Prospects for Integrating Augmented Reality Visualization of Nondestructive Testing Results into Model-Based Infrastructure Inspection

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ABSTRACT

Non-destructive testing results of civil infrastructure have so far been presented on a case-related basis. To enable comprehensive quality management over the entire life cycle of a structure, it would be desirable to combine the various results, monitor their development over time, and use them for on-site maintenance tasks.

In this contribution, prospects are developed for the integration of non-destructive testing results into digital building models within the framework of building information modeling (BIM). As an example of integrated utilization of planning and measurement data, an innovative visualization approach using augmented reality (AR) is presented. An AR application has been implemented that superimposes the camera image of a tablet viewing a concrete specimen with ultrasonic and radar images of the interior of the specimen (actual data) and the three-dimensional planning geometry of the built-in parts (target data). When the tablet is moved or rotated, the geometric relationship between the camera image and the inner views is maintained. The display of the tablet thus opens a window into the interior of the concrete structure.

Steps necessary for the preparation and interpretation of non-destructive testing results are compiled, and possibilities for implementing markers for coupling the virtual world with the real world are discussed. The goal is to evaluate the condition and facilitate model-based inspection and maintenance tasks directly on the structure by presenting planning data and measurement results in their real context and enriching them with additional information.

Keywords: Non-destructive Testing, Infrastructure, Augmented Reality, Visualization, Building Information Modeling, Ultrasound, Radar

INTRODUCTION

The functional efficiency of structural-technical infrastructure such as bridges, tunnels, roads, or tracks can be ensured by recording and evaluating physical and functional conditions throughout their life cycle. Meaningful analysis requires the consolidation of all available information and its presentation in line with the task at hand. For this purpose, digital Building Information Modeling (BIM) can be used to integrate information on the current condition of a building or infrastructure. An important part of this information can be provided by non-destructive testing (NDT) so that quality control, condition analysis, or damage diagnosis are possible at all points in the life cycle. This concept thus goes beyond the use of BIM only in the planning and construction phase of a structure.

Three-dimensional components can be represented by imaging techniques. A two-dimensional representation of results is sufficient for individual tests, but not for the clarification of complex, three-dimensional relationships. Three-dimensional visualization can be achieved by virtual reality (VR) or augmented reality (AR) glasses, which generate individual views for each eye of the viewer. In augmented reality visualization, the real environment in which the virtual representation is displayed is also visible. The geometrically correct positioning of virtual objects can be done by recognizing characteristic features of the environment or by markers used to calculate the relative position of the observer. On the flat display of a tablet computer, the impression of space can be achieved by moving the tablet, which makes the relative positioning of space and objects visible. The use of AR applications is discussed in various application scenarios [1]; initial thoughts for superimposing radar data with the 3D CAD model of a bridge for clamping channel location were developed in [2].

Augmented reality visualization can be used to facilitate the geometric correlation of non-destructive imaging results to each other, to the outer geometry of the component, and to inner objects. This can be done on-site directly at the component. The visual image of the component is superimposed with virtually generated images of the planning data and with the imaging results. The objectives are to assess the condition and facilitate model-based inspection and maintenance tasks directly on the structure by presenting planning data and measurement results in their real context and enriching them with additional information.

The paper discusses the use of Building Information Modeling for the integration of condition data and the possibilities of implementing markers for coupling the virtual model with real space. The application perspectives and requirements of an augmented reality visualization are compiled and discussed. An example demonstrates the visualization of ultrasound and radar imaging results in an augmented reality environment. For this purpose, an AR application was developed in which the camera image of a tablet can be superimposed with the measurement results and the geometric data of a concrete test specimen.

BUILDING INFORMATION MODELING

Introduction

Building Information Modeling (BIM) is a cooperative working method whose idea is based on the consistent use of a digital, three-dimensional building model over the entire life cycle of civil infrastructure. The digital building information model represents the computer-internal, virtual representation of a building or infrastructure with geometric, physical and functional properties and is exchanged between all project participants such as architects, engineers, managers, builders during the project phases design/planning, construction, use and repair. Working on a consistent model can facilitate many of the upcoming tasks, and it offers the possibility to include non-destructive techniques into the work flow (Figure 1).

