A preliminary study for a marker-based crack monitoring in ancient structures

Danila Germanese
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Maria Antonietta Pascali
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Andrea Berton
Institute of Clinical Physiology - CNR
Pisa, Italy
name.surname@ifc.cnr.it

Giuseppe Riccardo Leone
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Bushra Jalil
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Davide Moroni
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Ovidio Salvetti
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

Marco Tampucci
Institute of Information Science and Technologies - CNR
Pisa, Italy
name.surname@isti.cnr.it

ABSTRACT

Historical buildings are undeniably valuable documents of the history of the world. Their preservation has attracted considerable attention among modern societies, being a major issues both from economical and cultural point of view.

This paper describes how image processing and marker-based application may support the long-term monitoring of crack patterns in the context of cultural heritage preservation, with a special focus on ancient structures. In detail, this work includes a state of the art about the most used techniques in structural monitoring, a description of the proposed methodology and the experimentation details. A discussion about the results and future works concludes the paper.

CCS CONCEPTS

• **Computing methodologies → Computer vision**; **Interest point and salient region detections**; *Scene understanding*; *Image and video acquisition*; *Object detection*; *Object recognition*; *Object identification*; *Reconstruction*;

KEYWORDS

crack monitoring, cultural heritage preservation, image processing, marker detection

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1 INTRODUCTION

Culture is the backbone of every population around the world. Cultural heritage can raise a sense of unity within a group, allowing to understand the history of where we come from. In this perspective, local and national policies more and more frequently allocate resources for the preservation and restoration of cultural heritage.

The structural deterioration of cultural heritage structures is an old problem. It is assessed by monitoring and measuring missing or deformed structural elements, cracks and fissures. Visual inspection remains the most commonly used technique to detect damage and evaluate their progress and severity. Nonetheless, such technique may be time consuming and expensive. Moreover, in some cases, access to critical locations may be difficult.

The constant growth of digital technologies, also boosted by the advent of low-cost hardware and applications, plays a role in facilitating the monitoring of specific regions and the assessment of the mechanical stability, thus preventing critical events.

The aim of the presented work is propose a methodology for tracking, over time, a representation of the variations of the fissure patterns in buildings and to show its applicability in a challenging case study, namely the *Fortezza Vecchia* – an ancient fortress in Livorno (Italy). The study was carried out in the framework of MOSCARDO project ([8]), which aimed at developing an autonomous monitoring system, able to collect and process data about the structural health of ancient buildings. Also, the acquired data are processed to provide alert notifications to experts if the fissure pattern becomes critical; of course, the implementation of such a functionality requires the acquisition of a reference data set over at least one year, in order to set reliable threshold values, e.g. with respect to the effects of seasonal variations.

Among the large family of techniques aiming at monitoring the structural integrity of buildings, we used the marker-based method, as it allows for a non-destructive analysis of crack patterns. We also demonstrated, in a previous pre-application study [7], the feasibility of such approach.

Here we propose a method to represent the variations over time of the crack opening by analyzing the 3D location and pose of a set of square planar markers placed along the crack, and present the first set of results.

2 STATE OF THE ART

The literature devoted to the structural monitoring of architectural cultural heritage and, of course, of civil structures (e.g. buildings, bridges) is very rich. In general, the most used approaches split into two different groups: invasive and non-invasive methods. Here we briefly surveyed those more suitable to be applied in cultural heritage.

Among the most used approaches, we list those based on photogrammetry, or close-range photogrammetry. They provide, at each acquisition, a 3D point cloud of the scene and the segmentation of the crack [16]. To monitor over time the variation of the crack pattern, the most used techniques include: *(i) conventional* analysis, i.e. the estimated 3D coordinates of the same points are compared by using statistical tests, [19]; *(ii)* shape analysis, e.g. by matching surfaces [9] or comparing their shape signatures [3], or comparing a specific shape parameter (the surface area associated to each crack) complemented with a bootstrap testing to detect only statistical meaningful variations in crack opening [1].

Other methods are based on pure image processing, such as in [5]. In this work two pipelines for the crack segmentation are described: the crack pattern is filtered out by automatically detecting edges (by applying a Gaussian blur and subtracting the filtered image from the original one); or by evaluating the color level for each pixel, to enhance the structural discontinuities .

In [12], Jahanshahi et al. propose a method which include a 3D reconstruction of the scene, image segmentation and binarization to isolate the pattern related to small cross-sectional structural defects; two classifiers are trained to distinguish crack from non-crack patterns. Nonetheless, the proposed method (further improved in [11]) is suitable only for detection of anomalies over homogeneous background (e.g. concrete).

A "Digital Rissmess-System" (DRS) is presented in [14] by Niemer et al. Such system is based on a commercial camera, with dedicated software, and it was developed to monitor cracks and damages in civil structures. The authors also report three approaches to extract crack parameters: *(i)* Fly-Fisher algorithm, which allows for automatically monitoring crack dimensions over time; *(ii)* evaluation of crack profile and manual measurement of the crack size at a pre-selected point; *(iii)* correlative approach, which infers crack parameters by the 2D rigid transformation necessary to line up and join the two sides of the fissure.

