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DEVELOPING A DIAGNOSTIC SYSTEM: COMBINING ULTRASOUND AND ELECTRICAL IMPEDANCE TOMOGRAPHY FOR ENHANCED URINARY TRACT ANALYSIS

OPRACOWANIE SYSTEMU DIAGNOSTYCZNEGO: POŁĄCZENIE ULTRASONOGRAFII I TOMOGRAFII IMPEDANCYJNEJ W CELU ULEPSZONEJ ANALIZY DRÓG MOCZOWYCH

Abstract

The study aims to develop a reconstruction and measurement system for data analysis using ultrasound transmission tomography (UST) and electrical impedance tomography (EIT), which can be implemented in wearable solutions for non-invasive monitoring and diagnosis of functional urinary tract disorders. Functional disorders can be associated with many urinary system defects, constipation, and central nervous system defects (spina bifida, cerebral palsy). The lack of non-invasive diagnostic methods for a functional and comprehensive analysis of the state of the urinary tract reduces the likelihood of a correct diagnosis and effective treatment. Furthermore, constructing a physical model of a tomograph is problematic due to the complexity of acoustic phenomena necessary for modeling in the case of a heterogeneous environment of propagation of waves in small, limited spaces. Nevertheless, the radial propagation model used in UST is sufficient for effectively detecting disturbances in the interior of objects and is used in medical solutions. The innovation of the solution lies in the simultaneous assessment of urinary tract function based on the analysis of images obtained using EIT and UST. As a non-invasive diagnostic, UST allows for visualization of the body's internal structures (including muscles, blood vessels, and internal organs). However, UST-based diagnostic systems of the urinary tract are not present in world markets. Moreover, building such a system requires solving many problems: limited research fields, dependence on the body structure, difficulties in imaging bone structures, and areas filled with gases. The final version of the system will be implemented in clinical practice, where it will be used to diagnose diseases of selected groups with established urinary tract dysfunction.

Streszczenie

Celem badań jest opracowanie systemu rekonstrukcyjno-pomiarowego do analizy danych z wykorzystaniem ultradźwiękowej tomografii transmisyjnej (UST) i elektrycznej tomografii impedancyjnej (EIT), który będzie można zaimplementować w rozwiązaniach umożliwiających nieinwazyjne monitorowanie i diagnostykę czynnościowych zaburzeń dróg moczowych. Zaburzenia czynnościowe mogą wiązać się z wieloma wadami układu moczowego, zaparciami i wadami ośrodkowego układu nerwowego (rozszczep kręgosłupa, porażenie mózgowe). Brak nieinwazyjnych metod diagnostycznych umożliwiających funkcjonalną i kompleksową analizę stanu dróg moczowych zmniejsza prawdopodobieństwo postawienia prawidłowego rozpoznania i skutecznego leczenia. Ponadto konstrukcja fizycznego modelu tomografu jest problematyczna ze względu na złożoność zjawisk akustycznych niezbędnych do modelowania w przypadku niejednorodnego środowiska propagacji fal w małych, ograniczonych przestrzeniach. Niemniej jednak stosowany w UST model propagacji promieniowej okazuje się wystarczający do skutecznej detekcji zaburzeń we wnętrzu obiektów i znajduje zastosowanie w rozwiązaniach medycznych. Nowość rozwiązania polega na jednoczesnej ocenie czynności układu moczowego na podstawie analizy obrazów uzyskanych za pomocą EIT i UST. UST jako nieinwazyjna metoda diagnostyczna pozwala na wizualizację wewnętrznych struktur organizmu (w tym mięśni, naczyń krwionośnych i narządów wewnętrznych). Jednak systemy diagnostyki układu moczowego oparte na UST nie są obecne na rynkach światowych. Ponadto zbudowanie takiego systemu wymaga rozwiązania wielu problemów: ograniczonych pól badawczych, zależności od budowy ciała, trudności w obrazowaniu struktur kostnych oraz obszarów wypełnionych gazami. Ostateczna wersja systemu zostanie wdrożona w praktyce klinicznej, gdzie będzie wykorzystywana do diagnozowania chorób wybranych grup z rozpoznaną dysfunkcją dróg moczowych.

