# QUANTIFICATION OF DAMAGE PROCESSES AT SURFACES AND INTERFACES OF BUILDUNG STRUCTURES USING OPTICAL METHODS AND ACTIVE THERMOGRAPHY

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## 1 INTRODUCTION

A large amount of damage of building structures induced by environmental influences like sun radiation, air pollution, moisture, freeze thaw alterations, vibration and settlements are either starting or appearing first on the surface of the building structure. The aim of the presented research is the development and qualification of an efficient strategy for early digital detection, spatial recording and quantification of damage at and close to the surface by using innovative automated electronic methods. With these methods, structural changes can also be observed for longer periods and appropriate measures and repair can be applied at an early stage. Beyond that the effectiveness and sustainability of protective measures can be analyzed.

This strategy is based on the optimization and combination of the following methods:

- Light section method by using a laser scanner and robotic pivot arm for recording the geometry, topology of the surface and geometric alterations (e.g. cracks, bulging, deformations)
- Active thermography by using different heat sources and an infrared (IR) camera for detecting of inhomogeneities in the surface near area, which are not directly visible at the surface (e. g. delaminations, masonry structure behind plaster, cracks, voids, moisture)

In this presentation, the specifications, advantages and limits of both methods will be presented. With the light section method, a very precise determination of position is possible. Arbitrary surfaces can be surveyed with an accuracy of about 0.1 mm [1, 2]. 2D photos can be concatenated [3]. The disadvantages are the complexity of the experimental set-up as well as the data analysis. Latter will be further developed in the presented work.

With active thermography, inhomogeneities below the surface can be detected up to a depth of about 10 cm [4]. A maximum spatial resolution of 0.3 mm is possible, but can be enhanced by using a close-up lens.

For recording of congruent mappings of the object under investigation, first the internal aberrations of the IR cameras have been corrected (internal camera calibration) by using a freeware matlab toolbox. This calibration reveals, that uncorrected thermograms show considerable distortions up to 5 % at the boundaries, which cannot be neglected for datafusion. For facilitating the fusion to the 3D data, parallel to the capturing of thermograms digital photos are taken from the measurement object. For this, IR camera and digital camera were both mounted into a common frame structure enabling a reproducible relative position.

Both methods have been applied to several historic buildings, compiling experimental data that will be presented in the following. Investigations of a sculpture (Madonna with child in the dome of Halberstadt) and of a sandstone column (dome of Magdeburg) are presented below.

## 2 ACTIVE THERMOGRAPHY

Active thermography is based on a specific unsteady heating of the structure to be examined using a suitable heat source. The temperature variations at the surface during heating and cooling are observed with an IR camera [5]. If there are any inhomogeneities within the structure whose thermal materials parameters differ from those of the surroundings, the heat flux changes in these local areas. Therefore, inhomogeneities can be located with the IR camera in the cases in which they cause a measurable difference in temperature on the surface. For the realization of the measurements suitable heating sources and measuring parameters must be adapted to the tasks. As heat sources, IR radiators, halogen lamps, flashlights and fan heaters are available.

For periodic heating (lock-in thermography), the surface temperature is modulated with a step function or a sinus, e. g. by using halogen lamps. Thus, the surface background temperature is increasing. The generated thermal waves are reflected at interfaces, where the effusivity is changing abruptly. These reflexions superimpose with the incident thermal waves and generate a temperature field at the surface. Intensity and phase of the temperature field vary with position and time and depend on depth and material properties of the reflector. This temperature field is recorded as a sequence of thermograms by the IR camera. Afterwards, the sequences, which are correlated to the frequency of the heat source, can be analyzed by Fourier Transformation.

New software tools for signal and image processing can improve the contrast of the defects. This includes data analysis based on pulse-phase thermography (PPT), e. g. the analysis of transient cooling down processes in the frequency domain. PPT is very helpful for the reduction of the sturgeon influence of surface inhomogeneities and irregular heating [6, 7].

