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Standard quantification and measurement of damages through features characterization of surface imperfections on 3D models: an application on Architectural Heritages

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Abstract

Reverse Engineering techniques lead to easily obtain, even in case of wide and complex objects, high-resolution 3D models, suitably adoptable in the field of surface analysis and characterization. This research aims to propose innovative quantification and measuring approaches to diagnose and monitor damages affecting artefacts of different nature, from manufacturing to architectural heritage, performing non-destructive analyses with advanced surface metrology instruments and the potential integrations of the existing sectorial standards.
General condition assessment is proposed to recognize and classify characterized pathologies by meaningful features in the form of surface imperfections, through the analysis of acquired point clouds. The method is applied to decay phenomena of an architectural artefact.

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Keywords: Surface characterization; Surface imperfection; Feature-based detection; Standardization; 3D modelling; Photogrammetric point clouds.

1. Introduction

Surface imperfections or defects refer to a group of features, unintentionally caused, characterizing a surface, which can affect its functionality [1]. Due to their general definition*, they can be related to surfaces of very different nature, from industrial manufacturing [2,3] to Architectural Heritage [4–6]. For all these fields, surface defect detection is, indeed, of great importance. In industrial manufacturing, it is the beginning of the decisional process of holding or discarding a just manufactured product, or of simply replacing a mechanical component subjected to high stresses after a period of time. In civil and building engineering, it is of paramount importance, as well, for the assessment of the general conditions, the state of conservation or the eventual presence of risk, in civil infrastructures or in architectural artefacts, in order to decide whether or not planning an intervention.

A very general defects identification consists of different parts and purposes: colour analysis, dimension verification, and the single defect detection, which is the main purpose of this work. Several methods exist, which can vary from human observation/judgment to 3D surface analysis, but the very missing part concerns the parametrical characterization of those defects, which is mainly due to a lack of the existing standards. This absence precludes the possibility to make defect detection and classification completely automated, as it almost happens for the basic geometries.

* According to the ISO 9000:2015, a *defect* is a "non-conformity of a product for an intended use or function", which seems to be mostly related to manufacturing errors. In this work, it is intended as a generic surface imperfection due to manufacturing errors but also as a subsequent result of different factors (wear, stresses, etc..) which can compromise its integrity and functionality, so the terms *surface imperfection* and *defect* are used with the same meaning.

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On the other hand, it makes sense to describe a surface imperfection through a set of features, corresponding to its main characteristics, which could be considered invariant, regardless of the nature of the surface and its scale. Thus, it is important to identify a set of parameters describing each defect, which can be valid for various purposes and field.

The problem related to surface defects inspection is a topic already discussed in literature. In the manufacturing field, even if the entire manufacturing process is automated, in some cases, defects detection is still based on the judgment of human operators. Among the automatic processes, there are mainly 2D visual inspection techniques, which could be easily implemented for in line process monitoring [2,7]. Although, 2D inspection has its limitations and, more recently, 3D detection of surface defects has been introduced, thanks to more advanced optical instruments capable of acquiring 3D point clouds instead of 2D images [8,9]. Apart from the surface analysis itself, the other still open issue is related to the surface defects classification. Once a defect is detected, it is still difficult to automatically classify it into a specific category.

The ISO 8785:1998 is, indeed, a first example of surface defects classification, but each defect is not described by any parameter, or identified by any quantitative threshold, which could be useful to automatically distinguish different defects typologies and to evaluate the risks connected to that surface. Standards about welding defects, UNI EN ISO 13919-1:1997, the UNI EN ISO 12932:2013 and the UNI EN ISO 6520-2:2013, are still few examples of parametrization of surface defects, which offer the possibility to develop quality indexes for the evaluation of the influence of different type of defects in a weld [10]. In Cultural Heritage, there are standards and guidelines like the ICOMOS 2008 and the UNI 11182: 2006, which are landmarks for the qualitative definition of the main kinds of surface imperfections, alterations or damages occurring on stone materials of an architectural artefact. The similarities existing between heterogeneous fields like manufacturing and Architectural Heritage, as far as it concerns the defects typologies, make them treatable by means of the same features/descriptors.

For example, in [11], an approach was proposed, based on an integration of standards from Cultural Heritage field with existing standards from the manufacturing field, and it was developed for a quantitative description of surface defects on an architectural artefacts.

