Advanced damage detection techniques in historical buildings using digital photogrammetry and 3D surface anlysis

Contents lists available at ScienceDirect

Journal of Cultural Heritage

journal homepage: www.elsevier.com

Original article

Advances damage detection techniques in historical buildings using digital photogrammetry and 3D surface analysis

Rosella Alessia Galantucci*, Fabio Fatiguso

Department of Civil, Environmental, Land, Building, and Chemical Engineering (DICATECH), Politecnico di Bari, Bari, Italy

ARTICLE INFO

Article history:
Received 2 April 2018
Accepted 23 September 2018
Available online xxx

Keywords:
Non- destructive techniques
Damage detection
Monitoring
Digital photogrammetry
3D surface analysis

ABSTRACT

In the last twenty years, advances in technology led to a progressive digitalization in photography and photogrammetry and to the development of a considerable number of image processing software. In several fields, Digital Image Processing techniques began to spread. For example, in Civil Engineering there are many methodologies for the monitoring of reinforced concrete structures or road pavements. In most cases they involve the application of mathematical and morphological filters to two-dimensional images, to obtain quantitative information about the decay of the analyzed structures. Instead in Architectural Restoration there are still few researches focused on these methodologies, because of the great complexity and uniqueness of historical buildings. Furthermore, until now architectural photogrammetry mainly concerned geometric survey and it was not widely used to diagnose the presence of alterations on buildings, despite the great potential of a non-invasive, contactless survey technique. Therefore, the aim of this research is to create an analysis approach, to detect damages on three-dimensional models, richer in information about depth and volume. The analysis can be carried out through a specific set of spatial and morphological filters for advanced surface analysis, adopting software tools mostly used for three-dimensional metrology and surface topography. A sequence of operations can be executed, allowing to obtain quantitative information about some kinds of alterations damages (cracks or features induced by material loss) from three-dimensional models like point clouds or polygonal meshes. The procedure was tested and validated on a case study (Palazzo Palmieri, Monopoli – Italy). The result of the research is a low interaction approach, through which it is possible to identify and quantify damages on the surfaces.

1. Introduction and state of art

Architectural Restoration has a great importance in Italy, due to the vast amount of buildings heritage. Today many of these buildings are widely degraded, because of the obsolescence process and the lack of maintenance. Therefore, it is necessary to act to ensure its preservation over time. While approaching a cultural heritage which needs to be restored, the first step, for a correct planning of the interventions, is the survey of the existing decay and its mapping, in order to identify the different kinds of alterations and pathologies, for example using the definitions contained in the UNI 11,182 standard [1] or in the "Illustrated glossary on stone deterioration patterns" (ICOMOS international glossary) [2]. It is necessary to rely on an adequate scientific knowledge and specific technical instrumentation. In fact, the initial phase of building's general conditions and performances assessment is managed by technicians. Generally, they make on-site surveys, with the help of instruments such as flexometers, laser distance meters, Vernier calipers, crack-meters or deformeters. The result is a thematic decay map, supplemented by the photographic documentation. It is quite a complex and time-consuming procedure, in which the technician's knowledge and experience play a fundamental role in determining the precision and accuracy of the result.

In Civil Engineering, there are numerous works focused on methods that combine image acquisition and Computer Vision techniques (photogrammetry, laser scanners, robotic devices, charge couple devices). The main purpose is the automatic detection of objects and data by means of specific algorithms, with the aim of assessing and monitoring reinforced concrete structures or road pavements conditions. Mohan et al. [3] provided a critical review and analysis of 50 research papers existing in literature. They compared various automatic crack detection techniques on concrete surfaces, according to different criteria (accuracy level, error level, image data sets…).

Valença et al. [4] proposed an Image Processing approach, integrated with Photogrammetry. They mapped cracked areas by identifying the strain field on the surface. Various Image Processing algorithms are applied to these areas: High-Pass Filter, to improve the

* Corresponding author at: Department of Civil, Environmental, Land, Building, and Chemical Engineering (DICATECH), Politecnico di Bari, Via Edoardo Orabona, 4, 70126 Bari, Italy.

Email address: r.galantucci@studenti.poliba.it (R.A. Galantucci)

https://doi.org/10.1016/j.culher.2018.09.014
1296-2074/ © 2018.

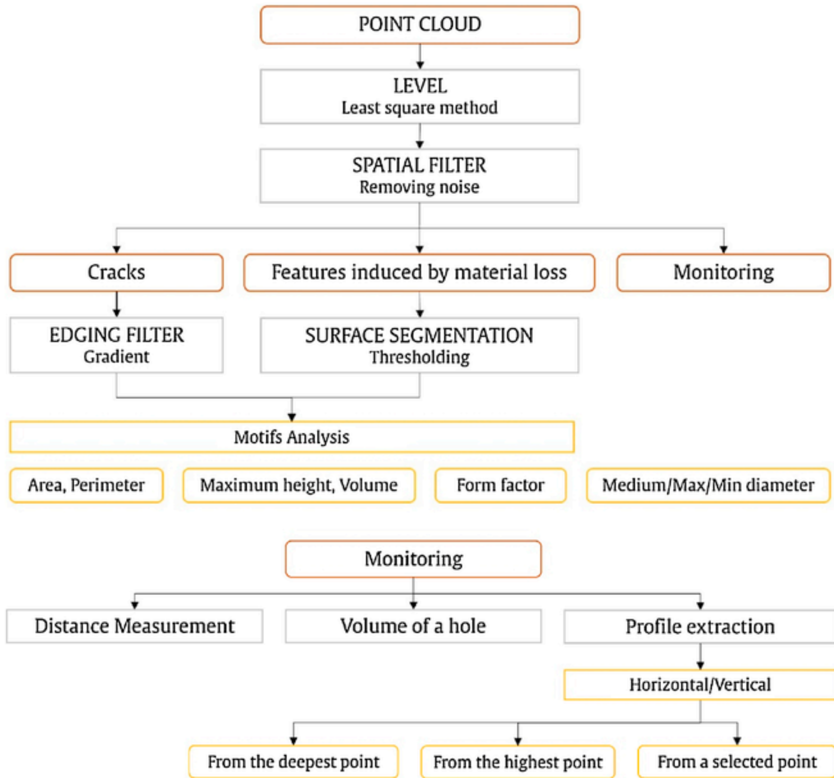


Fig. 1. Flow chart illustrating the sequence of operations composing the protocol, to obtain information on cracks or features induced by material loss; flowchart of the process proposed for monitoring the alterations.

Table 1
Spreadsheet for the planning of shootings.

Scanning number	Object area	Shooting distance	Overlapping between consecutive images	Overlapping between adjacent lines	Total number of images	Step in X	Step in Y	Ground resolution	Height resolution	Smallest characteristic on the sensor	Focal length
	m^2	m	%	%		m	m	cm	cm	mm	mm
1	249.2	5.7	89%	59%	114	0.74	2.97	0.12	0.25	1.2	20.00
2	364.9	13.9	87%	55%	44	1.86	4.45	0.27	0.54	2.7	22.00
3	764.75	10.0	87%	70%	138	1.90	2.92	0.27	0.54	2.7	16.00
4	9.45	1.1	89%	58%	120	0.18	0.45	0.03	0.06	0.3	16.00

Table 2
Comparison of data between the three campaigns.

Survey Campaign		06/11/2015	19/02/2016	09/06/2017
Shooting distance	m	5.72	13.90	10.00
Overlapping between consecutive images	%	89	87	87
Overlapping between adjacent lines	%	59	55	70
No. photos		114	44	138
Distance in X	mm	7400	18,600	19,000
Distance in Y	mm	29,700	44,500	29,200
Area	m^2	24,920	36,490	76,465
Z focal length	mm	20	22	16
f focal length	px	4675	5123	3762

quality of the image; Otsu's Thresholding, to transform the image into binary code; morphological operators, for noise reduction.

Other authors such as Prasanna et al. [5] [6] developed an automatic system for cracks recognition and classification, integrating Image Processing (Gaussian Filter, Intensity Gradient, Non-Maximum Suppression, Double Threshold) and Pattern Recognition. To obtain a correct classification, the authors implemented a Supported Vector Machine, an automatic algorithm that allows computers to perform an inductive reasoning based on a series of learning data (training examples). In 2016, the same authors improved the proposed system, introducing a new algorithm for automatic crack detection, the STRUM (Spatially Tuned Robust Multifeature) Classifier. It consists of three steps: curve cracks' approximation to straight segments; computation of Multifeatured Vectors; classification with Machine Learning, by comparing three different techniques (Supported Vector Machine, Adaboost, Random Forest).