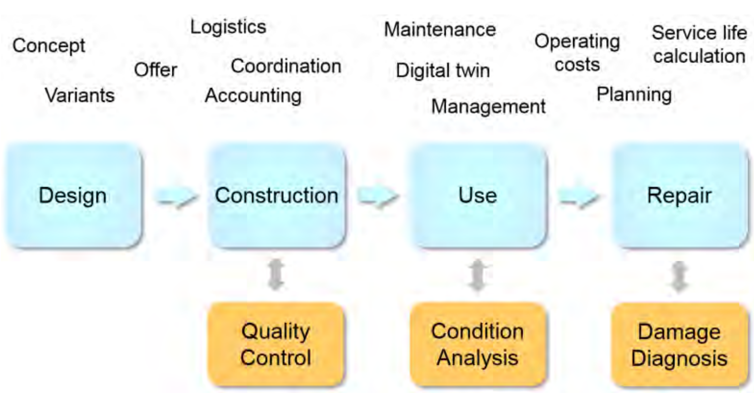

Figure 1: Building Information Modeling (BIM) facilitates working on a building or infrastructure throughout its life cycle and simplifies the inclusion of non-destructive techniques.

For a long time, the development of BIM methods such as standardized data models focused on the description of buildings in classical building construction. In recent years, infrastructure structures such as bridges, tunnels, roads and track systems have also been the subject of consideration [3]. This fact is reflected in the openInfra-Initiative of the international standardization organization buildingSMART and in the working group INFRABIM established by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) [4]. Among other things, data modeling standards for bridge structures (IFC bridge) including the definition of component geometries, types, relationships and properties are developed here.

BIM in the management of buildings and infrastructure

Although by definition BIM can support all phases of the life-cycle, various literature studies have shown that the BIM working method is mainly used for new building projects and in the planning phase (e.g. [5]), both in practice and in research. The aspect to use of BIM for maintenance structures, in particular for digital support of maintenance planning and execution as well as repair tasks, is less frequently considered.

A prerequisite for the application of BIM in the management phase is the availability of a digital image of the existing structure (as-built model), either in the form of an updated planning model (as-designed model) or a newly generated as-built model based on scans (e.g. laser scans or photogrammetric reconstruction). In addition to purely geometric information, semantic information, i.e. information on component types and properties, must also be collected and modeled.

Within the scope of the project described here, the geometric and semantic modeling of structural damage is of decisive importance. In this context, the extent to which measurement data from non-destructive testing methods can be linked to or integrated into a digital building model both in the form of raw data and as interpreted damage and component information in the sense of the BIM methodology is to be investigated. There are currently very few published research results on this subject. An example of the application and extension of BIM for bridge inspections is the international project SeeBridge [6].

AUGMENTED REALITY AND DETERMINING THE CAMERA POSITION

In the course of digitalization, technologies such as Augmented Reality and Virtual Reality are becoming part of our everyday lives. In contrast to Virtual Reality, where VR glasses present 3D worlds with only virtual content, Augmented Reality adds virtual content to the view of the real world. In an AR application the live camera image of a tablet is superimposed with virtual 3D objects that are true to scale and correctly displayed in perspective (Figure 5). In order to do this, position and orientation of the camera in the real world must be determined and successively updated as the camera moves (camera tracking). Various camera-based procedures exist for this purpose, which are differentiated into marker-based and markerless procedures.

Marker-based motion detection is based on reference objects in the real world – so-called AR markers – whose appearance and dimensions are known. AR markers are usually two-dimensional symbols, usually with a wide black border (similar to QR codes), or images or photos that are placed in the real world. The former are detected using edge detection methods in order to calculate the camera position and orientation based on their position. The latter must have a clear texture in order to be able to precalculate feature points and then detect and assign them in real time.

Markerless methods, on the other hand, do not require physical 2D markers in the real world. Here, either the real world is reconstructed photogrammetrically in order to use a thin point cloud as a 3D feature map to register the camera (reconstruction-based tracking), or a 3D edge model of a real reference object, e.g. a component, is created and brought into agreement with the live camera image in real time (model-based tracking). Often the camera-based methods are combined with sensor-based methods such as GPS or inertial sensors to improve the efficiency of motion detection (e.g. [7]).