The goal of this paper is to propose a parametrization of the most common defects, divided into categories, based on the data retrieved on a case study referring to the Cultural Heritage field. Moreover, it could represent a step forward a possible integration of standards belonging to different sectors.

2. Materials and Methods

2.1. Standards definitions and defects parametrization

According to the standards, ISO 8785:1998 referring to the manufacturing field, and according to the ICOMOS 2008 (or UNI 11182:2006), referring to Cultural Heritage, there are different types of surface imperfections, which are qualitatively described through simple pictures but without any parameters and threshold values, which can distinguish between one type or another. There are, indeed, several defects, which can be grouped in two main categories: cracks (resulting from the separation of one part from another) and feature induced by material loss. A correlation emerged between those surface imperfections, as defined and described in the two standards (Table 1). The first category comprises fracture, fissure, groove, scratch and crazing/craquele, while the second includes pore, blowhole, cavities, alveolization, erosion, etc..

Table 1. Correlations between the main defects or surface imperfections according to ISO 8785:1998 and ICOMOS 2008 (or UNI 11182)

Category	ISO 8785	ICOMOS 2008/ UNI 11182
Cracks (A)	Crack/Groove/Scratch	Fracture
	Fissure	Hair Crack (micro-crack)
	Crazing	Craquele (network)
Features induced by material loss (B)	Pore/Blowhole	Cavities/Alveolization
	Erosion	Erosion
	Dent	Impact Damage
	Cleavage	Microkrast
	Pitting	Pitting
	Wart	Crust

It was observed that these imperfections, may be described, quantified and classified, through the identification of common features/descriptors, which refer to the geometry or to the topology of the single element. The features introduced by the ISO 8785:1998, such as *Length*, *Width*, *Depth* and *Area*, could be integrated with other geometrical and topological descriptors, typical of Digital Image Processing, like *Eccentricity*/*Aspect Ratio*, *Form Factor*, *Roundness*, *Compactness*, in order to represent the geometry, the shape or the extension of selected regions of points, corresponding to surface imperfections, see Table 2 [12,13]. It is important to underline that each parameter can be significant for a specific aspect of the single imperfection, and, moreover, a variation in terms of values of the parameters could be a discriminating factor to include a region in a specific category of defects.

Table 2. Features characterizing surface imperfections, according to the ISO 8785, integrated with the Region Descriptors in Image Processing [12,13]

Features Associated to Imperfections (UNI 8785)		
Single Imperfections (S. I.) Features	S.I. Length	Max-Diameter (D)
	S.I. Width	Min-Diameter (d)
	S.I. Depth	Height (H)
	S.I. Area	Area (A)
Proposal of Features Integration		
Regional and Topological Descriptors	Perimeter (P)	Border lenght
	Eccentricity/Aspect Ratio (AR)	D/d
	Orientation	Angle of the axis
	Form Factor (FF)	$4\pi A / P^2$
	Roundness (R)	$4A / \pi D^2$
	Compactness (C)	$\sqrt{(4A/\pi)}/D$
	N° Connected Components	