Also, Jahanshahi et al. [7] proposed a non-contact crack detection and quantification approach based on three main phases: 3D model reconstruction, Image Processing and Pattern Recognition. In this case, segmentation algorithms and morphological or mathematical operators are applied, to identify properties to classify cracks and create a multi-scale map with all the cracks detected. Morphological

Fig. 2. Three-dimensional models: polygonal meshes with and without texture.

Table 3
Comparison of information about the three-dimensional models as reconstructed by Agisoft Photoscan.

Survey campaign	06/11/2015	19/02/2016	09/06/2017
No. dense points	60.519.474	31.242.288	39.561.646
No. mesh	8.047.213	5.534.505	3.540.423
No. vertices mesh	4.033.021	2.776.172	1.776.008
Processing time	1h4′	21′19″	37′8″
Ground resolution	1.20 mm/px	2.71 mm/px	2.67 mm/px
Height resolution	2.41 mm/px	5.37 mm/px	5.34 mm/px

Thinning operations are carried out to determine the axis of each crack, its orientation and thickness, applying perspective error compensation algorithms.

Lins et al. [8] combined Statistical Filtering techniques for automatic cracks detection and Machine Vision Concept methods, with the aim of automating the measurement of cracks amplitude and length. The system employs an IP camera, a video camera that produces video signals in digitized form. Two algorithms were implemented: Crack Detection algorithm, Crack Measurement algorithm. The first detects cracks through the Particle Filter, based on RGB (Red-Green-Blue) and HSV (Hue-Saturation-Value) colour models, because the colour distribution around cracks stands on a Gaussian curve. The second algorithm determines the detected cracks amplitude and length, by multiplying the image resolution in pixels to the number of pixels detected by the Crack Detection algorithm.

Su et al. [9] adopted Charge Coupled Devices for the images acquisition. Then the images were transformed through a series of filters (Weighted Median Filter, Image Opening, Otsu's Thresholding), to obtain cracks area and eccentricity (focus/major axis length). The classification method was verified through the Sensitivity Analysis, which estimates the model uncertainties, with the aim of differentiating, among the segmented regions, those cracked and those that are not, according to their correspondence to given criteria.

Nguyen et al. [10] developed a method that allows to remove non-cracked objects from two-dimensional images, through the "Phase Symmetry-Based Crack Enhancement" filter, identifying crack edges, by means of the cross-section Gaussian distribution.

Instead, Adhikari et al. [11] completed the damage recognition and detection with Neural Network techniques. They are artificial neuron networks, whose connections carry unidirectional signals, proportional to the connection forces. Their innovation lies in the possibility of monitoring the evolution of crack phenomena, through image acquisitions at different times. These authors compared quantitative information derived from Spectral Descriptors.

There are other non-invasive methods, such as the one proposed by Hamrat et al. [12], to detect cracks, to know their width and their development over time, through Digital Image Correction techniques. They use the digital system "GOM – Aramis", a three-dimensional non-contact measurement system, generally used to determine material properties. It is possible to identify the first cracking point (the one with the maximum value of tension and bending moment), knowing the stresses to which the structure is subjected.

For the identification of cracks on road pavements, Salman et al. [13] used the Gabor filter, a linear filter whose impulse response is defined by a combination of a harmonic function multiplied to a Gaussian function. It allows crack detection, regardless of their orientation. The adoption of a filter with many freedom degrees, leads to more accurate results, but also longer processing time. Then the image is segmented by means of binarization algorithms.

Also, Oliverira et al. [14] dealt with integrated systems for automatic detection and characterization of cracks on flexible road surfaces. Their method is based on the processing of grayscale images, in order to distinguish cracked pixels from non-cracked pixels, creating a binary matrix (blocks with cracks = 1, blocks without cracks = 0). The detected cracks are then classified according to the Portuguese Distress Catalogue (longitudinal, transversal, complex cracks). A level of severity (related to the amplitude) is also associated to each of them.

In Architectural Restoration the automatic detection of defeats is still little explored, but, in recent years, some methodologies were experimented. The critical review from Bruno et al [15] represents a methodological discussion on research papers, according to selected criteria, regarding Building Information Modelling and Historical Building Information Modelling, with the aim of diagnosis, performance assessment, monitoring and therefore supporting refurbishment interventions.

Stefani et al. [16] starting from the case study of Chambord Castle, elaborated an approach to connect 3D models and 2D mapping data, with the aim of providing a digital documentation about the conservation state of buildings, through the creation of alteration mapping.

Nespeca et al. [17] investigated the possibility "to extrapolate useful information in diagnostics using spatial annotations" through the use of mathematical procedures and the development of software platforms They started from 3D models of the artefact to obtain thematic maps with the classification of stones, the recognition of the carving and previous restorations, the presence of detachment, corrosion or loss of material.

Muñoz-Pandiella et al. [18] proposed "a workflow to map the weathering effect known as "scaling" on monuments with very little user interaction", by generating 3D models with photogrammetry techniques, and then elaborating them with image processing filters (like the adaptive anisotropic Gaussian Filter), integrated with the RANSAC algorithm that allows to estimate the shape of the original surface. Lombillo et al. [19] [20] adopted an integrated system to remotely control the condition of historical buildings, create a register

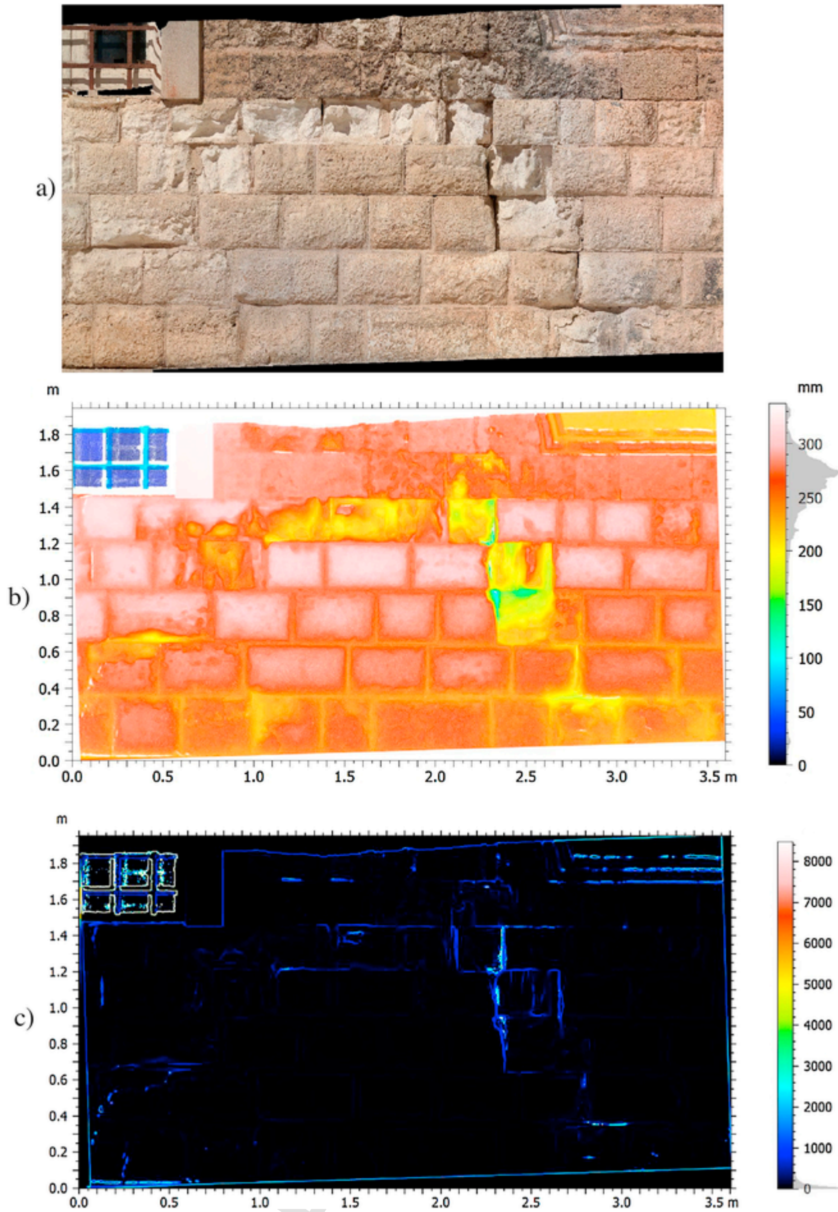


Fig. 3. a: small area (3.5 × 1.8 m^2) extracted from the rusticated basement, on which the protocol was applied; b: three-dimensional model of a small area of the main façade transformed in a false-colour depth map by the software; c: studiable resulting from the application of the gradient filter (matrix 9 × 9).

of historical information, evaluate data through computer-based protocols and define proper maintenance strategies.

