Short Report

Development of a methodology for time-resolved 3D mapping of deformation and damage of buildings and structures

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1 Objectives

The research project titled "Development of a methodology for time-resolved 3D mapping of deformation and damage of buildings and structures" was funded by the research initiative *ZukunftBau* of the Federal Office for Building and Regional Planning, Germany, and was handled by the Federal Institute for Materials Research and Testing (BAM), Division 8.4 "Acoustical and Electromagnetic Methods", together with the Fraunhofer Institute for Factory Operation and Automation (IFF), the Institute for Diagnosis and Conservation on Monuments in Saxony and Saxony-Anhalt (IDK) and Ernst Thomas Groll as restorer. The project started in January 2010. The originally planned duration was extended by 6 month, not affecting costs and thus the project ended in June 2013.

3D mapping of building damage is an important requirement for three-dimensional and time-resolved visualization of structural modifications, e.g. of deformation, distortion and crack propagation. Therefore, this project and the preceding project titled "Reliable quantification and assessment of damage processes at building surfaces and interfaces using optical and thermographic non-destructive testing methods" are parts of an integrated concept for the acquisition and visualization of modifications of geometry and material parameters. Later on, subsequent CAD models can be used in numerical simulations of mechanical and thermal properties of the building structure.

The main objective of the actual project was the development of a methodology, which allows an efficient and repeatable 3D mapping of damage and distortions and thereby enables visualization and monitoring of these structures. Among others, the 3D mapping is based on the super positioning of geometrical 3D data, 2D images and especially locally probed surface features, similar to the preceding project. The main focus however, was put on the detection of damage close to the surface and especially of cracks. For 3D acquisition of surface braking cracks a method was developed which is based on optical tracking. In addition, a photogrammetric method was applied for the digitalization of the surface topology and selected surface features. For capturing thermal data, active thermography was further developed concerning the detection and characterization of cracks. Further on, also larger facades have been investigated with thermography using sun radiation and natural shadowing for homogeneous heating and cooling. Crack depths have been determined using 1D ultrasonic measurement.

During the project, these methods have been further developed and optimized. For that purpose, two case studies were selected at the beginning of the project. These case studies represent different damage aspects and materials and enabled local investigation of details as well as measurements along larger areas:

- Giebichensteinbrücke in Halle (1926-1928):
    - Investigation of the crack structure at two sculptures as an accompanying measure to the restoration works
    - Investigation of the bridge slab concerning voids and inhomogeneities
- Plaster scratches at the Cathedral of Magdeburg (13th century):

- Investigation of local areas for acquisition and visualization of the plaster scratches and surveying of damage areas
- Investigation of the whole facade for classification of different damage areas

Selected areas have been investigated with multiple methods; parts of the results are presented below in the case studies.

For the four presented methods, guidelines have been developed. For crack characterization, a catalogue was developed with the main aim of supporting users and operators for selecting the appropriate method for crack investigations.

2 Realization of the research

The accessibility of a methodology like 3D visualization, which can give an overview about the dynamics of motion and deformation of buildings, is an ideal precondition for selecting problems concerning static. Thus, these problems can be monitored before a serious damage might occur.

In the following, it is outlined how the different methods have been further developed and how these methods can be applied for repeated measurements of cracks and for investigating further damage like plaster detachment. The results of these methods can be captured three-dimensional and can be integrated into the 3D visualization.

Concrete aims of this project have been:

- further development of 3D methods for crack characterization
- further development of active thermography as imaging method for crack characterization
- investigation of larger building structures for damage classification
- supplementation of a 3D model by damage classification
- development of a 3D mapping system with a tool for measurement, visualization and monitoring

The project was realized by introducing work packages, whose contents and results are summarized below in table 1.

