# New trends in the ultrasonic imaging of concrete structures by means of 3D-FMC technology

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**Summary**

The novel technologies in ultrasound generation and data processing offer new opportunities for three-dimensional imaging of concrete structures. Especially the Full-Matrix-Capture (FMC) technique with its real-time imaging capability can be successfully utilized for quality assurance in the construction industry. Although, the available testing instruments on the market implement the principle of linear transducer array with its two-dimensional reconstruction of B-Scan images based on the Synthetic Aperture Focusing Technique (SAFT) principle.

The Dry-Point-Contact (DPC) transducers utilized in commercially available instruments for concrete testing with their matrix-like layout offer a direct opportunity to implement a three-dimensional Full-Matrix-Capture (FMC) data acquisition cycle. The obtained data can be in real-time processed by 3D-TFM reconstruction and visualized and evaluated three-dimensionally.

In the present contribution both state-of-the-art and novel true-3D imaging approaches and data assessment are considered on real concrete inspection objects and the advantages of enhanced data processing with respect to improved information content and easiness of result, interpretation is discussed. The article also addresses the advantages of three-dimensional data acquisition with DPC transducer systems in relation to increasing the information content of ultrasonic concrete testing and improving its detection capability. Among other things, the quantitative crack depth assessment is discussed, which provides a practical dimension through the new approach.

## 1. Introduction

The application of imaging ultrasonic testing of concrete in the civil engineering [1] has become widespread in the last decade. The reasons for this are, on the one hand, the aging infrastructure and increasing need for non-destructive quality assurance, and on the other hand, the significant advances in the development of testing technologies and the growing range of modern imaging testing systems on the market.

While the ultrasonic testing devices for metallic products and lightweight composite materials have a long history of use, the concrete testing devices belong to an “emerging market” in which there is still a lack of standards and regulations. Nevertheless, the modern testing instruments, with their two-dimensional and three-dimensional imaging, offer clear added value in terms of quantitative nondestructive testing and reliability of the condition assessment of the building construction.

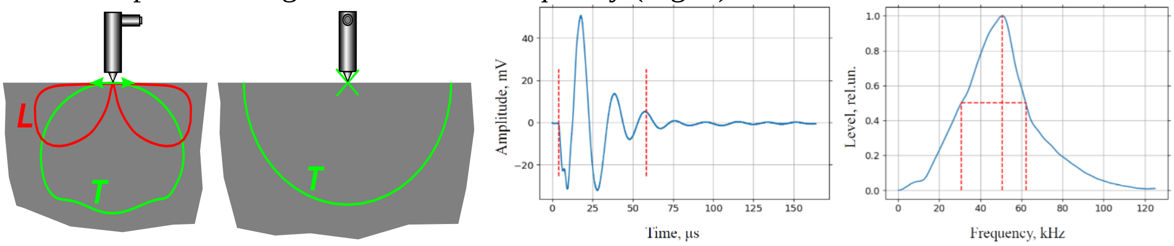
The aim of the current article is to explain the latest trends in the implementation of modern ultrasonic testing instruments for concrete testing – in particular, the processing and visualization of ultrasonic measurement data—and to show the potential for expanding their area of application.

## 2. Modern ultrasonic testing instruments for concrete testing: Design and functional principle

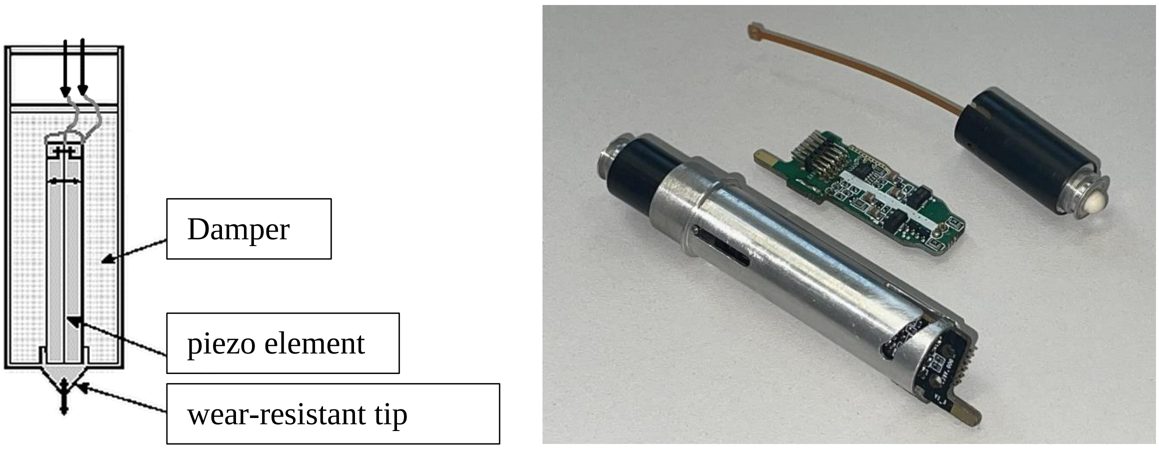
Similar to the modern ultrasonic flaw detectors for metal testing, the concrete testing instruments represent multi-channel phased array systems [2], which display the test results as images (Fig. 1).


