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# Ultrasonic tomograph for industrial research

***Abstract**. This paper presents an ultrasonic tomographic device dedicated to monitoring and optimizing various technological processes. The design of the device features high mobility, ease of integration with monitoring systems, and the possibility of implementing desired algorithms to control the quality of the desired technological process. This work presents the fundamental idea of the ultrasonic tomograph, its underlying hardware design, and an example of implementation into a technological process in a laboratory condition. Additionally, the paper briefly discusses the possibility of applying an optimization method using a feedback control system and presents possible modes of operation of the tomograph adapted to selected research problems, e.g., field of view reconstruction and object detection.*

***Streszczenie.** W artykule przedstawiono ultradźwiękowe urządzenie tomograficzne przeznaczone do monitorowania i optymalizacji procesów technologicznych. Konstrukcja urządzenia charakteryzuje się wysoką mobilnością, łatwością integracji z systemami monitorowania oraz możliwością implementacji algorytmów kontroli jakości procesu technologicznego. W niniejszej pracy przedstawiono kluczową ideę tomografu ultradźwiękowego, jego konstrukcję sprzętową oraz przykład implementacji w procesie technologicznym w warunkach laboratoryjnych. Dodatkowo, w pracy krótko omówiono możliwość zastosowania metody optymalizacji z wykorzystaniem układu sterowania ze sprzężeniem zwrotnym oraz przedstawiono możliwe tryby pracy tomografu dostosowane do wybranych problemów badawczych, np. rekonstrukcji pola widzenia i detekcji obiektów (**Tomograf ultradźwiękowy do badań przemysłowych**).*

**Keywords:** ultrasound, tomography, industrial
**Słowa kluczowe:** ultradźwięki, tomografia, przemysł

## Introduction

Ultrasonic tomography enables non-invasive imaging of the internal structure of objects [1,2,3] by exploiting the phenomenon of scattering and absorption of ultrasonic waves in a material. In this article, we will focus on the construction of a new version and operation of ultrasonic tomography in the context of industrial processes. Process tomography is a handy tool for monitoring and optimizing industrial processes [4,5,6] due to the fact that it does not affect the process under study. What distinguishes our multimodal ultrasonic tomograph is that it performs tomography in a system of multiple ultrasonic transducers mounted around the perimeter of the object being monitored, rather than using a single ultrasonic head. This method of measurement, also known as the transmission method, allows monitoring of the entire cross-sectional area of a given process, as opposed to traditional ultrasonic tomography, where only a fragment is examined.

## Motivation

The main motivation for designing a multimodal ultrasound tomograph was to develop a system that is open to researchers and adaptable for industrial use [7]. Such a system aims to give researchers access to advanced measurement tools that can be customized to meet specific experimental needs. With the ability to integrate with various imaging technologies, the multimodal ultrasound tomograph allows for more comprehensive information about the object under study, which is crucial for many fields, from chemical processes to materials engineering. In addition, the flexibility of such a solution makes it easily adaptable to changing industrial requirements, which significantly increases its usefulness in commercial applications. As a result, such a system not only supports innovation in scientific research, but also contributes to improving the quality of manufacturing processes, which directly impacts the efficiency and competitiveness of companies [8].

## Hardware

The design of the tomograph device for analyzing a multiphase industrial process is divided into several components arranged on separate Printed Circuit Boards (PCBs). Its core consists of two main parts: a measurement module (motherboard with sixteen ultrasonic measurement cards) and a reconstruction and signal processing module. The system is neatly packaged in a convenient and portable case along with a 15.6-inch touchscreen LCD display.

Figure 1 shows the detailed design of the tomograph and an example of its use in pipeline flow studies.

