous mode or we want to receive a specific number of frames,
- The Send Parameters button collects the above parameters and sends them to the server as a JSON built on a form dictionary.

Functionality:

- Display the measurement frame as an array (data frame taken from the location set on the device or obtained from the measurement device, the area responsible for the reconstructions will be explained in more detail).
- Option to change the color palette to one from the set [,default,' ,Greys,' ,Viridis,' ,hsv,' ,cool,' ,hot'].

Reconstruction area

Figure 8. *The tab responsible for measurement*



Area for visualization of cross-sections

Figure 9. *The tab responsible for visualization*

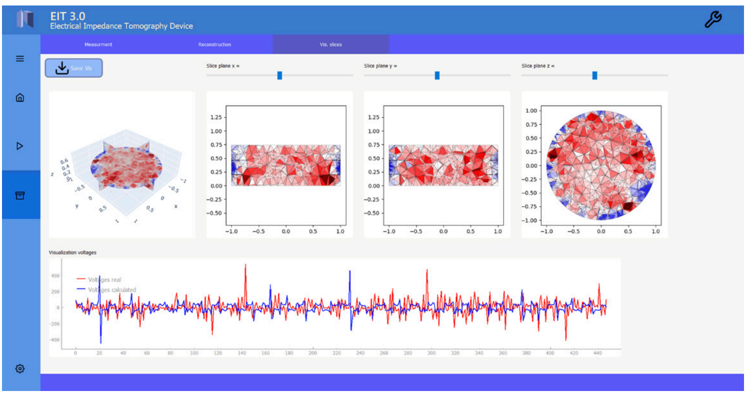
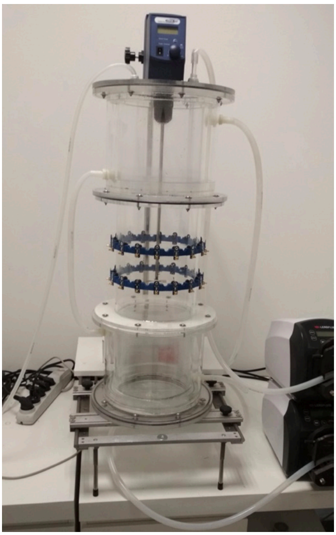


Figure 10 visualizes the running process for a system of two pumps feeding two different ingredients into the main tank, where their mixing process takes place.

Figure 10. *Visualisation running process*

During dosing, process parameters such as pH and temperature are measured, and a reconstruction is made from the tomographic measurements (reconstructions can be observed in another tab of the application). In turn, the unit controls the feeding of the two substrates and the mixer in the main tank.

Figure 11. *Constructed tank for process production measurement and analysis*



Analysis of data sent from the device

Measurements were made for an empty tank and a tank with three inclusions. For both cases, measurements were carried out in 6 series. An analysis of the differences between the measurements, including the average of the six measurements, was carried out to estimate the process variability in the subsequent measurement series. First, for the reference measurement shown in Table 1.

Table 1.

Characteristic	**1**, N = 256[1]	**2**, N = 256[1]	**3**, N = 256[1]	**4**, N = 256[1]	**5**, N = 256[1]	**6**, N = 256[1]	**p-value**[2]
signal	-0.51 (12.18)	-1.21 (10.80)	-0.66 (11.68)	0.66 (12.19)	1.51 (12.68)	0.22 (12.09)	0.12

[1] Mean (SD)
[2] One-way ANOVA

The table above shows the order of magnitude differences for the individual measurements compared to the average of the six measurements. As seen from the particular measurements, the differences are minimal. The ANOVA test used to test whether these differences are statistically significant does not give grounds to reject the hypothesis of equality of mean differences. Furthermore, the estimated variances in standard deviation show that the variability oscillates around 12.

A similar analysis was carried out for measurements with three inclusions in the tank, as shown in Table 2.

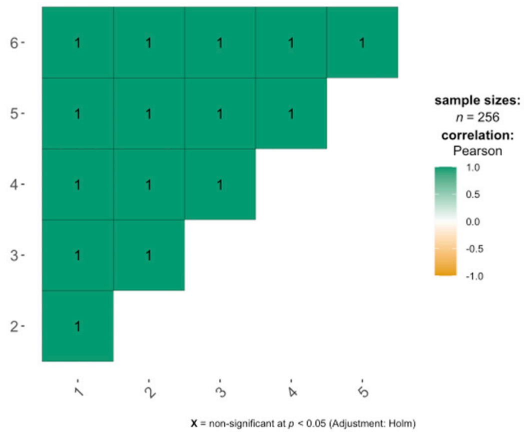
Table 2.

Characteristic	**1**, N = 256[1]	**2**, N = 256[1]	**3**, N = 256[1]	**4**, N = 256[1]	**5**, N = 256[1]	**6**, N = 256[1]	**p-value**[2]
signal	-0.21 (11.70)	-0.33 (12.27)	0.08 (12.58)	0.50 (10.62)	0.40 (10.34)	-0.44 (11.15)	>0.9

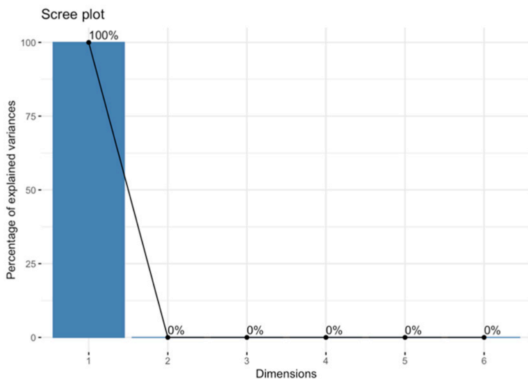
[1] Mean (SD)
[2] One-way ANOVA

In this case, the differences from the mean measurement of the 6 series are even smaller and not significant. The variances expressed by the standard deviation are also on a similar level. To check whether it is possible to extract features using the PCA technique, the correlation levels between the different measurement series will be checked (Kozłowski, 2021; Kozłowski, 2019; Rymarczyk, 2020).