Table 1: Overview of the single work packages of the project

WP	Title	Description
1	Analysis of requirements and development of a concept for the 3D mapping system	A summary was compiled about current mapping methods and desired functionalities were specified for a new 3D mapping system. The latter was used as a guide for the development of a tracking based method, which enables the user to capture surface features directly at the object under investigation (e. g. cracks at facades).
2	Comparison and evaluation of different methods for crack measurements	Monitoring systems for cracks, which can be applied at buildings, sculptures and reliefs, have to fulfill a large number of requirements. For this purpose, different sensors and methods are available. These methods have been collected, classified and compared in a catalogue.
3	Further development of imaging methods for crack measurements	With active thermography, systematic investigations for characterizing artificial cracks (notches) and real cracks have been performed. The interpretation of the measurement data required the development of models for considering the interaction of optical and thermal influences. Thus, cracks propagating perpendicular to the surface can be distinguished from tilted cracks. Further on, the angle of the cracks could be estimated or even be calculated using a calibration in the future. Up to know no information can be gained concerning crack depth.
4	Development and optimization of tools for analysis: selection and navigation modes inside the 3D data set	For 3D mapping directly at the object, software was developed, which is conducting the whole process. Among others, this includes functions for calibration of the measuring equipment, for data acquisition directly at the object, for data exploration and visualization using different navigation options, for selection, analysis and evaluation of the recorded 3D data and for data preparation for an efficient post processing.

WP	Title	Description
5	Visualization of mapped features, deformation and damage	The developed software comprises different visualization possibilities of 3D data. This includes, for example, the simple display and hiding as well as coloring of data areas on the basis of a classification, which is extracted from the measured data. A transparent representation of the data with blending allows the comparison of different measurement series and forms the basis for monitoring. An essential part of the software is the ability to fuse 3D data with 2D images.
6	Development of a monitoring strategy using 3D mapping	The measuring and software tools, which were developed in WP4 and WP5, form the basis for a monitoring method based on the different 3D data. Using the analysis tools and the visualization, an evaluation and display of damage propagation over longer periods is possible. The visualization is based on the fusion of 3D data with 2D image data (such as photos or thermograms) as well as the accumulation of these fused data sets with further metadata.
7	Data exchange and export	The recorded 3D data are stored in a xml format. In this format, information about the position, type and the assignment of individual measurement points are stored. The result of the fusion with 2D images will be saved as a PNG image with alpha channel. Then, an overlay can be made using common graphics software (e.g. Photoshop, Gimp, ...).
8	Development of technology and measurements at test specimens	For the laboratory tests on artificial and real cracks with active thermography and ultrasonic, sandstone blocks of Cottaer and Postaer sandstone were used. As artificial cracks, notches were made with water jet cutting, for real cracks prisms were broken.
9	On-site optimization of application	The sculptures of the Giebichensteinbrücke, the bridge itself and the plaster scratches at the Cathedral of Magdeburg were analyzed with the developed methods in different combinations. The results were discussed with the restorer.
10	Documentation	Guidelines were developed for 3D crack mapping to be performed with the tracking-based method and with the stereo-photogrammetry system, for crack depth determination using ultrasound and for active thermography. These are annexes of the research report.

3 Results

3.1 Results of further development of methods

3.1.1 Tracking based 3D mapping of surface features

For 3D mapping of cracks directly at the object, a method was developed in which the user runs a measuring tool along the crack. The position and orientation of the tool in space is determined and recorded continuously. The recorded data serves as a basis for mapping the cracks. The location of the tool is determined by an optical tracking system. Tracking means a continuous determination of the position of a recognizable object (here: known arrangement of optical markers). With the information of the tracking systems the pose, i.e. position and orientation of the tip of the measuring tool, can be determined. In addition to the tool and the tracking system also software is used, which was developed specifically for the purpose of convenient data recording directly at the object. Thus, the whole system consists of three components: tracking system, measurement tool and software module. The recording of data can be done either for individual discrete points or continuously. For motion detection of the measurement tool, an infrared (IR) tracking system from NaturalPoint was used.

The usual application of this system is the recording of human movements for MotionCapturing applications. However, in these applications variations in the positioning of the markers can be tolerated in the centimeter range, as in general the data is reworked and corrected afterwards.