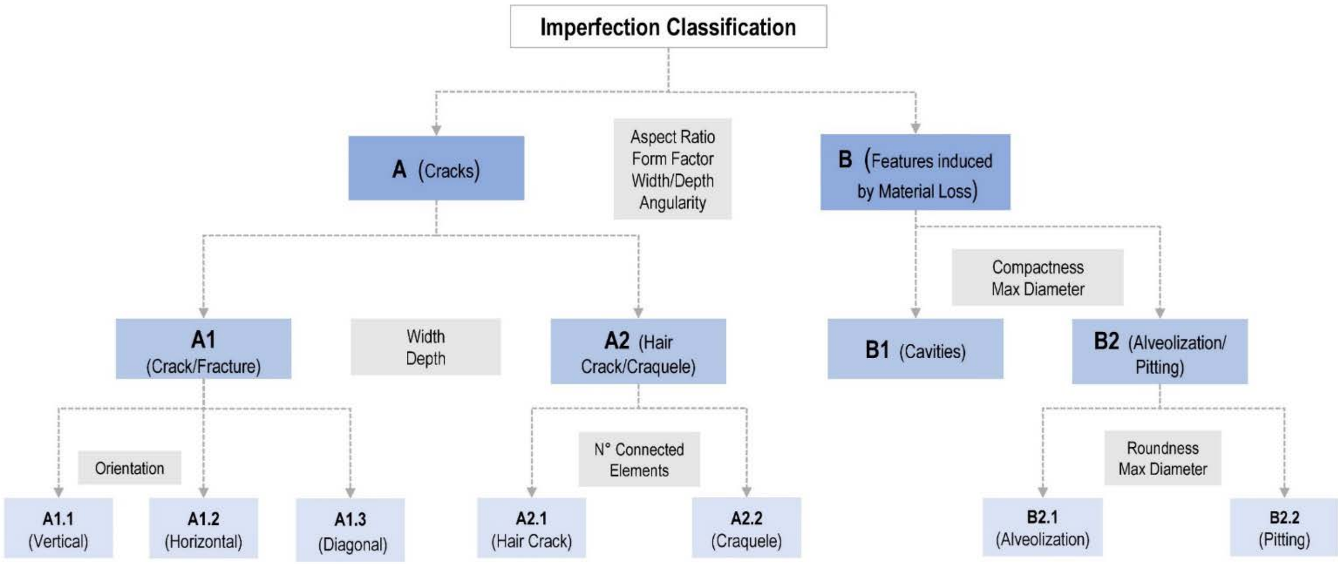

Fig. 1. Methodological workflow for a proposal of Classification of Imperfections.

2.3 Proposed approach for characterizing surface imperfection

In this paper, the geometrical characterization of surface defects, through selected features and thresholds, is proposed, see Fig.1. The main goal is to find some characteristic parameters able to distinguish from defects belonging to different categories, e.g. to distinguish between a crack (group A) or a defect induced by material loss (group B), and then, to differentiate defects within the same general category (A or B), such as, for example, fractures from hair cracks, or cavities from alveolization. This would serve a subsequent phase of evaluating the risk connected to that surface, in order to understand if the damage compromises its integrity or functionality.

Considering the descriptors reported in Table 2, a first classification is possible through *Aspect Ratio* and *Form Factor*, which can discriminate defects belonging to the first (A) or the second category (B). The former parameter is defined as the ratio between the major and the minor axis of a grain (D/d). The latter expresses a relation between the area and the perimeter of the grain.

For the purpose of detection and analysis, the two main surface imperfections (A, B) can be associated to two simple planar geometries: a circle/disk for an ideal cavity, and a rhombus for a crack, due of its elongated shape. If a grain is circular, both the numerical values of the aforementioned parameters correspond to 1, but the more the values diverge from it, the more the grain is oblong, and can be approximated to a rhombus. In order to find significant thresholds, for the *Aspect Ratio* and consequently for the *Form Factor*, able to discriminate grains between a crack (A) and a cavity (B), a geometrical approach was followed. Given the same area of a grain, varying the ratio between the two diagonals (or diameters of the grain), it is possible to find a specific threshold value of the *Aspect Ratio* equal to 4, starting from which, the grain can be considered elongated, because the acute angle of the rhombus is lower than 30°. As a consequence, it is possible to find an appropriate value for the *Form Factor*, which, in the case of a rhombus, can be express also as a function of the *Aspect Ratio*:

$$\textit{Form Factor} = \frac{\pi(\textit{Aspect Ratio})}{2(1+\textit{Aspect Ratio}^2)} \tag{1}$$

Therefore, in correspondence of the *Aspect Ratio* = 4, the *Form Factor* is 0,38, and this value can be used as the threshold to isolate grains pertaining to the two main classes (A, B).

Afterwards, other parameters will enter the analysis, according to the selected category, in order to deepen the classification into various sub-categories (Fig. 1). Regarding the first category, A, a significant parameter is the *Depth*, which provide a check on the first classification, i.e. if a grain is classified as a crack (class A), the quantitative information about the depth of the grain is useful to verify if the grain is actually a crack. Going further, the *Width* can be considered as a discriminant factor for the classification between crack (A1) and hair-cracks or craquele (A2). In fact, for example in the Architectural Heritage, the standard ICOMOS 2008 defines a hair-crack as a crack characterized by a *Width* < 0,1 mm. Then other features/parameters like the *Orientation* (A1.1, A1.2, A1.3) or the *Number of Connected Elements* (A2.1, A2.2), are relevant for finalizing the analysis. The same procedure is followed for the category B, with different parameters such as the *Compactness* and the *Roundness*, (Table 2), as well as, the *Max Diameter*.