BIM-BASED AUGMENTED REALITY VISUALIZATION FOR ON-SITE INSPECTION

The additional benefit of an augmented reality visualization of measurement results compared to a two-material representation on a computer monitor is above all to enable the interpretation of the data in the context of the real, three-dimensional object environment and to be able to recognize the properties of the examined object in its contexts and dependencies. Planning data and measurement results can thus be displayed in their geometric context and enriched with additional information, e.g. on their functionality. This allows a direct target/actual comparison, and the result of non-destructive testing, i.e. the fulfilment of the requirements, can also be displayed as additional information. Possible contents of an augmented reality representation of a test object are:

- Real image
  Visual outside view of the infrastructure component, here by the tablet camera.
- Reference positions
  Displayed geometry features of the component such as edges or fastenings or markers attached for this purpose for verification of the correct geometric assignment.
- Planning information
  Object geometry from CAD drawing, if necessary further data such as designation, material, technology and installation parameters.
- Measurement results of imaging procedures
  Object, geometry and error representations, possibly from different techniques.
- Abstracted geometric data
  Result of a manual or automated interpretation of the measurement results, e.g. detected defects, objects or built-in parts, catalogued features.
- Additional information
  Designations, position in the coordinate system, information from the test report.
- Monitoring data
  Linking with online data from sensors installed in the element.
- Simulated data
  Results of modeling and simulation of the imaging measurements for comparison with the measured results.
- Processed Data
  Results of further processing and combination of measurement results, e. g. reliability of measurement results, failure probability, condition grade.

The application of augmented reality seems to make particular sense for infrastructure objects such as reinforced concrete bridges or tunnels, which are large and complex by containing a large number of individual elements, which are repeatedly tested during their life span, and which are tested using several methods. This is where two-dimensional representations on computer monitors reach their limits. A visualization as virtual reality has similar advantages, but does not include the test object in the representation.

The integration of BIM and AR within the framework of facility management of buildings is the subject of current research. For example, Neges et al. have shown how BIM and AR can be used for navigation to maintenance objects in buildings [7]. In the context of the project described here, however, it is necessary to investigate to what extent AR methods can be used to superimpose BIM-based damage information (raw data and interpreted damage and component information) accurately and in real time with the live camera image of existing infrastructure in order to digitally support maintenance and repair tasks within the framework of inspections.

An obvious, short-term implementation of the camera's position, orientation and motion detection during infrastructure inspection could be based on the use of calibrated 2D markers. This solution is quick and easy to implement, but has the disadvantage of the measuring and maintenance effort of AR markers, which can possibly interfere or impair the building aesthetics. The more sustainable and long-term implementation of the AR tracking problem lies in the use of markerless methods for motion detection. The first task is to investigate to what extent reconstruction-based and/or model-based procedures can be used in the on-site infrastructure inspection. It is generally assumed that model-based procedures in the far range (visible component edges) and reconstruction-based procedures in the close range (no visible component edges) have their respective advantages.

Content and type of visualization should be adapted to the objective of the evaluation. For example, different representations of the same data can make sense by hiding individual contents or displaying them in different degrees of complexity, depending on whether inspection specialists or maintenance personnel use the visualization.

The integrated display of test object, planning data and measurement results can support the planning and execution of inspection and maintenance work on complex test objects. This applies in particular to repeated inspections as part of continuous quality management. The discussion of several persons on site, e.g. about causes of damage, is facilitated, and the clear representation can improve the accessibility and interpretability of the results for persons not familiar with the subject. An application in the training of testing personnel is also possible.

PREREQUISITES FOR THE APPLICATION

The Augmented Reality visualization of results requires the merging and presentation of data from different sources. This requires a technical and administrative framework that includes the following components:

- Data base
  Common database of all content with interface definition, data management, controlled access and long-term maintenance.
- Data formats
  Uniform, manufacturer-independent data formats for all contents including the geometry data.
- Coordinate system
  Consistent coordinate system for the entire bridge, tunnel, or building; possibly subsystems for individual components. Definition of reference characteristics and calibration points.
- Overall view
  General view of the outer shape and inner objects from CAD drawings or optical scanners.
- Measurement, simulation, and evaluation results
  Resulting data in compatible data formats with additional information on measuring methods, preparation, imaging and presentation.
- Orientation in space
  Determination of the position of the observer from the external object geometry, from markers, with GPS, or with the help of sensors.
- Software
  AR and VR visualization software, software tools for data preparation and integration into the database.