For mapping of cracks, significantly higher demands are made; i.e. only deviations in the millimeter range can be accepted. To obtain a reliable indication of the actual achievable accuracy of the position, detailed investigations were carried out on the tracking system concerning the accuracy. The different measurements to determine the tracking accuracy have shown that a determination of the positioning of single markers is possible with a precision of ± 0.5 mm. This accuracy can be achieved with a camera set-up as illustrated in figure 1. However, a very good calibration of the camera system is essential.

Fig. 1: Tracking system with sensor in use

3.1.2 Photogrammetric 3D capturing

Also for the visualization of surface topologies such as the plaster scratches noted below, stereo photogrammetry was further developed and applied. This method has the advantage that for each measurement position, only two images are required. Further on, a high spatial resolution (in ideal case one 3D value per pixel) is achieved. The fast data acquisition was required for the measurement, as no fixed distance between the object under test and the measurement system could be guaranteed over long measurement times. The high spatial resolution is relevant for a registration of the individual images to each other. Furthermore the method requires a stochastic texture of the surface to work properly. This is usually achieved by the projection of a suitable pattern; however, due to the texture of the plaster of the selected measurement object, this was not necessary in this case.

After the measurement, in a first step the 3D data for each set of two single images are generated. This is done using the camera calibration and the selection of a suitable correlation technique. The parameters of the correlation must be adapted to the texture of the investigated object surface. In order to obtain a complete 3D data set of the whole measurement object, in a second step multiple recordings must be registered to each other.

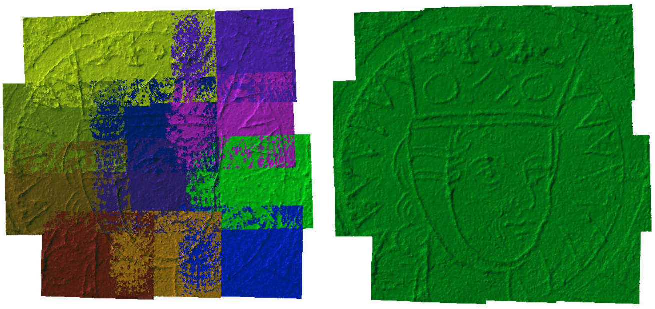

Fig. 2: Results of photogrammetric 3D capturing: Merging of single measurements (left) and the measurement result as 3D data set (right).

An automatic registration was not possible due to the flat topology of the 3D data. Therefore, a manual step for coarse alignment of the data was introduced. For this purpose, corresponding points must be identified and assigned in both data sets, which is facilitated by coloring each texture information of a data set, see figure 2 left. After the manual registration, a fine adjustment is carried out with the "Iterative Closest Point" procedure. In addition, for the registration a fixed overlapping area of the individual images should be set. Here, an overlapping of about 1/3 of the image areas was selected. Finally, using a program the point data were transferred into a triangle mesh, see figure 2, right.

3.1.3 Active thermography for crack characterisation

With thermography methods, in principal open surface cracks as well as hidden cracks can be located and characterized.

Within the project, only the open surface cracks were examined. Various studies on sandstone specimens in laboratory with sawed notches and real cracks have shown that these can be easily detected by a transient heating of the surface of 1 min using IR radiators, see figure 3. Directly after heating, in particular the notches appear as cooler (dark) lines. During cooling down, there is a contrast reversal (figure 3).

This *afterglow* can be explained by the scheme shown in figure 4. Shortly after the excitation only a thin layer of the material parallel to the surface appears warmer. Thus, the surface has a higher temperature than the bottom of the crack. Therefore, the edges and the bottom of the crack appear cold (dark). In the further course of time, the heat diffuses into the specimen heating up also the crack edges. During and after external heating, heat losses due to convection and radiation occur at the surface. Both loss processes are significantly reduced at the crack faces. Therefore, the crack faces remain warmer for longer times than the surface.