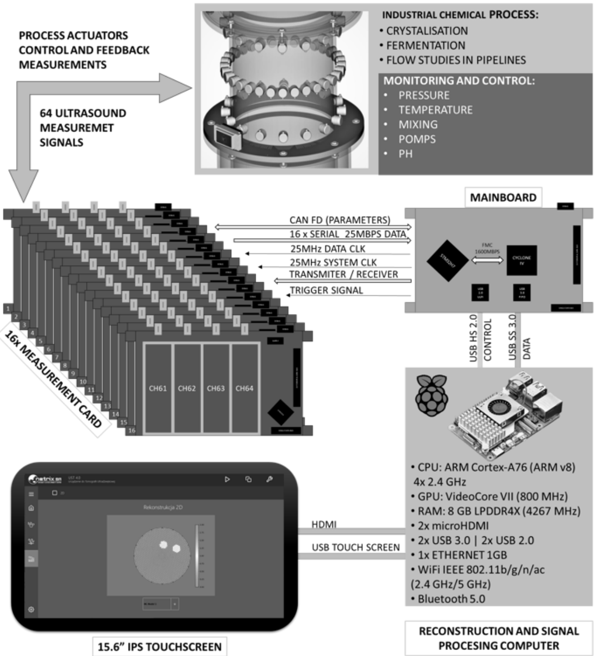

Fig. 1. Multimodal ultrasound tomograph – construction block diagram

The multimodal ultrasound tomograph's measurement module (Fig. 2) is a complex separate system consisting of 17 PCBs made with multilayer technology. The entire embedded system runs on a common 25MHz clock, which provides synchronization for all measurement channels. Data exchange between the measurement cards and the main board is carried out using a 16-bit synchronous differential SPI bus (Fig.1). This is a non-standard solution, which made it possible to extract speeds of up to 400MBps from the entire set of cards. The measurement cards and the motherboard are also connected by a common CAN FD bus, which distributes the measurement parameters. TRIGGER line, synchronizes the beginning of the measurement, while TRANSMITTER/RECEIVER signals control the order of excitation in the measurement sequence.

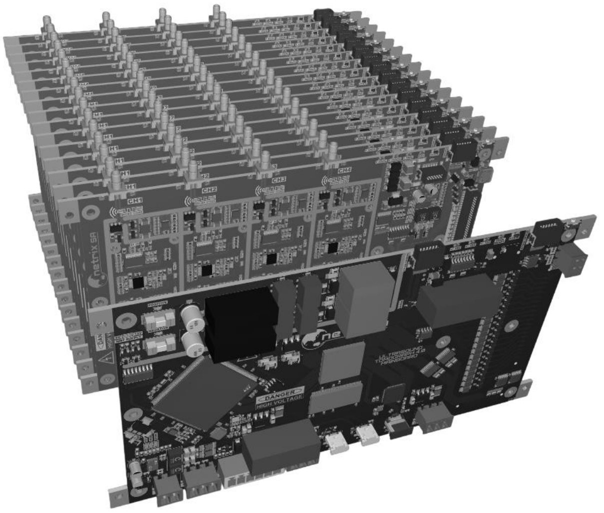

Fig. 2. Multimodal ultrasound tomograph – measurement module

Each ultrasonic measurement card comprises four channels and complex measurement instrumentation consisting of low-noise amplifiers and band-pass filters tuned to three different frequencies. Specialized integrated circuits (ICs) are designed to convert analog data into envelope signals, enabling precise and detailed industrial process measurements. Figure 3 shows a detailed representation of the measurement card.

