



Fast and real-time inspection of concrete structures using a rolling 3D ultrasound scanner

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Abstract

A multilayer piezoelectric PVDF (Polyvinylidene fluoride) array transducer is used to develop an ultrasonic rolling scanner for concrete structure inspection. The eight-element transducer array units are assembled in two separate rollers to operate in transmission and receiver modus (pitch-catch mode). The scanner is equipped with a rotational encoder that keeps track of positional information with reference to a starting point during scanning. A large area of concrete surface can be scanned and inspected in a relatively short time. An image of good quality is acquired using a customized electronics platform and an adaptation of the SAFT (Synthetic Aperture Focusing Technique) algorithm. The system setup yields easy interpretation of real time 3D images showing the concrete's internal state. The broadband characteristics of the PVDF transducer made it possible to use a wide range of adjustable operating frequencies. This is highly beneficial for concrete imaging where typically aggregates with a large variation in sizes will limit the image quality and enforce a trade-off between penetration depth and required resolution.

1. Introduction

NDT (Non-Destructive Testing) refers to the method of examining materials/components to detect the defects/discontinuity in them without causing any damage. It is used to ensure the safety of engineering structures and evaluate product quality and performance upon production. Most of these structures are usually constructed by reinforced concrete which need regular monitoring for operation and safety. The large concrete structures pose many challenges for inspection due to surface roughness, inhomogeneities and size of aggregates.

ELOP has developed a novel ultrasonic scanning array system with adjustable pulse shapes in the range of 50-250 kHz to analyze the defects inside the concrete structures. The array of transducers is fabricated from multilayer piezoelectric polymer, PVDF. PVDF has low acoustic impedance, broadband frequency response, and it is flexible, light weight and chemically stable. However, they have low electro-mechanical coupling efficiency compared to commercial ceramic transducers. This limitation is overcome in this design by using the multi-layer PVDF transducer resulting in a higher pulse echo sensitivity (1), (2).

This paper will describe the progress on development of 3D ultrasonic scanner along with images obtained from concrete structures using the scanner in the laboratory and in the field.

2. Materials and methods

2.1 Rolling unit

A complete assembly of the ultrasonic scanner with all elements is shown in figure 1. The scanner uses a separate Tx (Transmit) and Rx (Receiver) roller wheel in a pitch-catch mode to analyze the defects inside the concrete structures. Elastomer rings are used as coupling material to the concrete surface. Separate Tx and Rx roller further makes electronics simpler as no Tx/Rx switching is required for the transducer elements and resolves issues with blind zones due to acoustic main bang coming back from the concrete surface interface.



Figure 1. The handheld scanner unit connected to the external electronics box inside the backpack. The cable features robust, waterproof connectors at both ends for rugged outdoor use.

2.2 Transducer assembly

A multilayer transducer unit was made by stacking pre-polarized PVDF films in a folded sequence using an adhesive as described in (3) and (4). In this configuration, the multilayers are connected electrically in parallel and acoustically in series. As a result, this configuration shifts the resonance frequency closer to the range suitable for concrete inspection and improves the piezoelectrical efficiency (5). A customized backing matched acoustically to the PVDF was adhered to the rear side of transducer. This backing design was able to maintain important broadband features of the PVDF transducer. The front side of the transducer was coupled to the cylinder wall of the roller. The transducer arrays were assembled in two separate rollers and coupling to the concrete surface was achieved by segmented elastomer rings. The material properties of all layers in the acoustic path of the roller assembly (backing, transducer, front layer, wheel, elastomer rings) were optimized to yield minimal acoustic reflections between the layers.

2.3 Electronics Platform

The electronics platform for the scanner was developed in-house and it consists of a high voltage pulser unit together with a multi-channel amplifier and a receiving unit that is capable of handling 16 individual channels. The electronics platform is shown in figure 2.