However, this effect can be observed at cracks which are nearly perpendicular to the surface, but almost vanishes in the case of tilted cracks. In the bottom of figure 4, it is shown how the heat conduction into the specimen is reduced for tilted cracks. Thus, the area on the surface above the crack appears warmer. A localization of the cracks as well as an estimation of the crack angle and crack depth is possible by analyzing the surface temperature evolution. Depending on the crack angle, different temperature profiles over the crack are formed.

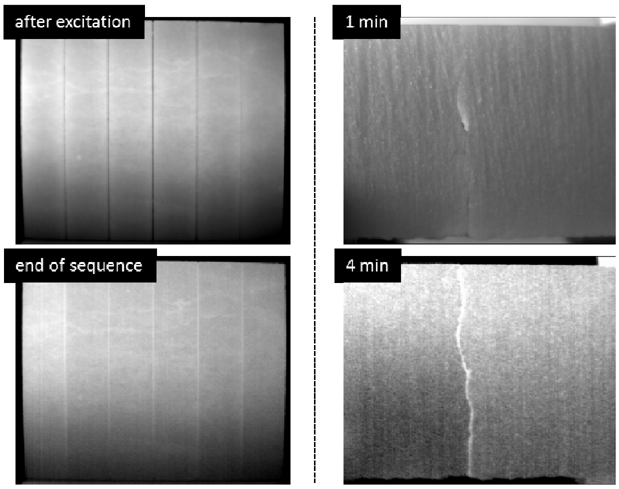

Fig. 3: Thermograms of Cottaer sandstone specimens with notches (left) and with a real crack (right) after 1 minute of heating with an IR radiator (top) and after 4 minutes of cooling down after heating (bottom). During cooling down, there is a contrast reversal: the notches and cracks appear warmer in relation to the environment.

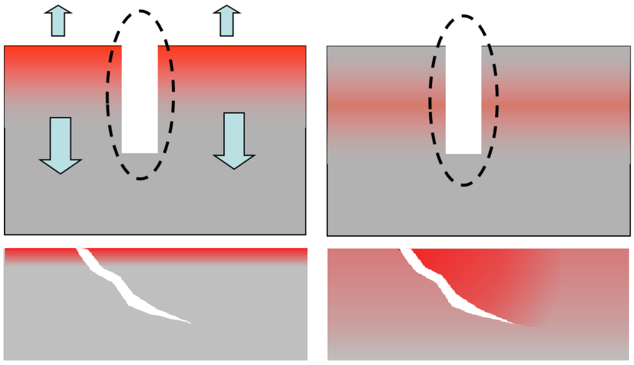

Fig. 4: Schematic representation of the thermal contrast development of cracks after heating. **Top:** Perpendicular cracks: Shortly after heating the surface, the cold notches appear colder, as one looks into the still cool interior (left). The edges cool down more slowly than the outer surface, as convection and radiation losses are significantly reduced (right). Now the notches appear warmer. **Bottom:** Tilted cracks: The heat transport into the interior of the structure is reduced, thus there is a region of higher temperature at the surface.

3.2 Results of the case studies

3.2.1 Plaster scratches at the Cathedral of Magdeburg

One of the most important works of art of the Magdeburg Cathedral are the plaster scratches on the east wing of the cloister from the 13th century, see figure 5, left. In the central image emperor Otto I and his two wives, Edith and Adelhaid, are displayed (not visible in the picture). Of the plaster surface, only fragmentary remnant areas are preserved. The majority of the single plaster surface parts have been repaired or renewed during various phases of restoration and repair. The significantly smaller part consists of original plaster, which only exists as islands between the various repair patches. During the project, in the context of restoration measures sub-areas below the window have been re-solidified and partially re-plastered. The surface of the original plaster in the central image has been cleaned.

One of the aims of the project was the localization of not yet recognized damage (delamination) and the more accurately surveying of known voids. Furthermore, it should be attempted to optimally represent the plaster scratches by using the crack detection method. Here, especially the non-contact 3D photogrammetric surveying was applied.

