Automated measurement and imaging systems towards a regular quality control of concrete structures

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Abstract
Several non-destructive methods have been developed for the evaluation of concrete structures. Some of these methods have been advanced to automated data collection, enabling the scanning of larger parts of concrete structures. The data recorded by single or combined methods can be processed to visualize conditions and features of the structure and to image construction elements and flaws.

This contribution presents own and others’ examples of actual semi-automated and automated measurement and imaging systems including scanners and array systems, highlights the interdependence of automated measurements and advanced imaging, and tries to open a perspective of using the data for quality management of concrete structures.

The technical prerequisites and a formal framework necessary to establish quality management during construction and operation of concrete structures are discussed. A line is drawn from today’s examinations on a case-by-case basis to general quality management of concrete structures with the further perspective of Building Information Modeling.

Keywords: Concrete structures, automated measurement systems, imaging, visualization, quality management, civil engineering

1. Introduction

A variety of non-destructive evaluation (NDE) methods has been developed over the years for application at concrete structures. The German Society for Non-destructive Testing (DGZfP) has issued eight guidelines each describing a NDE method applicable to civil structures [1].

Currently NDE methods are mainly used on demand when problems occur with the construction of structures or during their operation. Usually some visible defects cause the responsible person to search for a NDE method that is able to locate faulty regions. The evaluation is then carried out manually or partly automated. But to guarantee build quality after construction, to avoid or to solve problems before larger damage occurs, to detect changes over time, or to estimate the remaining lifetime of a structure, quality management is necessary. Quality management starts with inspection plans and relies on examinations carried out in regular intervals, like today’s visual bridge inspections. In order to apply different NDE methods and to capture large amounts of data, automated measurement systems could be of great help.

Automated measurement systems have been developed mainly to be able to cover large areas of concrete structures with measurements. Mechanical scanners, autonomous robots, or unmanned aerial vehicles effectively carry out pointwise measurements on a large grid. The grid size depends e.g. on the rate of change of the measured quantity or on the wave length of the used wave type. Automated systems often hold several sensors to increase the measurement speed or to measure different quantities.

Automated data acquisition leads to large amounts of data that need to be presented in a clearly arranged way to facilitate interpretation. The presentation of data in images helps the human eye to interpret noisy or unclear measurement results. In the presented visualization examples,
the use of colors, transparency, or other image attributes enhances the significance of the images. Color can also be used to represent attributes of imaged objects such as the filling state of tendon ducts.

2. Automation

2.1 Examples

A multi-sensor air-coupled impact-echo test configuration is shown in Figure 1, left (University of Illinois at Urbana-Champaign, [2]). While a linear microphone array is manually moved over the surface, impacts are automatically generated, and near-surface delamination damage in concrete bridge decks can be detected, located and characterized. The system includes a fully automated data processing and image presentation scheme that uses image opacity for easy interpretation of the resulting images (see also Figure 7). In the depicted application, an active bridge deck of about 94 m² was scanned in 90 minutes.

For non-contact surface wave testing of pavements and concrete structures, a rolling microphone array with automatic impact source was developed (Lund University, [3]). Measurements are taken while the system is manually moved over the surface (Figure 1, right). The results are evaluated for the dynamic elasticity modulus and yield a map of pavement strength. The set-up can also be used for cement stabilized pavement layers.

The automated ultrasonic measurement and imaging system FLEXUS was developed for the evaluation of concrete structures (MFPA Weimar, [4]). The system consists of a commercial low-frequency ultrasonic instrument, a mechanical 3-axis scanner with a scanning area of about 1.00 m x 0.80 m, and a software environment for operation and on-site imaging (Figure 2). The measurement head consists of a transducer array and an electronic multiplexer. The linear transducer array is made of 48 transducers which are arranged in 16 groups, and are dynamically switched during the measurements. Arbitrary control patterns can be configured to realize any SAFT and CSAFT (Combinational Synthetic Aperture Focusing Technique) data acquisition scheme (see also Figure 9). Electronic and mechanical scanning are combined for effective surface scanning. By choosing between different SAFT-variants, the scanning process can be optimized either for high image quality or for fast scanning of down to 12 min/m².
The modular OSSCAR scanner was developed specifically for easy transportation and practicability (BAM, IZFP, [5]). Its demountable design make it particularly mobile; e.g., it can be transported through dense openings. The scanner is held by air suction and has a 1.00 m x 0.50 m scanning range (Figure 3, left). Different heads for ultrasonic, radar, and eddy current rebar locator testing can be mounted. Special attention has been paid to use only customary hand-held instruments. The system includes an integrated software for scanner control, measurement, and imaging.