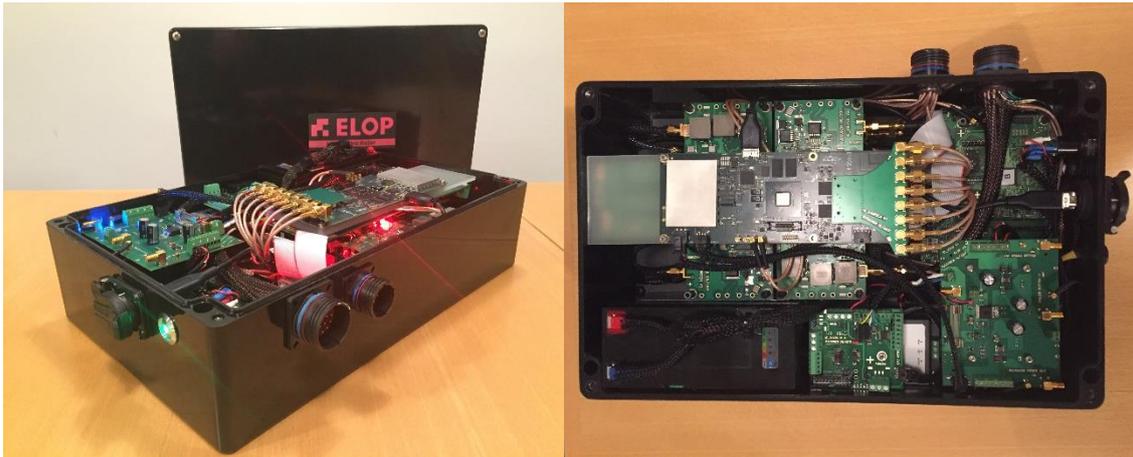


Figure 2. All circuit boards mounted inside the external electronics box together with battery unit. Also shown in the figures are connectors to Tx roller, Rx roller and rotational encoder, power button, charger connector, and USB connection to computing unit.

The receiving unit consists of a multi-channel low noise amplifier (LNA), variable gain amplifier (VGA), anti-aliasing filter (AAF) and analog-to-digital converter (ADC). The transmit electronics is capable of producing a high voltage bipolar pulse (sinusoidal, Ricker approximation, etc.) of a chosen frequency. The transmit electronics will excite a pulse into the concrete structure and the acoustical reflections caused by this pulse at boundaries (such as defects) are then picked up by each Rx transducers and sent into the trans-impedance amplifier (used as a first amplifier stage). This signal is then fed to the Rx board for digitizing and further processing in software. The scanner is manually rolled across the concrete surface while the rotational encoder keeps track of positional information with reference to a starting point. For each rolling position, all 8 Rx channels receive data for each Tx element firing. The firing sequence continues until all 8 Tx channel completes firing. In this way, we were able to gather 64 A-scans for each rolling position. The A-scans thus obtained are used to create 3D images of the scanned concrete structure. Synthetic aperture focusing technique (SAFT) is used for image reconstruction improving signal to noise ratio (SNR) of the received signal.

2.4 User Interface and Signal processing unit

Synthetic aperture offers a different way of focusing, where a sequence of pulses from each transmitter element and their positions are applied. This can be used to create a focused transmitter and receiver beam synthetically (a synthetic aperture) from all the pulses and receiver positions. SAFT on a fixed array has the potential to increase resolution and improve the SNR, whereas SAFT on a moving array utilizes the movement to synthesize a larger array (6), (7), (8). For SAFT processing, we are using time-domain beamforming by back projection. This is done by back propagating the received signal via each grid point in the volume to be imaged. To improve the result, the processing was modified to include SAFT in both the along-track direction (parallel to the rolling direction), and cross-track direction (perpendicular to the rolling direction).

The SAFT sub-routine was tested in MATLAB. In a portable laptop with Intel core i7 processor and 32 GB memory, the routine took about 13 seconds to run for along-track

length of 60 cm and cross-track length of 10 cm with sampling distance of 0.2 cm. To reduce the computational cost, the routine is tested in the same portable laptop with Nvidia graphics processor. With parallel computing toolbox in MATLAB which utilize the Graphics Processing Unit (GPU) to process large blocks of data in parallel, the program became more efficient than general purpose CPU. The routine took about 3.5 seconds in the same portable laptop with Nvidia graphics processor GeForce GTX 1070 (8GB) which is about 3-4 times faster than without using GPU. This computation time makes it possible to achieve real-time 3D images for a roll speed of 10 cm/s. The computation time can further be decreased by choosing a slightly larger sampling distance or larger grid size with minor loss in image quality.

A graphical control user interface has been developed for the scanner system. During the design and development, it was weighted to present the data in a human intelligible way. The main screen during a scan is shown in figure 3. The GUI main screen has been designed to appear minimalistic not to overload the user with information during a scanning operation, and several of the controls are embedded into the graphics. Effort has been made to make it as intuitive as possible, so the user doesn't require any special training to use it and interpret the images.

