Chapter 3

A Nondestructive Distributed Sensor System for Imaging in Industrial Tomography

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Additional information is available at the end of the chapter

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Abstract

The proposed solution is based on the construction of a cyber-physical system for acquiring, processing, and reconstructing the image of measurement data. Industrial tomography enables observation of physical and chemical phenomena without the need of internal penetration. Process tomography gives the possibility to analyze processes taking place inside the facility without disturbing the production, analysis, and detection of obstacles, defects, and various anomalies. The presented measuring system has a specially designed measuring structure (including electrodes, thanks to which it is an innovative solution in the field, particularly effective in analysis). Knowledge of the characteristics of each tomographic technique allows to choose the appropriate method of image reconstruction. The inverse problem is the process of identifying optimization or synthesis, wherein the objective is to determine the parameters describing the data field.

Keywords: process tomography, electrical impedance tomography, inverse problem, electrical capacitance tomography, ultrasound tomography

1. Introduction

The system is based on a tomography in a cyber-physical system (CPS) of self-control. Active control-optimized functions can only be implemented using a system that allows electronic control. The algorithms concern issues related to the processing of data obtained from various sensors located in nodes. Monitoring takes place within the scope of acquired and processed data and the automation of parameters. Advanced automation and control of production processes play a key role in maintaining the competitiveness of the economy. While costly process equipment and production lines can be seen as the heart of industrial production, control systems and information technology are his brain. They provide flexibility to quickly adapt production processes to changing customer requirements and ensure safety and performance at the lowest possible cost of resources and energy. Therefore, developing and applying advanced process control is one of the most effective levers for immediate and long-term energy savings, better product quality, increased process security, and higher production flexibility and will ensure and stimulate business development in conventional and emerging areas, create new jobs, and improve social standards in Europe. In addition, cyber-physical systems (CPS) are physical and engineering systems whose activities are monitored, coordinated, controlled, and integrated by the computing and communication core. CPS combines discrete and powerful computational logic to monitor and control the continuous dynamics of physical and engineering systems. Precision of calculations must be connected with uncertainty and noise in the physical environment. The lack of perfect synchronization in time and space must be solved. Component errors in cyber and physical domains must be tolerated or restricted. These needs require the creation of innovative science and engineering principles. The trial-and-error approach to building computer-oriented systems must be replaced by rigorous methods, certified systems, and advanced tools. Security and privacy requirements must be enforced. The system dynamics should be addressed on many time scales. The scale and growing complexity must be tame [1, 2].

Tomography is a technique of imaging the interior of a tested object using measurements made on the edge. Depending on the technological specifics, you can see both advantages and disadvantages in terms of accuracy, frequency, and resolution of reproduced images. In order to get information about the object being studied, it uses a variety of physical phenomena that are carriers of information: X-rays, gamma rays, ultrasounds, electron beams, electric currents, magnetic fields, and photons [3, 4]. Knowledge of the characteristics of each tomographic technique allows to choose the appropriate method of image reconstruction [5–7].

The main purpose of this work is to design a system for data acquisition and analysis by reconstructing the image for various tomographic methods [8]. Control methods include issues related to the processing of data obtained from various sensors located in nodes. Monitoring takes place as part of the data processing and parameters obtained and processed. Multiphase flow measurement technologies are still being built and improved. There is a clear tendency in the industry to implement more optimal related functions with an emphasis on active inspection and monitoring.

Although there are many methods to optimize technological processes, there is no universal solution that would be optimal in a wide range of measurement conditions. A new hybrid solution was proposed using imaging techniques together with appropriate sensors. This article describes several types of algorithms and models of reconstruction. The solution to this optimization problem is obtained by combining several numerical methods. The reconstruction of 2D examples with the use of numerical and experimental data is shown. The proposed tomographic system consists of a set of sensors (devices) and software that uses Cloud Computing and the Big Data cluster to process, visualize, and analyze data (cyber-physical system) [9].

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2. System architecture

The article presents a model of intelligent platform enabling configuration and cooperation with various external systems. The platform enables the management of a smart company structure in terms of processes, products, simulations, and virtual products. This allows optimization and automatic optimization of production processes. It will also allow you to follow the production cycle and ensure cooperation with external applications. The system can operate autonomously, monitor, control, collect, and collect measurement data. The open platform model of intelligent devices and sensor technology based on tomography in the cyber-physical self-monitoring system includes new measurement techniques and the construction of innovative intelligent measuring devices, system structure along with communication interface, unique algorithms for data optimization and analysis, image reconstruction algorithms, and monitoring technological processes.

The system consists of the following components (see **Figure 1**):

- New measurement techniques and designing of innovative devices and measuring sensors
- Algorithms of processes of reconstruction and monitoring of processes
- New unique algorithms for data optimization and analysis
- System structure and communication interface
- Cyber-physical platform.