The diverse use of database content requires the reliability of the information contained therein. Objective agreements on the type and content of the presentations must be made in guidelines or standards. Only recognized measurement and evaluation methods should be used which may need to be validated. The performing and interpreting inspector should be trained according to recognized standards in order to ensure uniform interpretation and evaluation of the measurement data.

EXAMPLE OF AN AUGMENTED REALITY VISUALIZATION

Test objects and measurements

An example of augmented reality visualization will be demonstrated by means of ultrasound and radar measurements on a concrete test specimen with built-in, practical targets. The measurements were performed on specimen TK0901 containing lens-shaped and linear objects (Figure 2). The test specimen measures 1.20 m x 0.80 m x 0.30 m and consists of concrete with a maximum particle size of 16 mm [8]. It contains three empty pipes with diameters of 69 mm and 69/40 mm, three cavities (styrofoam lenses) of 80 mm diameter and a section with reinforcement of 12 mm diameter and 150 mm mesh width.

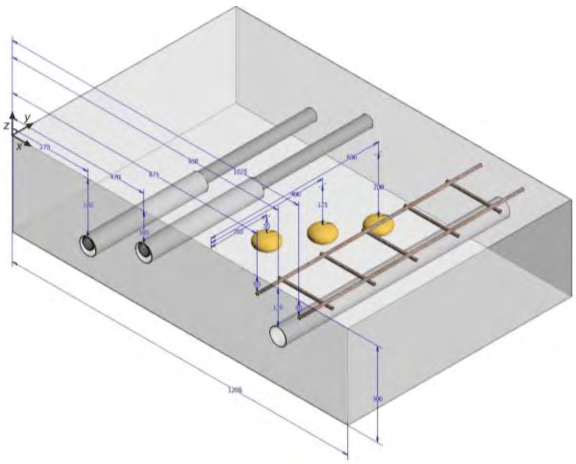

Figure 2: CAD drawing of the test specimen TK0901.

Ultrasonic measurements were carried out with an electronically controlled ultrasonic probe array with 48 probes in 16 groups on the FLEXUS scanner of MFPA Weimar [9]. The low-frequency ultrasound device NFUS2 of the engineering office Dr. Hillger was used as the measuring system. 120 individual measurements were recorded for each array position, each of which was recorded by one transformer group acting as transmitter and the others as receiver. For the measurements, an aperture of 0.90 m x 0.72 m was automatically scanned in five tracks with slight overlap; the measuring grid was 20 mm x 20 mm (Figure 3, left). The measuring positions of the individual measurements were known from the scanner control.

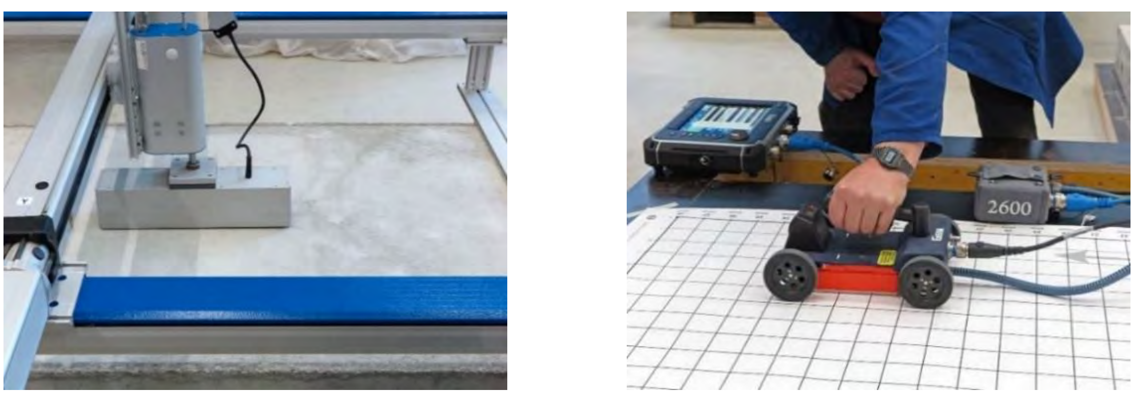

Figure 3: Ultrasonic measurements (left) and radar measurements (right) on test specimen TK0901.