For the detection of voids, thermography sequences have been recorded during the heating by solar radiation and during shadowing by a tower of the cathedral. In figure 5, right, a thermogram of the facade is shown after exposed to sunlight radiation for several hours. Voids are visible as clearly warmer areas. Particularly in the area below the central image, these are accumulating. This belongs to the area that was solidified later.

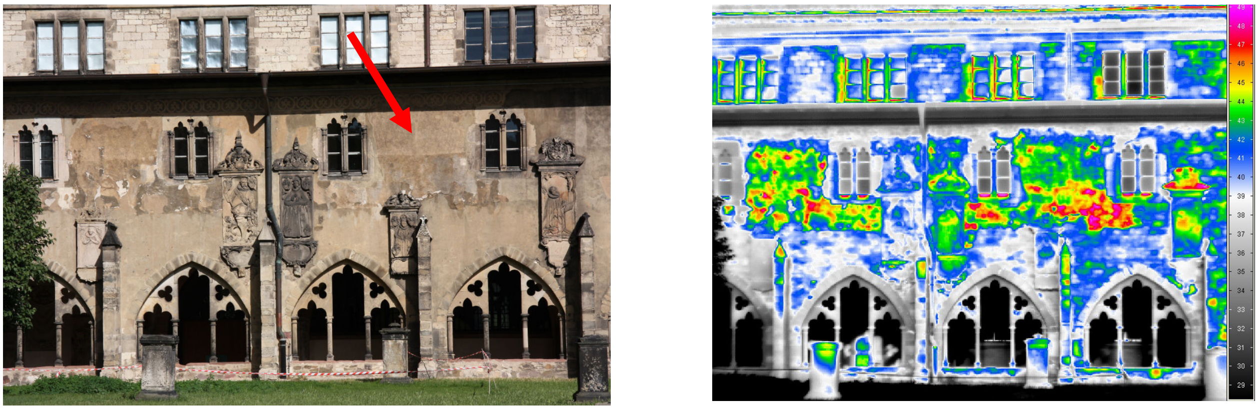

Fig. 5: West facade of the cloister of the Cathedral of Magdeburg with the plaster scratches. Left: view of the facade, the arrow indicates the position of the central image. Right: thermogram of the facade after exposed for several hours to sunlight radiation.

The almost complete three-dimensional acquisition of the plaster scratches of the central image was made using the photogrammetric method. Based on the three-dimensional data, visualization methods were tested, allowing a better visibility of the plaster scratches. The measurements were made after the construction of a scaffold on the west facade with very wide walkways. For capturing the central image, a measuring area of 2500 mm x 1000 mm was selected. The sensor was mounted on a tripod in a defined initial height. After each single measurement the tripod was moved horizontally in a pre-defined distance. In addition, care was taken that the sensor was always aligned parallel to the wall. The results of the measurements are shown as visualized 3D data in figure 6, left. A direct overlay of a section of the central image with a thermogram is shown in figure 6 right. The thermogram was taken from the scaffold after heating and therefore shows a much higher spatial resolution than the overview screen in figure 5, right. The larger voids (warmer or red areas) can be easily found from the fusion of the thermogram with the 3D data.