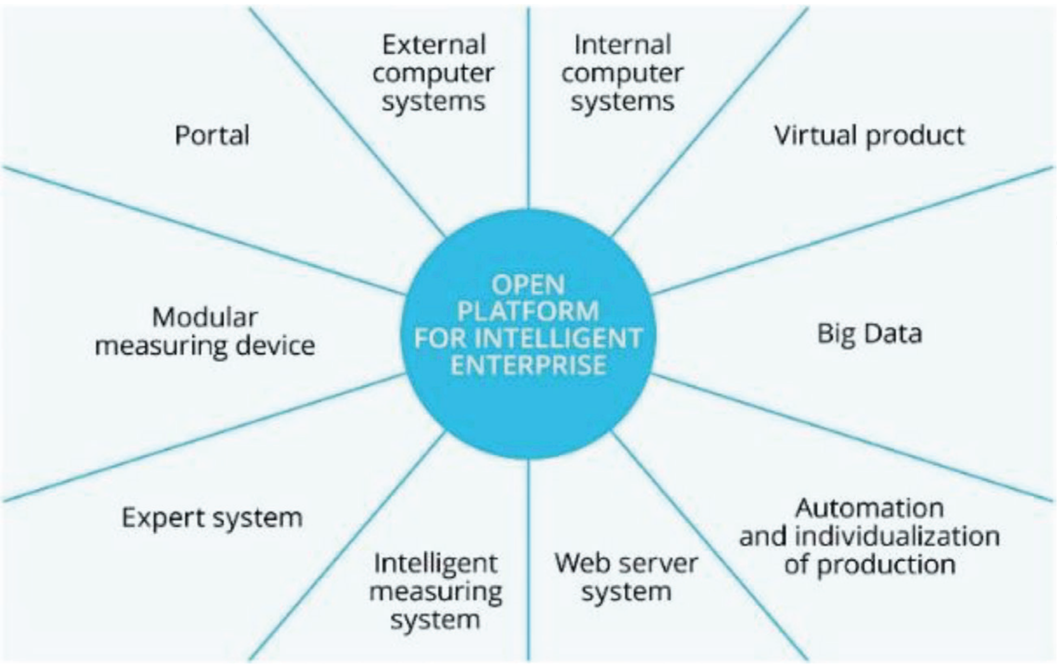

Figure 1. The idea of the system.

The system allows management of the intelligent enterprise structure in terms of processes and simulations. **Figure 2** shows the model of the system for optimization and automation of production processes with data analysis and product virtualization. Individualization of the system in the cooperative model is presented in **Figure 3**. It will also allow to follow the production cycle and ensure cooperation with external applications.

Wireless technology has been used as the first open wireless standard to control industrial processes in sensor networks. In order to monitor the infrastructure of linear and hierarchical projects, various wireless transmission standards can be applied at different levels of the hierarchy. In the tomography system, we often use the MQTT (Message Queue Telemetry Transport) protocol. Many standards of wireless networks, such as Bluetooth, ZigBee, and DASH7, are often used in integration to implement sensor networks. In the case of pipelines located in remote areas, it is desirable to use long-distance networks such as GSM and GPRS for sending data collected in the backhaul network. After successful measurement and registration of parameters from the sensors, a mechanism for sending data to the base station is required. Reliable and secure data transmission is extremely important. For this purpose, various network architectures and topologies can be used. Factors such as designing real-time detection nodes, pipeline and network infrastructure, connecting nodes with the base station, and battery life or work cycle directly affect data transmission.

The algorithms based on tomographic techniques can be used to automatically control and solve problems related to the processing of data obtained from various sensors located in key nodes of the system. Supervision and control are in the scope of acquired and processed data and parameters of devices implementing automation, such as servo valves, pump supply,