For radar measurements, the radar system GSSI SIR-4000 with 2.6 GHz antenna was used. The aperture of 1.15 m x 0.80 m was recorded manually with track spacings of 50 mm, with a tracking wheel recording the linear antenna position (Figure 3, right). For better detection of the linear targets, the surface was scanned in the longitudinal direction and, with rotated antenna polarization, also in the transverse direction.

Both measurement methods result in three-dimensional data fields. The 120 individual ultrasound measurements at each array position were reconstructed during the measurement using the CSAFT method (Combinational Synthetic

Aperture Focusing Technique) in the REKONS program and the resulting sectional images were entered into the three-dimensional data field [10].

The result was displayed as a spatial isosurface image after completion of the measurement. Figure 4 shows in its left part an overview of the rear wall, all three pipes and two of the three cavities (styrofoam lenses). The rear wall is partially shaded by the objects above it. The uppermost cavity and the reinforcement are partly still in the pulse-affected zone and are not shown in this image.

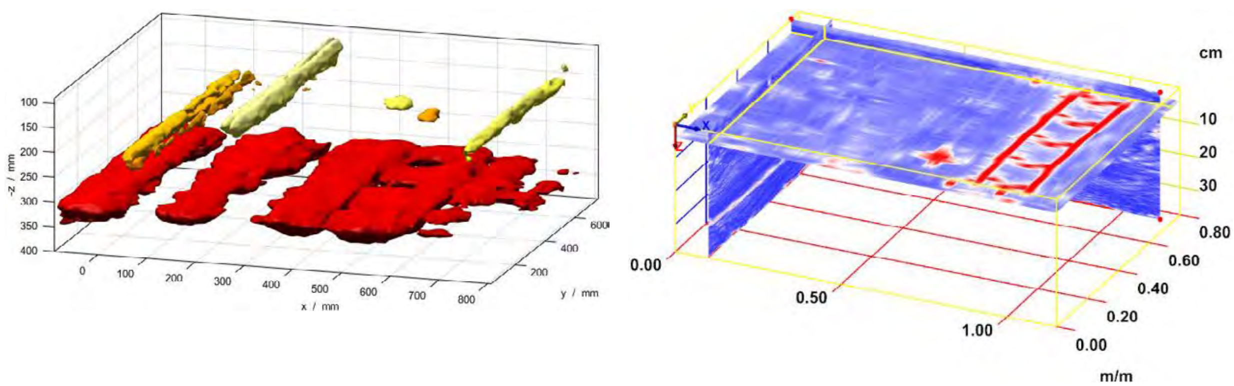

Figure 4: Three-dimensional SAFT reconstructions: Ultrasonic image represented as three-dimensional isosurfaces (left), radar image represented as two-dimensional C-scan and B-scans (right).

After completion of the measurement, the radar measurements were available as 41 B-scans (radargram). They were read into the RADAN program and SAFT reconstructed (migrated) and displayed there. The evaluation was carried out in B-scans and C-scans. Figure 4, right, shows the C-image at a depth of 45 mm, in which the reinforcement and the topmost of the three cavities can be seen. The pulse-affected zone is smaller than with ultrasonic measurements, so that objects close to the surface can also be displayed, which supplements the ultrasonic result.

Augmented Reality Visualization

For visualization the isosurfaces of the ultrasound representation were exported as geometry data. Minor corrections and modifications were made in the 3D CAD software. The radar C-scan in Figure 4, right, was exported as an image. The CAD data of the test specimen and the built-in targets were also exported as geometry data.

The position-dependent generation of the 3D scene takes place in a 3D animation program, which via an extension also allows the processing of optical markers for camera positioning. The marker used here was a photo of a flat gravel fill, which resembles an irregular surface texture such as a concrete surface. An application software was then generated embracing the entire functionality of the 3D representation including marker processing and the geometric object data, and it was installed as an app on an Android tablet.