One of a series of scanners developed at BAM for on-site inspections is the lightweight Hannibal GPR (ground penetrating radar) scanner. The measurement time is less than 15 minutes for the maximum scan area of 2.30 m x 1.80 m, even if both antenna alignments of 0° and 90° and a line separation of 1 cm are employed. The application shown in Figure 3, right, is the test of sluice walls for concrete segregation. In this application case, the scanner is mounted on a vehicle with a balancing rope system.

The autonomous robot RABIT is designed to characterize rebar corrosion, delamination, and concrete degradation in concrete bridge decks (Rutgers University, [6]). It holds a comprehensive selection of sensors including GPR radar, ultrasonic surface waves, impact-echo, and electrical resistivity (Figure 4). Digital cameras provide for surface imaging and a panoramic view. Data collection is rapid and fully autonomous, and the position of the robot is
registered using global positioning system (GPS). Online data analysis and fusion comprise maps for concrete condition, concrete cover, concrete quality, and delamination. The visualization software presents all information in a common 3-D space, in which objects describing different severity levels are displayed. Data sources can be switched on and off allowing for plausibility checks and for enabling a rapid review of possible correlations between the damage observed on the surface and the internal deterioration processes.

Another autonomous measurement system is the BetoScan (IZFP, BAM, [7], not shown). It consists of a self-navigating mobile robot with a modular fixture for different contact and non-contact sensors, e.g. potential mapping, microwave humidity measurement, radar, and ultrasound. The system is especially designed for the investigation of reinforced concrete floors exposed to de-icing salts. Large surfaces can be investigated in a comparatively short time.

An unmanned aerial vehicle (UAV) is used to inspect buildings and structures at places that are difficult to access (Bauhaus-University Weimar, [8]). The UAV carries a digital camera for surface imaging, with image stitching and feature extraction are currently being under development. Image processing is used for crack detection. The case example in Figure 5 shows the UAV inspecting a bridge near Geschwenda, Germany, and a crack detected at the structure.
2.2 Issues and consequences

Most problems with the application of automated measurement systems are connected to the specific conditions on site, caused either by the condition of the structure or by the weather. Hence a simple set-up and handling of the scanning system are important. An increased measurement speed is always welcome to reduce costs and to avoid obstructions of the normal use of the building or structure.

One point of great practical importance is the assignment of a suitable coordinate system. It should be consistent throughout the whole structure, possibly including subsystems for construction parts and elements. Origin, axes directions, and axes units should be clearly marked and agreed on with customer and contractor. Often survey measurements are necessary to connect to a given coordinate system. Distributed survey marks would be of great help. Electronic marks could provide additional information such as relations and subsystems.

3. Visualization

3.1 Examples

The thickness measurement of the inner linings of highway tunnels is mandatory in Germany [9]. Measurements are to be carried out on a 0.80 m x 0.80 m grid, which is condensed to 0.40 m x 0.40 m if a reduced thickness is encountered. The results are to be presented block wise as tables and contour line representations. Figure 6 shows an example of a manual impact-echo measurement (MFPA Weimar, [10]). The measured surface of the block is developed in a bottom view, the joints being parallel to the upper and lower edge, respectively. In this representation, colors are used to indicate important thickness levels. A color change from green to yellow marks the transition to faulty areas. In the roof, an area of reduced thickness is visible close to the upper joint. Grey circles indicate measurement points; the grid is condensed in the faulty area.