Several authors, such as Alshawabkeh et al. [21], Quagliarini et al. [22], Herráez et al. [23] analysed ortho-photos or three-dimensional models obtained through laser scanner, with the help of Image Processing algorithms (threshold operator, Canny Edge), in order to obtain information about geometry, previous interventions and conditions of structural elements.

Quagliarini et al. [24] [25] proposed non-destructive techniques, based on a hybrid ultrasonic system or a Scanning Laser Doppler Vibrometry, to detect defeats on historical plasters on light thin vaults.

Others, like Hallerman et al. [26] [27] [28] utilised high-quality pictures, achieved through unmanned aerial vehicles (UAV) and processed through Computer Vision techniques, such as Structure from Motion, a three-dimensional structures estimation technique based on sequences of two-dimensional images. The objective is to locate visible damages on the surface of masonry, and to consider their evolution, by comparing point clouds acquired at different times. A damage assessment quality index is also determined, to show the difference in results between a high-quality image and an image affected by blurring.

Sánchez et al. [29], instead, proposed a semi-automatic system to recognize and classify materials composing a façade, by means of near-infrared digital images, with low-cost photogrammetric equipment. Results are represented by multiband images, composed of visible and infrared.

Other authors, like Bello et al. [30], developed a structural monitoring system, applied to the case study of the Cathedral of Conegliano. They adopted hardware and software, such as the Structural-X platform (National Instruments). Thanks to the application of some optical targets and video images acquisition, it is possible to make an evaluation of displacements or structural damages.

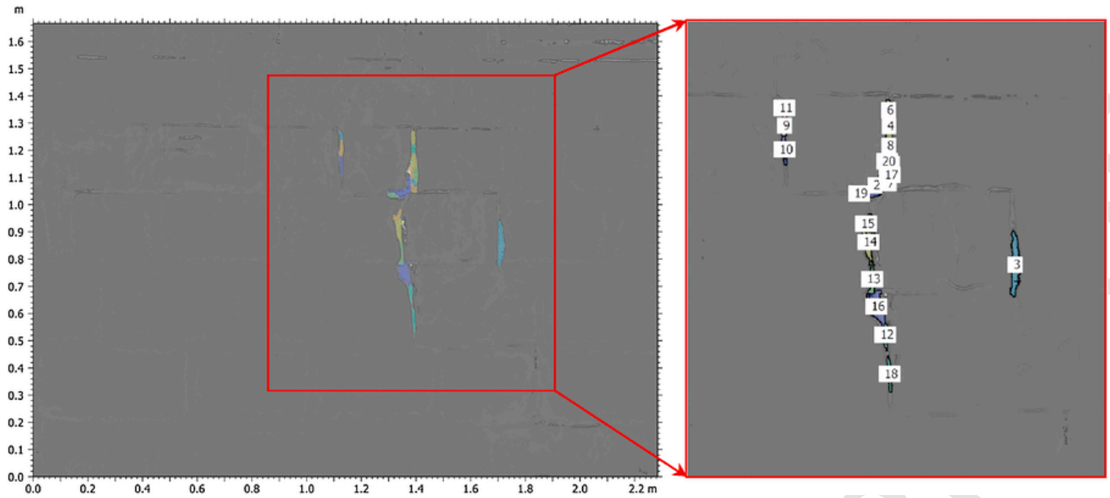


Fig. 4. Cracks detection by segmentation of areas deeper than a selected threshold (the window top-left visible in Fig. 3 has been excluded manually from the segmentation process, because if included in the segmentation, it would protract the processing time, without specific reason).

Table 4
Table with the parameter corresponding to each motif identified through the motifs analysis.

No. of motif	Height	Area	Volume	Perimeter	Coplanarity	Minumum diameter	Maximum diameter	Form factor	Orientation
	mm	mm^2	mm^3	mm	mm	mm	mm		°
2	10.7	2318.9	24,766.5	372.0	14.9	24.5	84.5	0.2054	43
3	26.5	2589.6	68,744.6	363.1	1.7	22.8	155.6	0.2414	89
4	12.5	426.8	5332.6	96.4	2.8	9.7	36.2	0.5567	91
5	11.3	705.8	7983.8	143.7	12.3	14.2	56.2	0.4156	93
6	11.5	671.9	7721.5	120.2	3.8	14.5	52.5	0.5668	91
7	14.4	588.1	8457.6	121.4	3.8	19.7	43.5	0.4845	112
8	10.4	1167.2	12,145.8	201.3	11.4	20.4	59.5	0.3521	82
9	12.1	664.1	8020.3	129.0	4.2	11.8	56.9	0.4858	87
10	17.4	668.8	11,634.0	148.0	4.2	10.4	73.9	0.3692	94
11	1.1	329.3	371.6	85.0	5.0	10.1	35.7	0.5494	100
12	21.3	642.5	13,712.2	148.8	5.2	12.2	68.3	0.3503	93
13	28.4	703.7	20,016.0	179.4	5.5	5.9	83.5	0.2629	89
14	25.4	1380.2	35,116.7	232.0	6.0	16.5	78.9	0.3134	92
15	14.5	702.3	10,196.8	151.0	6.4	11.9	46.1	0.3744	59
16	13.3	2644.1	35,224.8	266.3	6.4	38.2	88.2	0.4610	107
17	11.0	353.6	3888.6	104.8	8.1	7.1	33.6	0.3858	118
18	12.5	599.2	7488.8	169.7	7.5	7.0	93.1	0.2486	94
19	24.9	498.7	12,414.9	119.7	10.6	16.6	38.7	0.4219	169
20	16.1	485.6	7799.7	111.5	14.9	11.5	45.9	0.4729	89

2. Research aim

The main purpose of this research is to investigate methodologies for the quantitative assessment of degradation, in the context of Architectural Heritage Restoration, and to develop a possible detection and monitoring approach, which uses digital photogrammetry (a low-cost scanning method) and image processing techniques applied to three-dimensional models. The idea heading the experimentation is to process three-dimensional models of buildings with a series of operations, through high-end surface imaging and advanced surface analysis software. These tools are created for 3D surface topography and metrology, but so far adopted only in three-dimensional optical profilers and microscopes. The final aim is to define an approach and an operating method to highlight, quantify and monitor the alterations on the surfaces of buildings.

3. Methodology

The proposed approach is divided into three main phases:

- survey of the architectural heritage, through close range digital photogrammetry, and creation of two and three-dimensional models, by means of 3D photogrammetric elaboration software;
- analysis of the models, through surface analysis software;
- development of monitoring procedures based on the comparison of results obtained from models acquired at different times.

The first phase consists on the acquisition of several images of the building, through close range photogrammetry, in parallel with a traditional survey based on observations "in situ" and direct measurements. The images are then elaborated to reconstruct two and three-dimensional models, using a 3D photogrammetric reconstruction software (Agisoft Photoscan). Particularly photogrammetric scanning leads to the reconstruction of three kinds of models:

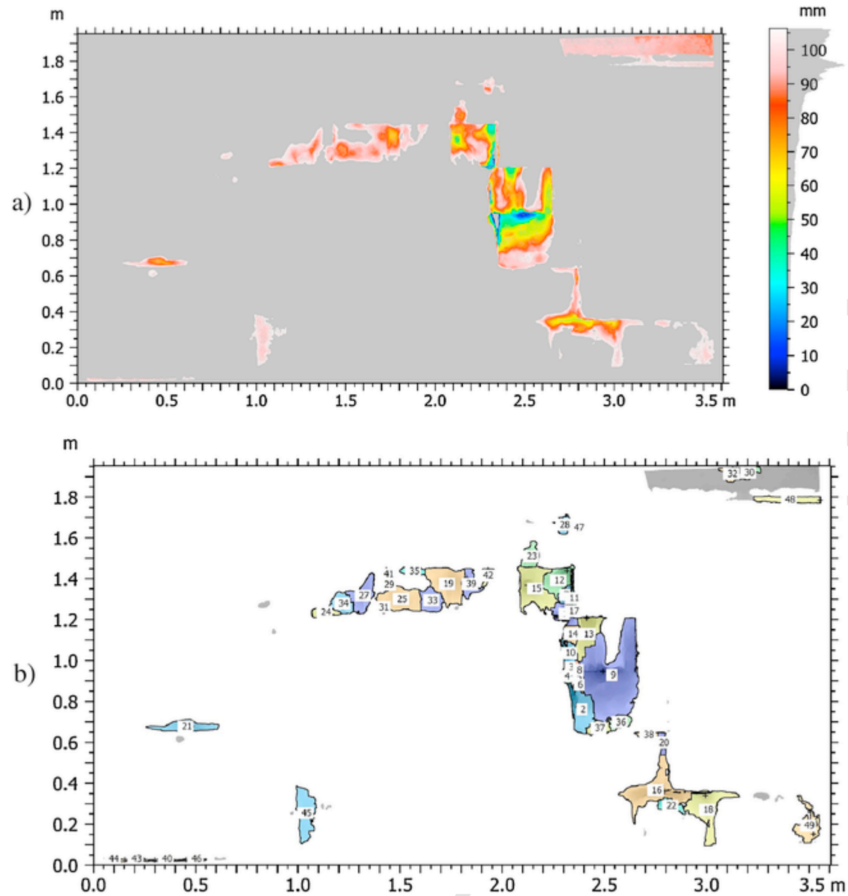
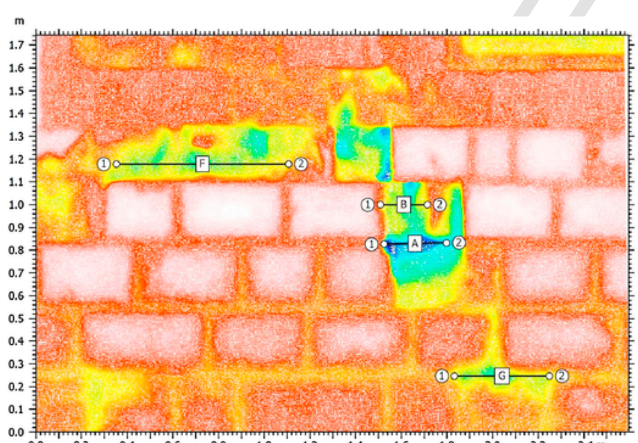


Fig. 5. a: application of the threshold, in order to include all the areas affected by alveolizations, differential erosions, mechanical damage, perforation, missing parts; b; motifs analysis obtained through the surface segmentation.



a)

Name	Unit	A	B	F	G
Distance	mm	265	209	741	401
X1	mm	1487	1466	342	1797
Y1	mm	792	954	1138	216
X2	mm	1752	1675	1083	2197
Y2	mm	793	955	1139	217

b)

Name	Unit	A	B	F	G
Distance	mm	273	206	754	416
X1	mm	1525	1508	352	2
Y1	mm	827	1000	1178	0
X2	mm	1798	1714	1106	2
Y2	mm	833	1000	1178	0

Fig. 6. Distance measurement (A, B, F, G); Table 5 Comparison between corresponding distances (A, B, F, G) in the two models: a: years 2015; b: year 2017.

- point cloud;
- polygonal mesh;
- high-resolution ortho-photo.

Each of these models need to be further processed by means of other programs, which allow the acquisition of information about alterations and damages on the buildings. The level of details depends on the resolution and complexity of 3D models.

3.1. Proposed analysis protocol

The reconstructed three-dimensional models represent the basic data for the analysis protocol, which can be carried out through different analysis software. In fact, models must be preliminarily processed with a rectification algorithm and a spatial noise reduction filter.

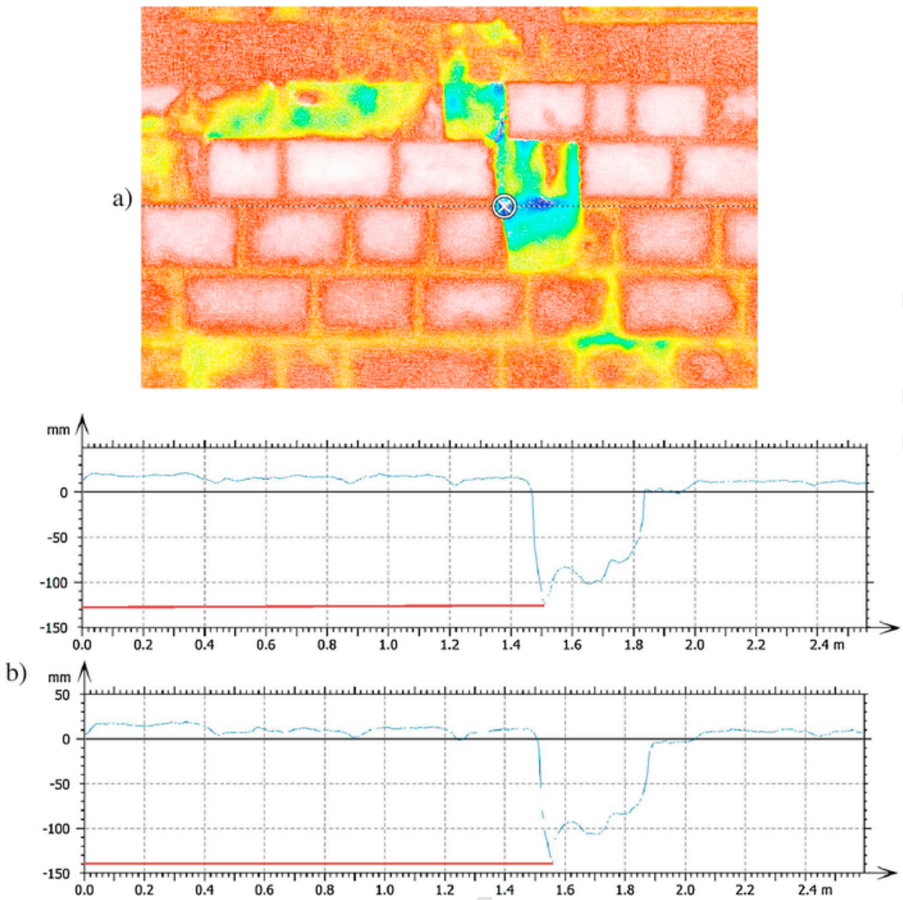
a)
b)


Fig. 7. Profile extraction: a: indication of where the deepest point is located on the analysed surface; b: horizontal profiles passing through the deepest point (up: years 2015 down: 2017).

Table 5
Comparison between corresponding distances (A, B, F, G) in the two models: a. years 2015, b. year 2017.

Name	Unit	A	B	F	G
Distance	mm	265	209	741	401
X1	mm	1487	1466	342	1797
Y1	mm	792	954	1138	216
X2	mm	1752	1675	1083	2197
Y2	mm	793	955	1139	217
Name	**Unit**	**A**	**B**	**F**	**G**
Distance	mm	273	206	754	416
X1	mm	1525	1508	352	2
Y1	mm	827	1000	1178	0
X2	mm	1798	1714	1106	2
Y2	mm	833	1000	1178	0

The first is an algorithm which allows to level the surface, so that it is mainly orthogonal to the point of view. There are two levelling methods: the three-point method and the least squares method. In the three-point method the plane is simply determined by three user-defined points on the surface. This way, it is possible to carry out quick calculations on complex surfaces. Instead the least square method consists in calculating the equations of a plane P, which minimizes the sum of the squares of distances d (x, y), between each point (x, y, z) to be levelled on the surface and the point (x', y', z') on the plane (geometric reference form). The geometric reference is the form that best fits the measured points, it means that if the surface is predominantly flat, the geometric shape is the plane. This method works better than the first one for surfaces, with random surface texture.

The spatial noise reduction filter ensures the removing of anomalous values, deriving from acquisition errors. Among various existing filters the one selected is the median denoising filter, which is more efficient in reducing noise, without smoothing the surface too much. The filter works by replacing with the median value only the points whose coordinate Z is between the quartile 0–25% or 75–100% of the neighbours' Z-values (z-axis is perpendicular to the plane, parallel to the façade, identified by the rectification algorithm). This means that the value is not modified, if it is close to its neighbours' values [31].

Then there are different processing ways, depending on the fixed purpose:

- identifying and measuring;
  - o cracks,
  - o features induced by material loss;
- monitoring.