Fig. 1: Ultrasonic concrete testing device with 4 x 8 = 32 array elements

The key element of such a testing instrument is the ultrasonic sensors. In contrast to conventional ultrasonic devices for metal testing, in which the piezoelectric transducers are coupled via a liquid coupling medium, the probes for concrete testing used here implement the so-called “dry point contact” principle (DPC) [3], in which a special type of excitation is used via a pin vibrating at the nominal frequency (Fig. 2).




*a) Beam directivity, pulse characteristic and frequency spectrum of a DPC transducer*

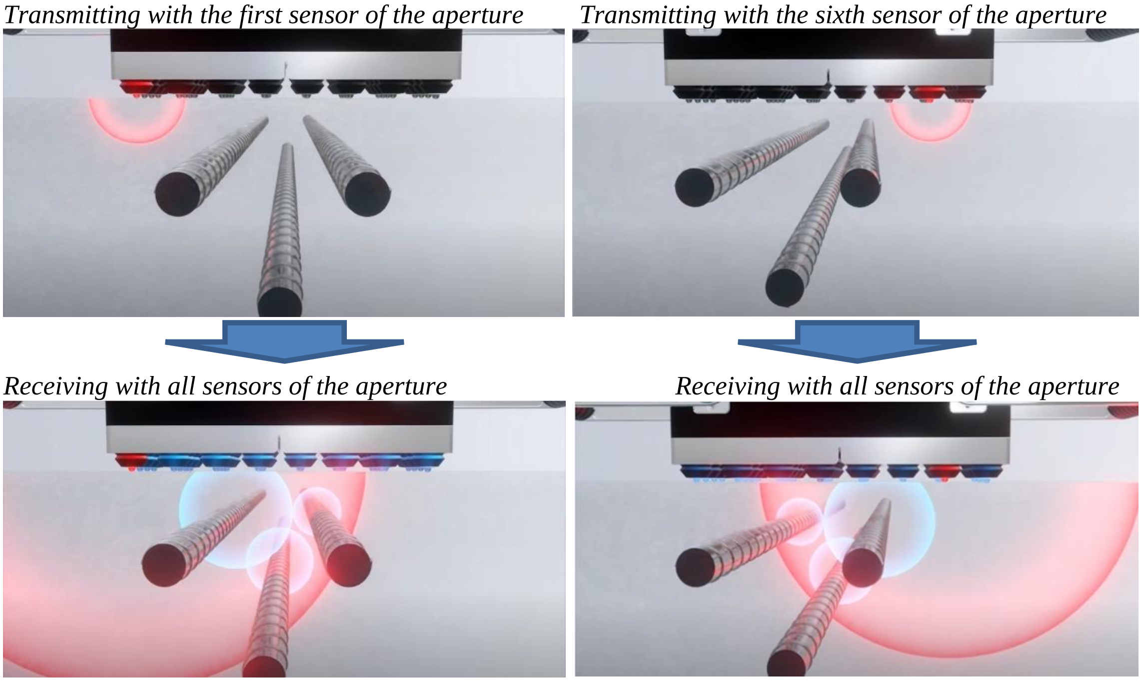



*b) Design of an active DPC transducer*

Fig. 2: Active DPC ultrasonic transducer with integrated transmitter/receiver electronics

Depending on the desired ultrasonic wave type (longitudinal or transverse), operating frequency and bandwidth, the construction of the transducer can vary. Broadband shear wave transducers with a center frequency of around 50 KHz are typically used for ultrasonic imaging in concrete [4]. The latest trend in the implementation of modern DPC sensors is the integration of the complete transmitter/receiver stage directly into the transducer housing. In addition to the low-noise electrical properties, this design enables the excitation and reception of the ultrasonic waves with each individual element of the two-dimensional matrix aperture.