## 3 3D LASER SCANNER

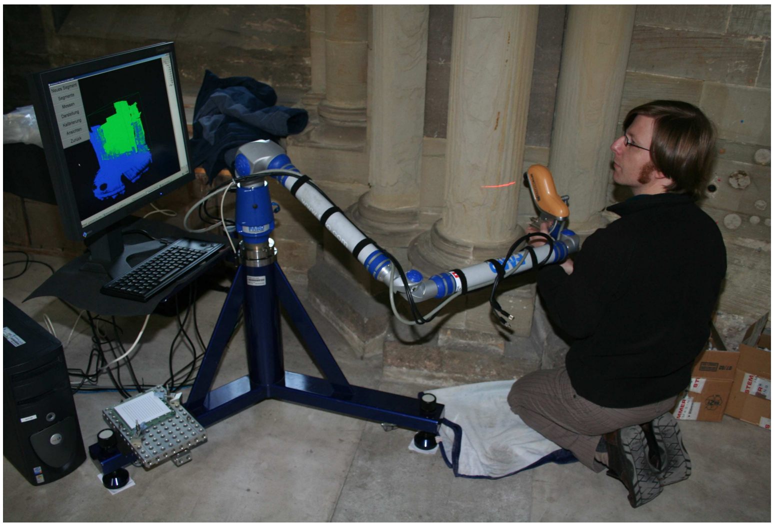

**Figure 1:** Light-section sensor with robot arm during the performance of measurements.

For the capture of the surface geometry of building surfaces and sculptures, a measuring system with two essential properties is necessary: The system should be suitable for a mobile application on the objects to be examined; and the data recording must be contactless. For the case studies described in the following, a light-section sensor developed at Fraunhofer IFF which is fastened to a measuring arm (figure 1) is used. The sensor consists of a camera and a line laser. By applying integrated hardware-based image processing, the measuring system can detect up to 100 contour lines per second, with 1536 3D points each. Larger and complicated freeform surfaces can be covered. It is designed for flexible applications and can be used directly on the objects to be examined.

Using this equipment a 3D point cloud is generated representing a spatially dense and detailed image of the object surface. The accuracy of the 3D measuring points is about ±0.1mm. To achieve a smooth and complete reproduction, a geometric surface model is generated: Single 3D points are connected with each other using triangles. During this procedure measurement errors as well as redundant data are filtered. Such a triangle model is the support for the visual representation and subsequent processing of the measuring data. If suitable, the number of the triangles can be reduced, e. g. for distinct application cases.

## 4 COMBINATION OF METHODS

Additional information can be achieved by the combination of the results of both introduced measuring techniques. As the thermograms only include 2D information (in high geometric resolution), the spatial allocation of the data on objects with complicated surfaces is difficult. This becomes particular clear with the admission of single details of a sculpture and with the comparison of data, which were recorded at different time and from different perspectives. Thus, the determination of spatial dimensions of single features as well as predictions for their temporal behavior are restricted.

The transformation of the 2D thermograms into the 3D space solves these problems partially. Here, in a first step, the measurement position of the IR camera in relation to the object is determined.

Afterwards, every 3-D measuring point is assigned to the view ray that project this point on the camera sensor chip. So, every point in a thermogram can be assigned to one or more 3D points on the surface of the investigated object.

## 4.1 Camera Calibration

The mapping of the 3D object space onto the 2D image level of the camera is described by a camera model, mostly delineated as a central projection. For this transformation, extrinsic and intrinsic camera parameters are required.

### *4.1.1 Extrinsic camera parameters*

The extrinsic camera parameters describe the spatial position and orientation of the camera in relation to the object. For the determination of the extrinsic parameters, the intrinsic parameters have to be known (see below). Then, the extrinsic parameters can be determined in two different ways: The triangle model requires a minimum of four points in order to obtain the projection center and the view angle of the camera. If possible, ten or more points should be considered to improve the accuracy of measurement. For the application of the model, the 3D and corresponding 2D points have to be picked manually in the 3D model as well as in the thermogram. The calculations can be performed using functions from the OpenCV library.

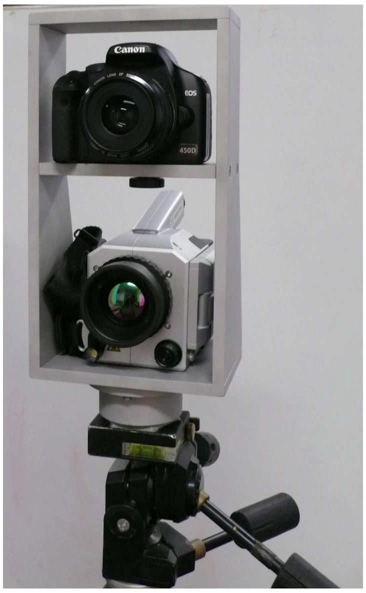

**Figure 2:** Frame for a stable connection between visual and IR camera.

If it is not possible to locate enough features (especially in the thermogram), an additional visual camera is required which has to be calibrated, too. This camera has to be mounted in a fixed connection to the IR camera. For each position, data have to be recorded with both cameras simultaneously.