3.1.1. Cracks

To identify cracks, it is necessary to use an edge-extraction filter. The gradient filter is the most efficient because it subtracts points near the central one, looking for the major slopes in four directions at least. In fact, the aim of edging filters, is precisely to enhance discon-

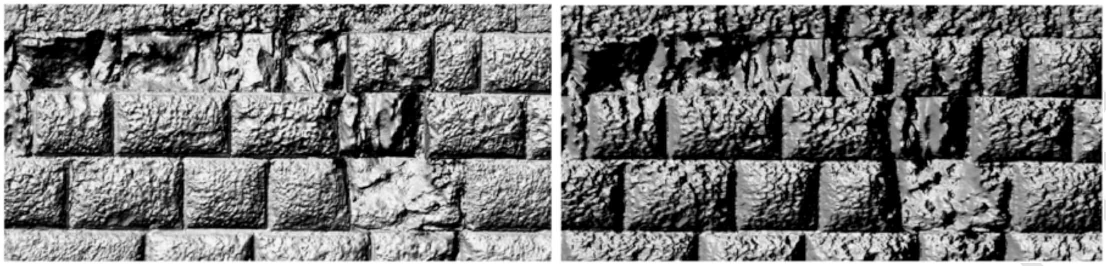


Fig. 8. Simulation of photographic texture of the point cloud (left) and the polygonal mesh (right) of the same portion.

tinuities in intensity (high frequencies), and to eliminate small variations in intensity (low frequencies). The gradient calculates the first derivatives corresponding to each point, in the direction of maximum discontinuity:

$$\frac{\partial f}{\partial r} = \frac{\partial f}{\partial x}\frac{\partial a}{\partial r} + \frac{\partial f}{\partial y}\frac{\partial y}{\partial r} = \frac{\partial f}{\partial x}\cos\theta + \frac{\partial f}{\partial y}\sin\theta \quad (1)$$

This equation represents the gradient of the function *f (x, y),* at a point in the generic direction *r*, with angle *θ*. In order to obtain the maximum value of the gradient $\partial f/\partial r$, it is necessary to derive it in *θ* and assigning it equal to zero:

$$\frac{\partial}{\partial \theta}\left(\frac{\partial f}{\partial r}\right) = -\frac{\partial f}{\partial x}\sin\theta + \frac{\partial f}{\partial y}\cos\theta = 0 \quad (2)$$

The gradient vector represents the maximum value of the derivative $\partial f/\partial r$ in the direction of maximum variation:

$$\text{Gradf} = \nabla \text{f} = \frac{\partial f}{\partial x}\text{i} + \frac{\partial f}{\partial y}\text{j} \quad (3)$$

where *i* and *j* are the unit vectors of *x* and *y* axes [32].

The extracted contours may be elaborated through the motifs analysis, to get quantitative information on geometrical characteristics of cracks. This study segments a surface into significant hill or dale motifs, leading to a localization of peaks (high points) and holes (lower points). Segmentation works according to user-selected thresholds: minimum height and minimum area.

3.1.2. Features induced by material loss

To identify features induced by material loss (alveolizations, differential erosions, mechanical damage, perforation, missing parts), the threshold operator artificially trims the surface in correspondence to selected depth values, and analyses only the elements within this range. This allows to easily identify areas affected by these alterations, since they are generally located at a greater depth than the remaining surface. In fact, by changing the threshold value, it is possible to isolate degraded areas, in order to estimate their size and depth, through a false-colour map.

Then it is possible to extract quantitative information through the motifs analysis.

It is important to realize a preliminary on-site survey, with traditional techniques, defining the scope of the survey also in terms of minimum size of the detectable alterations, in order to ensure the selection of adequate values for a correct behaviour/functioning of the filters and to verify the results obtained through their application.

3.1.3. Monitoring

The protocol may be applied to 3D models of the same object, acquired at different times, to evaluate the development of the decay. Then it is possible to perform other studies, to identify the geometric properties of some specific elements.

For example, multiple measurements can be done through the distance measurement study:

- *x*, *y*, *z* coordinates of a point;
- coordinates of the lowest and the highest point;
- horizontal, vertical, oblique distance between two points;
- angle between two segments;
- distance between two parallel lines.

They could be interesting, for example, to easily measure the amplitude of a specific crack, the distance between two neighbouring cracks, the size of a missing part, or the diameter of a cavity.

It is also useful to extract profiles in correspondence of the most significant points (less deep and deepest point), for the purpose of monitoring. Profiles can be horizontal, vertical or diagonal, for an immediate and complete comprehension of the variation of depth along *z*. This is a valid support in the analysis of the alterations mentioned in Sections 3.1.1 and 3.1.2. In Fig. 1, there is a workflow showing the process to obtain quantitative information about them, and to evaluate the monitoring over time.

3.2. Software support

There is a variety of software, specifically created for the surface analysis, which can be adopted in the protocol illustrated in Section 3.1. The one selected in this work is TalyMap 3D™ [33], a Mountains Map product developed by the company Digital Surf [34]. It is a high-end surface imaging, advanced surface analysis, 3D surface topography and metrology software. It is generally used in industrial researches, product-development, process-improvement and behaviour estimation.

What makes TalyMap 3D ™ extremely suitable to many applications, is the possibility to import and export various formats and therefore to carry out analysis on different kinds of documents (indicated as studiables). In this research, it is considered only the spectrum of analysis and studies that can be performed on surfaces, three-dimensional point cloud models, polygonal meshes, and ortho-photos. This software facilitates the repetition of tests, because once the protocol has been carried out on the first case, it is possible to create a template, so that the sequence of operations is automatically repeated on any other studiable.

4. Case study

The case study is Palazzo Palmieri in Monopoli (Puglia, Italy), located in the homonymous square largo Palmieri. The construction dates to the 18th century, by the Marquis Palmieri's family, native of France. The building is an example of late-Baroque architecture, with a coexistence of influences from Lecce and Naples, like typical elements of the Neapolitan palace house.

The main façade is marked by rusticated ashlars at the base and a smoothed stone cornice at the top. The main entrance is composed by limestone Ionic columns. The upper floor loggia is decorated by the family emblem. The designer wrote that the building "consists of three apartments, with internal courtyard, partly covered and partly uncovered. From this courtyard there is the access to the stone staircase that reaches the sun deck. The highest point is the turret that covers the stairwell" [35].

Over the centuries, Palazzo Palmieri changed many times: in fact, from the beginning of the 20th century, it was firstly used as a children's school, then as a location for the institution for disabled people, and finally as an art institute.

In the 20th century, the palace underwent several interventions, because of years of neglect and the appearance of structural problems. In 1930 the first structural works were carried out by Eng. Sant'Erchia, with the application of the "sew-unsew" method in the piers of the internal façade, collapsed in consequence of compression stresses. In 1950 further interventions were carried out, and the latest restoration works date back to the 1980's [35].

4.1. Survey and models reconstruction

The approach illustrated in Section 3 was applied to the chosen case study and particularly to some specific areas of the main façade, affected by damage. The survey was based on three photogrammetric campaigns performed "in situ", as part of the MIUR Start-up project: PAC02L2_00101 "Contactless diagnosis system of artefacts of significant cultural interest and difficult accessibility with augmented reality" [36].

4.1.1. Planning of the shootings and equipment

Before each campaign, it is necessary to carry out a planning of the shootings, inserting some datasets in a spreadsheet, to obtain: ground resolution, height resolution, the number of photos and the shooting positions (Table 1).

It is useful to place markers at known distances on the object, which represent a dimensional reference to scale the model once the three-dimensional reconstruction has been completed. The more the markers are distant, the less the result of the 3D model scaling is affected by error.

The photogrammetric shootings are made with APS-C sensor digital camera, with high-resolution (20 Mpx to produce ortho-photo maps). This camera can be mounted on supports such as UAV's vehicle or telescopic sticks in carbon fibre, which allow to reach all the heights needed for a complete survey. Therefore, the shots must be controlled with remote control systems, using tablets and specific software or apps [37].

4.1.2. Survey campaigns

The campaigns were realised in a period of eighteen months:

- 06/11/2015;
- 19/02/2016;
- 09/06/2017.

All the times the same equipment was used, except for the kind of lens, with a different focal length, depending on the chosen distance of shooting and the dimensions of the areas to be acquired.

In each campaign, different shooting parameters were chosen, to test the accuracy of the photogrammetric method. The purpose was to understand what kind of solution is necessary to obtain sufficiently detailed information, for an accurate mapping of the alterations. In this regard, some authors, like Napolitano et al. [38] and Lavecchia et al. [39,40], wrote about the influence of various sources of error in the photogrammetric process.

