The Chapel of Sant'Agata in Pisa. 3D surveying, Artificial Intelligence and archival heritage

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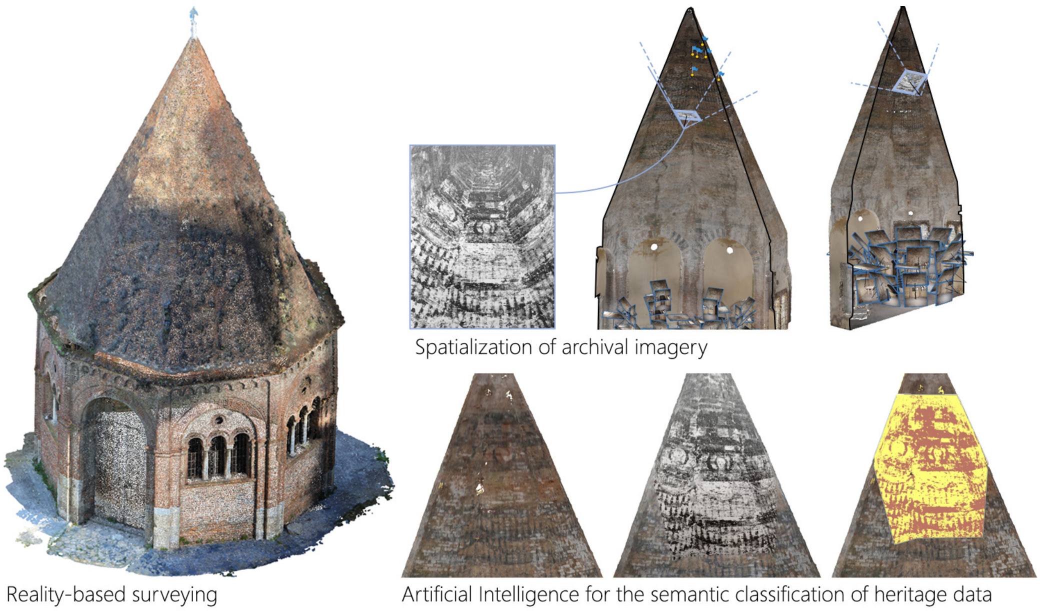
Abstract

In this contribution, 3D surveying, Artificial Intelligence and archival documentation are combined together for the documentation of different temporal states and deterioration processes of the interior walls of the Chapel of Sant'Agata in Pisa. The Chapel, located in the immediate vicinity of the Church of San Paolo a Ripa d'Arno, is of medieval origin. Its interior spaces have undergone a series of alterations, that modified over time the original layout and decorative apparatus. In the 1960s, an intense restoration activity brought to light the medieval frescoes of the Chapel, hidden under a thick layer of plaster. However, exposure to atmospheric agents and lack of maintenance have ruined those discovered walls, and only few traces of the ancient paintings are still visible today.
Starting from these considerations and exploiting the elaboration of both survey data and existing documentation, the aim of this work is to compare the different states of conservation of the Chapel's frescoes in time, even relying on semantic classification techniques leveraging Artificial Intelligence. The result is a project of spatialization and classification of 2D (images) and/or 3D (mesh, point clouds) colorimetric data that can be applied to other case studies, to analyze the evolution of the painted surfaces related to other objects making part of the historical-architectural heritage.

Keywords
Artificial Intelligence; 3D surveying; classification of archival images; architectural heritage; Cappella di Sant'Agata



Graphical abstract.