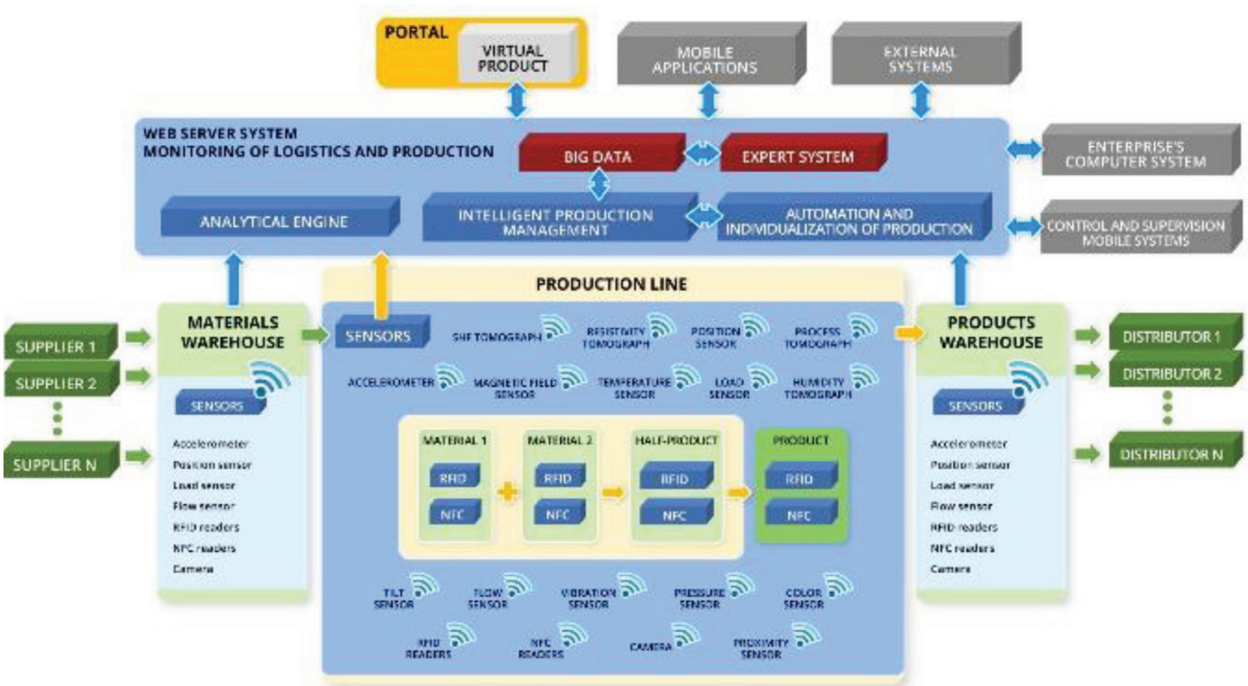

Figure 2. Model of functional system.

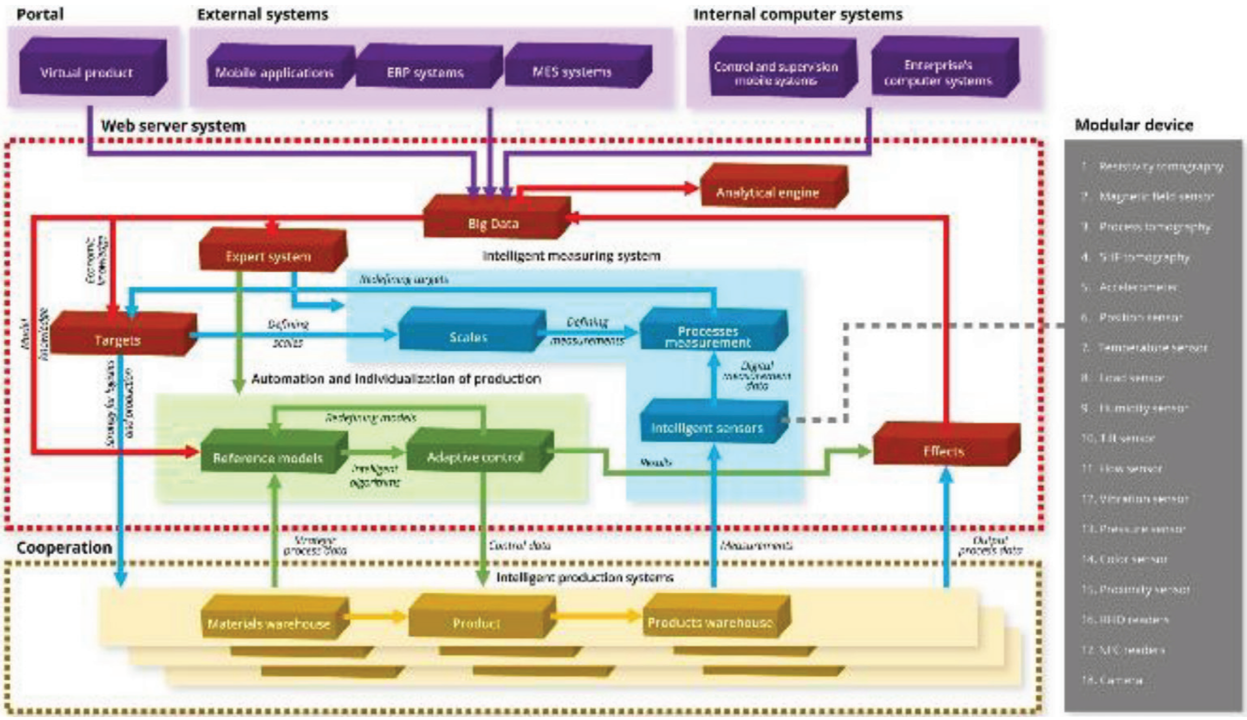

Figure 3. Model of production processes.

and rotary flow. The basic feature of using wireless methods is to obtain important information about the process and the state of installation in real time [10–13].

3. Process tomography

Process tomography gives the opportunity to analyze the processes taking place inside the facility without interfering with the production, analysis, and detection of obstacles, defects, and various anomalies. The tomography belongs to the opposite problems of the electromagnetic field. The inverse problem is the process of identification, optimization, or synthesis, in which the goal is to determine the parameters describing the data [14–16]. Process tomography aims to determine the properties of the tested object from measurements at its edge [17, 18].