In Table 2 there is a synthesis of the principal information about the three campaigns mentioned in Section 4.1.2, from which it is possible to compare the main parameters chosen for each survey. The principal differences regard the shooting distance and the focal length.

4.1.2.1. Two and Three-dimensional models

The reconstruction of two and three-dimensional models was carried out by means of a computer, with dual Intel Xeon processor (128 GB of RAM, 64-bit operating system). Agisoft PhotoScan is the software used for the reconstruction of models, based on Structure from Motion (SFM) algorithms and Dense Multi-View 3D Reconstruction (DMVR).

The first one is an estimation process of three-dimensional structures, extracted from sequences of two-dimensional images; the second one allows to build three-dimensional models from an unordered set of images of the object, from different points of view [41].

The first kind of model produced by the program, is the point cloud, which represents the basis for the construction of the other models. The quality of a point cloud is greatly influenced by the resolution and the limit imposed to the number of points. A point cloud of a large object, like an architectural artefact, is composed by several tens of millions of points. Clearly, a greater number of points corresponds to a higher level of detail and a greater number of information, but, on the other hand, to a longer processing time.

The polygonal mesh (Fig. 2) is generated on the basis of the point cloud, so its quality is strictly influenced by the resolution of the cloud. The results can be further modified by choosing the geometry and the number of polygons in which the model must be divided, in order to obtain a better approximation of the surfaces, especially if they are mainly curvilinear and complex. The polygonal mesh may be completed by textures, which make it easier to identify alterations on the surface, since the texture provides a real-colour representation and from the three-dimensional models it is possible to calculate all the geometrical characteristics. From Table 3 three-dimensional models characteristics can be observed and compared. The high-resolution ortho-mosaics (obtained from the point cloud model) have a superior quality than single images and they are not affected by perspective errors and distortions. Moreover, since the buildings façades are large and often with physical obstacles in their surroundings, it is difficult to realize a complete survey with a single image. Instead the ortho-mosaic is reconstructed from a great number of images, which are aligned and joined together by the software. The quality of the result varies according to the chosen pixel size and resolution.

4.1.3. Accuracy of 3D models

The experimentation was conducted on three-dimensional models of a small portion ($3.5 \times 1.8\,m^2$) of the main façade (Fig. 3a). For the scans of a restricted area (like the one used in Section 4), it was adopted a shooting distance of 1.1 m, 49 images covering an area of $6.51\,m^2$ ($3.5 \times 1.8\,m^2$), with an overlapping of 88% between consecutive images and of 55% between adjacent lines. The Ground Resolution (or Ground sample distances) of the images is of 0.267 mm/pixel and the Height Resolution is of 0.534 mm/pixel. The dense cloud is made by 30.758.837 points. The accuracy is high and the processing time of about 1 h 5 minutes. For the computation of the 3D models' error the method adopted was the one proposed by Lavecchia et al. [40] that considers the uncertainty of a photogrammetry model, according to according to ISO GUM (JCGM 100:2008) [42] and ISO 15530-3 2011 [43], which is the combination of several causes (procedure reproducibility, resolution of the system and form errors of workpieces), comparable with the Ground Resolution of the model. Therefore, in this case the error/uncertainty is about 0.267 mm. Instead the density of the point cloud is of 3.5 points/mm^2.

4.2. Application of the proposed analysis protocol

When the models are imported in TalyMap 3D™, the program recognizes the coordinates (x, y, z) of each point and uses this information to realize a false-colour map automatically. A colour scale is created, corresponding to depths (Fig. 3b). Various elaborations were carried out in order to outline the best procedure.

As mentioned in Section 3.1, the orientation errors were corrected through the least square method and then a spatial noise reduction filter was applied to remove anomalous values resulting from acquisition errors. It would be interesting to use an adaptive anisotropic Gaussian filter, based on the strategy that different parts of an image should be smoothed differently, choosing the degree of smoothing at each step, instead of using a constant smoothing term, as the other denoising techniques (Muñoz-Pandiella et al. [18], Deng et al.[44]). However this kind of denoising filter works on three-dimensional surfaces composed by polygonal meshes (Ohtake et al. [45]). This work is based mainly on dense point clouds, which are richer in details than polygonal meshes. Three methods of analysis have been distinguished, depending on whether it is to detect:

- cracks;
- features induced by material loss;
- monitoring.

4.2.1. Cracks

The gradient filter allowed the edge extraction. The edges identified by the program are located in the deepest areas, which correspond to cracks. Several tests were carried out, choosing different sizes of the kernel matrix and obtaining different information:

- smaller matrices (3 × 3, 5 × 5, 9 × 9) allow a clearer identification of the contour lines, where the slope variations are maximum (Fig. 3c);
- larger matrices (13 × 13, 19 × 19, 27 × 27) allow a more detailed comprehension of the variation of slopes.

It is important to underline that the values shown in the colour scale in Fig. 3c), do not correspond to the depth (z), but to the gradient (slope variation). The reading of this scale is therefore useful to locate the areas where gradients vary gradually and those where they change suddenly.

To perform the motifs, thresholds (area, depth) were chosen, according to the smallest dimension detectable and consequently the resolution of the analysed model. In Fig. 4 it can be observed that the software identified 19 patterns, corresponding to the cracked areas. For each of the detected regions, it was possible to obtain quantitative information (Table 4). Then all these data were exported as tables in Excel format.

4.2.2. Features induced by material loss

Alveolizations, differential erosions, mechanical damage, perforation, missing parts were detected through two chosen depth thresholds, which identify the study interval (Fig. 5a). The depth thresholds were chosen in accordance with preliminary on-site observations, performed with traditional instruments. Through the motifs analysis (Fig. 5b), the program created 48 motifs, corresponding to the areas identified by the threshold operator. Consequently, also in this case, it was possible to quantify the geometric characteristics of these motifs: area, perimeter, volume, minimum, maximum, average diameter, height, number of adjacent elements, form factor, coplanarity, orientation.

4.2.3. Monitoring

This process has been applied to three-dimensional models, acquired in a period of 18 months (from 06/11/2015 to 09/06/2017), to compare numerical results and evaluate the development of alterations. We considered two point clouds with the same resolution in both directions (parallel and perpendicular to the plane of the façade). The Ground Resolution is of 2.3 mm/pixel in 2015 and 2.4 mm/pixel in 2017. The Height Resolution is of 4.6 mm/pixel in 2015 and 4.8 mm/pixel in 2017. The points composing the dense clouds are 960.000 in the first case and 951.021 in the second case. It means that the two point clouds are comparable. Further analysis was carried out: some distances were measured (Fig. 6), in correspondence of the affected regions and the quantitative variations between the models were estimated in order of some centimetres. It is necessary to specify that the distance points (A, B, F, G) are introduced manually by the user and, although it may introduce some error, this problem could be avoided by the apposition of markers directly on the object. Then horizontal and vertical profiles were extracted in correspondence of the most significant points of the analysed portion. In the specific case, the considered points were the highest and the deepest (Fig. 7).

5. Discussion of results

The analysis protocol was applied on dense point clouds of an affected area of the façade. This led to achieve quantitative data on alterations. It was possible to detect also very small motifs (up to an area of 7 mm^2 and a depth of 3.5 mm). Although it was observed that the minimum detectable dimensions are strongly influenced by the resolution of the 3D models acquired. For this reason, further investigations are taking place, consisting in direct comparisons of three-dimensional models, to understand the distribution of the major distances between two models of different resolutions.

Until now, the field of experimentation has been extended only to planar models, like the small basement area (3.5 × 1.8 m^2) in Fig. 2. However, the idea of the authors is to widen, with further investigations, the applicability of this approach also to more complex surfaces with a non-planar/curvilinear evolution, using filters and operators like the Form Removing or robust Gaussian filter, which remove or separate the main curvature of the surface from the model.

Furthermore, actually it is necessary to handle the presence of sculptions and carvings manually, because the threshold operator could erroneously identify them as cracks or features induced by material loss, according to the value of the deep threshold. However, there is a real intention to continue the research, deepening these two aspects.

For the damage detection, it was possible to recognise only alteration like cracks or features induced by material loss, through the illustrated protocol. But for each of these alterations, as it can be observed from Fig. 4 and Fig. 5, it was possible to locate them precisely, and calculate area, perimeter, average, maximum, minimum diameter, orientation, form factor, without the use of other more complex instruments (crack-meters, deformeters), normally used for the diagnosis of the damage. Anyway, it was important to choose the right thresholds for each case, in order to get an accurate detection.