Keywords: *ultrasound tomography, electrical impedance tomography, inverse problem, sensors, image reconstruction, non-invasive medical monitoring*

Słowa kluczowe: *tomografia ultradźwiękowa, tomografia impedancyjna, problem odwrotny, czujniki, rekonstrukcja obrazu, nieinwazyjny monitoring medyczny*

Introduction

In medical diagnostics, many methods of imaging the human internal structure are used, each as an independent or complementary method. We should mention here the systems widely used today, with moderate prices, using ultrasound waves (ultrasonography and Doppler apparatus), as well as costly systems (requiring specialized equipment), but providing images (diagnostic information) of excellent quality and high resolution, using Magnetic Resonance Imaging (MRI).

Another class of imaging systems uses X-rays (X-ray equipment, computed tomography). Computed tomography (CT—computer tomography) provides us with images of the best quality so far (carrying the most diagnostic information).

The computer tomograph is built based on an X-ray tube with which a sequence of layered images is made. The data set is then subjected to the analytical image reconstruction process. The resulting image, called a tomogram, is obtained and carries information about the linear X-ray attenuation coefficient distribution in the examined tissue cross-section. X-ray methods (as opposed to the first two) are harmful to the patient's health, which is particularly important in CT systems, as the patient's absorption dose during a single examination is many times greater than a typical chest X-ray examination.

Ultrasound Transmission Tomography

Ultrasound tomography, particularly ultrasound computed tomography, is generally divided into two broad categories: conventional and diffraction tomography, with these two groups further divided into transmission and reflection (Rymarczyk et al., 2021). Ultrasound transmission tomography (UST) is a non-invasive measurement technique for imaging the inside of the test object from measured data of ultrasonic sensors placed on the edge of the test object. UST allows the analysis of the processes inside the object and the detection of obstacles and various anomalies without interference with the test object. Depending on the type of tomography, the sensors can collect information about the time of flight of the sound wave or the amplitude. In applications, these sensors serve as both transmitters and receivers of the waves, and the entire measurement sequence is controlled by an electronic system (Rymarczyk et al., 2021; Kozłowski et al., 2021; Wójcik et al., 2021; Mazurek et al., 2021).

The proposed measurement system allows using different types of ultrasonic sensors for on-site control. A picture of the internal structure of the object under study (with appropriate transformations for reconstruction) can be obtained by measuring parameters such as signal transit time, attenuation coefficient, and frequency derivative. The basis of these images is the difference between the local values of specific acoustic parameters. The images produced by suitable reconstruction methods show the internal structure of the medium, which is obtained by measuring the scan data at different angles after the ultrasonic pulse has passed through the medium under investigation. In addition, this technique provides a quantitative image of the internal structure. In this image, the digital data of each pixel represents a characteristic of the test object, e.g., temperature, pressure, or viscosity distribution. The presented measurement system has a specially designed measurement structure that includes transducers. Thanks to this, it is a particularly effective solution in analyzing and controlling industrial processes. The radial propagation model used in UST is sufficient for effectively detecting interference inside an object and has been used in industrial solutions (Majerek et al., 2021).

Electrical Impedance Tomography

Electrical impedance tomography (EIT) contains electrical capacitance tomography (ECT) for systems dominated by dielectrics and electrical resistivity tomography (ERT) in conductive processes. This is due to an alternative hardware design approach for each sub-modality, but the basic theory for solving electrical tomography problems can be obtained from Maxwell's equations. Electrical tomography is an imaging technique that uses the diverse electrical properties of different materials. This method connects a voltage or current source to the test object, and measurements are taken on the shore. The collected information is processed by an algorithm that performs image reconstruction. ECT measurements determine the capacitance between electrodes at the edge of an object that serves as a capacitor electrode. Electrical Resistance (Impedance) Tomography is an imaging technique that uses the diverse electrical properties of different types of materials. In this method, an energy or voltage source is connected to the object, and then current flows or voltage distributions occur at the object's edge. The collected information is processed by an algorithm that re-constructs the image. This tomography is characterized by a relatively low resolution of the spatial image. Difficulties in obtaining high resolution are mainly due to the limited number of measurements, non-linear current flow through a given medium, and the voltage measuring apparatus's low sensitivity to changes in conductivity in a given area. Image reconstruction is very sensitive to ubiquitous modeling errors caused by inaccurately known auxiliary variables of the measurement model. In practice, the object's shape has yet to be discovered. It has been shown that errors in its modeling especially have serious consequences.