For AR visualization, the optical marker is positioned at the intended position on the surface of the test specimen. Its position couples the coordinate systems of the real and the virtual world. The app on the tablet is started and displays the camera image of the tablet with the test specimen and the marker. Soft buttons can now be used to display the virtual objects individually and superimposed. The app recognizes the marker, calculates the position and orientation of the camera from its perspective distortion and can thus display the virtual objects in their correct position and orientation in three-dimensional space. Figure 5 shows the tablet with the app, in which all representations except the radar image are switched on, above the test specimen with the optical marker.

Figure 5: Augmented Reality visualization using a tablet: Tablet showing the AR-app, the test specimen, and the optical marker.

Currently, the following representations are being visualized in the augmented reality app:

- Real image from the tablet camera
- Outline of the test object from the CAD drawing (Figure 6)
- All objects in their target positions from the CAD drawing (Figure 6)
- Object indications of rear wall, pipes and cavities in actual positions from the ultrasonic CSAFT image (Figure 7, left)
- Object indications of reinforcement and the inner objects near the surface from the radar migration image (Figure 7, right)
- Superposition of several individual representations (Figure 7)

Figure 6: Screenshot of the AR-App: Camera image of the test specimen with CAD drawing.

When the tablet is moved or rotated, the view follows the camera position so that the geometric relationship between the outer and inner views of the objects is maintained. This enables a direct target-vs.-actual condition comparison of target data and measurement results. The display of the tablet thus opens up a window into the interior of the component.

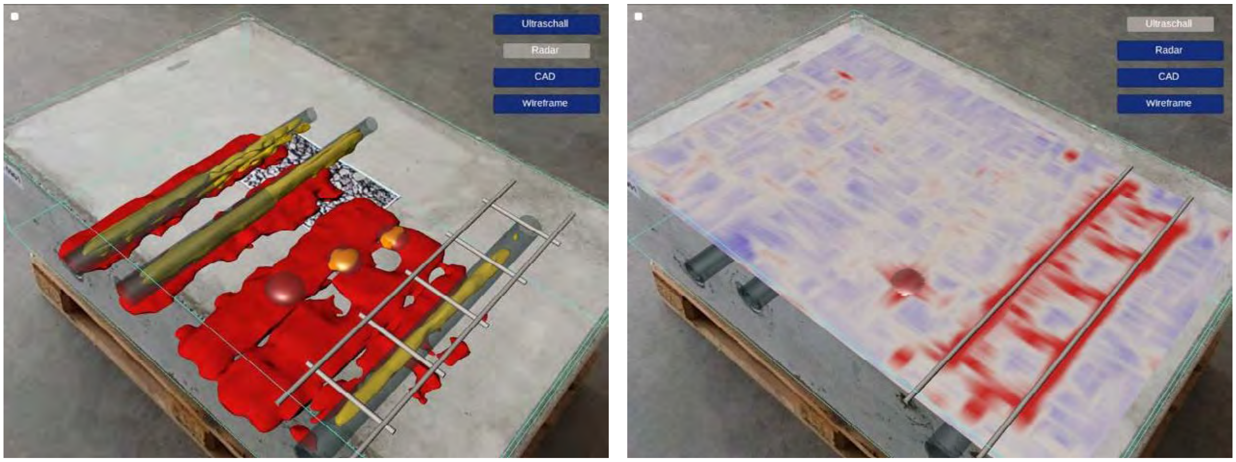

Figure 7: Screenshots of the AR-app: Superposition of the CAD drawing with the object indications from the ultrasonic CSAFT image (left) and with the radar migration image of the reinforcement plane (right).

Summary and Outlook

The article shows that Building Information Modeling (BIM) is well suited for the integration of planning and condition data of civil infrastructure. The geometric data available in the model of the building or structure can be combined with two and three-dimensional NDT imaging results, and it can be used for visualization and for further evaluation.

The augmented reality visualization of ultrasound and radar SAFT reconstructions was demonstrated on a concrete test specimen containing internal objects. In an AR application, the camera image of a tablet is superimposed with the three-dimensional ultrasonic image and the two-dimensional radar depth section of the interior of the component (actual data) and the 3D geometry of the test object and its inner components (target data). The data sets can be switched on individually or superimposed. For a complete representation of all internal objects, the different ranges of the ultrasound and the radar images are complementing each other. The geometric relationship between the outer and inner views is maintained when the tablet position is changed, so that the tablet display acts as a viewing window into the interior of the component.