In order to retrieve those parameters, a preliminary phase is needed: the grains and particles analysis. This kind of surface analysis is very useful for separating surface data into grains and particles to make them further analysable. The grain detection could be based on binary thresholding or binary segmentation. Both of those methods provide binary images. Then, each grain, which results to be meaningful for the purpose of the analysis, can be fully characterized by a set of parameters, some of them are reported in Table 2. The above-mentioned steps are useful for a first discrimination and for the analysis of defects belonging to the groups A and B. Cracks, and more generally, defects belonging to the group A, need further investigations. The *Width*, *Depth* and, eventually, the

Angularity of the vertical sides of the crack, indeed, can be checked through a profile analysis. The latter allows to determine the nature of the defect and to assess, if it is a crack or a groove, defined as reported in the ISO 8785, which can have the same *Form Factor* but, obviously, a different meaning. The photogrammetric survey allows this kind of analysis, since it is able to reconstruct the vertical sides of the crack. It would not be possible otherwise, with a non-destructive 2D visual inspection.

2.4 Photogrammetric reconstruction

The proposed approach exploits the use of a case study: the medieval Fortress of Bashtovë, (Albania, XV century), a national monument candidate to be included in the UNESCO World Heritage Site list. It is an architecture made of stone and brick, with a quadrangular development and four towers at the corners (of which only two still exist).

A particular attention was dedicated to the north tower which is affected, on one hand, by phenomena of structural deficiency, visible from a huge vertical crack covering almost the whole height of the tower (8 m), and, on the other hand, by widespread alterations (cavities, holes, alveolization), ascribable to stone deterioration.

It is interesting to notice that architectural artefacts offer the possibility to find, even in a small portion of the overall surface, many kinds of surface defects/imperfections simultaneously, which is very relevant for the purpose of the present work. Furthermore, as discussed in the previous sections, surface defects are similar, regardless of the specific field (manufacturing or cultural heritage) to which they belong (Table 1).

The 3D models were retrieved through a photogrammetric reconstruction [14], carried out with a compact mirrorless camera (Samsung NX 2000 - 20 MPx) with fixed wide-angle lenses (16 mm). The scanning strategy established a shooting distance of 3 m, for a covered area of about 60 m^2 (corresponding to the external area of the north tower), with 58 total images (Fig. 3).

For the dense point cloud reconstruction, conducted with the software Agisoft Photoscan, ultra-high quality reconstruction parameters and a mild depth filtering were chosen,

Fig. 2. North tower of the Fortress of Basthovë. The red portion identifies the analysed area.

Fig. 3. Point cloud of an extended portion of the north tower (covered area of about 60 m^2), with the indication of the two samples (1, 2) used for the application of the methodology.

in order to maintain the original size of the photographs and to prevent the loss of small details, essential for the investigation of surface alterations.

The outcoming model is composed by 192’000’000 points, with a resolution of 0,55 mm/pixel in a direction parallel to the object. This is quite appropriate for the purpose of detection and classification, but, as a consequence, it requires great computational costs. For this reason, the following analyses were performed on polygonal meshes, deriving from limited portions of the dense clouds, with an order of magnitude of 5’000’000 of faces (corresponding to about 25’000’000 of points), for each portion analyzed, (samples 1, 2, see Fig. 3).

All the analyses were conducted using the MountainsMap® software [15], which is widely used for surface imaging, analysis and metrology.

3. Results and discussion

The approach proposed in the previous section was then implemented to the selected areas (1, 2) of the processed polygon mesh, see Fig.3. Due to the typical curvature of the tower, first it was necessary to apply to both regions the form removal operator, which consists in approximating the general form of a surface using a mathematical function and subtracting this function from the measured surface. In the specific case polynomial functions of degree 8 were removed from the analysed polygon meshes. The surfaces were then segmented through the setting of a depth threshold value, isolating the defects from the background, see Fig.4,7,8. The following step consisted in a binary segmentation of the surface, which divides the surface in a series of grains and retrieves a set of parameters, such as *Form Factor, Aspect Ratio, Compactness,* see Table 2.

