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3D Heritage Data Fruition and Management. Point Cloud Processing for Thematic Interpretation

Technologies and digital tools such as laser scanning and photogrammetry are nowadays widely used in the field of architectural heritage survey, being able of producing 3D models characterized by high metric and morphological accuracy. These databases are becoming essential also for the development of more effective interventions on heritage buildings. Despite the advancement of increasingly automated analytical procedures, the management and analysis of point cloud models can still be quite time-consuming and complex, depending on specific assessments to be carried out. In the direction of optimizing these processing steps, several research is being carried out by applying Artificial Intelligence processes to make predictions based on sample data.

The aim of the paper is to analyse point clouds processing focusing on geometric and radiometric features for diagnostic analysis. A specific focus aims at analysing possible in-depth uses of the intensity value as a benchmark for historical surfaces assessment, toward an optimized models' interpretation and classification of the 3D data points, integrating data and information from different sensors.

Point clouds under analysis have been carried out by different acquisition techniques; this provides an interesting opportunity to compare the results in terms of intensity value produced by different sensors.

The paper will analyse the State of the Art, also illustrating a set of outcomes obtained by the authors, deepening two specific case studies, in order to outline not only the main background and shortcomings in managing complex database, but also possible innovations pointing out new research questions.

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Keywords:
Heritage data analysis; Point cloud processing; Surface features; Thematic interpretation; SCAN-to-HBIM

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INTRODUCTION

Technologies and digital tools such as laser scanning and photogrammetry are nowadays widely used in the field of architectural heritage survey, being able of producing 3D models characterized by high metric and morphological accuracy. These information or "dense" databases are becoming essential not only for the documentation of built and cultural assets but also for the development of more effective interventions on heritage buildings. On the point cloud models it is possible to "read" morphological, structural, textural, and conservation features, and to embed Scan-to-H-BIM workflows (Croce et al., 2021). These practices are gaining ground because of the significant advantages in knowledge and management of even complex buildings over time, thanks to semantics and web platforms by processing ontologies of datasets.

Despite the advancement of increasingly automated analytical procedures, the management and analysis of point cloud models can still be quite time-consuming and complex, depending on specific assessments to be carried out. Raw data lack semantic information (Lo Turco et al., 2017) and data segmentation and classification can still require manual procedures managed by specialists able to correctly interpret the source data. In the direction of optimizing these processing steps, several research are being carried out by applying Artificial Intelligence (AI) processes, in order to automate the hierarchization of data (Grilli et al., 2018). These techniques allow computers to make predictions based on sample data, preventing specialists from being overburdened by quantitative operations possibly delegated to AI but focusing on qualitative ones, concentrating efforts on critical-interpretative analysis, so crucial in the field of Cultural Heritage.

The aim of the paper is to analyse point clouds processing focusing on geometric features (such as coordinates of points and normals), and radiometric features (such as RGB values and HSV) for diagnostic analysis and material and degradation mapping. A specific focus aims at analysing possible in-depth uses of the intensity value as a benchmark for historical surfaces assessment (Maietti, 2023), toward an optimized models' interpretation and classification of the 3D data points, integrating data and information from different sensors.

This focus is framed within a broader research involving a set of experimentations on heritage buildings characterised by different levels of complexity and conservation conditions aimed at applying the cultural and interpretive expertise into procedural steps able to automatically discriminating a large amount of input data while minimizing output error to generate thematic sub-models with high critical-interpretive value.

In addition to 3D digitization and classification by processing intensity value ranges, the research includes the projection of 2D outcomes (textures, visual apparency and features) on the geometries also toward advanced H-BIM (Heritage Building Information Models) (Avena et al., 2024), overlapping interdisciplinary data and information.

Results obtained until now still need further development to fine tuning added values in mapping heritage surface features.

Experimentations to include the intensity value in the set of analysis have been performed on different case studies. Point clouds under analysis have been carried out by different acquisition techniques; this provides an interesting opportunity to compare the results in terms of intensity value produced by different sensors. On these databases, different automated segmentation procedures are ongoing; the outcomes will be cross-referenced to achieve a greater and more meaningful definition of the searched features.

This procedure can open possible innovations in the management of 3D databases, pointing out new research questions.

RESEARCH FRAMEWORK

The concept of accessibility and inclusive fruition of digital models or datasets related to data capturing and documentation, opens up the opportunity to explore the crucial issue of the actual use of digital data, depending on the purpose of documentation and surveying.