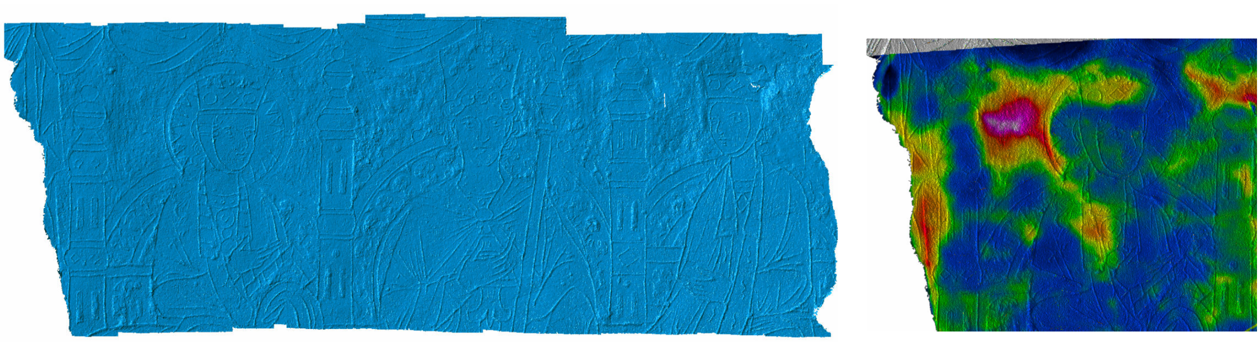

Fig. 6: Visualization of the plaster scratches. Left: triangle mesh as a result of photogrammetry. Right: overlay of a section with a thermogram that was recorded with higher resolution from the scaffold.

3.2.2 Sculptures of Giebichensteinbrücke

From 1926 to 1928, a new bridge was built over the Saale River below the castle ruins Giebichenstein in Halle. On the accompanying icebreakers on both sides of the bridge, two animal sculptures - a cow symbolizing the rural side and a horse on the city side – were mounted. The precise manufacturing procedure of the concrete sculptures is not known. Each consists of a compressed solid body of Portland cement as a binder and an additive mixture of quartz sand, porphyry gravel and copper slag in different size fractions.

First damage to both the sculptures and the bridge were already detected shortly after completion as crack pattern on the surface. Over decades, these cracks have widened and deepened to several millimeters. From 2011 to 2012, the sculptures were restored as part of a research project on conservation practice of concrete funded by the *Deutsche Bundesstiftung Umwelt*. The objective of the restoration project was the reduction of moisture incorporation into the sculptures by filling and closure of the numerous cracks and honeycombs. Within the project and in the process of restoration, 3D mapping of the cracks with the tracking method and with active thermography was applied in selected areas. The results of these methods were compared with manual crack mapping.

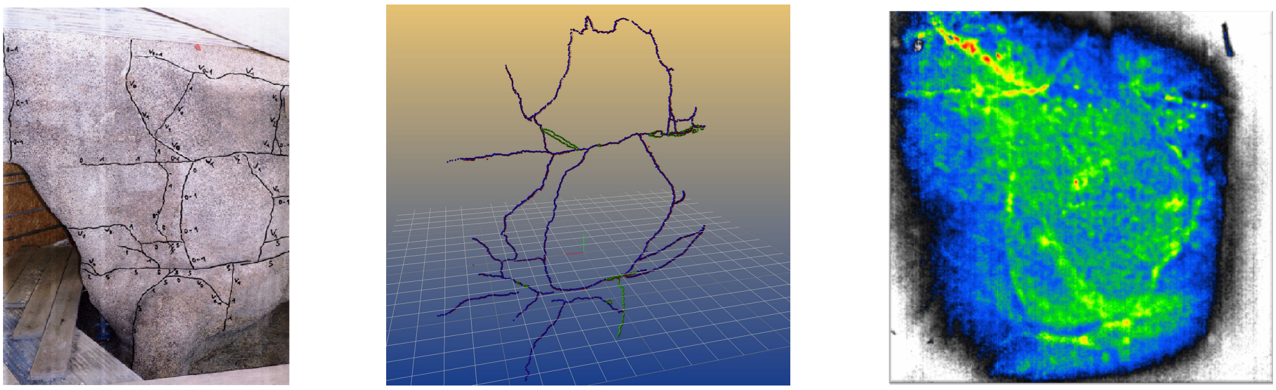

Fig. 7: Left: Manual mapped cracks on the cow of the Giebichensteinbrücke. Middle: 3D mapping of the cracks with the tracking system. Right: Phase image of a thermal sequence.