In addition, a number of application possibilities and requirements for augmented reality visualization were listed and discussed. The aim is to make non-destructive images of element geometries, built-in parts and defects directly available on site and to enrich them with additional information. AR visualization can ameliorate on-site inspection and maintenance by making spatial and content relationships visible, which facilitates assessing the results and simplifies interpretation.

The use of object geometry and object texture as reference features for position determination [11] as well as the use of augmented reality glasses are currently under development.

Acknowledgements

The authors thank Alexander Ulanov and Bernd Müller from MFPA Weimar and Felix Kremp from Bauhaus University Weimar for their support in measuring, evaluating and implementing the AR-app.

REFERENCES

[1] Dini, G. and Dalle Mura, M., 2015, "Application of Augmented Reality Techniques in Through-life Engineering Services," 4th Int. Conf. on Through-life Engineering Services 2015, Cranfield, UK, November 3–4, 2015, *Procedia CIRP* 38, pp. 14–23.

[2] Kurz, J. H., Moryson, R. M., Eschmann, C., Burrier, G., Chassard, C., Wundsam, T. and Exner, J.-P., 2014, „CURe MODERN – Initiative moderne Bauwerksprüfung, Stadt- und Regionalplanung," *Schriftenreihe zum Symposium Grenzüberschreitende Infrastruktur – heute und morgen*, 14 S. (in German).

[3] Borrmann, A., König, M., Koch, C. and Beetz, J. (Eds.), 2015, *Building Information Modeling – Technologische Grundlagen und industrielle Praxis*, Springer, Berlin (in German).

[4] Borrmann, A., König, M., Braun, M., Elixmann, R., Eschenbruch, K., Hausknecht, K., Hochmuth, M., Liebich, T., Scheffer, M. and Singer, D., 2016, *Wissenschaftliche Begleitung der BMVI Pilotprojekte zur Anwendung von BIM in Infrastrukturbau – Zwischenbericht*, Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), (in German).

[5] Volk, R., Stengel, J. and Schultmann, F., 2014, "Building Information Modeling (BIM) for Existing Buildings – Literature Review and Future Needs," *Automation in Construction*, **38**, pp. 109–127.

[6] Sacks, R., Kedar, A., Borrmann, A., Ma, L., Brilakis, I., Hüthwohl, P., Daum, S., Kattel, U., Yosef, R., Liebich, T., Barutcu, B. E., Muhic, S., 2018, "SeeBridge as Next Generation Bridge Inspection: Overview, Information Delivery Manual and Model View Definition," *Automation in Construction*, **90**, pp. 134–145.

[7] Neges, M., Koch, C., Koenig, M. and Abramovici, M., 2017, "Combining Visual Natural Markers and IMU for Improved AR Based Indoor Navigation," *Advanced Engineering Informatics*, **31**, pp. 18–31.

[8] Schickert, M. and Hillger, W., 2010, „Erste Messergebnisse mit dem scannenden Ultraschall-Multikanal-Mess- und Abbildungssystem FLEXUS für Betonbauteile," *DGZfP-Jahrestagung*, Erfurt, 10.–12.5.2010, Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP), Berlin, S. 1–9 (in German).

[9] Schickert, M. and Hillger, W., 2010, "Automated Ultrasonic Scanning and Imaging System for Application at Civil Structures," *10th European Conference on Non-Destructive Testing (ECNDT)*, Moscow, 7–11 June 2010, Russian Society for Non-Destructive Testing (RSNTTD), Moscow, pp. 1–10.

[10] Schickert, M., 2014, "Three-dimensional Ultrasonic Imaging of Concrete Elements Using Different SAFT Data Acquisition and Processing Schemes," D.E. Chimenti, L.J. Bond (Eds.): *Review of Progress in Quantitative Nondestructive Evaluation (QNDE)*, Boise, Idaho, U.S.A., 20–25 July 2014, AIP Conf. Proc. 1650 (Selected Papers), **34**, pp. 104–113.

[11] Koch, C., Neges, M., König, M. and Abramovici, M., 2014, "Natural Markers for Augmented Reality-based Indoor Navigation and Facility Maintenance," *Automation in Construction*, **48**, pp. 18–30.