The ultrasonic data is acquired according to the so-called "full matrix capture" (FMC) principle, where the array elements act individually as transmitters and receivers (Fig. 3).




***Red:*** *spherical shear wave emitted by a sensor*
***Blue:*** *spherical shear waves reflected back from the reinforcing bars*

Fig. 3: The principle of sequential excitation of the matrix aperture (3D-FMC)

Ultrasound data originating from the two-dimensional instrument aperture consisting of 4 x 8 DPC transducers, including all 32 x 32 = 1,024 combinations of transmitters and receivers, are superposed using the "total focusing method" (TFM). The TFM method, in turn, represents a variant of the "synthetic aperture focus technique" (SAFT), in which the aperture to be synthesized is limited to the aperture of the phased array with alternating transmitter and receiver elements. In this way, a three-dimensional image of the component volume can be generated in each measuring position of the ultrasonic tomograph (Fig. 4).

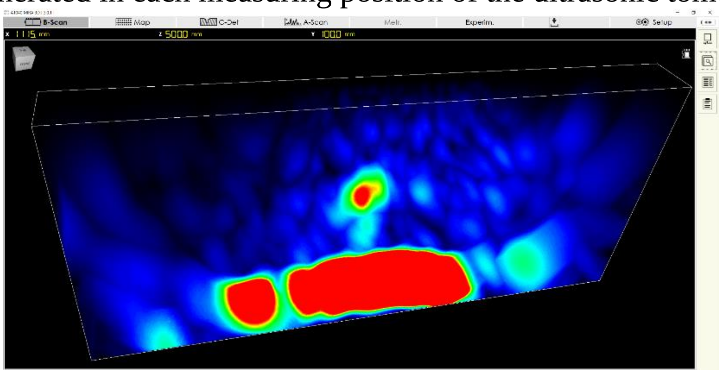


Fig. 4: A 3D image of a material defect in a test position of the ultrasonic device

Another advantage of the FMC data acquisition with the matrix aperture is the possibility of combining the array elements or several aperture blocks in any way in order to expand the near field size and thus the achievable depth of focus (Fig. 5).

Fig. 5: Possible matrix aperture combinations for 3D TFM data acquisition

Finally, another feature of the design structure of modern ultrasonic concrete tomographs can be mentioned, which under certain circumstances can also prove to be groundbreaking for other phased array systems, e.g., for metal testing. The image reconstruction according to the TFM principle – in particular, when calculating matrix apertures from 32 x 32 or 64 x 64-point sources – requires significant computing power in order to be able to carry it out in real-time. Modern tablet PCs have multi-core graphics processors that are perfectly capable of real-time 3D SAFT reconstruction of matrix aperture data.

The function of the data acquisition electronics is limited to the excitation and reception of the ultrasonic signals, as well as digitization and transfer of the raw ultrasonic data via a WiFi data interface. The entire data processing (incl. digital filtering), image reconstruction, visualization and evaluation (incl. reporting) is taken over by a high-performance tablet PC or, alternatively, a desktop or laptop computer (Fig. 6).

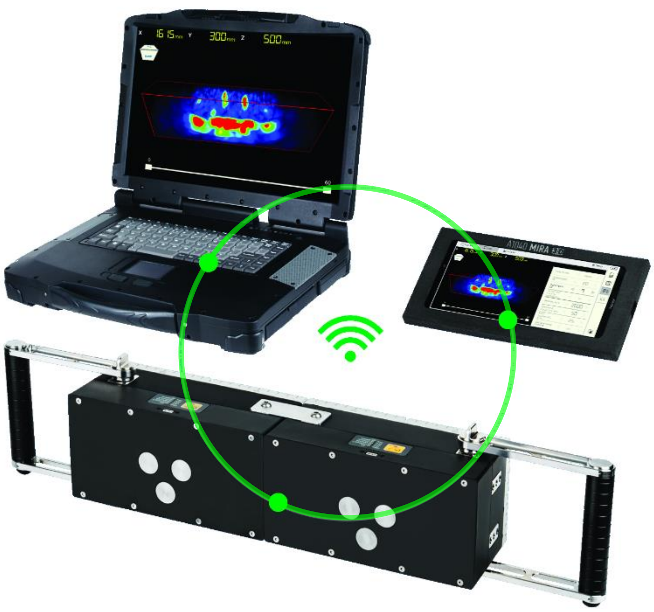


Fig. 6: Communication of the measurement electronics unit with various processing units