Figure 7 left shows a section of the manual crack mapping in the chest area of the cow. For the cow, a crack length of 222 m was detected in total. About 50% of these cracks have been intended for grouting. The manual mapping was used as a template for recording the tracking-based 3D crack mapping. With the tracking system 41 cracks with a total of 4451 measurement points were taken in this area. Besides the cracks several reference points were also included in the survey, which are marked by colored tiles on the sculpture, so that they are easily visible in photos. The result of the 3D mapping is a 3D data set as shown in the middle of figure 7. The crack structure is in good agreement with the manually recorded ones, but shows some more details.

The required heat for active thermography was introduced with an IR radiator (2.4 kW). This was done by moving it in a distance of 5 to 15 cm above the surface to be examined. A homogeneous heating was controlled by simultaneous observation with an IR camera. Due to the highly curved surface, this was difficult to achieve. Therefore, the cooling sequence was analyzed with the pulse-phase thermography, which typically is less sensitive to global inhomogeneities. In figure 7 right, a phase image of the measurement area is shown. Here, the cracks can be identified much better as in the raw thermograms (not shown here). The cracks can be represented by a similar resolution as the manual mapping, but provide only 2D images. In summary, the most accurate 3D acquisition of the cracks can be performed using the tracking method.

3 Summary of results and Outlook

Specifically, the following innovations were achieved during the project period:

- Development and qualification of a new measurement method for three dimensional mapping of cracks and crack structures based on a 3D tracking method. Extensive tests concerning accuracy and precision have been performed and new measurement tools have been developed and optimized.

- With the optimization of the 3D photogrammetry, a non-contact method was found by which the plaster scratches at Magdeburg Cathedral could be visualized optimally. So far even with ideal lighting, the photos of the plaster scratches do not give sufficient contrast.
- Further development of active thermography for the effective crack mapping, which can distinguish between cracks which are either oriented perpendicular to the surface or tilted. For homogeneous materials, the crack angle can also be estimated.
- Thermography sequences of large facade surfaces, which were recorded during heating by sunlight and/or cooling through shadowing, provide a lot of information about defects and material inhomogeneities
- The methods for crack mapping are perfectly complemented by the quantitative determination of crack depth using ultrasonics
- Efficient 3D mapping using the results of the individual methods. The combination of these methods allows unambiguous classification of defects and inhomogeneities.
- Four guidelines were developed for each single method of crack mapping
- To assist in the selection of an appropriate crack measurement methods for crack analysis, a catalog was developed

In summary, with the methods developed during the project period reliable tools for monitoring applications are now available. The data and in particular their combination through data fusion allows a comprehensive assessment of the investigated structures. In this project the principal applicability of data fusion could be demonstrated for different case-studies and with different image data (photographs and thermograms).

The development of measuring methods and the measurements in the context of the case studies have been carried out in close collaboration with restorers and conservators. In practice, the methods can be implemented at relatively low cost. When surveying the voids at the plaster scratches of Magdeburg Cathedral, partially the data have been recorded by the restorers themselves and they have also tested the measuring tools. Since the 3D photogrammetry enabled an optimal visualization of plaster scratches, which previously was not possible with photos, it is planned to publish this presentation in a flyer. Thus, the results will become available to the visitors of Magdeburg Cathedral. Results of the thermographic measurements with solar heating and cooling through shadowing can be adopted quickly by users of conventional building thermography. Also, active thermography with other heating sources can be easily implemented with a few tools. However, so far there are only a few commercial software products available, which allow processing of time shifted cooling down curves in such a way that data analysis based on pulse-phase thermography of sequences is possible.

The guidelines developed for these procedures and for crack depth determination with ultrasonics will inform potential users about the possibilities and limitations, thus contributing to a rapid propagation of the methods. Target groups for these guidelines include civil engineers, architects, restorers and conservators, thermographers for buildings and surveyors. An overview of crack measurement methods provides a catalogue, which has also been developed in the project. The guidelines and the catalogue about the crack measurement methods may soon be published together with the final report of the project by the Fraunhofer IRB Verlag.

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