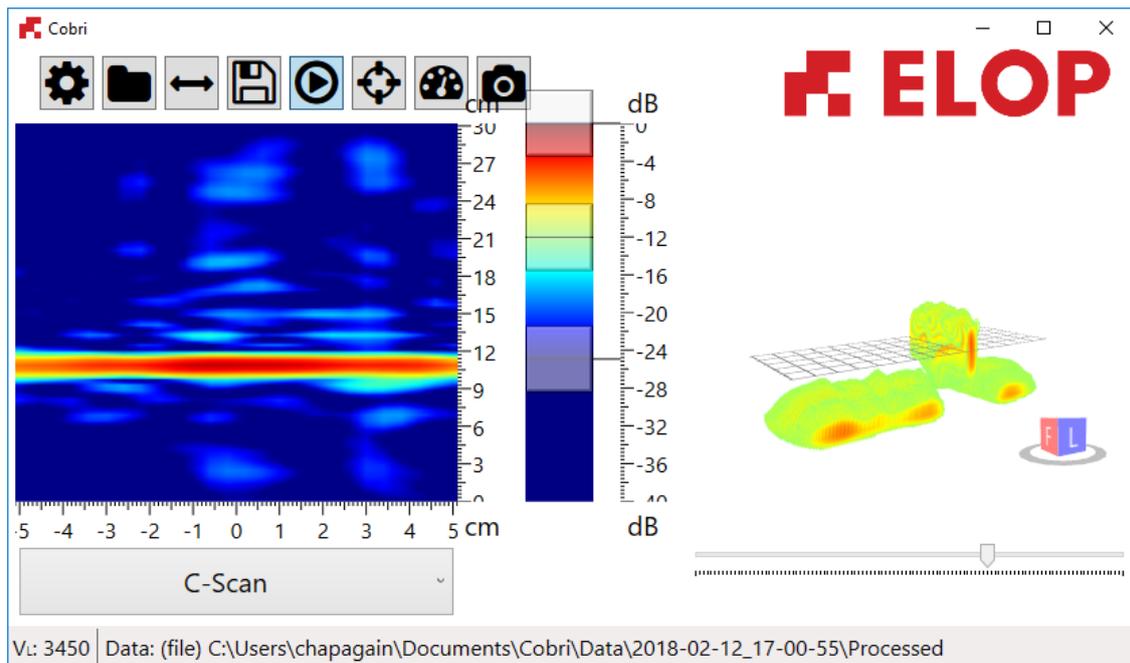


Figure 3. A screenshot of the main screen of the user interface with a cross-section (C-scan) and 3D view. The data is from a calibration block with known defect scanned by the ultrasonic roller.

A normal scanning sequence is presented in the flowchart shown in figure 4. The capture button is pressed in the GUI to reset the starting point, empty display and prepare for reception of a new scan. The user is informed to press the scan button on the roller unit to activate the encoder to register forward movement (activation is indicated by a green LED on the scan button). Each time the scanner forward movement passes a preset increment a full SAFT acquisition sequence is stored as raw data (A-scans) for processing. The user pauses the scanning sequence by depressing the scan button (button

LED is turned off). The scan is finalized by pressing the capture button in the GUI and the scan is processed and displayed.