Tomography of industrial processes is a harmless, noninvasive imaging technique used in various industrial technologies in processes. It plays an important role in continuous measurement data, which allows better understanding and monitoring of industrial processes, providing a fast and dynamic response, which facilitates process control in real time detecting failures and abnormal system operation. Tomographs allow us to "look inside" pipes in flow reactors. Industrial tomography enables observation of physical and chemical phenomena without the need of internal penetration. In order to obtain information about the test object, measurements are used in various physical phenomena, in which information carriers are X-rays, gamma rays, ultrasounds, electron beams, electric currents, and magnetic fields. The main advantage of tomographic examinations is their noninvasiveness in the

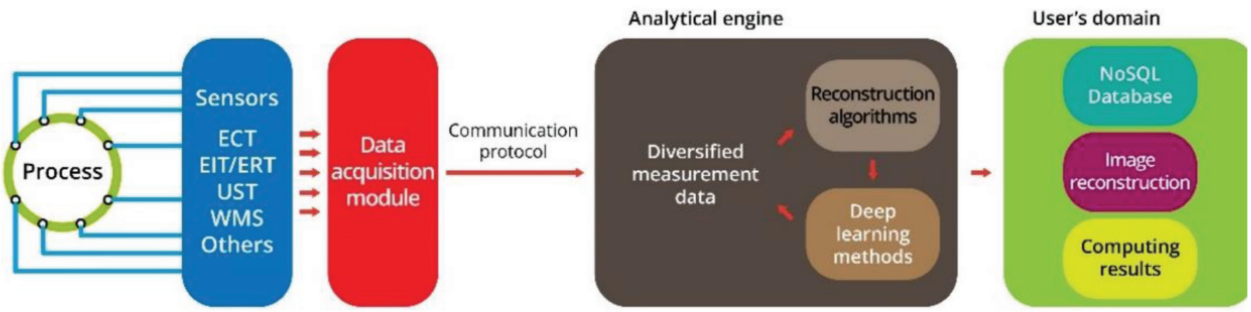

Figure 4. General measurement model for tomography sensors.

studied environment. Such measurements do not change physical and chemical parameters. In the reconstruction of the image, the key parameters are the speed of analysis of flowing raw materials and the accuracy of reconstructed processes. The measurement must be fast because some industrial processes run at high speed. The measuring system consists of a sensor, specialized electronics for capacitance measurement, and data reconstruction and analysis system. Industrial tomography applications are usually a challenge for obtaining spatial distribution data from observations that go beyond the process boundary. The biggest challenge is to achieve effective coverage of closed spaces using practical resources at a reasonable cost. Sensor networks with feedback loops are the basic elements of production control. Distributed infrastructure requires various tasks related to detection and startup and is usually characterized by internal spatial organization. The decisive difference in the mass production of chemicals, food, and other goods is that joint process sensors only provide local measurements. In most production systems, such local measurements are not representative of the entire process; therefore, spatial solutions are necessary. The general measurement model for tomographic sensors is shown in **Figure 4**.

4. Methods and models

4.1. Electrical tomography

The solution to the electrical impedance tomography (EIT) problem is to determine the potential distribution in the region Ω in given boundary conditions and full information about the analyzed region [19–21]. In order to obtain benefits, the accuracy of EIT has historically been divided into capacity (ECT), for systems dominated by dielectrics and resistance (ERT), for conducting processes. The basic theory can be obtained from Maxwell's equations. A complex "admittivity" is defined as follows:

$$\gamma = \sigma + i\omega\varepsilon \tag{1}$$

where σ is the electrical conductivity, ε is the permittivity, and ω is the angular frequency. For an electric field strength (E), the free current density (J) in the area under investigation will be related by Ohm's law:

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$$J = \gamma E \tag{2}$$

The gradient of the potential distribution (u) is as follows:

$$E = -\nabla u \tag{3}$$

Assuming there are no current sources within the examined region then from Ampère's law:

$$\nabla \cdot J = 0 \tag{4}$$

The potential distribution in the isotropic, inhomogeneous region is as follows:

$$\nabla \cdot (\gamma \ \nabla u) = 0, \tag{5}$$

where u is the potential.

As above the ratio of ωε/σ, when the capacitance or the resistance term is dominant, the governing equation is further simplified:

$$\nabla \cdot (\sigma \ \nabla u) = 0 \, for \, \frac{\omega \varepsilon}{\sigma} \ll 1 \, (\text{ERT}) \tag{6}$$

$$\nabla \cdot (\varepsilon \ \nabla u) = 0 \, for \, \frac{\omega \varepsilon}{\sigma} \gg 1 \, (\text{ECT}) \tag{7}$$

As a result of the inverse problem solution, the conductivity distribution in the tested area is obtained.

A set of electric currents are injected into the examined object through these electrodes, and the obtained voltages are measured using the same electrodes. **Figure 5** shows the opposite method of acquiring boundary potential data illustrated for a cylindrical volumetric guide and 16 equally spaced electrodes: (a) first measurement and (b) second measurement.