![Figure 6. Impact-echo contour map of tunnel thickness (MFPA Weimar, [10])](image-url)
A special “4-D” representation has been developed to present the results of the multi-sensor air-coupled impact-echo system in Figure 1 (University of Illinois at Urbana-Champaign, [2]). After automated data processing, image opacity is used to allow for the identification of areas containing near-surface delamination damage. Figure 7 shows the result of semi-automated data collection in a 3.66 m x 25.6 m area on a bridge deck, with dark spots representing defects. The findings were verified by cores taken at the positions of the red circles in the image. Here solid circles represent solid concrete, whereas open circles stand for delaminations.

![Figure 7. Resulting “4-D” map of air coupled impact-echo data collection at a bridge deck (University of Illinois at Urbana-Champaign, [2])]()

A quick survey of 3-D data can be obtained by iso-surface representations. In Figure 8, a CSAFT-image of a concrete test specimen is displayed that was automatically measured using the FLEXUS scanner in Figure 2 (MFPA Weimar, [4]). The 3-D image consists of 185 2-D CSAFT reconstructions which were collected at five adjoining mechanical tracks. Each 2-D CSAFT image was reconstructed from 120 measurements of the ultrasonic array, in which all possible transmitter/receiver combinations of the 16 transducer groups were utilized. The iso-surface representation was produced by thresholding the 3-D block of data. It shows the back wall of the specimen, three tubes, and two of the three lens-shaped voids contained in the specimen.

![Figure 8. 3-D iso-surface representation of a test specimen made from 2-D CSAFT reconstructions (MFPA Weimar, [4])]()

The method of ultrasonic phase evaluation can be used to provide additional information in special SAFT images. This technique was applied to the SAFT image of tendon ducts in a bridge box-girder shown in Figure 9 (BAM, University of Kassel, [11, 12]). Measurements were carried out using an automated scanner at a step width of 20 mm. The data was evaluated by means of the InterSAFT software. The magnitude image in the upper part of Figure 9 clearly shows the shape of the tendons. Any delamination of the ducts from the surrounding concrete would result in an increased magnitude, but the impression is not clear in this case. In contrast, the phase image in the lower part of Figure 9 explicitly indicates delaminations of two of the ducts (green colors).
Building Information Modeling (BIM) is a method to enhance a computer model of a structure or a building by functional data. The functional data can be visualized in the CAD (computer aided design) model of the structure making relations and dependencies visible and accessible for further measures.

Figure 10 presents an example where GPR results of tendon duct localization in a bridge in Rosbruck, France, are included in the 3-D CAD model of the bridge (IZFP, [13]). This result is part of the French-German database project CURe MODERN for the monitoring of structures and cultural monuments.

3.2 Issues and consequences

The acquired data may be of different type, and it may be linked to the underlying effects in different ways. For example, SAFT-reconstructed radar data of the first rebar layer is pretty directly connected to the imaged rebars, whereas electric potential maps reveal only a certain probability of corrosion. In general, measurement results can be quantitative, qualitative, stochastic, statistical, or descriptive, making specific methods of processing and data representation necessary.

The presentation of the data has great impact on how the results are perceived. Color maps should be thoughtfully used, since unsuitable color maps can emphasize unwanted features and
can distract from the main findings. Today, color maps are not standardized. Vector results measured on a two-dimensional grid yield a three-dimensional data block that needs to be treated by thresholding or using transparency to be viewed as a whole. The imaging threshold greatly affects the perceived result and should be set with caution. Approaches exist to set the threshold based on objective criteria [14]. Especially imaging methods with a higher level of abstraction such as SAFT or migration may add artefacts to the image introduced by the imaging algorithm.

The type of the visualization method must be chosen in order to present measurement results as clearly and as easy accessible as possible. Since all data needs specific interpretation, key points are to prepare the data in a way such that interpretation of the data becomes facilitated and features of the structure can be revealed. In this process, indications in images are transformed to properties of real objects, and stochastic or statistical data is converted to regions marked as anomalous. The purpose of data interpretation is feature extraction, namely to convert measurement results into features of the structure an engineer is used to deal with: structural elements, dimensions, flaws, regions of interest. Today humans are interpreting the data manually, but automatic or semi-automatic methods should be introduced. Helpful are the combination of data of different origin in a single image by some form of data fusion and, for human interpretation, the consistent use of image attributes such as color. If a different person is evaluating the measurements than the one who has measured, the measurement, imaging, and interpretation processes should all be standardized to avoid ambiguity with the measurement circumstances possibly affecting the results of data interpretation.