The current (and rapidly evolving) State of the Art in the field includes several relevant research and promising results at international level on the topics of classification, segmentation and critical analysis of source data (Fiorucci et al., 2020; Grilli & Remondino, 2020; Pierdicca et al., 2020).

However, in the field of Cultural Heritage there is still plenty of room for development to meet the accuracy and quality of data required to make digital models of effective support for knowledge, understanding, analysis, conservation and restoration processes.

Recent research are working on Machine Learning processes for 3D segmentation of state of conservation features (Galantucci et al., 2023) and mapping of heritage assets also through the assessment of 2D representations by applying AI-based methodologies (Trivi et al., 2024), enhancing the information included in architectural drawings as a source to semantically enrich 2D/3D digital heritage. This is particularly significant considering that two-dimensional drawings are often the primary means of metric-morphological representations (often extracted from 3D survey models) and thematic mapping in the field of conservation and restoration.

Several studies are related to the great potentials of close-range and aerial photogrammetry in the field of assessment and control of the state of conservation of heritage buildings, producing data accessible to specialists involved in architectural diagnosis and conservation (De Fino et al., 2023; Bruno et al., 2023), also facing specific issues in data management, such as colour information digitally acquired and decay analysis using colour (Gaiani et al., 2021), or representation of the surface pathologies of heritage objects combining diagnostic analysis and three-dimensional segmen-

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tation techniques (Adamopoulos & Rinaudo, 2020).
A further relevant topic concerns the use of digital technologies to enhance data aggregation preventing possible dispersion or alteration of information during semantic annotations on digital models (Croce et al., 2023), fostering multidisciplinary collaboration making digital outcomes in 2D and 3D more findable and accessible. In this direction, several European initiatives, recommendations and guidelines have been set up in order to create shared "spaces" for wider and more efficient access to digitised Cultural Heritage data.
A very topical example is the common European data space for Cultural Heritage (The deployment of a common European data space for Cultural Heritage, 2022), aimed at allowing Cultural Heritage institutions across Europe to share digitised contents, with high-quality metadata, including in 3D, promoting the reuse of digitised Cultural Heritage among different users.
The research starts from state of the art technologies in the field of Heritage digitization and data assessment in order to contribute to the crucial aspect of the interpretation of heritage features by leveraging on critical-interpretative methodologies to process large amount of data outlining surface features such as materials, previous interventions, and conservation conditions in general.
Starting from geometric and radiometric data, segmentation and classification include the intensity value as a feature to be processed through algorithms. Preliminary applications have been tested on different case studies of which two in particular are presented.

Figure 1 - Tiberius Bridge in Rimini, south elevation. Photo by the authors.

SELECTED CASE STUDIES

Both of the case studies described below were surveyed using laser scanning and digital photogrammetry (Structure from Motion) in order to obtain digital 3D metric-morphological models, to be used as informative "containers" to apply new data assessment methodologies also with regard to surface features and conservation aspects.
The first case study analyzed is the Augustus and Tiberius Bridge in Rimini, Italy (Fig. 1). The structure has preserved its function unchanged over the centuries, conserving all the traces of the interventions that have taken place over time (Ferrari, 2022), and this is particularly interesting for in-depth assessment of surface features using digital data.
The bridge, connecting the two banks of the Marecchia river, was built during the time of Emperor Tiberius and influenced the city growing and its strategic location within the Roman Empire, connecting Rimini to the network of commercial roads (Ballance, 2013). An epigraph on the parapets of the bridge allows to date the construction, which was begun at the end of the principate of Augustus in 14 AD and finished by Tiberius in 21 AD. The bridge rests on four piers (inclined to better adapt to the flow of the current, and not oriented according to the road axis) that delimit five round arches, four of which are of equal width and the central one is slightly wider.
From a material-structural point of view, the bridge consists of a sack masonry composed of brick fragments, pebbles and stones bonded with mortar and completely covered with blocks of Istrian stone of a white color and great compactness. The blocks, ashlar-worked in the exposed face, are laid in the typical opus quadratum arrangement in regular rows with very precise vertical and horizontal joint planes. The upper part of the pillars has aediculae decoration, rectangular niches bordered by two small pillars with Tuscanic capitals supporting an Ionic-type entablature with a two-banded architrave and frieze overlaid by a triangular pediment. The archivolts of the five arches are independent, with the stones arranged

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in a semicircular crown and slightly projecting from the facing walls. The keys of the arcades have figures in relief. In contact with the arches and the top of the gables is a projecting crowning cornice with a denticulated molding (Ferrari, 2022). A series of investigations revealed restoration works carried out on the first arch, on one of the aediculae and the ashlars of the outer shell (Fiorini, 2018). The bridge was digitally documented [1] using topographic and GPS surveying methodologies together with 3D laser scanning and digital photogrammetry (Bianchini et al., 2022).