In electrical capacitive tomography, the information source is the electrical capacitance between the electrodes located on the perimeter of the measurement sensor (see **Figure 6**). An important feature of the measurement is the non-invasive contact of the sensor with the tested object. Such a solution does not interfere with industrial processes. The advantage of this technique is the quick acquisition of measurement data. The laboratory measuring system with sensors is shown in **Figure 7**.

4.2. Ultrasound tomography

Measurement methods using information contained in the ultrasonic signal after passing through the medium under investigation are called ultrasound transmission methods (see **Figure 8**). Ultrasonic waves belong to short waves and have propagating and radiation properties. The length of these waves depends on the medium to which they are emitted

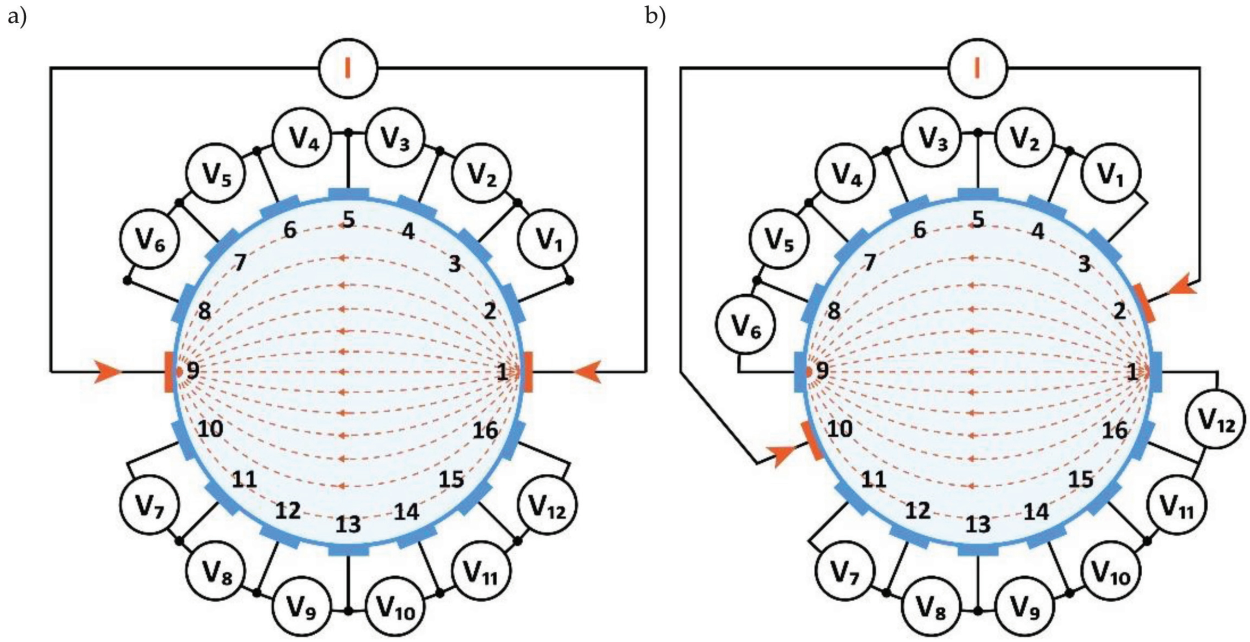

Figure 5. Opposite method in electrical resistance tomography.

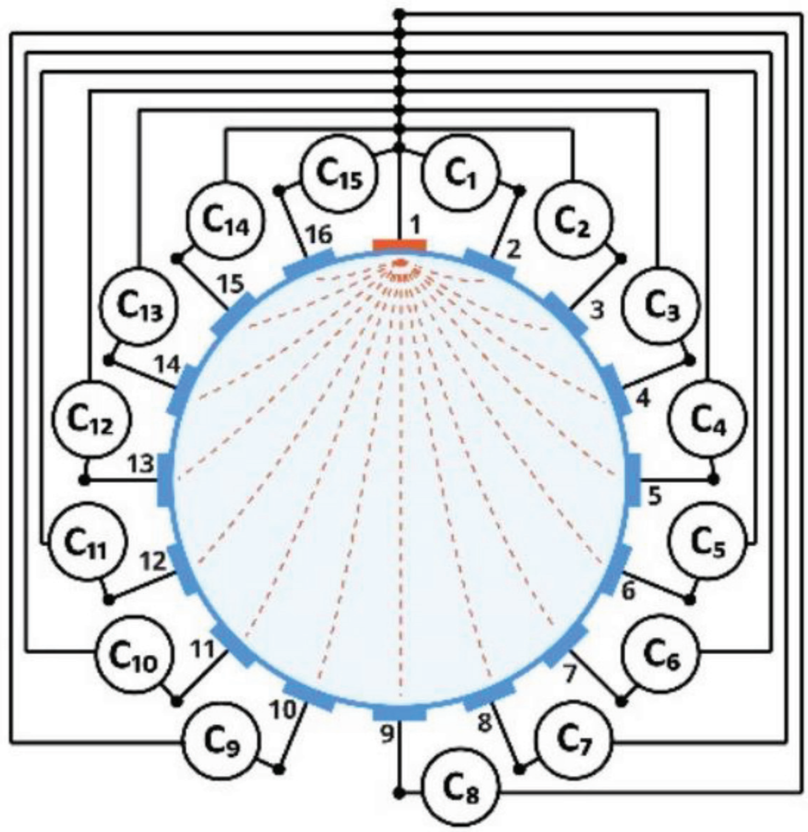

Figure 6. Measurement model of electrical capacitance tomography.