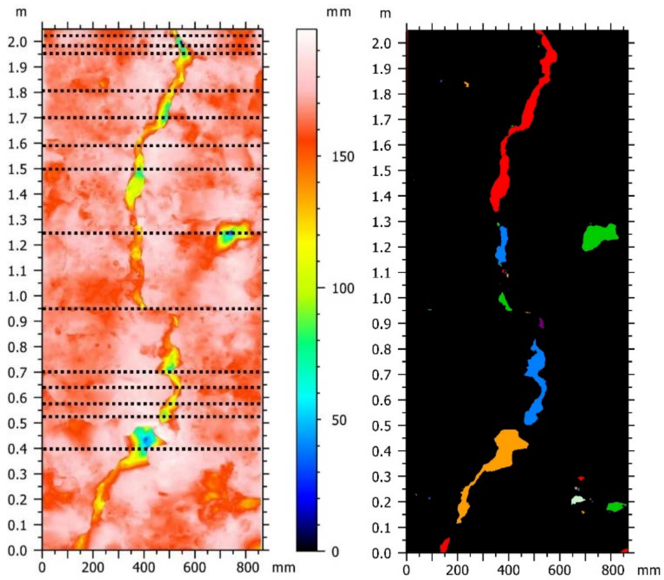

Fig. 4 Left: Pseudo-colour view of the surface (region 1), after the application of a form removing filter (polynomial of degree 8). Indication of the fifteen transversal profiles extracted from the surface. Right: Binarized surface after the application of a depth-threshold, where the segmented regions correspond to the surface imperfections.

These features were used to classify the detected grains into the different categories, according to the threshold values identified in *Section 2.3*, whose application to the two surfaces of the case study confirm their validity, see Fig. 6.

A step forward was the extraction of fifteen transversal profiles on each area 1 and 2, see Fig. 4,5. The profile contour analysis allows the measurement of certain parameters like the *Width*, the *Maximum Depth* and *Angularity* between the vertical sides.

Results obtained highlighted that also the *Width/Depth Ratio* is a discriminant factor between defects belonging to group A and group B, see Fig.7, and, through the analysed set of data, it was possible to obtain a threshold value. It was observed that all the cavities belonging to the category B and considered in this case study, presented a *Width/Depth Ratio* above or equal to 1, while all the profiles retrieved on the crack, showed a *Width/Depth Ratio* below 1.

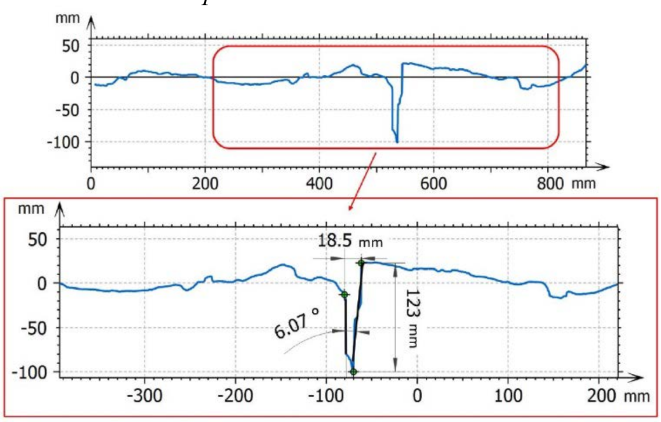

Fig. 5. Transversal profile extracted from the surface.

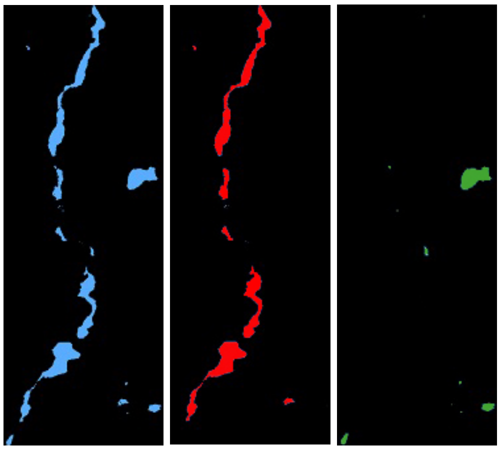

Fig. 6. Application of a threshold value for the Form Factor (0,38), to the binarized image of Fig. 4: from left to right, original image (light blue), grains below the threshold (red), grains above the threshold (green).