The Rocca Possente in Stellata, Ferrara, Italy, is a defensive building built along the Po river (Fig. 2). It is a peculiar structure, the morphology of which derives from its original use (a fortress) set in a floodplain area of the Po River that was listed as a UNESCO heritage site in 1999. The fortress was destroyed and reconstructed several times, until it reached its current shape. The first construction dates back to the second half of the thirteen century, under Nicolò II d'Este, as part of an articulated defensive system, expanding a previous structure built around the year 1000. Rebuilt in 1557 under Ercole II d'Este, it was destroyed only a year later. Rebuilt again after being burnt down in 1510, it was demolished in 1587. The present building was realised at the behest of Pope Urban VIII in 1629 (Maietti, 2004). The shape of the three floors building is of a five-pointed star. The first floor is the extended buttress basement and the last one is terraced to allow a view of the floodplain.

The brick building was structurally damaged by the 2012 earthquake and underwent restoration and consolidation work completed in 2021 [2]. The 3D survey of the Rocca Possente started to analyse the interventions carried out over the centuries and after the earthquake, and to contribute to the assessment of vulnerability in case of extreme events, considering in particular possible floods since the fortress is located in a very peculiar context (floodplain area).

The additional analyses carried out to assess surface specifications were focused on degradations, since materials are quite homogeneous (bricks), while the state of conservation varies according to the expositions of the elevations. Also, the shape of the Rocca was an interesting element to assess the laser reaction, in terms of intensity values, having the structure very angled walls and narrow edges; according to different scan positions, the angle of laser impact was assessed as a variable for intensity value ranges.

Both databases were processed selecting radiometric features for segmenting specific areas corresponding to classification of materials and state of conservation (Fig. 3).

Figure 2 - Rocca Possente in Stellata, Ferrara. Photo by the authors.

APPLIED METHODOLOGY

The radiometric features selected for the algorithms processing are color data, expressed as RGB or HSV values, and the intensity value or reflectivity index. Generally, a point cloud obtained from a laser scanner survey always includes the intensity value, this being the numerical value recorded by the instrument's sensor (emitted signal) corresponding to the intensity of the reflected signal. Color data, on the other hand, may or may not be acquired, depending on the specific needs and purposes of the survey. When present, it is not necessarily reliable for the purposes of material and state of conservation analyses. In fact, the cameras associated with laser scanners have limitations, mainly due to the fact that the exposure cannot be fully controlled and the automatic 360° acquisition may unintentionally capture external