A common frame for both cameras has to fulfil the following conditions:

- form-stability
- absolute reproducible positions for both cameras
- simple assembly and disassembly of both cameras
- operability of both cameras at fixed position

The frame shown in figure 2 is a compromise: It consists of firmly screwed aluminium structure-profiles. The fixation of both cameras occurs in each case with a screw from below. This screw is positioned inside a precise borehole. In addition, for every camera a stop position is realized by a pin. With it the position of every camera is fixed unambiguously. The operability of the IR camera is limited a little bit, because the display cannot be opened out, only the view-finder is accessible. But as a notebook is used for data acquisition, this limitation is not relevant. For recording of similar image sections, an objective with short focal distance length is used for the visual camera. Then, the visual image contains the whole image of the IR camera as a section.

*4.1.2 Intrinsic camera parameters*

The intrinsic camera parameters are modelling the optical imaging process. In the ideal case of the central projection the focal length of the objective would be sufficient. But in reality, undesirable changes occur due to optical distortion of the objective. Therefore, further intrinsic parameters are describing these abbreviations using several functional models.

For the determination of these intrinsic parameters, there exist effective methods based on photogrammetry. These methods analyse images of geometrically well known pass points. In the following, the „Camera calibration toolbox for Matlab“ from Jean-Yves Bouguet is used, which can be downloaded from http://www.vision.caltech.edu/bouguetj/calib_doc/. Here, a checkered pattern is employed as a pass point field. The software package contains suitable routines which support an automated pass point search in a selected image section. Recently, this approach was used by another group [8].

For applying the software tool to IR cameras, a pattern which delivers a sufficient contrast in the delicacy area of the camera is needed. A circuit board coated with tin and having a size of 21 cm x 29,7 cm (DIN A4 format) has turned out to be well suited. Figure 3 left shows a thermogram, which has been recorded under laboratory conditions. The measured thermal contrast results from a superposition of two effects:

i) different thermal radiation due to the various emissivities of tin an d circuit board material

ii) different reflection behaviour of both materials for the diffuse light coming from the ceiling.

In figure 3 right, the temperature profiles along two lines inside the thermogram are shown. The apparent thermal contrast is in the range of 0.1 – 0.3 K and, therefore, high enough for the identification of the crosspoints of the checkered pattern. Further investigations under different lighting conditions showed that, except in complete darkness, the contrast is always high enough. But, direct reflections of thermal radiation sources ought to be avoided, because they distorb the automatic pass point recognition leading to additional errors.

For a reliable determination of the camera parameters, the pass point field must be recorded under four different angles in four different orientations. This procedure was performed several times with variable distances corresponding to different focus settings. The ascertained camera parameters permit a correction of the image. The corrected images have a mean error of 0.2 pixels in both directions. In figure 4, the abbreviation of the camera optics (standard objective) is visualised. The largest aberration to be corrected is a radial-symmetrical divergence of the theoretical ideal form of the lens which entails a so-called barrel-shaped distortion of the original image. Repeated measurements after changing the camera objective revealed, that the mechanical position of the objectives is not necessarily reproducible. This led to striking changes of the ascertained calibration parameters. Hence, for on-site measurements the user must fix the objectives with special care to guarantee the validity of the before ascertained calibration parameters.