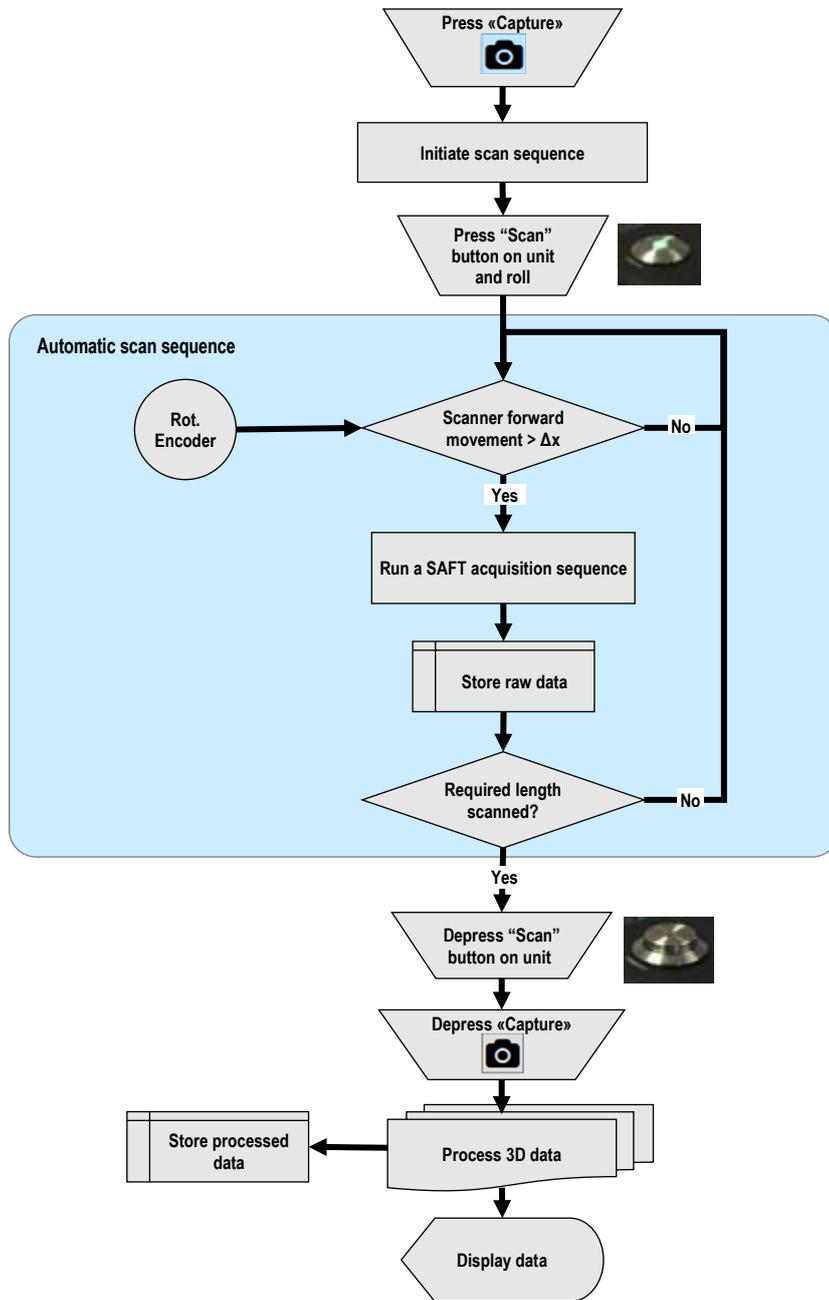


Figure 4. Flow diagram showing the current normal scan sequence.

3. Results and Discussion

The ultrasonic scanner was then used to analyze the defects inside the different concrete structures. Several fabricated defects and features such as delamination, air tubes, and rebar were imposed inside different concrete blocks for laboratory test. The scanner was also evaluated in a field test with concrete specimens used in actual structures. The scanning was carried out for different lengths in the along-track direction and 10-20 cm

in the cross-track direction. The scanning procedure was the same as shown earlier in figure 4.

Some of the results obtained from the laboratory tests are shown in figure 5. The concrete here has aggregate sizes up to 8 mm. The transmitted pulse is a wideband Ricker approximation pulse with center frequency around 150 kHz. Scanning interval was chosen to be 0.1 cm. The length of the synthetic aperture was chosen to be the full scan length for both cases.

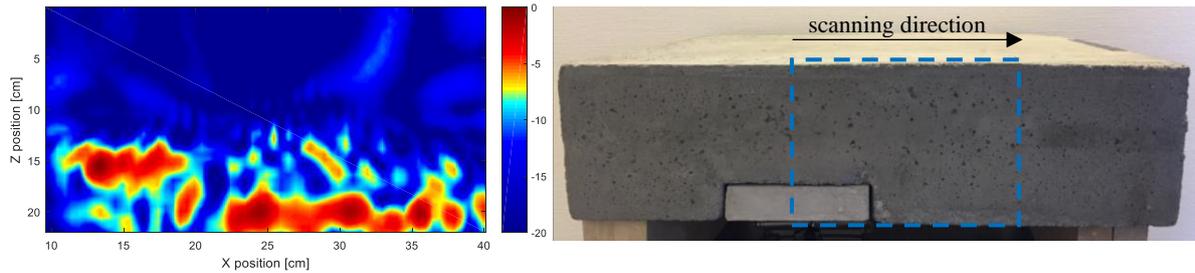


Figure 5 (a). D-scan of a 20 cm thick concrete block with a delamination present at a depth of 15 cm. The width of the delamination is 20 cm. The delamination at 15 cm is clearly visible of the left side of the scanned image together with back-wall echo from the concrete block. The dynamic range chosen is 20 dB. The scanning direction was from the delaminated section to non-delaminated section of the concrete block as shown in the figure.