The marker-based methods are focused on the analysis of the most critical points of a discontinuity [18], made easily and accurately detectable with markers. Nishiyama et al. describe a type of such targets in [15]: they are made by glass droplets, so as to reflect the light as much as possible. Nonetheless, the markers can also be home-made; in [17], Shortis et al. give useful suggestions on their dimensions, materials, etc. They are usually placed along the crack, allowing to perform periodic measurements of the crack features (e.g. the opening), usually under the assumption of a planar displacement. A number of images are acquired and the coordinates and centroids of the targets are assessed through photogrammetric techniques. Any displacement identified by the coordinates of the targets is used to calculate the force field (tensile and shear) along the defect inspected.

For instance, Benning et al. [2] tested different structural elements of pre-stressed, reinforced and textile concrete. For the photogrammetric measurements, the surfaces were prepared by a grid of circular targets. Three different digital cameras were used to simultaneously capture images of the surface. The measurements were repeated in time intervals and the relative distances between adjacent targets were calculated, thus allowing for monitoring the cracks and discontinuities evolution. In addition, a Finite-Element-Module was developed, which simulated the test: thus, the results of photogrammetric measurements could be compared with the numeric tension calculation and iteratively improved.

In [18], Hough transform is used to detect markers and identify their geometric centers. Then, the perspective error is corrected and the planar coordinates of the targets are identified using homography-based computation.

An overview of the main challenges related to cracks automatic detection in civil infrastructures performed with image-based methods is provided by the works of Jahanshahi [10] and Ellenberg [4]. The former describes and evaluates, in particular, several image processing techniques, including enhancement, noise removal, registration, edge detection, line detection, morphological functions, color analysis, texture detection, wavelet transform, segmentation, clustering, and pattern recognition. In addition, the issue related to the noise due to the unwanted edges (e.g. those due to doors, windows, and buildings in the scene) which are sharpened when edge detection algorithms are performed, is addressed. In [4], the main issues related to image acquisition are reported: the environmental conditions, the setting of camera parameters, the distance of the camera (the greater the distance of the camera, the lower the accuracy with which the crack width will be calculated), and angle of orientation.

3 METHODS

Our case study is the Fortezza Vecchia, an ancient fortress in Livorno (Italy): the majority of the defects on its walls are difficult to be monitored, as the fortress is partially surrounded by the sea (see Fig. 1). The peculiarity of the fissures in the Fortezza Vecchia, Bastione della Capitana, is that the sides of each fissure are quite far from each other (as is visible from the bottom images of Fig. 1); also they show a depth offset of at least 0.06 m. The non planarity of such defects makes it very difficult to obtain an absolute and accurate measurement of the separation of the sides with standard methods. Hence, we decided to use markers to provide a complete

Figure 1: Evident structural defects in the walls of the ancient fortress, in the area named *Bastione della Capitana* (Fortezza Vecchia, Livorno, Tuscany, Italy).

3D information about specific fiducial points along the crack, to be tracked over time. Such data include: *(i)* the set of the 3D coordinates of each marker's corners, *(ii)* the set of the distances between the barycenters of each pair of markers, and *(iii)* the angle variations between the reference frame associated to each marker. Other advantages of such minimally invasive technique are that it enables:

- reaching high accuracy when performing a quantitative analysis of the crack;
- using Unmanned Aerial Vehicles (UAVs) to acquire and, possibly, process on board the images.

Moreover, since photogrammetric reconstructions performed with images acquired by UAV can benefit from fiducial points, the markers represent optimal reference points in this respect. It is worth noting that UAV-based technologies allow for a fast and highly repeatable data acquisition, even in area difficult to access, thus reducing costs and risks.

We chose to use the ArUco markers because they are black and white square planar coded markers [6] easy to use, and they can be reliably detected under a wide range of environmental conditions; in addition, such markers allow for an accurate and robust camera localization. Our method is based on the Simultaneous Localization and Mapping, described in [13], which is optimized for the creation of 3D map of the markers visible in the images acquired. A sequence of frames of the same scene is acquired and at each frame the graph-pose is estimated minimizing the re-projection error in the detection of the marker corners. The output of the algorithm are the 3D coordinates of the corners with marker ids. Then, the Euclidean distances between the markers' barycenters and poses are computed.

In the previous pre-application work [7], we showed the feasibility of such a marker-based approach for the assessment of the crack opening, simulated in a laboratory. We estimated a measurement accuracy of less than 1 mm, using a 18 Mega-pixels mirror-less (Canon EOS M), with a focal length set at 24 mm. The acquired images have a resolution of 5184 x 3456 pixels. The same hardware has been used for the experimentation, described in the Section 4.

Figure 2: ArUco fiducial markers have been placed along the crack in the most critical points.