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Introduction

In recent years, the cultural heritage sector, on the one hand, has increasingly benefited from the use of incremental photogrammetric techniques for the spatialization of archival imagery [Bevilacqua et al. 2017; Manuel et al. 2013]. On the other hand, the exploitation of Artificial Intelligence (AI) techniques has allowed to improve and automate the interpretation of digital models [Fiorucci et al. 2020]. In application to 2D (images, orthophotos, UV maps) and 3D (point clouds, meshes) data, Machine Learning (ML) and its subset Deep Learning (DL) are emerging as effective tools to attribute semantic information to a set of otherwise unstructured data. The application of supervised ML approaches to the processing of survey data has indeed boosted some common semantic mapping processes, e.g., concerning the insertion of annotations related to degradation, pictorial elements or material types, by relying on a certain amount of training data while always pertaining a certain degree of supervision by an experienced operator. The so-called semantic segmentation process has so been understood as the reasoned subdivision of survey data on the basis of the more automated recognition of architectural components, degradation patterns or textures sharing common or at least similar features. Referring to a semi-automated semantic segmentation procedure for the enrichment of digital heritage data, purpose of this work is to analyze the evolution of the decorative apparatus of the remarkable case study of the Chapel of St. Agata in Pisa (figg. 01, 02) [1]. The result is a methodological approach that can be extended to other case studies, for the documentation of architectural objects characterized by a complex decorative and material apparatus, as well as by different temporal states that have altered over time the level of preservation, or even the presence, of some relevant elements and surfaces.

State-of-the-art

Recent developments of photogrammetry have revealed how digital 3D reconstructions can include archival documentation for the recovery of past architectural heritage. Metric knowledge can be extracted from archival data so to derive valuable information on the virtual restoration, anastylosis and reconstruction of destroyed or transformed objects, and also to compare previous and actual states of a building [Al Khalil, Grussenmeyer 2019; Croce et al. 2019]. Previous studies [Martinez Espejo Zaragoza et al. 2021; Bevilacqua et al. 2017] underlined the potentials of integrating existing surveying models with data coming from historic and archival photography, by appropriate spatialization of historic documentation within currently existing photogrammetric models. The calibration of the images and the orientation steps are fundamental in such pipelines, as the results are affected by the calculation of camera calibration information and by the appropriate detection of control

a. b. c.

Fig. 01.Texture-based approaches can be applied to images (a), ortho-photos (b) or UV maps (c).

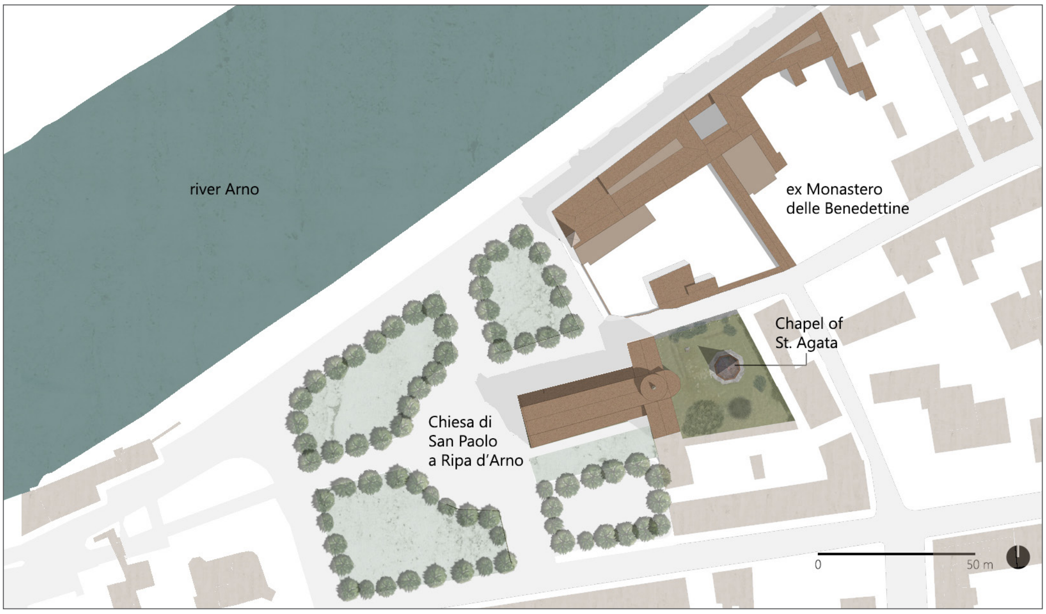


Fig. 02. Current in-plan configuration of the Chapel and spatial correlation with the Church of San Paolo a Ripa d'Arno. Adapted from the original drawing by L. Tenchini.

