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Cascaded image analysis for dynamic crack detection in material testing

U. Hampel, H.-G. Maas *

Dresden University of Technology, Institute of Photogrammetry and Remote Sensing, Helmholtzstraße 10, 01069 Dresden, Germany

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ABSTRACT

Concrete probes in civil engineering material testing often show fissures or hairline-cracks. These cracks develop dynamically. Starting at a width of a few microns, they usually cannot be detected visually or in an image of a camera imaging the whole probe. Conventional image analysis techniques will detect fissures only if they show a width in the order of one pixel. To be able to detect and measure fissures with a width of a fraction of a pixel at an early stage of their development, a cascaded image analysis approach has been developed, implemented and tested. The basic idea of the approach is to detect discontinuities in dense surface deformation vector fields. These deformation vector fields between consecutive stereo image pairs, which are generated by cross correlation or least squares matching, show a precision in the order of 1/50 pixel. Hairline-cracks can be detected and measured by applying edge detection techniques such as a Sobel operator to the results of the image matching process. Cracks will show up as linear discontinuities in the deformation vector field and can be vectorized by edge chaining. In practical tests of the method, cracks with a width of 1/20 pixel could be detected, and their width could be determined at a precision of 1/50 pixel.

1. Introduction

Photogrammetry has been applied in a wide range of civil engineering material testing and structure monitoring tasks, for instance for the measurement of beam deflections in load tests (Whiteman et al., 2002), the long-term measurement of bending effects of concrete probes during the drying phase (Maas and Niederöst, 1997), the measurement of the deformation of bridges under load (Albert et al., 2002) or the monitoring of seasonal deformations of large water reservoir dams (Maas, 1998).

Civil engineering material testing procedures often contain load tests, where the effects of pressure or tensile load on concrete probes are to be analyzed. Besides deformations and structural damages of an object, these load tests may produce hairline-cracks or fissures in the object surface. As a proven technique, strain gauges are often used to monitor the width of cracks. Strain gauges measure electrical resistance changes, which are related to length changes. They offer high accuracy and a good temporal resolution. However, they perform only a one-point one-dimensional measurement. If the position and the direction of a crack can not be predicted a-priori, strain gauges are of limited value. The same holds in the case of multiple cracks in a probe.

An alternative crack measurement tool can be realized on the basis of a camera imaging the whole probe and taking image sequences during the load test. As a non-contact time-resolved multi-dimensional full-field technique, an image-based measurement method offers many advantages in crack analysis. It allows for the measurement of the location and the width of multiple cracks on a probe, plus their temporal development. Challenges here are in handling complex crack patterns and in detecting fine cracks. For instance, a 2000 × 2000 pixel camera imaging a 100 × 100 mm^2 probe (Fig. 1) will have a surface pixel size of 50 × 50 μm^2, while fine cracks will often have a width in the micrometer-range.

The requirements to be imposed on an image sequence processing based crack detection and measurement technique are:

- Fully automatic detection of cracks in time series.
- Capability of detecting cracks with a width of a few micrometers in probes of typically 10 × 10 cm^2 (subpixel crack detection potential).
- Subpixel-precision for crack width determination.
- Localization of crack position.
- Capability of detecting and measuring multiple cracks in a probe.

In the following, we present a full-field crack detection and measurement approach (Section 3ff.). After an overview on related work (Section 2), we briefly describe the image data acquisition system and a typical load experiment with a concrete probe in Section 4. Section 5 describes the determination of dense

* Corresponding author. Tel.: +49 0 351 463 32859.
E-mail addresses: uwe.hampel@tu-dresden.de (U. Hampel), hans-gerd.maas@tu-dresden.de (H.-G. Maas).

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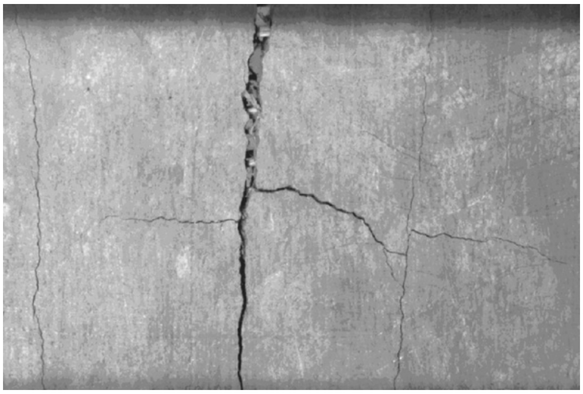

Fig. 1. Concrete probe with cracks.

displacement vector fields by image matching techniques, which are used to detect cracks by edge detection techniques in Section 6. Section 7 shows the results of practical tests on textile reinforced concrete probes.