As regards the visual impact of the markers placed on an ancient structure, such as the wall of the Old Fortress in Livorno, we printed markers with two different side lengths: 0.1 m and 0.2 m. We found that, as all of them were detected correctly (Fig. 2), the smaller ones may be used for the next experimentations, without loosing in accuracy.

4 EXPERIMENTS

The crack inspected constitute a complete vertical cut in the walls of Fortezza Vecchia in Livorno, and it is located in the area called *Bastione della Capitana*. Six pairs of markers, four small pairs (0.1 m side length) and two big ones (0.2 m side length), have been glued

Figure 3: Four pairs of markers, correctly detected and identified.

to the wall: the highest pair of markers is glued to the wall about 3.3 m from the ground.

The camera has been calibrated using a ChArUco board as in [7], and a sequence of 6 images were acquired 3 m, 6.5 m and 9 m far from the wall. The focal length of the camera has been set at 24 mm; this implies that, for example, when the camera is 6 m far from the target, the field of view is of 5.575 m (width) and 3.725 m (height), and the pixel resolution (computed from the camera fact-sheet) is of 1 mm.

As shown in Fig. 3 all markers are correctly detected, and the corners' detection is used to compute the barycenter distances in order to roughly check the correlation with the measures performed with a flexible meter, inherently not accurate because of the peculiarity of the defect inspected, previously mentioned in Section 3.

The distances between the 6 pairs of markers are reported in Table 1: the first column provides the ids of the markers of the considered pair; the second column is the approximate ground truth, assessed manually with a flexible meter. In Table 2 and Table 3, the distances between the markers' barycenters computed through our method are reported for the two acquisitions sets of images manually acquired 3 m, 6.5 m and 9 m far from the crack. As expected, the approximately ground truth is not always close enough to the computed distances; nonetheless, the two sets of values from the two acquisitions seem to agree enough to justify further efforts and more experimentation to refine the method (also regarding the hardware settings for the image acquisition) in order to increase its accuracy in the outdoor setting; for so large cracks in brick ancient structure, we aim at an accuracy of 1 mm, considered a meaningful measure. Table 4 shows that in our tests the accuracy of the measurement, even if showing a bit large standard deviation, does not depend on the marker size. On the other hand, Table 2 and Table 3 show that the stability of the measurement should be increased with respect to the camera-target distance. This last point is quite important with respect to the usage of UAV for the data acquisition.

Table 1: Barycenter distances, approximate ground truth, all values are in m.

Marker pair (ids)	~ Ground Truth (m)
id: 27-20	0.33
id: 38-23	0.385
id: 3-4	0.55
id: 31-26	0.33
id: 25-18	0.42
id: 5-10	0.51

Table 2: Barycenter distances, first acquisition, all values are in m.

Marker pair (ids)	3 m	6.5 m	9 m
id: 27-20	0.329	0.333	n.a.
id: 38-23	0.386	0.391	n.a.
id: 3-4	0.555	0.557	0.562
id: 31-26	0.334	0.338	0.346
id: 25-18	0.428	0.434	0.444
id: 5-10	0.522	0.523	0.526

Table 3: Barycenter distances, second acquisition, all values are in m.

Marker pair (ids)	3 m	6.5 m	9 m
id: 27-20	0.332	0.333	0.336
id: 38-23	0.387	0.390	0.394
id: 3-4	0.552	0.558	0.559
id: 31-26	0.334	0.336	0.341
id: 25-18	0.428	0.430	0.436
id: 5-10	0.540	0.526	0.522

Table 4: Chart of average values and standard deviation computed with respect to the two acquisitions, not regarding the distance camera-target. All values are expressed in m.

Marker pair (ids)	average value	standard deviation
id: 27-20	0.332	0.002
id: 38-23	0.39	0.003
id: 3-4	0.557	0.004
id: 31-26	0.338	0.004
id: 25-18	0.433	0.006
id: 5-10	0.527	0.007

5 CONCLUSIONS AND FUTURE WORKS

Currently, the experimentation is at its early stages: only two acquisitions have been performed and the plausibility of the proposed method has been confirmed. Hence, further effort will be devoted to: *(i)* acquire and process more data acquired temporally close to each other in order to assess the robustness of the measurement method, under the assumption that in this short period of time nothing changed; *(ii)* acquire and process data on a monthly basis, for at least one year, to track the evolution of the crack features and possibly develop a model to detect critical trends; *(iii)* test the usage of an UAV and its acquisition payload for the monitoring of fissures.

In particular, *(ii)* will allow to set thresholds specific for each crack, in order to enable an automatic alert service.

Our solution could be considered a reasonable trade off between the minimal invasiveness required to work with cultural heritage, and the measurement accuracy required for a crack monitoring. Using the UAV for the data acquisition reduces risks and costs, and allows to monitor lesions difficult to access. Also, the present approach opens the way to further structural analysis based on the 3D geometric appearance of the marker configuration representing a structural defect, bypassing the main difficulties of a crack segmentation, almost impossible to be performed in such a challenging outdoor scenario, which may be subject to considerable environmental variations, e.g. in light, vegetation, dust.

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