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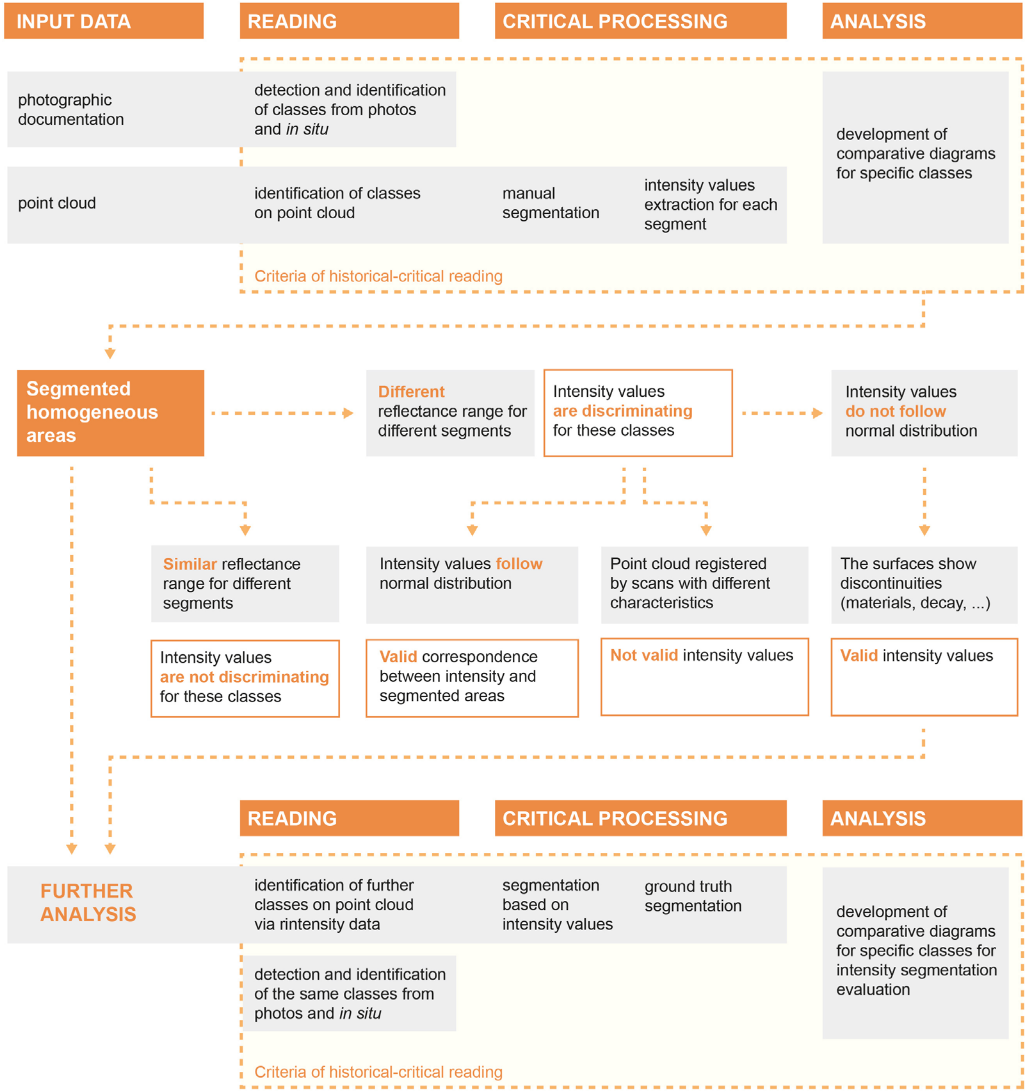

Figure 3 - Workflow and interpretation criteria for the use of the intensity value as a benchmark for historical surfaces assessment. Graphic elaborations by the authors.

objects interposed between the instruments and the object of the survey, and this can result in an improper coloring of the points. On the other hand, point clouds obtained from photomodelling processes do not include intensity value, but the RGB values are much more reliable and consistent, as they are derived from high-resolution photographs. The use of both components combined is therefore little explored. When working with intensity value, RGB values must be assumed to be not significant, if not unusable or absent. On the other hand, when working with solid RGB data, the intensity value would not be available. Since with the three RGB values (or HSV), more satisfactory results are obtained in terms of algorithmic prediction for the purposes of surface analysis, many more applications and experiments are to be found in the literature on clouds derived from photomodelling, thus lacking the intensity of the reflected signal.

In order to use both intensity value and color data effectively, it is therefore necessary to associate a more faithful RGB data with the points of a laser scanner cloud. Conversely, the possibility of transferring the intensity value from reflected signal to the photomodelling cloud, although technically feasible, is considered a less advantageous option because it would lose the geometric accuracy associated with the coordinates measured through LIDAR sensors. Indeed, point clouds from laser scanners are, in general, metrically more accurate than photogrammetric ones, as they consist of coordinates that are statistical values associated with measurements, not derived from probabilistic calculations, as is the case with Structure-from-Motion processes (Mora et al., 2019; Peterson et al., 2019).

Two different methodologies were explored to associate a consistent color data with the laser scanner point cloud. The first, in the case of the survey of the Tiberius Bridge in Rimini, consists in the coaxial photogrammetry procedure, where instead of using the camera integrated in the laser scanner instrument, a suitably calibrated camera was used. This, thanks a stand that, through support rods, allows the camera lens entry point to

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be alligned the instrumental center of the laser scanner, once the scan was performed and the instrument removed from the tripod. In this method, the photos are taken manually, thus controlling the exposure more and avoiding framing people interposed between the instrument and the surface to be surveyed (Fig. 4). A mid-range time-of-flight laser scanner (Leica HDS C10 - wavelength 532 nm visible) was employed to survey the external structures of the bridge, and a Canon EOS RP camera with 16mm fixed focal length was adopted for coaxial photogrammetry. It should be considered that a procedure of this type extends the acquisition time in situ.