In electrical impedance tomography (EIT), the solution to the forward problem is to determine the potential distribution in an object, given the boundary conditions and data. The numerical analysis of the situation at this point is presented using the example of electrical impedance tomography and the finite element method. It is currently the most widely used numerical method for the approximate solution of field problems of complex geometry, in which the medium may exhibit characteristics of current heterogeneity, conductivity, etc. Most of the currently used image reconstruction algorithms use this method. Depending on the geometry of the area, there is a tendency to use isoparametric triangular or quadrilateral finite elements.

Electrical Impedance Tomography is an imaging technique that uses the different electrical properties of various materials, including biological tissues. In this method, an energy or voltage source is connected to the object, and the current or voltage distribution at the object's edge is observed. The collected information is processed by an algorithm that reconstructs the image. Electrical impedance tomography has a relatively low image resolution. Difficulties in obtaining high resolution are mainly due to the limited number of measurements, non-linear current flow through a given medium, and too low sensitivity of the measured voltages depending on the changes in conductivity inside the area.

Materials and Methods

Ultrasound imaging is one of the most popular diagnostic techniques widely used in various medical fields. However, it mainly concerns stationary devices that require specialist knowledge to operate and interpret their results. To support people with lower urinary tract conditions, an innovative wearable device based on ultrasound tomography assisted by impedance tomography has been developed. The device can visualize the bladder and determine its filling level. Ultimately, the device will be connected to a mobile application informing the patient about incidents of involuntary urinary incontinence and the current state of the lower urinary tract.

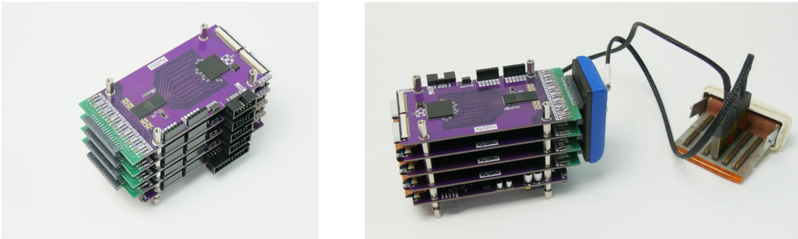
The measuring device is used for imaging the bladder (Fig. 1). The tomography method is based on alternating current stimulation and measuring the tension on the skin surface. It is possible to reconstruct the studied area from the collected measurements, i.e., to visualize the distribution of electrical conductivity values. This distribution is obtained using proprietary algorithms primarily based on solving the inverse problem. Using the tomography method, the system allows for real-time imaging and monitoring of the abdominal cavity. Separate pulses on each channel, adequately controlled, will enable the generation of an ultrasonic wave using beamforming technology (directing the ultrasonic wave using stationary, static transducers).

Figure 1. *The main module of the ultrasound tomography, the electronic unit controlling the measurement procedure*

The device uses two measurement techniques that are complementary to each other: ultrasonic tomography and electrical impedance tomography. The complementarity of these techniques is that EIT has high resolution at the edge of the measurement area, while UST performs better inside it. Therefore, the fusion of these two techniques is expected to produce an image with a much better resolution than relying on only one of them.

To conduct UST measurements, we used a dedicated MAX2082 board (Fig. 2). It is an ultrasonic 8-channel BGA system with integrated pulses, T/R switches, LNA, VGA amplifiers, AAF filters, ADC (12-bit 50MSPS) and digital filters.

Figure 2. *Beamforming tomograph with adapters mounted on measurement cards (a) and with the measuring plug installed (b)*



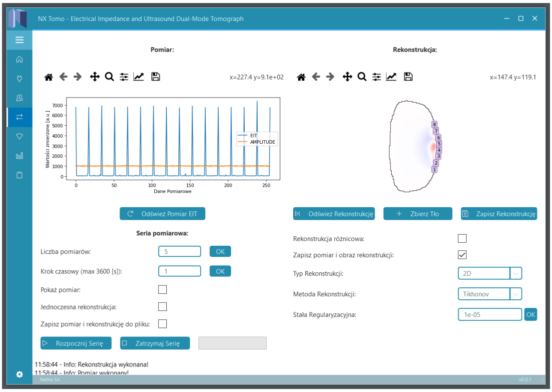
(a) (b)

The main advantage of this technology is the ability to perform a large number of reflection measurements using a small number of channels/transducers (and their number results mainly from the step with which the phase of the transmitting signal will be shifted). The phase shift on each of the transmitting transducers allows you to direct the wave beam at a specific angle, thanks to which static transducers can perform imaging similar to using one transducer with a mechanically controlled application angle.

The device has two USB ports for exchanging data with a computer, a measuring socket for the UST head, a measuring socket for EIT electrodes, a power socket, and an operating status indication in the form of LED diodes.