The advantages of such a separation of the measurement and processing electronics and their wireless communication are, among others:

⇒ Less expensive version of the measurement electronics

⇒ Flexible further development of the application software (APP) without "intervention" in the measurement electronics

⇒ Automatic advantages thanks to new generations of computing units with improved performance
⇒ Wide range of options for automated recording of ultrasound data, e.g., when integrating the ultrasound device into a scanner unit with remote control

## 2. Advanced signal processing methods to expand the testing range of ultrasonic testing

One of the unique selling points of the ultrasonic testing devices for concrete testing compared to other testing methods, such as ground penetrating radar testing systems, is their greater range with high resolution.
Even when testing reinforced concrete, inspection range of up to two meters can be implemented (Fig. 7).

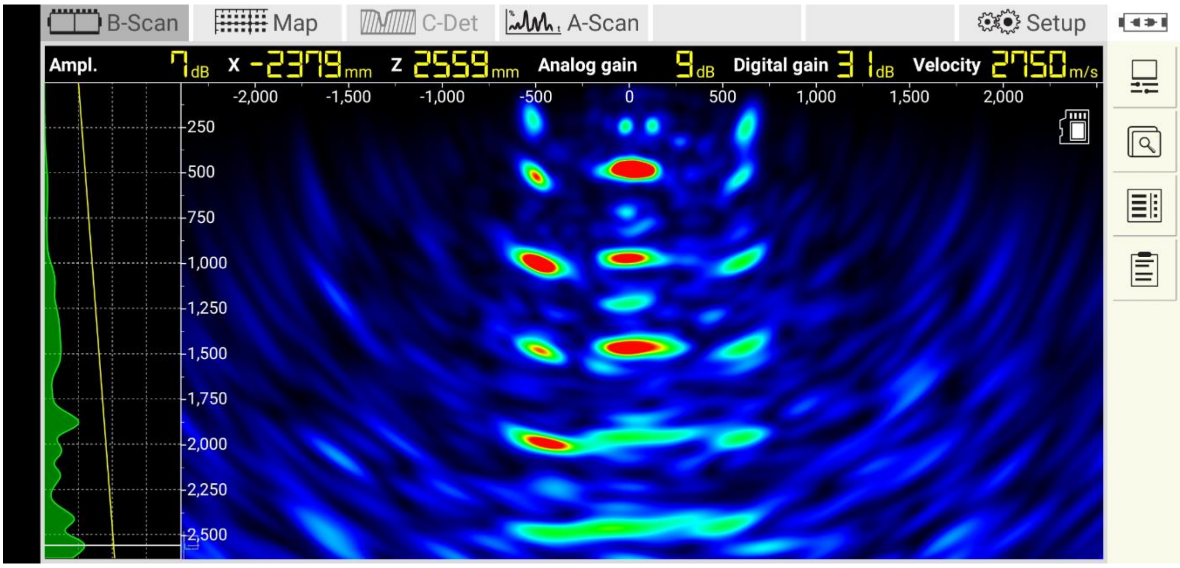


Fig. 7: B-scan representation of a reinforced reference block

Nevertheless, ultrasonic testing also has its physical limits if the material to be tested has increased sound attenuation, e.g., due to coarse aggregates, or if particularly thick structures, such as dams, with a wall thickness of several meters are being tested. The insufficient signal-to-noise ratio does not allow the recorded ultrasonic signals to be evaluated.

If you look at the raw ultrasonic echo signals in detail, you can divide the signal noise into three categories:

⇒ Coherent acoustic noise due to ultrasonic backscattering

⇒ Quantization noise due to the limited resolution of the analog to digital conversion

⇒ Thermal noise

The last two types of noise occur, in particular, with very long sound paths, where one has to deal with relatively weak signals despite increased amplification values. This can be successfully overcome using a so-called pulse compression technique. For this purpose, instead of a short monochromatic excitation sequence, a long-modulated excitation sequence is used to excite the ultrasonic waves, which is then extracted again in the received and digitized ultrasonic signal. As a result, a significant improvement in the signal-to-noise ratio and the spatial resolution can be achieved.