The second methodology, applied in the case of the Rocca Possente in Stellata, is to survey the building both with a laser scanner and with digital photogrammetry and reproject the colors of the second point cloud onto the first (Fig. 5). For the laser scanning, again a Leica HDS C10 was used, and for the digital photogrammetry, the camera integrated in the DJI Mini 2 drone. As described above, due to the different nature of the source data and processing methods, these two point clouds will necessarily have deviations and dimensional variations between them. Reprojection produces a more satisfactory result the closer the two point clouds are. It is possible to reduce the deviations by correctly applying the surveying and data processing methodologies, by including an appropriate number of measured points within the structure-from-motion calculation. However, it is necessary to establish a tolerance threshold within which these deviations can be considered acceptable, depending on the scale and purpose of analysis.

Figure 4 - Tiberius Bridge in Rimini: visualization of time-of-flight laser scanner point cloud with color data associated thorough coaxial photogrammetry. RGB values (top) are added to point cloud with intensity data (bottom). Graphic elaborations by the authors.

Figure 5 - Rocca Possente in Stellata, Ferrara. Visualization of time-of-flight laser scanner point cloud with color data reprojected from photogrammetric point cloud. Reliable RGB values (left) are associated to a point cloud with intensity data (right). Graphic elaborations by the authors.

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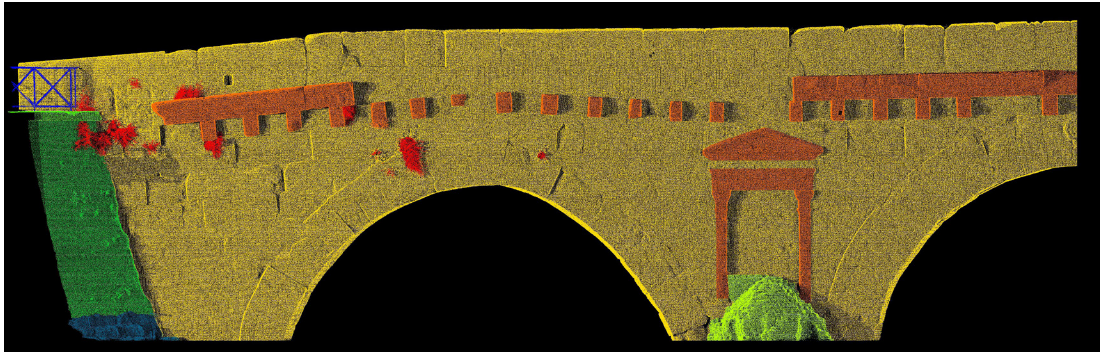
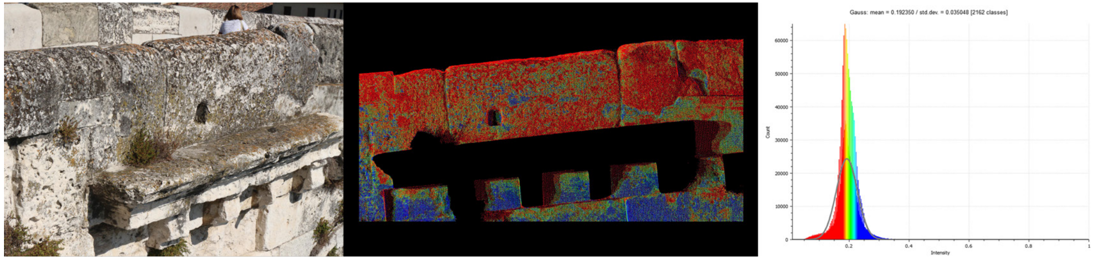


Figure 6 - Tiberius Bridge in Rimini: point cloud segmented according to materials and construction techniques. Graphic elaborations by the authors.