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Figure 7. Laboratory measurement system.

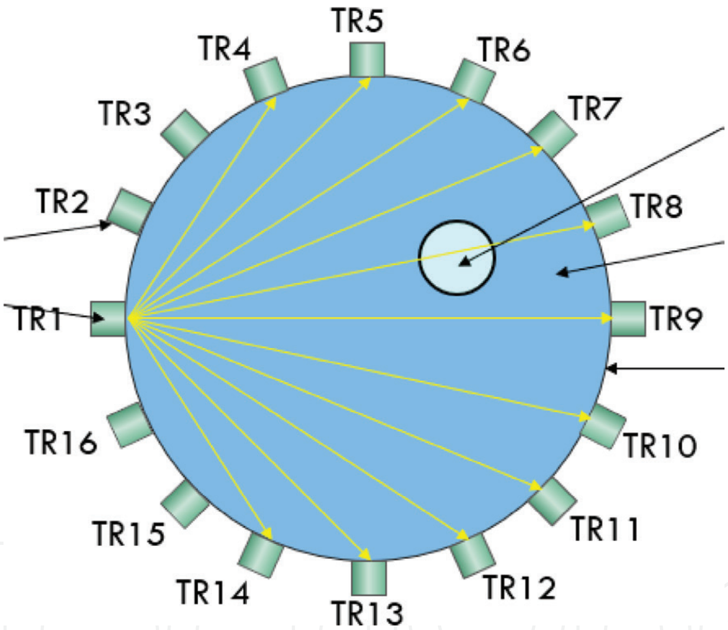

Figure 8. Idea of measurement model in ultrasound tomography.

and is in the range from a few micrometers in liquids to several dozen centimeters in metals. They can be used to measure the attenuation coefficient and ultrasonic time of signal transitions in the medium subjected to their influence. Many measurements can be made using ultrasound without fear of damage or irradiation of the examined objects. This technique allows to obtain quantitative images of the internal structure, in which the numerical values of each pixel describe such physical properties of the examined objects, e.g., temperature distribution, density, or viscosity. Measurements of parameters such as signal transitions, attenuation coefficient, and its derivative through frequency allow after appropriate reconstructive transformations, imaging of the internal structure of the tested medium, as well as flow parameters such as its speed, average speed, or profile speed. The basis for imaging is differences in local values of specific acoustic parameters. The image obtained by means of appropriate reconstruction methods presents the distribution (obtained from the measurement data using the scanning technique from as many directions as possible after the ultrasonic pulses have passed through the tested environment) [22].

The problem of image construction in the case of ultrasound very often leads to the overdetermined algebraic set of equations that can be expressed in the matrix form:

$$Wf = s, \tag{8}$$

where W is the matrix of dimensions m x n and m > n, s is the right-hand side vector (one column matrix), and f is the solution vector.

One of the ways of the solution (Eq. (7)) is to find the vector f^*, which minimizes Euclidean norm of residual vector r for the known matrix W and vector s, and it means:

$$\|r\|_2 = \min \|s - Wf\|_2, \quad \|f^*\|_2 = \min \|f\|_2 \tag{9}$$

where the last minimum is taken for all vectors f which fulfill the previous relation. Equation (8) is well known as a linear least squares problem (LSP).

5. Results

Numerical analysis of the problem in the process tomography takes place using, among others, finite element methods, finite difference methods, or boundary element methods. In the case of data shortages, we talk about fixed problems and in the case of excess with overdetermined problems. Automatic data analysis is an important part of the diagnosis of the process based on tomography. Knowledge of the process can make image reconstruction more resistant to incomplete or corrupted data. As a result of the calculations, we obtain a reconstructed image, for example, acoustic impedance, permittivity or conductivity, and dielectric loss to the parameters of a physical process (phase embolism, density, type of concentration). Advanced analysis leads to the extraction of features.

The example of image detection is shown in **Figure 9**. The images show the image reconstruction achieved by the Gauss-Newton method. A mesh of finite elements has been generated inside the area. The algorithm is solving for such a distribution of conductivity, so that the values of interelectrode voltages calculated on its basis are as close as possible to the measuring values of these voltages.