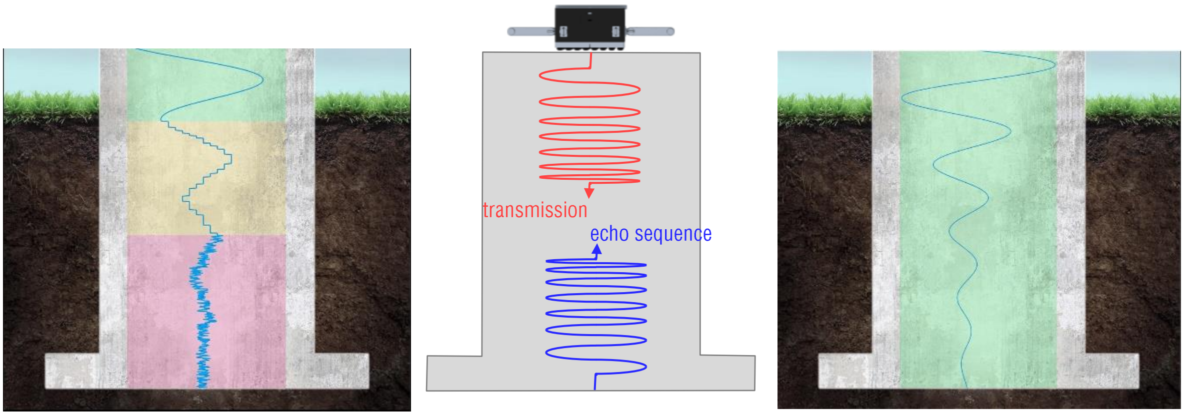
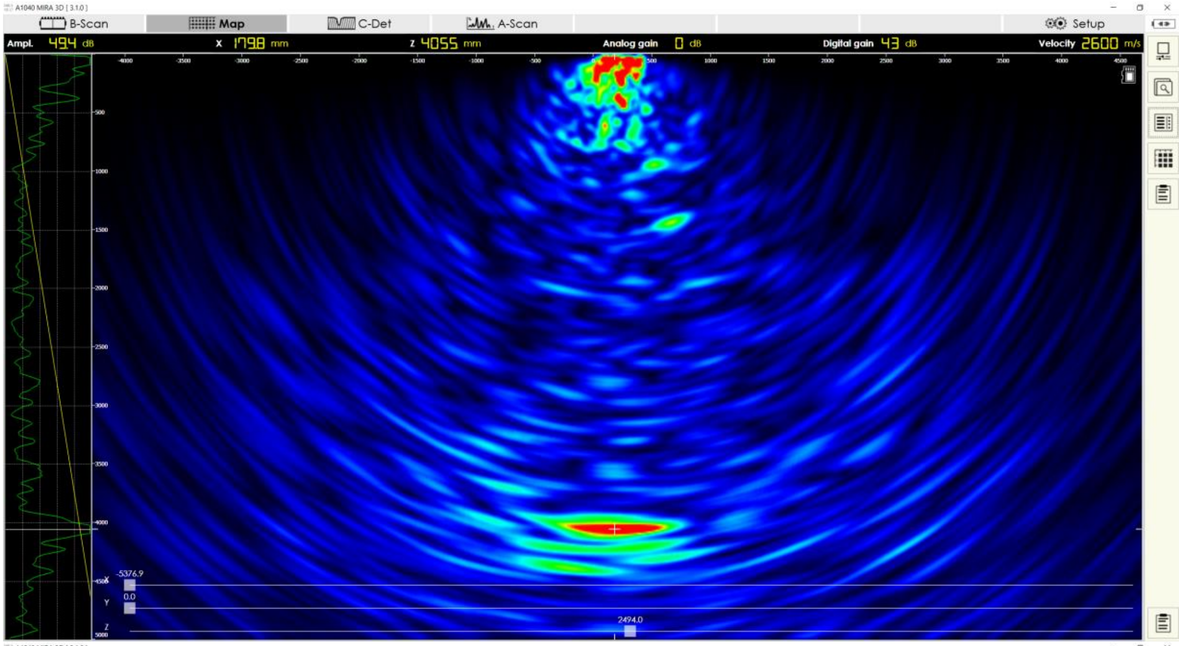
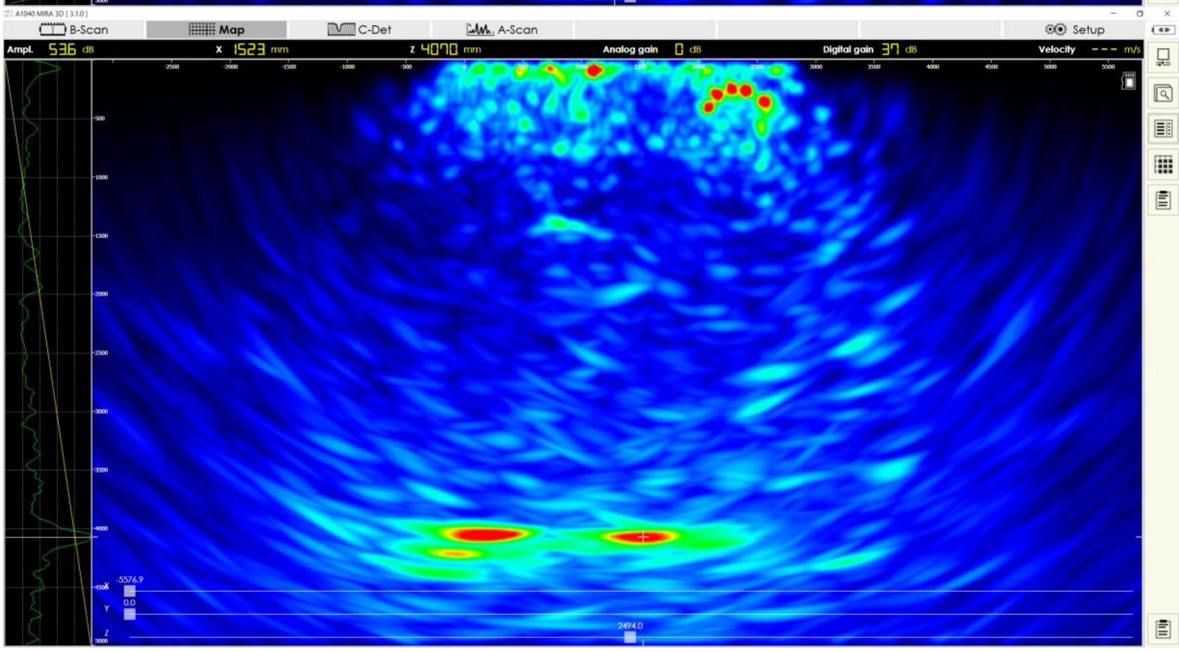