For the monitoring, the analysis of the three-dimensional models (years 2015 and 2017) showed differences in the order of a few centimetres. In fact, the discrepancies found in the distance measurement are significant and ascribable to the evolution of the decay over time. In fact, in Fig. 6 and in Table 5 the detected differences (measured in a plane parallel to the façade) are: 8 mm (A), 13 mm (F), 15 mm (G). Therefore, these differences are above the Ground Resolution (2.3–2.4 mm/pixel). From the profile extraction (Fig. 7) it can be also observed that the lowest peaks are lowered of 1.5 cm, in the second model (2017) that is above the Height Resolution (4.6–4.8 mm/pixel).

In this research, Digital Photogrammetry was preferred as three-dimensional survey technique (among others like Laser, LIDAR, Structured Light), for many reasons, such as the great affordability of the equipment, the simplicity and quickness of the scanning method. In fact, it is possible to use standard-level cameras, without specific requirements and therefore easily available on the market. This leads to further benefits consisting in simplicity of the using, which does not require the contribution of specialized users.

For all these reasons, there is a significant reduction in scanning and processing time, if compared with traditional survey techniques or with other Reverse Engineering techniques (Laser Scanner). As Segreto et al. [46] stated, while scanning the same object, the laser scanner takes about seven times more than the time used in photogrammetric scanning.

During the experimentation of the analysis protocol, evaluations were made on how and when it is better to apply each operator or filter and on how to interpret each study. The approach was tested on the first point cloud and then checked on other point clouds acquired through the photogrammetric scanning. Then the procedure created for point clouds was tested also on polygonal meshes. The elaborations obtained are of a lower quality than those of the corresponding point clouds, since when polygonal meshes are imported in TalyMap 3D™, the software only considers vertices of the triangles composing the meshes. It means that the meshes consist of less points, if compared to the point clouds. For example, the areas in Fig. 8 represent a point cloud of 30 million points, and a polygonal mesh of 3 million points. Since TalyMap 3D™ allows to import also image formats, such as *jpeg* and *tif*, also high-resolution ortho-photos were analysed. The field of intervention on ortho-photos is limited to mathematical and morphological transformations, typical of digital image processing: spatial filters for noise reduction, minimum/maximum, edge extraction, binarization, morphological corrections, like dilation, erosion, opening and closing.

Although, in this case the possible evaluations are mainly qualitative. However, it is possible to know some flat geometric characteristics through the binarization because the operator segments the image into motifs, and, for each of them, the software can calculate all the parameters mentioned in Section 3.1, except for volumes and depths.

6. Conclusions

The approach proposed in this work includes the adoption of digital photogrammetry for the images' acquisition and the 2D–3D models' reconstruction (high-resolution ortho-mosaics, point cloud and polygonal mesh). The analysis developed are applicable, regardless of the 3D scanning method. The models reconstructed from the photogrammetric scanning represent the starting point for the next phase of experimentation, aimed at building an approach for the damage detection and mapping.

The purpose was to create a protocol that can be easily executed by the user, to obtain information on cracks or features induced by material loss. These alterations are identifiable on 3D models, using false-colour maps and morphological filters (median noise removal, edge extraction), which eliminate useless information. Threshold and binarization operators have been adopted to segment surfaces and calculate their geometric characteristics, through the motifs analysis.

Specific tools were used for the direct measurement of alterations (distances, areas and volumes), which are particularly interesting for monitoring alterations over time. In fact, measuring the same points on 3D models acquired one eighteen months after the other, the growing of alterations was observed and calculated.

During the experimentation, it emerged a problem concerning the possibility to develop an automation in the process, through the software tools. For example, it was impossible to identify unique threshold values, which give significant results in all the cases in which they are applied. In some cases, the approach requires a post-production intervention by the user, to evaluate the accuracy of results and, eventually, make changes in the critical parameters. Therefore, this technique could be considered as a valid support to the expert judgement, allowing a better and faster assessment and comprehension of the alterations, compared to the traditional survey techniques. Further studies will be intended to avoid the interaction with the user, in order to get a semi-automatic or fully automatic approach.

This work is a first result for further investigation. In fact, the research is going on in order to verify the possibility of extending the protocol to the detection of other alterations and to implement the level of automation in the process.

Acknowledgments

This work was partially supported by Polishape 3D srl, a spin-off of the Politecnico di Bari, within the working group of MIUR Start-up project: PAC02L2_00101 "Contactless diagnosis system of artefacts of significant cultural interest and difficult accessibility with augmented reality" [36]. Polishape 3D srl has provided its equipment and technical-scientific know-how, in the acquisition phase and in the image processing phase.

The software support (Agisoft PhotoScan, TalyMap 3D™) was offered by the Department of Mechanics, Mathematics and Management (DMMM) and used on a computer of the Microtronic laboratory network [47] with dual Intel Xeon processor (RAM 128 GB, 64-bit, Windows 7 Professional operating system). The video card is the NVIDIA GEO FORCE GTX 980, with a dedicated memory of 8 GB.

References

[1] UNI 11182:2006, Beni culturali - Materiali lapidei naturali ed artificiali - Descrizione della forma di alterazione - Termini e definizioni, 2006.

[2] ICOMOS, ISCS, Illustrated glossary on stone deterioration patterns, 2008. http://www.icomos.org/publications/monuments_and_sites/15/pdf/Monuments_and_Sites_15_ISCS_Glossary_Stone.pdf.

[3] A. Mohan, S. Poobal, Crack detection using image processing: a critical review and analysis, Alexandria Eng. J. (2017) https://doi.org/10.1016/j.aej.2017.01.020.