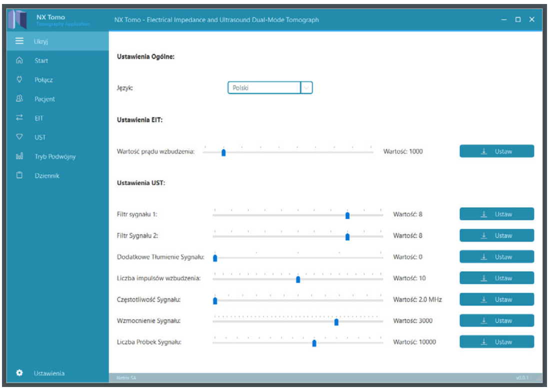
The application consists mainly of modules and widgets. Widgets replace the system application bar with its original counterpart. The functionality of the graphical interface itself includes an element that allows you to expand the application taskbar and display the settings bar. Expanding these bars results in a dynamic reduction of the window width of a given widget. The main functionalities of the application include connecting the application to the device, which is available by opening the *Connect* panel and then clicking the *Connect to UST-EIT device* button. After clicking the button, a message about the possibility of connecting to the device appears at the bottom of the application. Additionally, the user can perform a measurement series. The course of the performed series is presented on the progress bar. While performing the series, you can preview the EIT measurement and reconstruct the abdomen image. The next application panel performs measurements and reconstruction using the UST method, using an ultrasound head. The user can also measure a single channel of the head. Additionally, a panel has been created that allows simultaneous measurement with both techniques and reconstruction. The dual mode displays the EIT measurement, EIT reconstruction, and UST reconstruction (Fig. 3).

Figure 3. *Application panel containing the possibility of simultaneous reconstruction of EIT and UST*



The user can view all emerging messages in the log panel. To perform better measurements, the user can control the device parameters. These variables are configured in the Settings panel. Fig. 16 shows the settings panel showing the number of implemented variables.

Figure 4. *Settings panel*

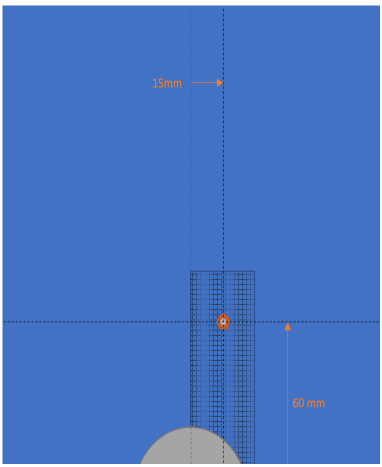


Beamforming experiments

Beamforming is a modern signal processing technique that relies on directional signal transmission. Obtaining the appropriate signal transmission direction is possible thanks to the proper arrangement of the antennas (in the so-called array). It is known that signal streams that intersect at certain angles strengthen each other, and at certain angles, they attenuate. Determining the appropriate position of the antenna allows you to *direct* the signal beam to the indicated place (Wang et al., 2021). Ultrasound imaging is widely used in biomedicine. High-quality anatomical information is obtained. Applications are also used: radar, sonar, communications, imaging, geophysics, and astrophysics. An infinite number of solutions to the wave equations generate the beams. Beam formation plays a vital role in medical imaging and tissue characterization—the principles of forming a biomedical ultrasound beam control diagnostic imaging quality. The beam parameters related to the quality of imaging are (1) lateral and axial resolution, (2) depth of field, (3) contrast, and (4) frames per second (Lu et al., 1994; Solgi et al., 2022; Mozaffarzadeh et al., 2020; Synnevåg et al., 2008).

The measurement method is based on beamforming. Its idea is first to discretize the surveyed area using a grid. The grid is then scanned using a beam of ultrasonic waves. Wave focus points on a grid of 6x16 points with a spacing of 5mm allow you to map an area with dimensions of 30x80 mm (Fig. 5).