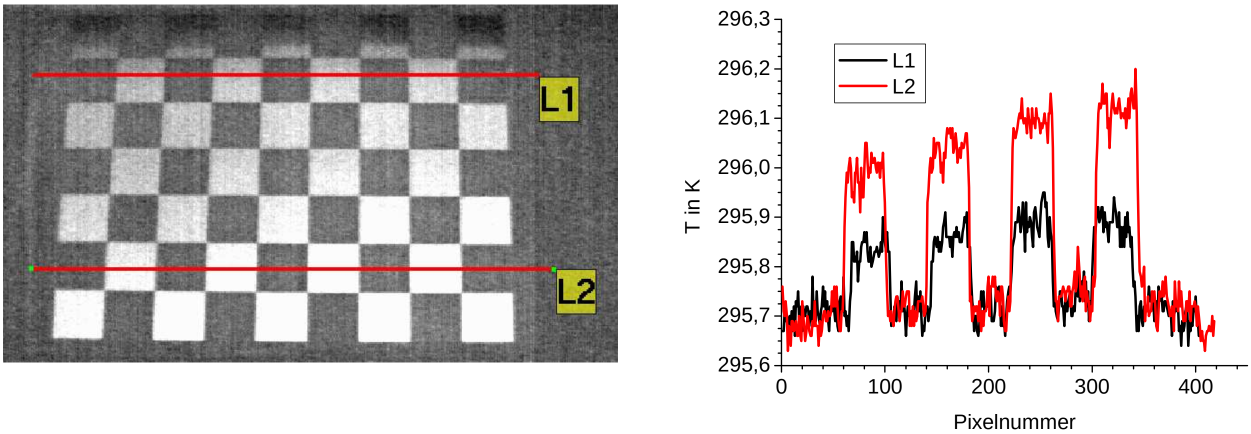


**Figure 3:** Left: Thermogram of a checkered pattern recorded at a distance of 90 cm (average of 50 images). Right: Temperature profiles along the lines shown left.

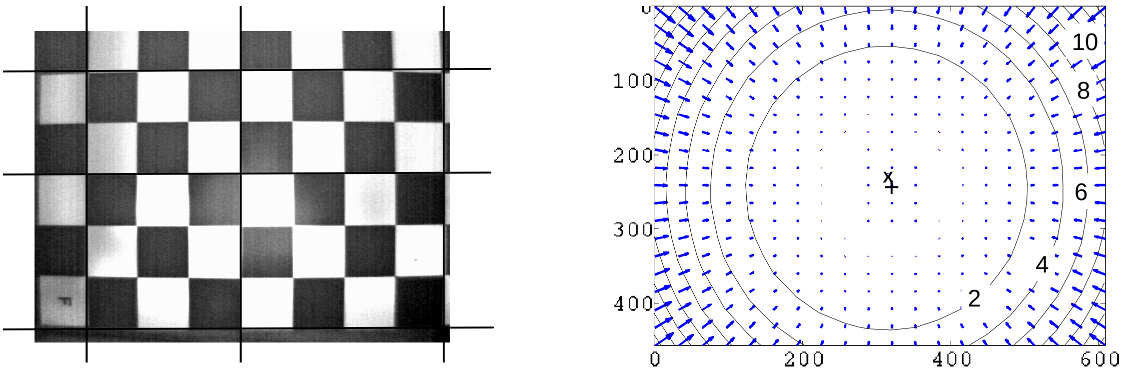


**Figure 4:** Left: Thermogram of the checkered pattern, recorded at a distance of 50 cm. Abbreviations are mainly visible at the corners. Right: Graphical visualization of aberrations of the IR camera with standard objective. The values give the displacement in pixels. +: Mid point of the detector array of the camera; X: Model point of the optical axis of the objective at the detector.

## 5 CASE STUDIES

### 5.1 Madonna with Child in Halberstadt

The Madonna with child in the chapel of Virgin Mary of the dome of Halberstadt was created in 1270/1280 (see figure 5). It consists of shell limestone from Halberstadt. The surface is covered with a polychrome rim. Originally, there have been several damages like various efflorescences, softening of limestone, sanding, derogations and faults, a strong damaged rim, blowy bulging and dirt. These damages have been the cause for restoration and preservation measures. The last restoration was carried out in 2004 under the specification of smallest possible intervention. The reconstruction or exposing of older rim layers was excluded before. Rather, it was the intention to preserve the current and to reduce damage causes [9]. This included the removal of efflorescences, desalination by pads, consolidation, retouch and stucco supplementation. Still, the chapel has a massive moisture problem, which puts the success of remediation into question. The main aim of the investigations performed with active thermography and 3D laser scanning was the location, quantification and monitoring of delaminations and possible new efflorescences.

**Figure 5:** Madonna with child in the dome of Halberstadt

The specifications and limitations for conducting the methods were given by the restorers: With active thermography, the sculpture should be heated up carefully and a maximum temperature rise of 5 K should not be exceeded. The spatial resolution should be at least 2 mm or less. The geometry of the whole sculpture should be captured and distinct areas should be located for further damage assessment.