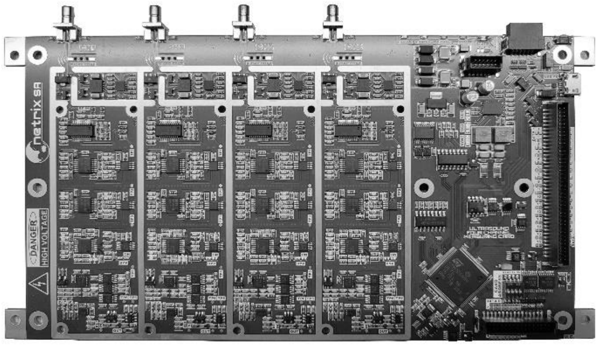

Fig. 3. Photo of a single measuring card with four independent channels

The motherboard is used as a central processing system. It is powered by a microcontroller from the STM32 family, which is known for its computational efficiency and adaptability. Its stable and high-speed communication with measurement boards is achieved using Controller Area Network Flexible Data-Rate (FDCAN) interfaces, allowing dissemination of important parameters such as excitation or sampling frequency, number of samples, and measurement modes. A motherboard built on an Altera Cyclone IV FPGA (Field-Programmable Gate Array) is responsible for data aggregation. It is a high-speed data collector that gathers measurements from ultrasonic cards and sends them instantly to the reconstruction and signal processing computer for later analysis. Furthermore, the high-voltage converter is integral to the main board, guaranteeing the ultrasonic transducers a constant and stable power supply.

The motherboard features communications using USB 2.0 and USB 3.0 interfaces, including ULPI (USB Low Pin Count Interface) and FIFO (First In, First Out) buffers. USB 3.0 provides the highest performance, facilitated by the FTDI FT601 chip, which stable connects to the FPGA via the USB Type-C connector, thus providing high-speed data transmission to the host computer. The motherboard is pictured in Figure 4

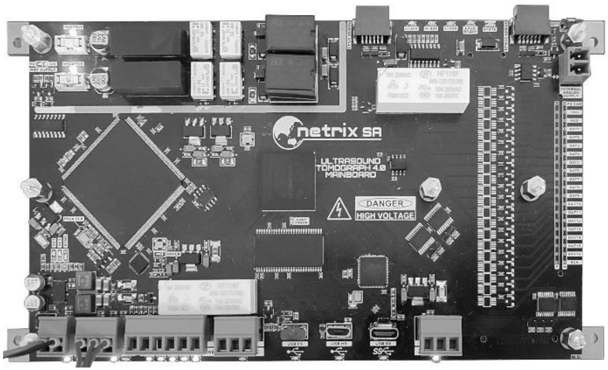

Fig. 4. Photo of the main board of the multimodal ultrasonic tomograph

The Multimodal Ultrasound Tomograph designed at Netrix S.A R&D in Lublin Poland can perform measurements in transmission and reflection modes. Each channel is shielded so that the influence of interference is minimized and the gain range of the received signals is extended. The operating bandwidth of the tomograph closes in the range of 40kHz - 1MHz. Each channel has an integrated three-state high-voltage pulse for generating rectangular excitation signals. Capable of generating a signal with an amplitude of up to 144Vp-p.

The signal processing section has been made using low-noise LNA (Low Noise Amplifier) and VGA (Variable Gain Amplifier) amplifiers with a TGC (Time Gain Compensation) function. These amplifiers, combined with analog filters and built-in envelope processing circuits, allow very clean reception of ultrasonic signals with small amplitudes.

In addition to steplessly adjustable gain, each tomograph channel is equipped with a high-speed 4MSPS ADC.

The embedded software allows real-time processing of analog signal data directly into ToF (Time of Flight) times with a resolution of up to 0.25μs and measurement of signal amplitude with a resolution of 12 bits.

Table 1. Multimodal Ultrasound Tomograph - parameters

| **Several channels:** | **64** |
|---|---|
| **Analog to digital converter per channel:** | 12bit 4MSPS |
| **ToF measurement resolution:** | 0.25μs |
| **Pulser per channel:** | 48V - 144V peak-to-peak 3A |
| **Bandwidth:** | 40kHz – 1MHz |
| **Filtration:** | Switchable bandpass filters |
| **Envelope converter:** | analog – 3 ranges settings |
| **Gain:** | 7,5dB – 55,5dB |
| **Transducers connection:** | SMB and ITT Cannon connectors |
| **Touchscreen LCD:** | IPS 15,6” 1920x1080px |
| **ETHERNET:** | 1000Mb/s |
| **Wi-Fi:** | 2.4GHz and 5GHz |
| **USB:** | USB 3.0 |

The tomograph has a ZIF (Zero Injection Force ) standard transducer socket installed, which is used for quick and easy connection with the test object on which the ultrasound transducers are placed. In addition, research purposes or non-standard measurement sensors can be connected separately using SMB connectors. Table 1 shows the detailed specifications of the multimodal ultrasonic tomograph, and Figure 5 shows the view of the device.