2. Review of related work

Three basic categories of methods to automatically extract cracks in a concrete probe surface from images can be distinguished:

- **Edge detection techniques**: A crack will appear as a step edge in an image under suitable illumination and can be detected by applying edge detection techniques such as the Sobel, Laplace or Canny operator. This is a relatively simple technique, which can be realized with off-the-shelf image processing software packages. This is, however, limited to the detection of cracks with a width in the order of one pixel or more. Very fine cracks, which cannot be detected in the image visually, will usually not be detectable. Moreover, the technique is rather illumination-dependent, and the crack width cannot be determined with a high accuracy.
  An example of an imaging system for monitoring cracks in concrete structures was presented by Riedel et al. (2003). The system requires some interaction (definition of start and end point of a crack) and is based on the analysis of across-crack intensity profiles. It is limited to the measurement of cracks with a width of several pixels. Also the approach presented by Sohn et al. (2005) is restricted to the detection of cracks with a width of at least one pixel.
- **Targeting**: If a photogrammetric system is used to determine the 3D coordinates of discrete targets attached to the surface of a probe (Fig. 2), cracks will show up as an increase of the distance between neighboring targets. At a proven relative precision potential in the order of 1:100,000 of the probe dimension, this technique will allow micrometer-resolution for a typical probe dimension of 100×100 mm^2. The measurement can be performed easily and reliably using commercial-grade industrial photogrammetry systems. However, the technical effort of signalizing a probe with targets can be rather large. The major disadvantage of a target-based approach is in the fact that it will lead to a strong generalization of the crack position: While the crack width can be determined with a precision in the order of 1/50 pixel, the position of a crack can not be located exactly: The target displacement pattern indicates only between which targets there has been a crack, but not where exactly. Moreover, the technique will deliver only an accumulated crack width when multiple cracks are present between two targets, and cracks passing through targets may cause indistinctness.

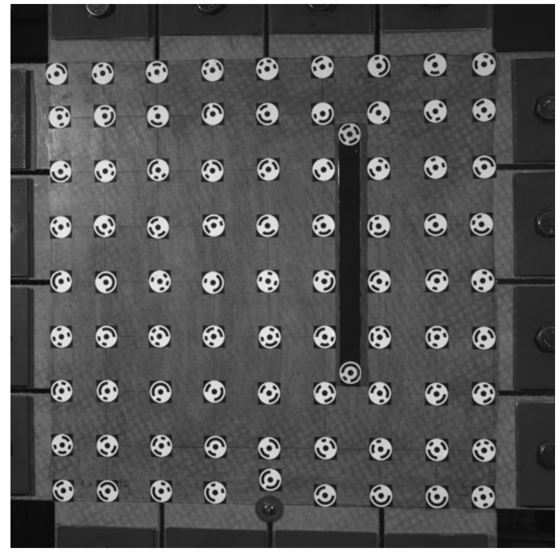

Fig. 2. Concrete probe with discrete targets.

  An example of a study on crack width measurement via discrete targets affixed to a concrete probe is given by Benning et al. (2004). They marked a reinforced concrete plate of 30×30 cm^2 with 3481 (59×59) targets at a target spacing of 5 mm. The coordinates of the targets are determined at a precision of 3 μm (corresponding to 1/30 pixel in image space), but due to the target spacing the crack location can only be determined roughly at a maximum error of $+/-$ 2.5 mm (25 pixel in image space) in each coordinate direction, which translates into a quantization noise of 1.5 mm (15 pixel).
  Barazzetti and Scaioni (2007) also use targets to measure crack width development. Their approach is, however, limited to applications with a-priori knowledge of the position and orientation of single cracks in a probe. Another system based on targeting has been presented by Robins et al. (2001).
- **Full field displacement vector analysis**: A targeting-free full-field subpixel-accuracy measurement technique can be accomplished by applying image matching techniques, which exploit natural or artificial probe surface texture to find homologous points in consecutive images of an image sequence. These matching techniques generate patch displacement vector fields on a dense regular grid (Hampel and Maas, 2003). By treating the lengths of these gridded displacement vectors as an image and applying edge detection techniques, cracks can be detected and vectorized.

3. Basic approach

In the following, a full-field crack detection and measurement technique will be presented. The technique is denoted ‘cascaded image analysis’, as image analysis techniques are subsequently applied at two levels: In a first step, image matching techniques are applied to consecutive images of an image sequence to generate subpixel-accuracy surface patch displacement vector fields. These displacement vectors are arranged on a dense regular grid. Taking the vector length as an attribute, the result of the image matching step can again be considered an image. This displacement vector length image will show discrepancies in the vector length at the position of cracks in the surface of the probe. In a second image processing step, these discrepancies are detected and extracted by edge detection techniques applied to the displacement vector length image. As a result, we obtain an image containing information on the position and the width of cracks. Applying the technique to image sequences delivers