4. Use of the data for quality management

The transition from flaw detection on a case-by-case basis to quality management demands a broader perspective than today’s point of view. Since quality management is based on regular quality control, large amounts of data need to be captured that automated measurement systems could deliver while simultaneously applying different NDE methods. Automated imaging systems simplify the process of setting up, carrying out, and evaluating the measurements. The standardized results are easy accessible for further evaluation, e. g. for maintenance planning or lifetime estimation.

Automated measurement and imaging systems need to be embedded in a comprehensive framework to allow for quality management. Several technical prerequisites are to consider, and a formal framework needs to be established.

Technical prerequisites:

- **Design to test**
  Provision for the requirements of automated measurement systems in the design process of concrete structures: survey points, mountings, guidance, appliances.

- **Surveying**
  Use of image stitching, 3-D spatial capture by infrared depth detection (Kinect, Realsense), laser point cloud scanner, and photogrammetry.

- **Choice of methods**
  Accepted knowledge about methods appropriate for a certain task. Allocation table relating tasks and applicable methods. Rating of strengths and weaknesses under different application conditions.
– Description of methods
Agreement on how measurement and evaluation are performed for each method. What kind of interpretation is necessary? Calibration alternatives and procedures. Methods to determine and specify accuracy. It must be guaranteed that tests carried out by different contractors at different times lead to comparable results. This can at best be achieved by approved and validated procedures. Necessary training level.

– Data interpretation
Transformation of indications in images into properties of real objects, and of stochastic or statistical data to regions marked as anomalous. Interpretation process manual by human interpretation or automated by algorithmic interpretation. Handling of ambiguous results and artefacts according to recognized standards, e.g. by a confidence coefficient. Conversion of measurement results into features of the structure (feature extraction). Feature description in a formal description format (catalog number, entry in a description tree).

– Data combination
Data fusion of different methods with complementing findings.

– Coordinate Mapping
Mapping from local measurement coordinates to global structure coordinates, treating transformations between different grid coordinate systems and grid sizes.

– Databases
Handling of quantitative, qualitative, stochastic, statistical, and descriptive data.

– Building information modeling (BIM)
Incorporation of NDE results in BIM models to improve the accessibility of the data and the interpretability of the results, especially for NDE non-experts. The representation of the results of building inspections in their context and the precise localization of defects using interactive 3-D models would allow to better assess the consequences and to plan further measures. Inclusion of quantitative data and object properties.

Formal framework:

– Implementation according to procedures
Written measurement and evaluation procedures covered by quality management. Validation procedures where possible.

– Guidelines, codes and standards

– Training of the personnel
Formal training of the operators and interpreters of measurements for each of the testing methods according to approved standards. Certification system with different levels according to the necessary skills: calibration and operation, interpretation of specifications and evaluation of results, developing and approving procedures (according to ISO 9712 [15]).

Also necessary:

– Testing needs to be profitable
Quality management using regular non-destructive testing needs to pay off in the long term. Calculation of costs over the whole life-cycle of buildings and structures would help.
5. Conclusion

The presented examples of automated measurement and imaging systems and visualization methods show the advanced state of solutions already available for the inspection of concrete structures. These and other systems can become important means for the regular quality control of concrete structures.

There are still technical prerequisites that need to be further improved to simplify the application of automated NDE systems. Appropriate visualization is an important precondition for effective data interpretation and feature extraction, which together are the most crucial challenges in the examination of automated measurements.

The next step is to establish a formal framework that defines and merges all components necessary for an integrated quality management. This requires combined efforts of authorities, system developers, and practitioners, and an increased awareness in the civil engineering community.

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