The reason for interest in testing the prediction algorithm also including intensity value lies in the fact that this value can, under certain conditions, provide indications about surface characteristics. The intensity value is determined by different factors, such as the material, the angle of incidence of the laser beam with the surface, and consequently reveals continuities and discontinuities in the surfaces, which can highlight material variations, different states of conservation and degradations. In addition to the other features, intensity can contribute to a more effective prediction.
In order to verify whether there is a significant link between the intensity value and the surface specifications to be researched, preliminary operations were carried out on several case studies, aimed at producing material samples and comparative diagrams. These case studies have the common feature of belonging to historical architectural contexts, so that the number of materials and construction techniques and the state of conservation were as diversified as possible, emphasizing both isolated and superimposed degradation conditions on historical surfaces. By extracting homogeneous samples per material and extrapolating the histograms of the intensity values of the selected points, it is possible to interpret the values, verifying whether or not there are discontinuities or anomalies in the trend of the graph. Possible incongruities must be further investigated, as may be caused by degradations altering the value of the reflected signal. All these operations should be carried out taking into account the different factors that make each point cloud unique, such as the characteristics of the building under analysis, the instruments and methods used for the survey, the different boundary conditions, etc.
The described procedure was applied on one and a half spans of the south elevation of the Tiberius Bridge. The point cloud was segmented manually according to the construction techniques (Fig. 6). This operation has a dual purpose: to manage the manually annotated portion of the model for algorithm training, and to identify homogeneous areas in which to cross-examine the intensity value.
As regards the first point, geometric features were calculated. The open-source software Cloudcompare makes it possible to calculate a series of parameters, such as roughness, planarity, verticality, etc., through a dedicated tool that performs mathematical operations based on the other characteristics of the coordinates (position and normal vectors). A first reasoning is to understand which features may be more representative and discriminating for the classes to be researched, in order not to risk "overfitting" the model and adding in-

Figure 7 - Comparative diagram for the main stonewall of Tiberius Bridge in Rimini. The non-normal distribution of the intensity values histogram may be given by decay pathologies of the surface. Graphic elaborations by the authors

Figure 8 - Comparative diagram for the main stonewall of Tiberius Bridge in Rimini. Visualization of intensity values range between 0.18 and 0.23. Decay pathologies such as deposit and biological crust, are visualized in red, clean surfaces in blue. Graphic elaborations by the authors.



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formation that is not useful, if not counterproductive. Secondly, it is necessary to establish the value of the radius of the surroundings to be imputed for the calculation of these features. This may vary depending on the type of feature to be calculated, the scale of analysis required, and the morphological characteristics of the surveyed object. The geometric features thus calculated are added to each point, and, together with the radiometric ones (intensity value and RGB associated with coaxial photogrammetry), the XYZ coordinates of the points and to the values of the components of the normal vectors, constitute the values on which to train and test the algorithm.

Concerning the second point, the Istrian stone samples of the bridge's decorative elements (cornice, aediculae) and block masonry were analyzed. From a visual investigation, several degradation pathologies are evident, such as coherent deposition, biological crust, erosion, presence of vegetation, etc. In fact, by extracting the graph of the intensity values present for each sample, a non-normal distribution of the histogram is observed (Fig. 7). By imposing a viewing range based on those values, these anomalies on the surface can be made explicit. Once an appropriate range has been identified, it is possible to split the point cloud according to the specific corresponding values, thus verifying in what percentage these values correspond, or not, to the degradation analyzed.

Once the range of intensity values corresponding to a specific degradation (according to visual investigation) has been traced, it is necessary to verify whether the points within this range belong significantly to that specific class or not. In the case of the Rocca Possente in Stellata a portion of the basement of the masonry, affected by different degradations of a biological nature, was examined. From the histogram analysis, it was possible to impose a viewing range that would highlight a specific class, i.e. the biological patina (Fig. 9). Subsequently, the cloud was segmented into two, one part inside the interval and one outside. The former should contain parts of the wall mainly affected by the searched decay, the latter should not. In order to verify this, a further segmentation of the cloud was performed on the basis of the RGB values of the point cloud, which could be considered sufficiently reliable because (I) they were obtained using the methodology described above and (II) for the sample under examination they were easily associated with the searched category. On the clouds obtained it is thus possible to calculate the points with and without degradation, displaying them in "false" colors for immediate perception (Fig. 10).

In numerical terms, the percentage of points with degradation present in the range is 83.25%, the percentage of points with degradation excluded from the range is 36.66%.