The 3D laser scanning of the sculpture generated a triangle net consisting of 14 x$10^6$ triangles with a resolution of 0.5mm. Here, only the front surface of the sculpture with a dimension of 1700 x 600 mm was digitized. In figure 6 top, selected areas with different damage pattern are shown.

In the present case study, delaminations of thin layers were to be analyzed. Therefore, the thermal excitation for active thermography had to be performed fast. This was realized using two flashlights (whole energy 6 kJ), which had an exposure time of approx. 25 ms. The cooling of the surface was recorded with a microbolometer IR camera (Variocam hr from Infratec) with a frame rate of 50 Hz and an array size of 640 x 480 pixels.

First of all, it was tried to avoid the whole calibration procedure utilising a very simple approach. After the identification of several reference points, the thermogram was directly mapped on the 3D-surface using pure geometrical distortion between the references. However, the quality of this alignment decreases rapidly with increasing distance to the fixed reference points. Therefore, the grade of alignment depends strongly on the spatial distribution of reference points and is not guaranteed.

The results of this approach are shown in figure 6 bottom. Some contours fit well, other do not match. Thus, a detailed calibration described above is required and is planned for the future.

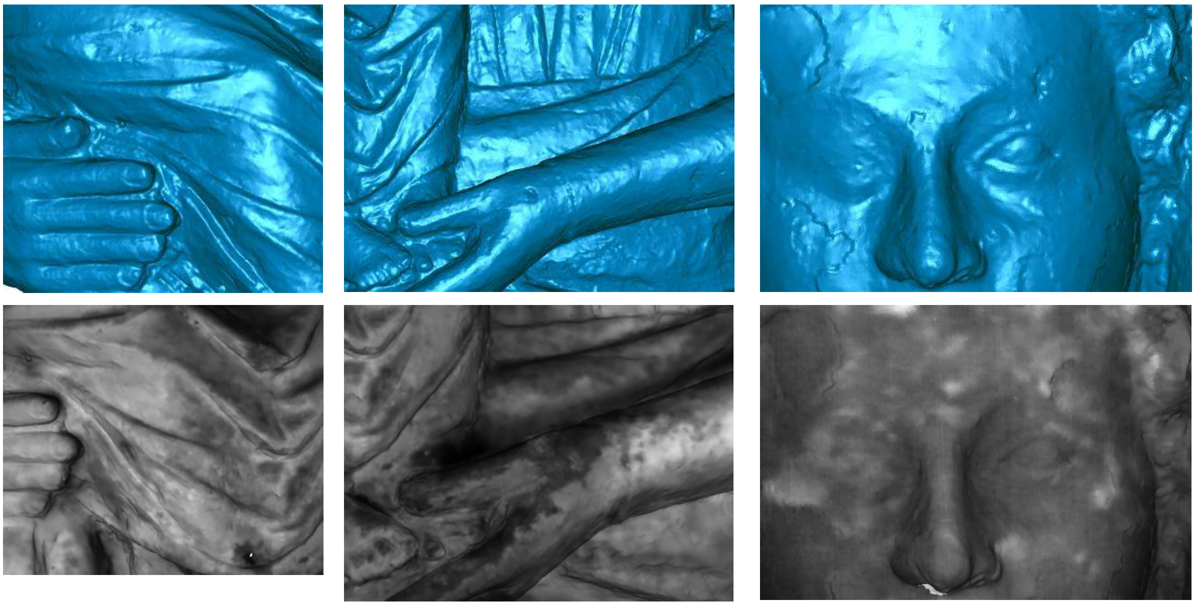

**Figure 6:** Top: Selected areas of the triangle net with inhomogeneities.
Bottom: Similar areas with projected thermograms (16.6 -18.7 °C from black to white) , dark lines mark contours resulting from 3D-scanning