Fig. 8: Schematic representation of the types of noise (left) and the suppression principle using a modulated excitation sequence

As a result of such a decomposition of the received echo-signals before the SAFT image reconstruction, a denoised test result is obtained.

*a) Measurements on a concrete block with a wall thickness of 4 m*




*b) Test results on a concrete block with a wall thickness of 4 m pulse compression technique*

Fig. 9: The test result without and with guided signal excitation on the thick concrete block*

**The results have been obtained on the reference object of the Federal Agency for Materials Research and Testing BAM at the test ground BAM-TTS at Horstwalde/Brandenburg*

### 3. Types of 3D visualization and presentation of results with modern ultrasonic concrete testing devices

The transition from the implementation of the line array principle to the matrix array principle offers new options for the visualization of ultrasonic test results. As an "elementary" data set in a test position, a three-dimensional volume data set is used for each recording, which has an improved spatial resolution compared to linear array devices. This is thanks to the implementation of the 3D TFM principle. Of course, this requires a more complex hardware implementation, such as a fully parallel design of the ultrasound channels and computationally intensive 3D SAFT reconstruction.

This means that three-dimensional data sets (Panorama B-Scan and Panorama D-Scan) are created for any type of component scanning with equidistant measuring points, both in the X and Y directions (see Fig. 10), which are visualized accordingly so that three side views (B, C, D scans) are respectively displayed. If the data is recorded in two-dimensional MAP mode with both scan axes X and Y, volume data sets (area scans) of any size can be created. These require appropriate tools, such as "zooming" and "scrolling" for their display representation.