Fig. 5.Netrix S.A Multimodal Ultrasound Tomograph

**Demonstrator**

To test the device, we built a process demonstrator, one of whose components is a reactor for the crystallization process. Figure 6 shows the entire measurement set-up, which consists of a PLC (Programmable Logic Controller) with HMI (Human-Machine Interface), peristaltic pumps, magnetic and mechanical mixers, two tanks, a pH-meter, a main reactor chamber with a water jacket, cooling unit, compressor, vacuum pump, and camera.

Fig. 6. A process demonstrator equipped with a reactor for the crystallization process

The reactor chamber comprises an upper and lower pipe with a cooling water jacket. These jackets serve the dual purpose of providing a temperature-controlled environment and ensuring the reaction occurs at the targeted temperature.

Specialized ultrasonic transducers and a connector are located in the center of the reactor chamber. These sensors are arranged to allow the acquisition of ultrasonic data from inside the reactor chamber. This is essential for real-time evaluation of multiphase industrial processes' characteristics and progress. The connector facilitates seamless integration of the transducers into the measurement device, ensuring reliable and consistent data flow.

The crystallization process was carried out using sodium carbonate and calcium chloride [9]. Two solutions of the above substances were prepared in the following proportions: 16.6 g of sodium carbonate per 1 liter of distilled water and 22 g of calcium chloride per 1 liter of distilled water.

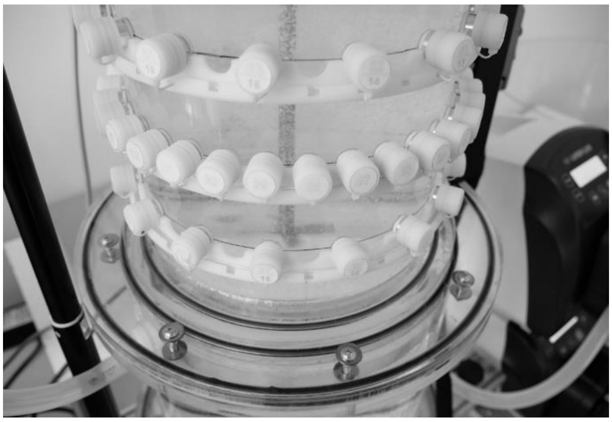

Fig. 7. Precipitated calcium carbonate inside the reactor with 64 transducers 300kHz frequency

The chemical reaction in which the product is calcium carbonate and sodium chloride solution can be written as:

$$Na_2CO_3 + CaCl_2 \rightarrow CaCO_3 + 2NaCl. \tag{1}$$

Figure 7 shows the process of precipitation of calcium carbonate as a residue.

**Results**

Measuring the speed of crystallization, or real-time crystal growth, can be done indirectly by analyzing the change in density of the test medium. Changes in the amplitude of the received ultrasonic waves and the time of flight are then analyzed. This is key information in the design of the crystallization process, allowing optimization of conditions to achieve the desired size and properties of the crystals. Then, parameters such as the addition of substrate to the process and the temperature at which the chemical reaction occurs are controlled.