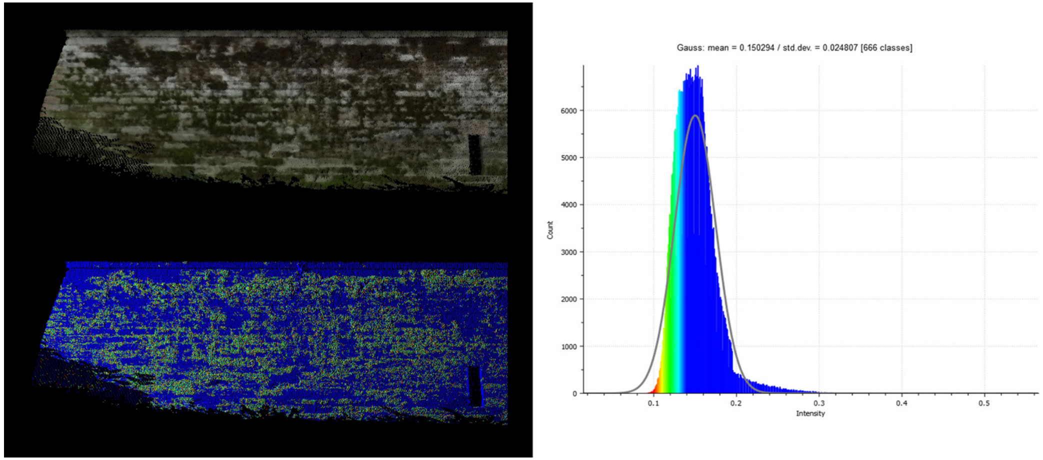

Figure 9 - Comparative diagram for the masonry wall in the basement of the Rocca Possente. Visualization of intensity values range between 0.10 and 0.14, highlighting some decay pathologies, mainly biological crust. Graphic elaborations by the authors.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The experiments carried out demonstrate, on the one hand, how the processing of digital data and associated radiometric features can open up many levels of investigation, useful to support the characterisation and mapping of the state of conservation or materials for computational and diagnostic purposes; on the other hand, the methodology requires further steps, as well as massive training data and dense cloud samples.

Regarding the source data (from laser scanner survey or digital photogrammetry), several issues are still open, since there are several factors that can influence the radiometric features.

For instance, in the case study of the main surface of the Tiberio bridge, the location in relation to the context made it difficult to approach and survey the surface by keeping the instrument "perpendicular" to it, except from fairly large distances. Thus, projecting elements, such as cornices and dentils, generate shadows on the plane behind, as they are surveyed from lateral positions with respect to the elevation. The intensity values of these areas can therefore be not valid or consistent for the assessment purposes, and should be excluded from the sample before extracting the histogram. This remark can be extended in general to other case studies; for this kind of analysis it might be more appropriate to work with single, non-unified scans, with data not "contaminated"

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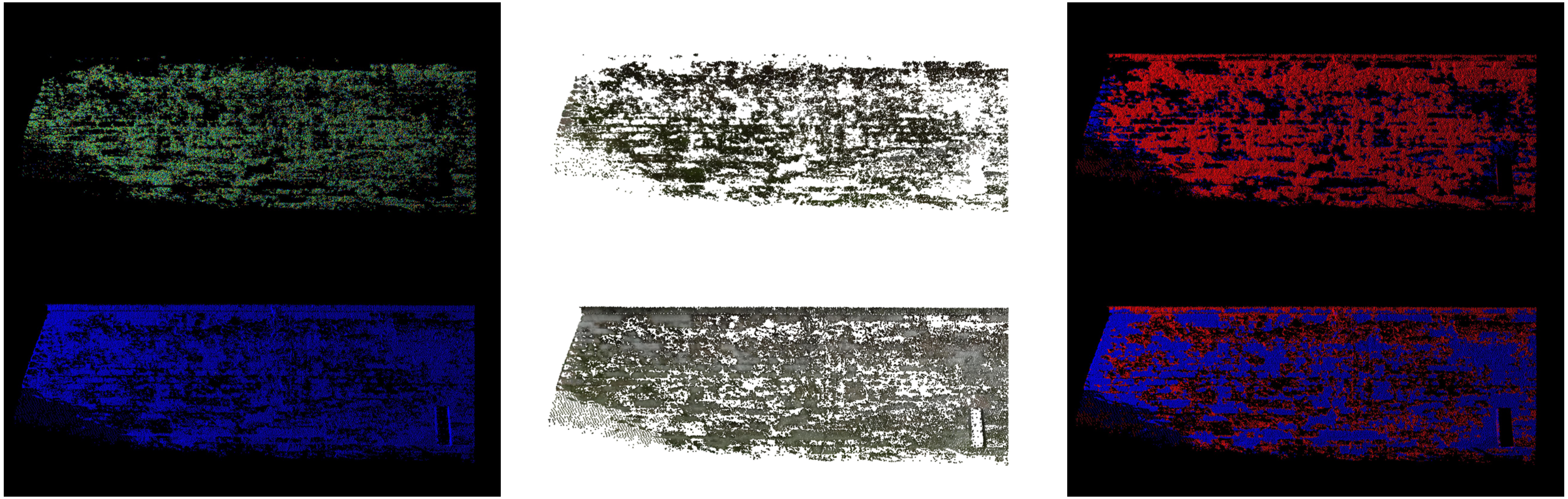
by data from other scan-stations, since the intensity also depends on the angle of incidence of the laser beam and the distance of the instrument from the surface, extending the obtained results to the entire model, where the intensity data could be inconsistent or altered.