Figure 10 presents the image reconstruction by electrical capacitance tomography using the Levenberg-Marquardt method and the modified Levenberg-Marquardt method. Grids used in calculations: rare 2218 nodes and 4146 finite elements and dense 7861 nodes and 15,146

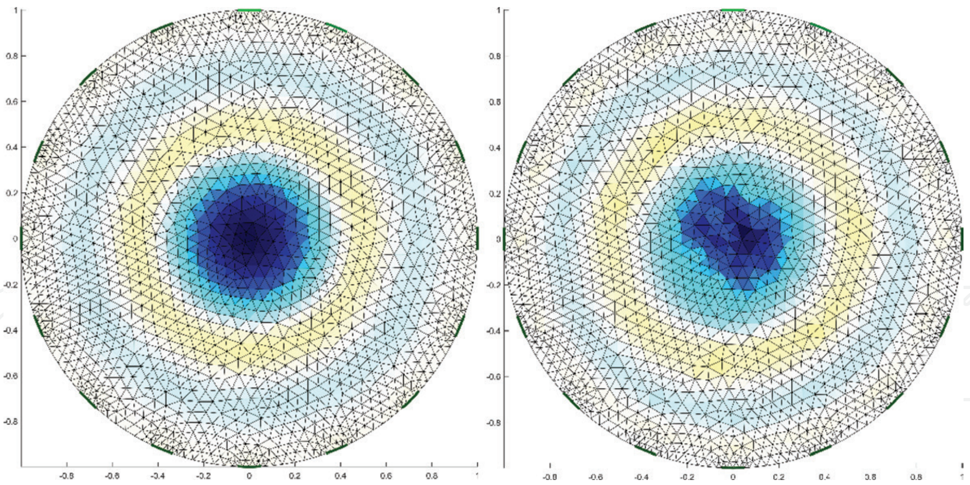

Figure 9. Image reconstruction (ERT): (a) Gauss-Newton with Laplace regularization and (b) Gauss-Newton with Tikhonov regularization (ERT).

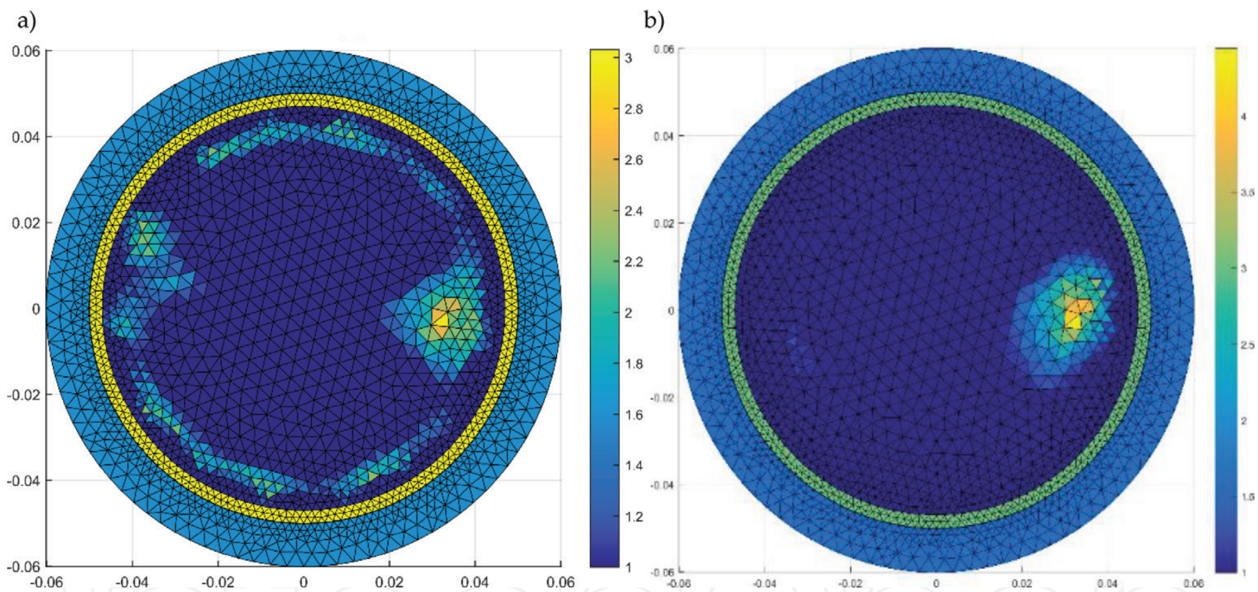

Figure 10. Example of the image reconstruction (ECT). (a) Levenberg-Marquardt method and (b) modified Levenberg-Marquardt method.

finite elements. The numerical experiment was carried out on noisy data. **Figure 11** presents the image reconstruction by elastic net method in ECT.

Figure 12 shows images of the experiments by ultrasound tomography. The algorithm was designed in such a way that an overdetermined system of equations could be generated, i.e., one for which the number of equations is greater than the number of unknowns. A feature of the tomography is, among other things, that the coefficient matrix is a rectangular deficiency of the pseudo-rank matrix. In such cases, you should consider trial solutions and choose only one of them. The obtained results are a raw tomographic image for synthetic data. In the numerical experiments presented, no additional adjustment method was used to obtain