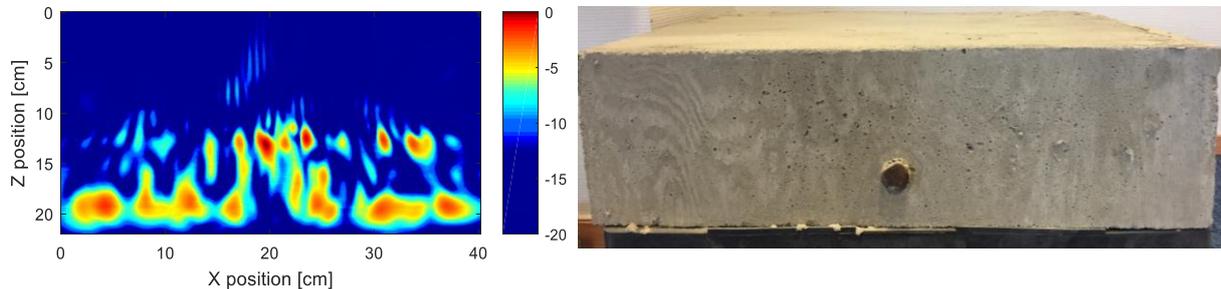


Figure 5 (b). D-scan of a 20 cm thick concrete block with a rebar present at a depth of 12.5 cm. The diameter of the rebar is 30 mm. The dynamic range chosen is 20 dB. The rebar at 12.5 cm is clearly visible in the scanned result together with back-wall echo from the concrete block.

During the laboratory test, we were able to scan concrete structure with fabricated defects and produce 3D images in real-time although there was some lag in the process due to file communication from hardware unit to the user-interface.

Field test of the ultrasonic scanner was performed in Consolvo facility in Tranby, Lier located in Norway. This company specializes in rehabilitation and construction of bridges, industrial buildings, tunnels, quays and power plants. Several 20 cm thick concrete blocks of dimensions 2 m by 1.5 m had been made for investigating a cathodic protection system. The blocks had aggregate sizes up to 22 mm. The scanning procedure was the same as for the laboratory test. We were able to locate the rebars of 20 mm size at depth around 13 cm from the top surface. The location of the rebars were also verified by visual inspection of the concrete sample. Because of the presence of rebar mesh in two depths in the concrete sample, the back-wall echo was masked and was not clearly present

as in the case of laboratory tests. As the aggregate size was much higher than what was tested in the laboratory, the high frequency part of the received signal was filtered out and only low frequency part was kept for further processing.