Figure 5. *Diagram of the experiment with the phantom in positions 15-60 mm*

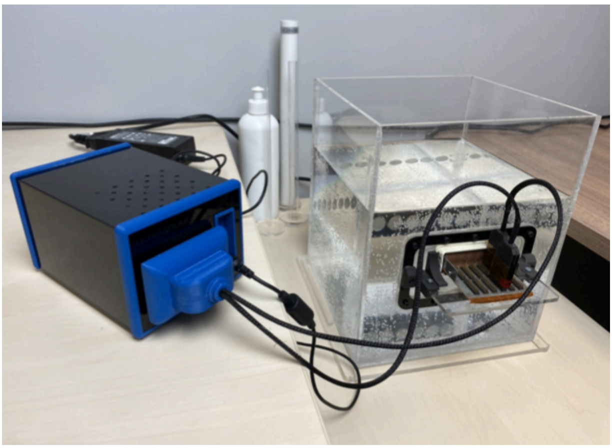


The beamforming proceeds by adequately controlling the phase shift of the wave on each transducer. With the appropriate phase matching, a wave with a homogeneous wavefront is formed, which can be directed at any angle. After several wave packets are emitted, the transducers go into listening mode and record the reflected waves.

This technique allows the entire measurement area to be scanned in three dimensions. In a way, this is similar to the premise of performing an ultrasound examination, where the doctor changes the angle and position of the transducer. However, in the case of our device, the ultrasound transducers are stationary, and the change in the angle of attack is performed using phase modulation.

Our method relies on the beamforming technique (shaping an ultrasonic wave with the static transducer) using the MAX2082 circuit. The main advantage of this technology is that many reflection measurements can be made with a small number of channels/transducers (and the number is mainly due to the step with which the phase of the transmitting signal will be shifted). The phase shift on each transmitting transducer directly allows the wave beam at a specific angle, so with static transducers, it is possible to perform imaging like using a single transducer with a mechanically controlled application angle. To develop the algorithms, experiments were conducted on a water tank with single inclusions in the form of air-filled cylinders.

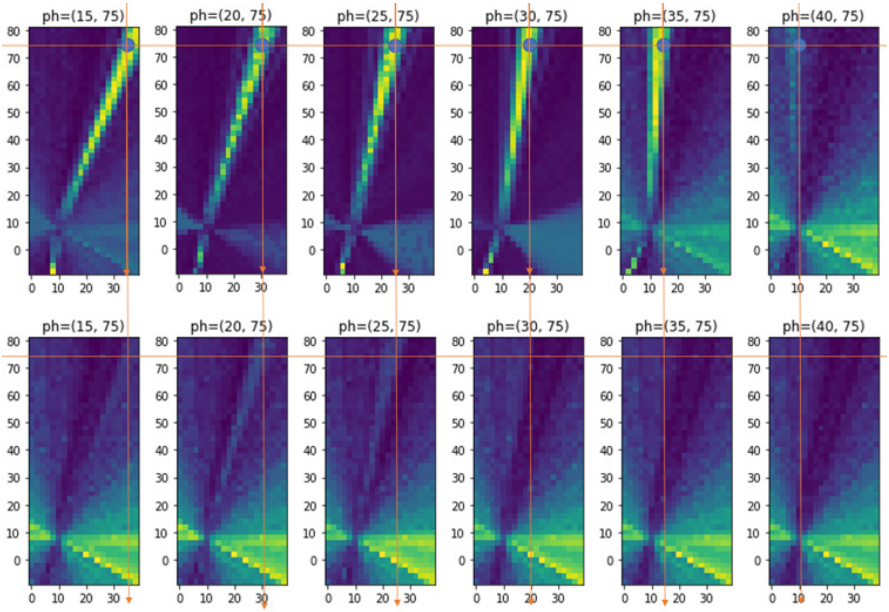
Figure 6. *Preparation of a beamforming tomograph for 32-channel measurements*



Results

Analysis of the measurements and reconstruction tests showed that we could accurately determine the angle/direction at which the inclusion is located in the measurement area by mapping the maximum amplitude value recorded at a given grid point. The spatial distribution of the signal amplitude on the measurement grid is presented below.

Figure 7. *Mapping measurements. The results for the phantom set in the x position are 15, 20, 25, and 30 mm, respectively. Position y=60*



A phantom with an outer diameter of 5 mm was placed in positions 15-60 [mm], 20-60 [mm], 25-60 [mm], 30-60 [mm], 15-35 [mm]. (see Fig. 7).