[4] J. Valença, D. Dias-da-costa, E. Júlio, H. Araújo, H. Costa, Automatic crack monitoring using photogrammetry and image processing, 46 (2013) 433–441. doi:10.1016/j.measurement.2012.07.019.
[5] P. Prasanna, K. Dana, N. Gucunski, B. Basily, Computer vision based crack detection and analysis, Proc. SPIE Int. Soc. Opt. Eng. 8345 (2012) https://doi.org/10.1117/12.915384.
[6] P. Prasanna, K. Dana, N. Gucunski, B. Basily, H.M. La, R.S. Lim, H. Parvardech, Automatic Crack Detection on Concrete Bridges, IEEE Trans. Autom. Sci. Eng. 13 (2016).
[7] M.R. Jahanshahi, S.R. Masri, C.W. Padgett, G.S. Sukhatme, An innovative methodology for detection and quantification of cracks through incorporation of depth perception, Mach. Vis. Appl. 24 (2013) 227–241.
[8] R. Gonçalves Lins, S.N. Gigivi, Automatic crack detection and measurement based on image analysis, IEEE Trans. Instrum. Meas. 65 (2016) 583–590.
[9] T. Su, Application of Computer Vision to Crack Detection of Concrete Structure, 5 (2013) 457–461. doi:10.7763/IJET.2013.V5.596.
[10] H.-N. Nguyen, T.-Y. Kam, P.-Y. Cheng, An automatic approach for accurate edge detection of concrete crack utilizing 2D geometric features of crack, J Sign Process Syst. 77 (2014) 221–240.
[11] R.S. Adhikari, O. Moselhi, A. Bagchi, Image-based retrieval of concrete crack properties for bridge inspection, Autom. Constr. 39 (2014) 180–194.
[12] M. Hamrat, B. Boulekbache, M. Chemrouk, S. Amziane, Flexural cracking behavior of normal strenght, high strenght and high strenght fiber concrete beams, using digital image correlation technique, Constr. Build. Mater. 106 (2016) 678–692.
[13] M. Salman, S. Mathavan, K. Kamal, M. Rahman, IEEE, Pavement Crack Detection Using the Gabor Filter, in: Proc. 16th Int. IEEE Annu. Conf. Intell. Transp. Syst. (2013) 2039–2044.
[14] H. Oliverira, P. Lobato Correia, Automatic road crack detection and characterization, IEEE Trans. Intell. Transp. Syst. 14 (2013) 155–168.
[15] S. Bruno, M. De Fino, F. Fatiguso, Historic building information modelling: performance assessment for diagnosis-aided information modelling and management, Autom. Constr. 86 (2018) 256–276, https://doi.org/10.1016/j.autcon.2017.11.009.
[16] C. Stefani, X. Brunetaud, S. Janvier-Badosa, K. Beck, L. De Luca, M. Al-Mukhtar, Developing a toolkit for mapping and displaying stone alteration on a web-based documentation platform, J. Cult. Herit. 15 (2014) 1–9, https://doi.org/10.1016/j.culher.2013.01.011.
[17] R. Nespeca, L. De Luca, Analysis, thematic maps and data mining from point cloud to ontology for software development, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch. 41 (2016) 347–354, https://doi.org/10.5194/isprsarchives-XLI-B5-347-2016.
[18] I. Muñoz-Pandiella, K. Akoglu, C. Bosch, H. Rushmeier, Towards Semi-Automatic Scaling Detection on Flat Stones, (2017) 49–58. doi:10.2312/gch.20171291.
[19] J.B.I. Lombillo, H. Blanco, J. Pereda, L. Villegas, C. Carrasco, Structural health monitoring of a damaged church: design of an integrated platform of electronic instrumentation, data acquisition and client/server software, Struct. Control Heal. Monit. 23 (2016) 69–81, https://doi.org/10.1002/stc.1759.
[20] L.V. José Pereda, Ricardo Vela, Antolín Lorenzana, Ignacio Lombillo, Haydee Blanco, Design and application of an integrated platform of electronic instrumentation, data acquisition and client/server software for remote structural health monitoring of heritage buildings, in: 2014: pp. 577–588.
[21] Y. Alshawabkeh, M. El-Khalili, Detection and quantification of material displacements at historical structures using photogrammetry and laser scanning techniques, Mediterr. Archaeol. Archaeom. 13 (2013) 57–67.
[22] E. Quagliarini, P. Clini, M. Ripanti, Fast, low-cost and safe methodology for the assessment of the state of conservation of historical buildings from 3D laser scanning: The case study of Santa Maria in Portonovo (Italy), J. Cult. Herit. 24 (2017) 175–183, https://doi.org/10.1016/j.culher.2016.10.006.
[23] J. Herráeza, P. Navarrob, J.L. Deniaa, M.T. Martínc, J. Rodríguezc, Modeling the thickness of vaults in the church of santa maria de magdalena (Valencia, Spain) with laser scanning techniques, J. Cult. Herit. 15 (2014) 679–686, https://doi.org/10.1016/j.culher.2013.11.015.
[24] E. Quagliarini, G.M. Revel, S. Lenci, E. Seri, A. Cavuto, G. Pandarese, Historical plasters on light thin vaults: State of conservation assessment by a Hybrid ultrasonic method, J. Cult. Herit. 15 (2014) 104–111, https://doi.org/10.1016/j.culher.2013.04.008.
[25] M. Martarelli, P. Castellini, E. Quagliarini, E. Seri, S. Lenci, E.P. Tomasini, Non-destructive evaluation of plasters on historical thin vaults by scanning laser doppler vibrometers, Res. Non destruct. Eval. 25 (2014) 218–234, https://doi.org/10.1080/09349847.2014.896964.
[26] N. Hallermann, G. Morgenthal, The application of unmanned aerial vehicles for the inspection, Adv. Struct. Eng. 17 (2014) 289–302.
[27] N. Hallermann, Vision-based monitoring of heritage monuments – unmanned aerial systems (UAS) for detailed inspection and high-accurate survey of structures, WIT Trans. Built Environ. 153 (2015) 621–632, https://doi.org/10.2495/STR150521.
[28] N. Hallermann, G. Morgenthal, V. Rodehorst, Int. Symp. Non-Destructive Test. Civ. Eng., Unmanned Aerial Systems (UAS) – Case Studies of Vision Based Monitoring of Ageing Structures (2015).
[29] J. Sánchez, E. Quirós, Semi-automatic detection and classification of materials in historic buildings with low-cost photogrammetric equipment, J. Cult. Herit. 25 (2017) 21–30, https://doi.org/10.1016/j.culher.2016.11.017.
[30] E. Bello, Nuove tecniche per il monitoraggio strutturale di monumenti e sale affrescate, (2012). http://sine.ni.com/cs/app/doc/p/id/cs-15324 (accessed January 25, 2018).
[31] DigitalSurf, TalyMap 3D - Reference Guide, (2016).
[32] Istituto Nazionale di Ottica, Operazioni locali: Edging, (2007). http://www.ino.it/home/cosimo/ttr/edging (accessed September 20, 2017).
[33] TaylorHobson-Ltd, Software di analisi tridimensionale TalyMap, (2016). http://www.taylor-hobson.it/products/3/64.html (accessed May 30, 2017).
[34] DigitalSurf, Surface imaging and metrology software for microscopes and profilometers: Integral surface analysis software solutions for microscopes and profilers, (2017). http://www.digitalsurf.com/en/mntproducts.html (accessed May 30, 2017).
[35] G. Todaro, I Palmieri e le dimore marchesali" in Tra i Muri della Storia, Materiali per un viaggio nel cuore di Monopoli, C.R.S.E.C Monop. Reg. Puglia, Assessor. Alla Pubblica Istruzione, Quad. d'identità Territ. N° 5. (2002). http://www.comune.monopoli.ba.it/ViverelaCittagrave/Learee/ArteeCultura/Villeepalazzi/Palazzinobiliari/PalazzoPalmieri/tabid/1371/language/it-IT/Default.aspx (accessed September 10, 2017).
[36] Polishape 3D srl; Politecnico di Bari; Building Refurbishment and Diagnostics srl; Università degli studi di Napoli Federico II, Progetto PAC02L2_00101 "Sistema senza contatto per la diagnostica con realtà aumentata di manufatti di rilevante interesse culturale e di difficile accessibilità" (documento di lavoro), Bari - Napoli, 2013.
[37] Agisoft LLC, Useful Tips on Image Capture: How to Get an Image Dataset that Meets PhotoScan Requirements? , 2014. http://www.agisoft.com/support/tips-tricks/.
[38] R.K. Napolitano, B. Glisic, Minimizing the adverse effects of bias and low repeatability precision in photogrammetry software through statistical analysis, J. Cult. Herit. (2017) https://doi.org/10.1016/j.culher.2017.11.005.
[39] F. Lavecchia, M.G. Guerra, L.M. Galantucci, The influence of software algorithms on photogrammetric micro-feature measurement's uncertainty, Int. J. Adv. Manuf. Technol. 93 (2017) 3991–4005, https://doi.org/10.1007/s00170-017-0786-z.
[40] F. Lavecchia, M.G. Guerra, L.M. Galantucci, Performance verification of a photogrammetric scanning system for micro-parts using a three-dimensional artefact: adjustment and calibration, Int. J. Adv. Manuf. Technol. 96 (2018) 4267–4279, https://doi.org/10.1007/s00170-018-1806-3.
[41] Agisoft, 3D Model Reconstruction of the building, (2016). http://www.agisoft.com/downloads/user-manuals/.
[42] ISO GUM (JCGM 100:2008), Evaluation of measurement data — Guide to the expression of uncertainty in measurement., (2008) 50:134. doi:10.1373/clinchem.2003.030528.
[43] I. 15530-3, Geometrical product specifications (GPS) -- Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement -- Part 3: Use of calibrated workpieces or measurement standards, (2011).
[44] G. Deng, L.W. Cahill, IEEE Conf. Rec. Nucl. Sci. Symp. Med. Imaging Conf. (n.d.) 1615–1619, An adaptive Gaussian filter for noise reduction and edge detection (1993) https://doi.org/10.1109/NSSMIC.1993.373563.
[45] Y. Ohtake, A. Belyaev, H.-P. Seidel, Mesh smoothing by adaptive and anisotropic Gaussian filter applied to mesh Normals, vision, Model. Vis. (2002) 203–210. https://pdfs.semanticscholar.org/19b4/31c843f4b37d2218e7e-fcd8f64b6ff589c1f.pdf.
[46] T. Segreto, A. Bottillo, R. Teti, L.M. Galantucci, F. Lavecchia, M.B. Galantucci, Non-contact reverse engineering modeling for additive manufacturing of down scaled cultural artefacts, Procedia CIRP. 62 (2017) 481–486, https://doi.org/10.1016/j.procir.2017.03.042.
[47] D. Politecnico di Bari, MICROlavorazioni Laser e Sensoristica di Processo per la Produzione di Componenti MeccaTRONICi (MICROTRONIC), (2016). https://sites.google.com/site/micropoliba/home (accessed May 30, 2017).