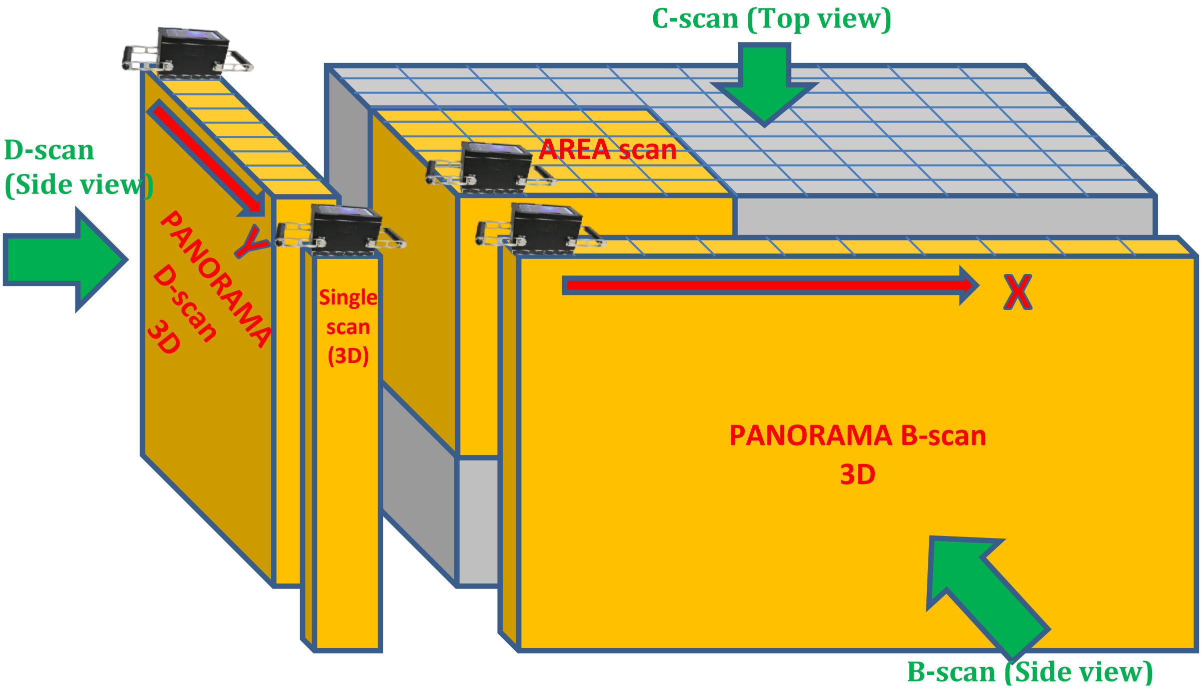
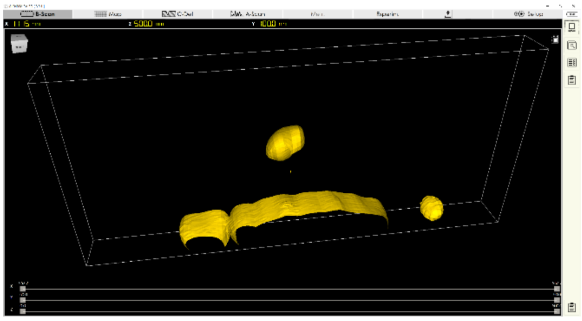
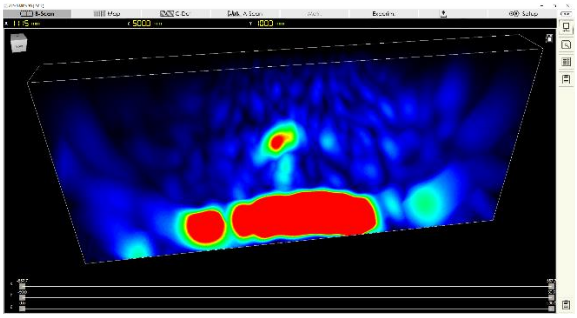


Fig. 10: Volume display modes when visualizing the ultrasound data

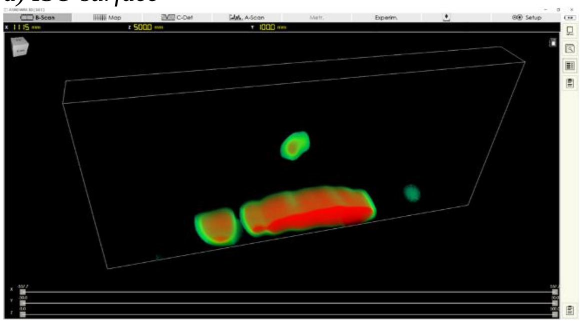
Furthermore, depending on the application, the actual visualization of the voxel data can be done in different rendering modes (Fig. 11).