From the signal, 299 samples were taken in ranges depending on the position of the phantom so that the peak corresponding to the phantom was approximately in the center of the sample (1200-1500; 1300-1600; 1400-1700;

1400-1700; 450-750; 550-850). Each pixel of the image corresponds to one wave focus on beamforming, and the mapped value per pixel was was:

$$I_{ij} = \max\big(gf(abs(probe - offset), 4.0)\big)$$

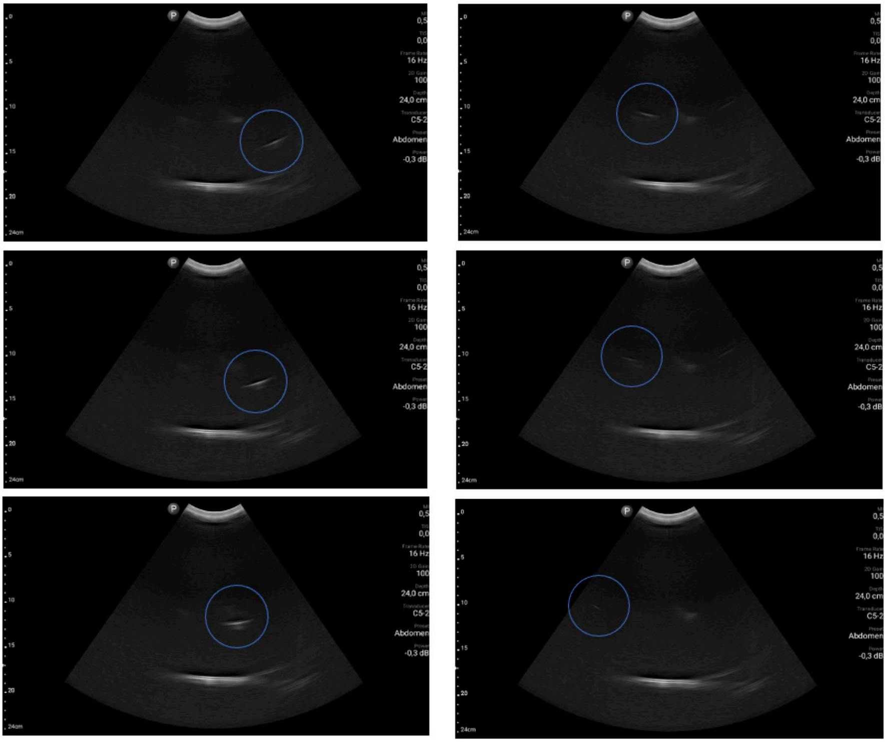
where: *gf (y,s)* denotes the Gaussian filter on the signal *y* with the standard deviation of *s*, *probe* is a fragment of 299 samples from the signal *abs* – absolute value *of f set* – signal offset, here amounting to $offset = 2^{15} - 50$.

The mapping time is less than 12 seconds by mapping precisely 96 points of the image. In beamforming mode, the data bus freezes repetitively after about 102-104 measurements – hence the limitation in resolution. On the other hand, we could also obtain the image of the object by casting the signal amplitude from transducers onto a cone. The result is visible in the picture below (Fig. 8). As part of the reference experiment, a Philips Lumify ultrasound kit was used to perform a series of measurement tests on a test cup—the experiment aimed to verify the imaging quality with a professional device. A single phantom, visible in the photo inside the tank, was used for the experiment.

The object is seen as an arc of wave reflection from the first face – sometimes a second, more minor trace is visible, which may indicate the second face. The visibility of the arc could be better. The arc size changes in the image depending on the distance from the head, but the angular width of the object is maintained with similar visibility.

The next step is to develop a low-cost algorithm for estimating the distance between inclusion and transducers. With these two parameters, we will be able to accurately localize the inclusions.

Figure 8. *Reference measurements on the tank. The object is seen as an arc of wave reflection from the first wall – sometimes, a second, more minor trace is visible, which may indicate the second wall. The size of the arc changes in the image depending on the distance from the head while maintaining similar visibility; the angular width of the object is also maintained*



Conclusions

The presented images prove that the main factor modulating beamforming is the direction of the ultrasonic wave beam without changing the transducers' position. The highest amplitude values are clearly arranged in a straight line from the transducer to the object. Thanks to such mapping, we can also determine the object's distance from the transducer. Still, at this stage, we can already see the phenomenon of *overexposure* of the object, i.e., the high amplitude of the signal when we focus on the beam behind the object. Practical imaging requires appropriate geometric accuracy – the method of calculating delay in beamforming results from the fact that we need to know precisely the position of the transducers. Nevertheless, despite the shortcomings of the current solution, a change in the angular position of the object within the cone corresponding to the part of the transducers can be noticed. Performing measurements with frequent changes of the delay register can be unstable and may cause the crash of communication with the data bus – this is a hardware/ software problem to be solved in our future research.

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