Automatic segmentation leads to degrees of uncertainty to be fixed thorough further testing and samples. Future developments will be focused on the identification of intensity value “standard” ranges according to a set of criteria based on historical-critical knowledge and interpretation and by combining outcomes from diagnostic analysis, identifying additional classes.

Figure 10 - Point cloud segmentation according to intensity value ranges for surfaces with moss presence in the basement of Rocca Possente. Range between 0.10 - 0.14 and outside 0.10 - 0.14 (left); RGB visualization of the two clouds (middle); false colors visualization for moss presence in the point cloud with intensity range between 0.10 - 0.14 and outside 0.10 - 0.14 (right), degraded areas are red, non-degraded in blue. Graphic elaborations by the authors.



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AUTHORS CONTRIBUTION

Although the contribution was conceived jointly and written in close collaboration between the three authors, the authorship of the paragraphs is as follows: Federica Maietti is the author of paragraphs “Introduction” and “Research framework”. Guido Galvani is the author of the paragraph “Selected case studies”. Gabriele Giau is the author of paragraphs “Applied methodologies” and “Conclusions and future developments”.

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NOTE

[1] The research activities were carried out within the framework of the Sapienza University of Rome project "Integrated digital surveying, reconstruction and virtual dissemination as a form of knowledge of ancient Roman stone bridges in Rome and the provinces," components Profs. Tommaso Empler, Carlo Inglese (proposers), Leonardo Paris, Paola Quattrini; geom. Marco Di Giovanni, technical manager of Liralab Sapienza. Contributors: Wissam Wahbeh, Maria Laura Rossi, Adriana Caldarone, Francesca Pierdominici, Giulia Umana, Daniele Maiorino. The research group also includes Antonio Pizzo, scientific titular of Instituto de Arqueología-Mérida, CSIC-Spain. Integrated digital three-dimensional survey by DIAPReM/TekneHub, Scientific Coordinators: Marcello Balzani, Fabiana Raco, Technical Responsible: Guido Galvani, Research group: Gabriele Giau, Fabio Planu, Dario Rizzi, Luca Rossato.

[2] The 3D survey of the Rocca Possente in Stellata was carried out as part of the project "Firespill - Fostering Improved Reaction of cross-border Emergency Services and Prevention Increasing safety Level", among different case studies selected in cooperation with the Agency for Reconstruction of the Emilia-Romagna region in order to contribute to the improvement of risk prevention and management of mitigation actions, improving digital documentation with a perspective of integrating different data sources, experimenting acquisition protocols, and optimizing the use of technologies by territorial administrations with the objective of security management. The project was financed in the framework of the Cross-border Cooperation Programme Interreg V-A Italy-Croatia 2014-20 and developed by Emilia-Romagna Region Reconstruction Agency, the Regions of Abruzzo, Friuli Venezia-Giulia, Marche, Apulia and Veneto and the Croatian Counties of Split-Dalmatia (representing the Lead Partner, RERA S.D.), Istria, Ara, Sibenik-Knin and Dubrovnik.
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