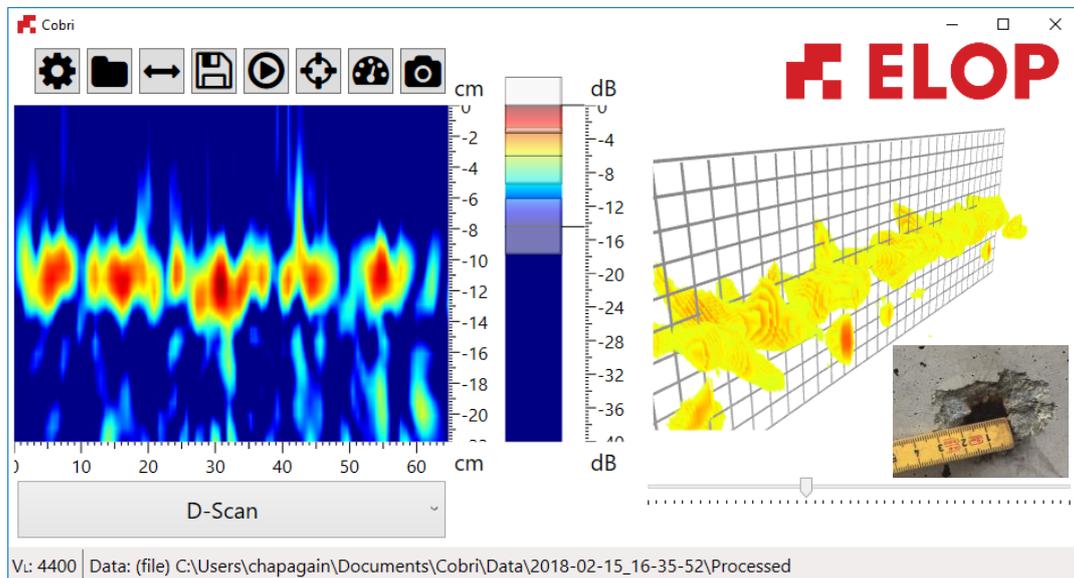


Figure 6 (a). A screenshot of the user interface with a cross-section (D-scan) and 3D view of the scanned concrete structure. The data is from a 20 cm thick concrete sample with rebar mesh at about 13 cm from the scanned surface. The rebar size is also shown in the inset.

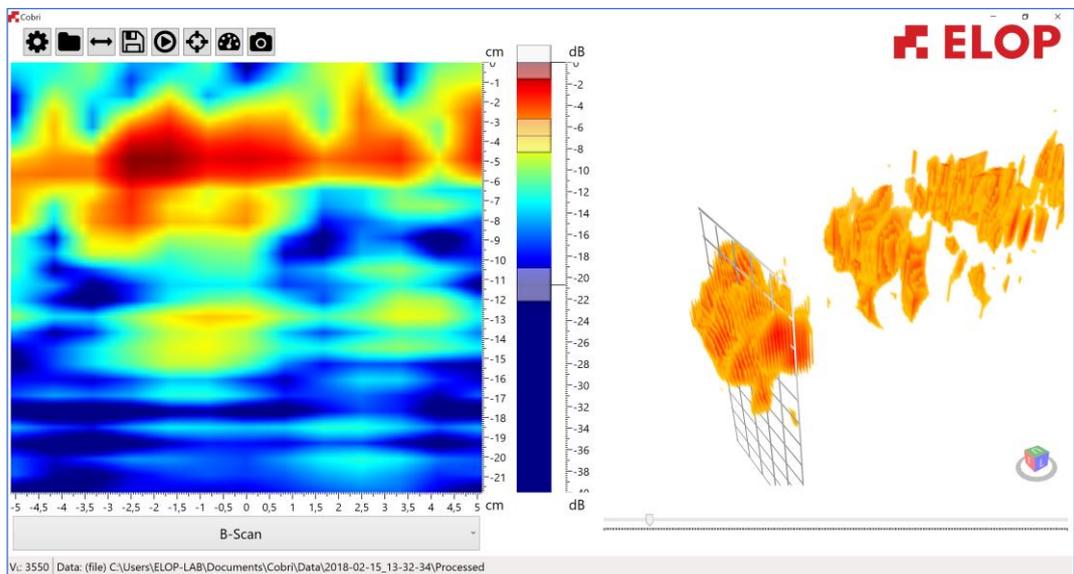


Figure 6 (b). A screenshot of the user interface with a cross-section (B-scan) and 3D view of the scanned concrete structure. The data is from a 20 cm thick precast concrete flooring element with air ducts and post tension rebars. The detail drawing of the specimens is not available now, but from our users feedback we get to know that it is usually common to have the periodic air ducts around 2-7 cm from the top surface. The ultrasonic concrete scanner is able to show the periodic air ducts in correct depth. Because of large size of air ducts, the back-wall of the concrete block was masked by them.

4. Conclusion and Further improvements

A broadband ultrasonic rolling scanner for concrete inspection was developed using multilayer piezoelectric PVDF transducers using separate transmission and receiver units. The scanner comprises a handheld unit with external electronics box together with computing unit and a display unit. A large surface area of concrete was scanned in a relatively short time and good image quality was obtained by using our adaptation of SAFT algorithm. The scanner is able to display real-time 3D images of the internal state of the concrete structures in an intuitive and human intelligible way.

Although there is some lag in real-time display now, it will be solved in newer version by streaming the raw data directly into the software without storing them in disk and process it as it comes from the hardware.

Acknowledgements

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