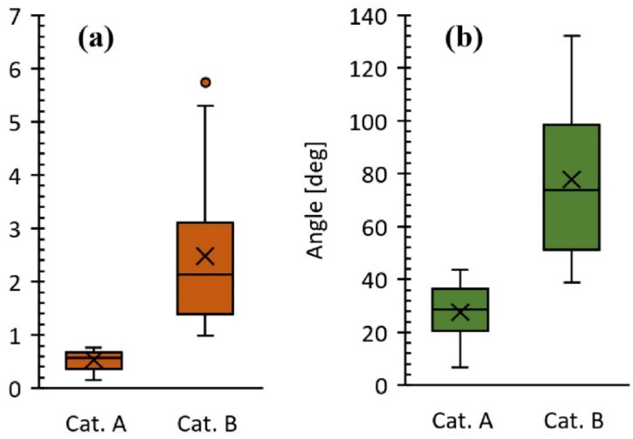

Fig. 7. Boxplot of the Width/Depth ratio (a) and the Angularity (b) with respect to the two categories, A and B. The X represents the mean value, while the line at the centre of the box is the median.

It is important to notice that all the parameters, reported in Table 3, are dimensionless, which makes this analysis invariant with respect to the scale and potentially valid for other cases, which is the main purpose of this work.

Table 3. Discriminant parameters and proposed threshold values assessed through the analysis.

Discriminant Parameter	Method	Threshold value Cat. A	Threshold value Cat. B
Form factor	Grain analysis	≤ 0,38	> 0,38
Aspect Ratio	Grain analysis	> 4	≤ 4
Compactness	Grain analysis	≤ 0,5	> 0,5
Width/Depth Ratio	Profile analysis	< 1	≥ 1
Angularity	Profile analysis	≤ 42°	> 42°

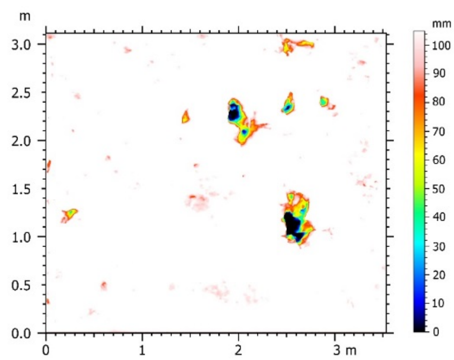

Fig. 8. Application of a depth-threshold to the surface (region 2).

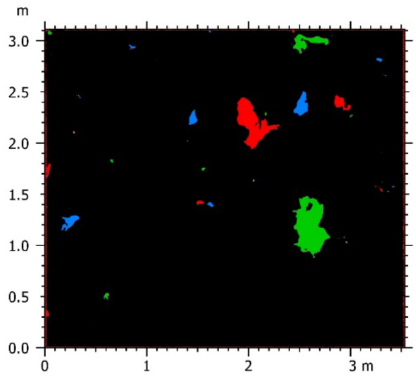

Fig. 9 Binarized surface (region 2), after the application of a depth-threshold, where the segmented regions correspond to the surface imperfections.

4. Conclusion

The availability of 3D point clouds/polygon mesh allowed to conduct a non-destructive and holistic analysis, which means different kinds of analysis starting from the same input. It is a very demanded feature within the paradigm of Industry 4.0.

It is worth to restate that a general classification of surface imperfections was performed, thus, the chosen features are related to the geometric shape and not to the size of the defect, in order to make it possible to apply the same methodology to different fields, with different kinds of objects and scales, from manufacturing to Architectural Heritage. The scale and the dimensions of the analysed objects and of the imperfections, have a great influence on the resolution of the 3D models, which must always lie below the smallest defect dimension to detect.

The peculiarity of 3D models acquired through Reverse Engineering techniques is that they embody a large quantitative of data, which can be processed only with the support of machine learning systems.

Therefore, the proposed approach could represent a starting point for a machine/deep learning system, in order to obtain an automatic classification of defects and a quantification of their entity. However, it is important to specify that, to this purpose, it will be necessary to collect and process a huge amount of data for training and testing the classifier.

The major contribution of this research could be the definition of a classification procedure and the selection of meaningful features and potential discriminant threshold values, among the wide range of information provided by 3D models.

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