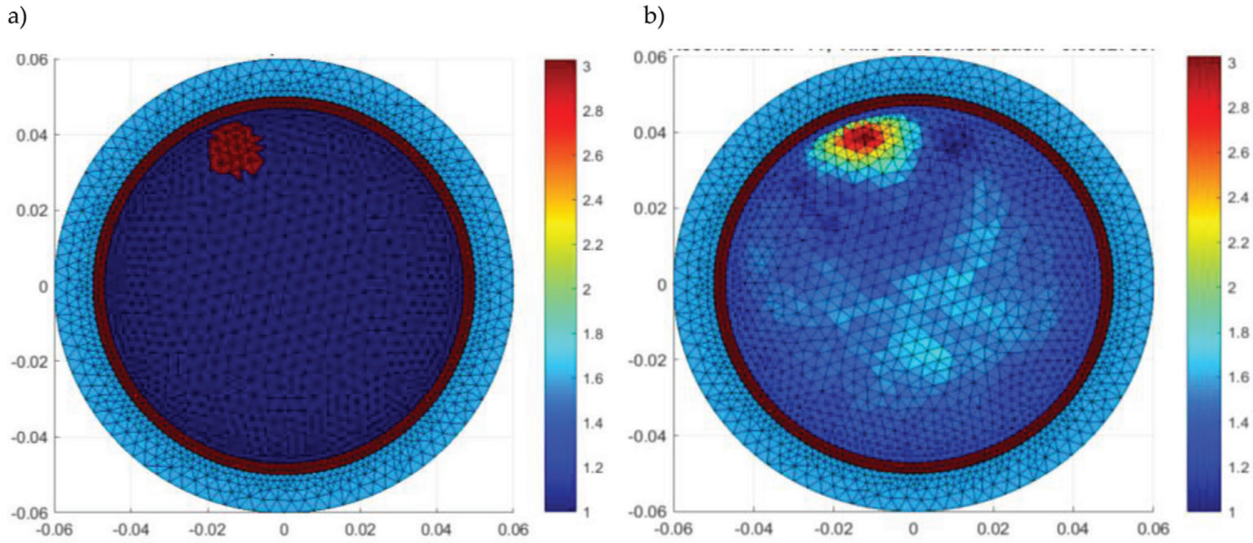

Figure 11. Image reconstruction by elastic net method (ECT): (a) model and (b) image reconstruction.

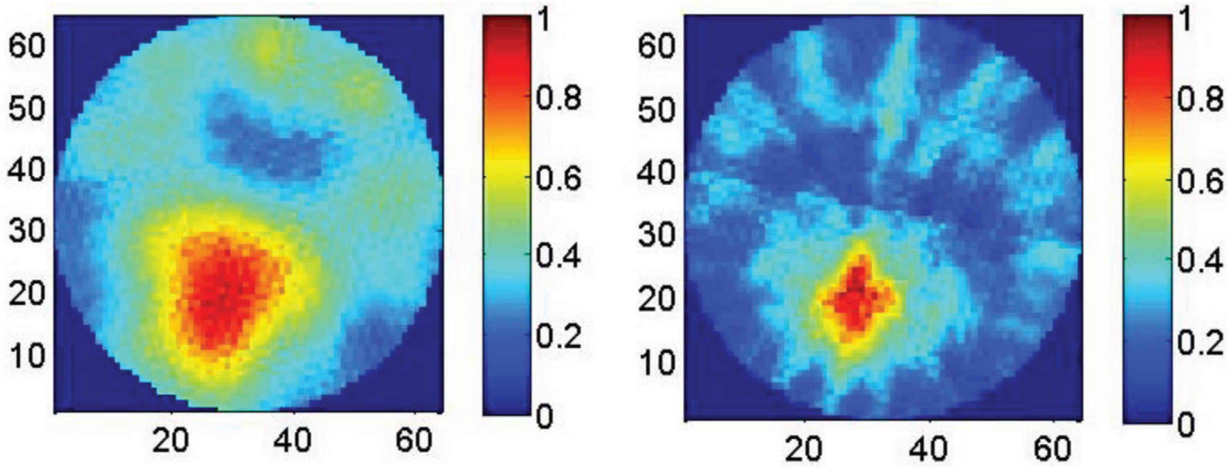

Figure 12. Localized on the 60 × 60 plane, tomographic images (UST).

images without streaks. The results obtained using the proposed method are a faithful representation of the modeled objects and enable their precise location in the considered area.

6. Conclusion

The chapter presents the idea of a control and optimization system based on tomographic sensors. Supervision and control belong to the scope of acquired and processed data and parameters of devices performing automation. Cyber-physical systems will change the way people interact and control the physical world. Industrial tomography can analyze physical and chemical phenomena without the need to penetrate into the interior. Electrical tomography and ultrasound tomography are included. The presented reconstructions were obtained by solving the inverse problem, which allows the imaging of processes. In the presented solution, we move from mathematical formalism to determining, analyzing, verifying, and checking systems that monitor and control physical processes. The system benefits various economic and industrial sectors. Advanced tools allow to capture both cybernetic abstractions and system dynamics. The system employs a communication interface, unique optimization algorithms, and data analysis algorithms for image reconstruction and process monitoring. The use of systems based on electrical and ultrasonic tomography can significantly improve industrial processes.

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