For the reference measurements and the three inclusions.



The correlation matrix above shows that all six measurement series are strongly correlated. This forms the basis for determining the principal components describing all measurement series.



A PCA analysis was conducted to extract the information in the six measurement series for the reference measurements with three inclusions. The first principal component transmits the information in the six measurement series virtually losslessly.

Conclusions

The construction of a mobile multimodal system for process production analysis points to several advantages and potential applications of this solution in industrial processes, especially non-destructive testing. The mobile multimodal system enables various measurements to be integrated using different techniques, such as EIT imaging and ECT. This provides a comprehensive picture of the object or process being analyzed. Mobile measurement equipment allows process production analysis to be carried out at various locations, including complex to-access or remote production areas. This is particularly important for large or distributed industrial installations. Using a mobile measurement system can significantly reduce the time required for process production analysis. This, in turn, translates into faster decision-making and identification of potential problems in the production process.

The system makes it possible to accurately monitor the condition of equipment and production processes, which translates into better control of product quality and increased occupational safety. Non-destructive testing allows the detection of defects or flaws without interfering with the tested object. Process optimization and cost reduction: Thanks to its ability to continuously monitor and react quickly to potential problems, the mobile multimodal system optimizes production processes and minimizes material losses and failure-related costs. Increased competitiveness: The introduction of innovative technological solutions, such as a mobile multimodal system, can significantly increase a company's competitiveness by improving the efficiency of production processes and offering higher-quality products. These findings confirm the critical role of mobile multimodal systems in analyzing process manufacturing, especially in the industry context, where precision, efficiency, and safety are crucial to success. Further research and development in this area can bring even more benefits to various industrial sectors.

References

Banasiak, R., Wajman, R., Jaworski, T., Fiderek, P., Fidos, H., Nowakowski, J., Sankowski, D. (2014). Study on two-phase flow regime visualization and identification using 3D electrical capacitance tomography and fuzzy-logic classification. International Journal of Multiphase Flow 58: 1–14. https://doi.org/10.1016/J.Ijmultiphaseflow.2013.07.003

Król, K., Marciniak, A., Gudowski, J, Bojanowska, A. (2021). Intelligent Sensor Platform with Open Architecture for Monitoring and Control of Industry 4.0 Systems. European Research Studies Journal. – 2021, vol. 24, nr Special Issue 2, s. 597-606.

Kłosowski, G., Hoła, A., Rymarczyk, T., Skowron, Ł., Wołowiec, W., Kowalski, M. (2021). The Concept of Using LSTM to Detect Moisture in Brick Walls by Means of Electrical Impedance Tomography, Energies, 14(10), p. 2777; https://doi.org/10.3390/en14102777

Kłosowski, G, Rymarczyk, T, Kania, K, Świć, A, Cieplak, T. (2020). Maintenance of industrial reactors supported by deep learning driven ultrasound tomography. Eksploatacja i Niezawodność – Maintenance and Reliability 2020; 22 (1): 138–147, http://dx.doi.org/10.17531/ ein.2020.1.16.

Kłosowski, G, Rymarczyk, T, Tchórzewski, P., Bednarczuk, P., Kowalski, M. (2020). *Neural hybrid tomograph for monitoring industrial reactors,* Przegląd Elektrotechniczny, ISSN 0033-2097, R. 97 NR 12/2020

Kłosowski, G., Rymarczyk, T., Cieplak, T., Niderla, K., Skowron, Ł. (2020). *Quality Assessment of the Neural Algorithms on the Example of EIT-UST Hybrid Tomography* Sensors 2020, 20, 3324; doi:10.3390/s20113324

Kłosowski, G., Rymarczyk, T., Niderla, K., Kulisz, M., Skowron, Ł., Soleimani, M. (2023). An LSTM network uses a hybrid approach to monitor industrial reactors using electrical capacitance and impedance tomography. Eksploatacja i Niezawodność – Maintenance and Reliability, 25(1), 11. https://doi.org/10.17531/ein.2023.1.11

Kozłowski, E., Mazurkiewicz, D., Sęp, J., Żabiński, T.(2021). The use of principal component analysis and logistic regression for cutter state identification, in Innovations in Industrial Engineering, Springer International Publishing, 2021: pp. 396–405.

Kozłowski, E., Mazurkiewicz, D., Żabiński, T., Prucnal, S., Sęp, J. (2019). Assessment model of cutting tool condition for real-time supervision system. Eksploatacja i Niezawodność – Maintenance and Reliability, 21(4), 679-685. https://doi.org/10.17531/ein.2019.4.18

Rymarczyk, T., Sikora, J. (2020). *Optimisation Method and PCA noise suppression application for Ultrasound Transmission Tomography,* Przegląd Elektrotechniczny, ISSN 0033-2097, R. 96 NR 2/2020

Rymarczyk, T., Szumowski, J., Cieplak, T., Niderla, K., Adamkiewicz, P. (2020). *Analysis of vertical and horizontal flows of liquids and gases through a wire-mesh sensor*, Przegląd Elektrotechniczny, ISSN 0033-2097, R. 96 NR 3/2020.