5.2 Column in the Cathedral Saint Mauritius and Saint Katharina in Magdeburg

The Protestant Cathedral Saint Mauritius and Saint Katharina in Magdeburg, Germany, is a Gothic monumental building with rich adornment. It was constructed from the early 13$^{th}$ to early 16$^{th}$ century and is the second largest cathedral in Germany after Cologne Cathedral. The Bishop's corridor constructed after 1232 is unusually wide and high [10]. Big windows correspond to the wide Gothic vaults of the choir. Columns made of lower Triassic sandstone run around the octagon pillars. Several of these columns show large amounts of sand spreading and spalling due to environmental influences. One of the columns (see figure 7a) has been an object of further research and thus has been selected for investigation with active thermography. The heating has been performed with an impulse for a duration of 60 s as well as periodically with different frequencies (here: 0.05 Hz) for several periods by using two halogen lamps. During and after heating, the thermal images have been recorded with a frame rate of up to 50 Hz with a microbolometer IR camera (VarioCAM hr from Infratec). In figure 7b, a thermogram recorded just after 60 s impulse heating is shown. Warm and cold areas indicate the structure of different layers clearly. Warm areas are belonging to delaminations. Figure 7c shows the amplitude image calculated from the cooling down after impulse heating at a corresponding frequency of 0.02 Hz. In figure 7d, the amplitude image calculated from lock-in thermography with 0.05 Hz is shown. In the latter, the best geometrical resolution is obtained.

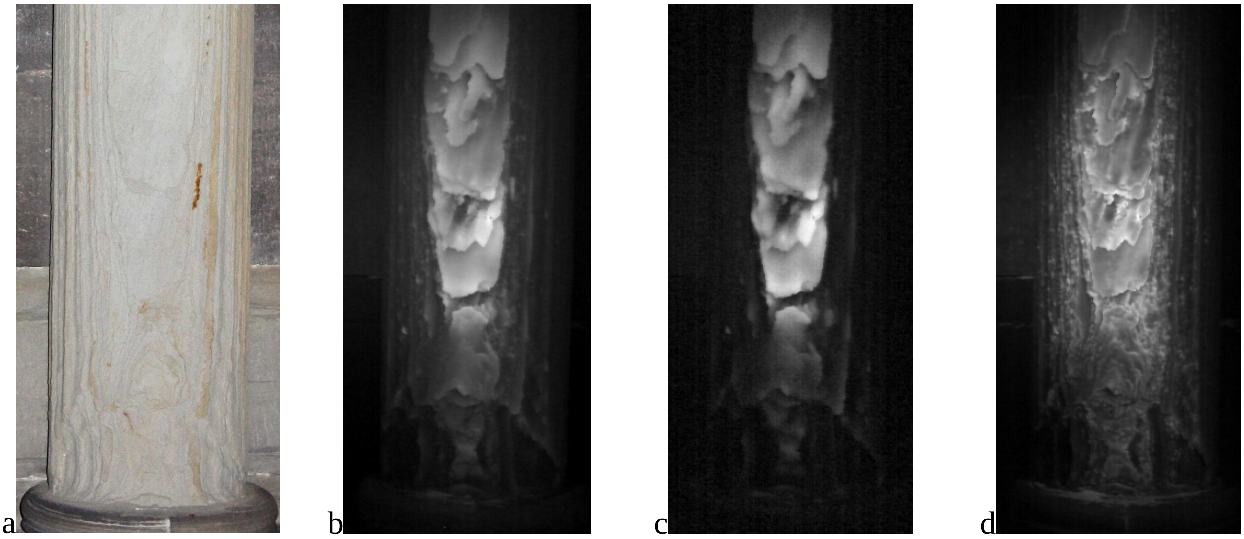

**Figure 7:** Bottom part of a sandstone column with spalling. a: Photo; b: Thermogram, directly recorded after a heating time of 60 s with two halogen lamps (10.6 to 18.0 K from black to white); c: Amplitude image at 0.02 Hz calculated by pulse-phase thermography after 60 s heating; d: Amplitude image calculated from lock-in thermography at 0.05 Hz.

Further results from different measurement campaigns in summer and winter will be compared in the future. After successful mapping to 3D-models the correlation between thermally noticeable areas and object regions with peculiar deformations or other structural features could be evaluated.

## SUMMARY

With the help of the introduced approach and the developed software the thermograms can be visualized and analyzed three-dimensional for any complex object geometry. The combination of infrared images of unsteady thermal heat transfer processes with geometric 3D data enables the discrimination between external geometrical effects due to material properties and internal faults. Temporal changes can be observed with the demanded high local accuracy and damage can be recognized on time.


## ACKNOWLEDGEMENTS

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