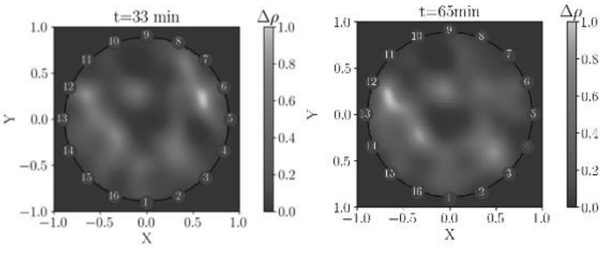

Fig. 8. Field of view reconstruction. Lowe and upper image represent normalized changes in the density of solution after 33 and 65 minutes, respectively using the GN + Tikhonov method

Figure 8 presents a reconstruction of the field of view of the upper reactor ring for the 33rd and 65th minute of the chemical process. Upper and lower plots indicate the changes in the density of the solution. Those results have been obtained by solving the inverse problem using a differential data frame, the difference between the current data frame and the background frame collected at the beginning of the process. Time-of-flight measurements were used to solve the inverse problem. The crystallization process took place without the operation of the mixer, which would result in homogeneous crystallization. This made it possible to show the local formation of precipitates.

### Tank tests with pipe fantoms

The ultrasonic tomograph is equipped with additional methods of operation. The device can detect objects in a medium of homogeneous density, such as contaminants, deposits of bulk materials, and coagulation formation. The device has several detection modes. Two modes are shown below: reconstruction mode based on a time-of-flight matrix and detection by simultaneous analysis of signals from three sensors. These modes will be demonstrated based on phantom measurements in a homogeneous medium. The measurement system is shown in Figure 9.

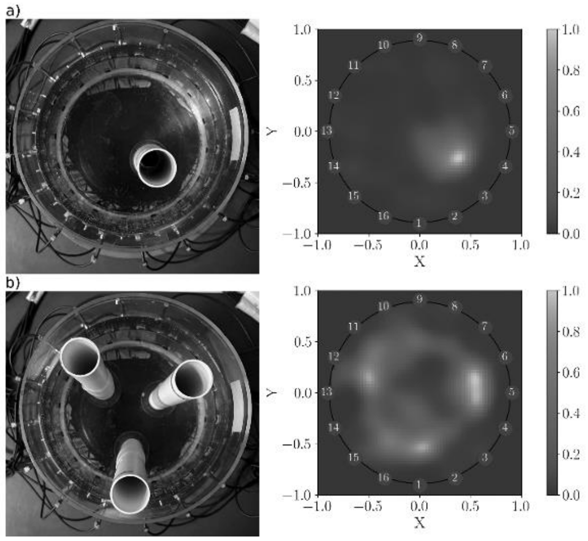

Fig. 9. A laboratory tank equipped with 16 ultrasonic 40kHz sensors filled with water and phantoms placed inside and their reconstruction using GN + Tikhonov method

The field of view (FOV) can be reconstructed using deterministic methods or machine learning by solving the inverse problem. The device has a built-in reconstruction module based on various numerical methods:

- GN + Tikhonov
- GN + Levenberg-Marquardt
- GN + Kotre
- Linear Back Projection
- Truncated SVD
- ML

This allows one to preview the reconstruction in real time.

Imaging using the time-of-flight measurement method is done by collecting data about the arrival of a sound wave to each detector sent from a single sensor. The number of sensors determines the size of the matrix. For 16 sensors, the matrix size is 16x16. Deterministic methods require defining a sensitivity matrix F for each measurement tank. The following equation describes the definition of the inverse problem:

$$p = F^{-1}m, \tag{2}$$

where p denotes a vector containing values of one numerical mesh, and m is a vector of measurements. In this example, the measurements were carried out for ultrasonic waves 40kHz and a signal amplification of 20dB. The inverse problem was solved using the damped Gauss-Newton method with Tikhonov regularization with a regularization parameter equal to 1e-5.

### Conclusions

In this work, we presented a solution based on a multimodal ultrasonic tomograph. The device is designed to act as a component in a larger technological process and as an independent unit that can be used for research and laboratory work. It allows one to implement any desired measurement configuration and to program process control via the feedback controller equipped with the device. The device's operating capabilities are extended to work with any measuring tanks, and the cross-section of the device can be reconstructed. Reconstruction of FOV can be done using built-in algorithms and a visualization module. The design of the device has been adapted to make it easy for end users to transport and use. Further development of the device was also taken care of, ensuring an easy process of implementing subsequent modules and algorithms.

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