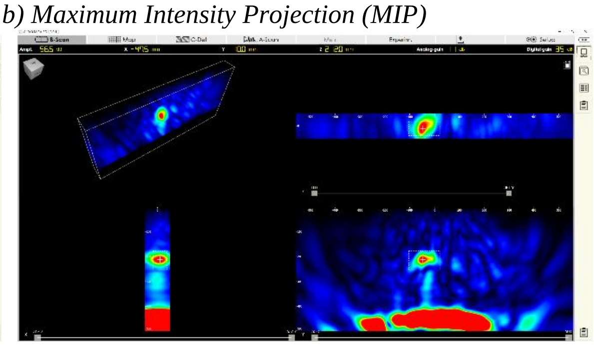
*a) ISO surface*



*b) Maximum Intensity Projection (MIP)*



*c) Texture mapping*



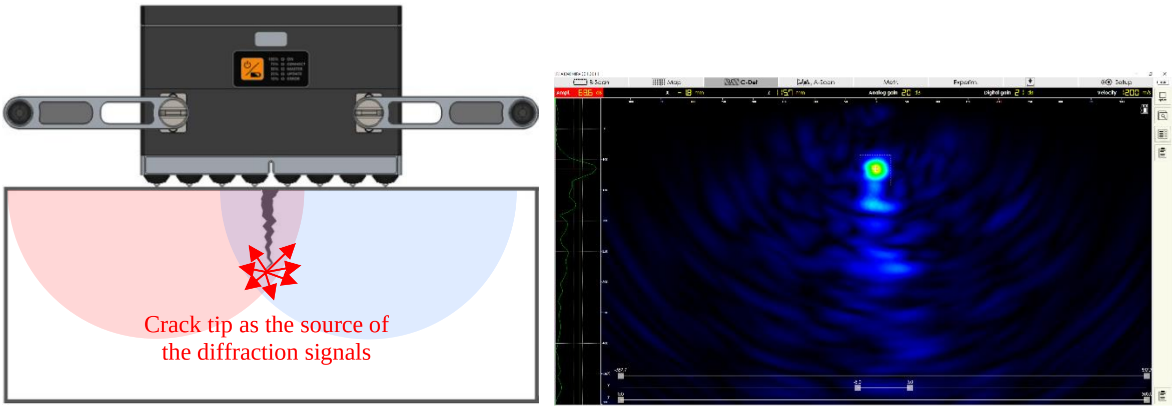
*d) B/C/D gated volume MIP*

Fig. 11: Volume display modes when visualizing the ultrasound data

## 4. Crack depth evaluation

Another significant advantage of the matrix aperture with extremely small single array elements is its very broad beam directivity characteristic, which, among other things, allows acquiring diffraction signals from unfavorably oriented material flaws, such as the tip of an outwardly open crack, to be detected. This makes it possible to determine the depth of such material defects without being able to insonify them "frontally".

When performing such a measurement, it is necessary that the number of DPC sensors on both sides of the open crack is equal and that the crack depth does not exceed the overall aperture size of the device.




*a) Arrangement of the instrument aperture in relation to the crack (left) in crack depth measurement mode of the ultrasonic tomograph (right)*


*b) Measurement of a natural crack in the structure*

Fig. 12: Determination of the depth of an open crack using ultrasonic tomography

## 5. Summary and Outlook

The article presents current trends in the implementation and application of imaging ultrasonic testing systems for non-destructive concrete testing.
These mainly consist of the application of the matrix apertures based on active DPC ultrasonic transducers and the implementation of three-dimensional FMC/TFM methods for tomographic imaging. Among other things, this sensor design allows the use of pulse compression techniques when exciting the ultrasonic waves and thus a significant expansion of the realizable inspection range to several meters.

Furthermore, the transition from the conventional line array principle to the use of matrix apertures allows three-dimensional tomographic imaging with improved spatial resolution in every position of the ultrasonic tomograph and the implementation of special functions for quantitative defect assessment in the near field of the ultrasonic sensor system, such as evaluating the crack depth.

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