points between archival imagery-existing data [Condorelli, Rinaudo 2018]. If on the one hand historic images can be aligned on an already existing image sets (incremental alignment) [Pamart et al. 2019], on the other hand semantic segmentation techniques making the most of AI are being more and more exploited to improve photogrammetric models: Malinverni et al. [2019] tested several supervised and unsupervised strategies for the classification of architectural and archaeological scenes, and proved that supervised ML algorithms, as the RF generally outperform DL methods; Stathopoulou & Remondino [2019] considered the insertion of semantically labelled images to boost the dense reconstruction of a scene, in the pair selection, depth estimation and filtering phases. Murtiyoso & Grussenmeyer [2019] exploited deep learning-based semantic image segmentation and masking to create classified dense point clouds by exploitation of the photogrammetric process. A first effort towards the combination of historical photogrammetry with AI was presented by Condorelli & Rinaudo [2018], who experienced the use of DL methods for the metric reconstruction of no more existing buildings starting from historical film footages. However, the use of classified archival images to improve already created photogrammetric datasets has not been investigated yet but may be essential in supporting the visual and metric comparison between actual and previous states of a certain heritage object.

The Chapel of St. Agata in Pisa

The Chapel of St. Agata in Pisa, built on an octagonal plan, is located behind the apse of the Church of San Paolo a Ripa d'Arno, in Pisa. Its construction was ordered by the Vallombrosian monks of the adjacent church in the second half of the 11th century; initially connected to the church by medieval buildings, the chapel is now surrounded by public greenery and closed by perimetral masonry walls articulated by pillars, three-mullioned windows and under-roof arches. It concludes upwards with a spire. In the 1960s, the restoration works of the interiors, entailing the removal of the outermost layer of plaster that covered the original walls, led to the discovery of frescoes dating back to the end of the 13th century – beginning of the 14th century, and attributed to an anonymous Pisan master. Between the restoration works and today, a progressive loss of the discovered frescoes has occurred, even caused by the exposure of the chapel to the atmospheric agents. For this reason, although not being characterized by very large extension (in plan, the edges of the chapel are about 3 meters long while the internal diameter is about 7 meters), the case study is relevant as

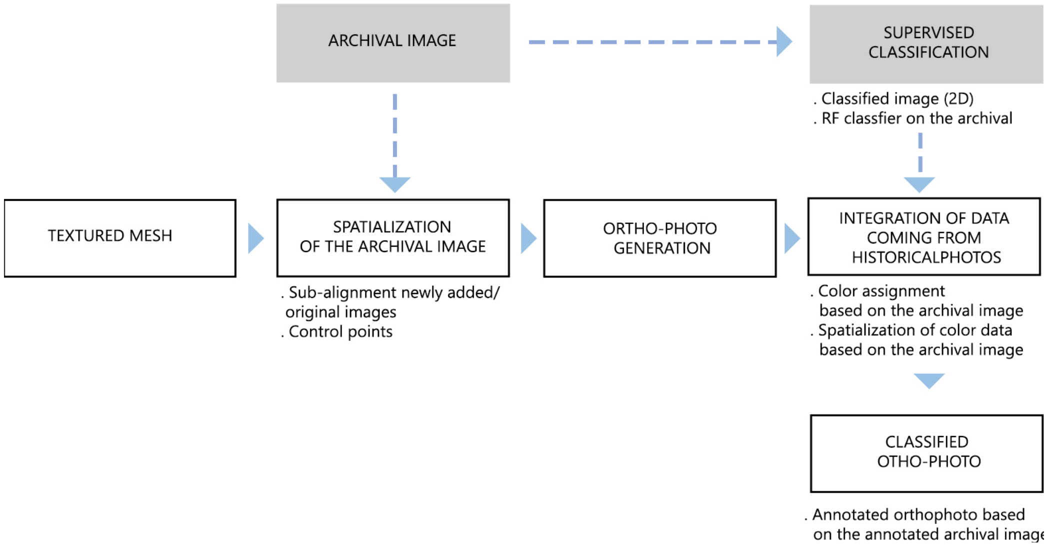


Fig. 03. Workflow of the proposed approach.

its investigation implies the comparison between the actual and previous condition of the building's internal space, in order to ensure the appropriate recognition of the parts of the brickwork that can be traced back to the original decorations. The Chapel is thus significative for the analysis of the integration between classification methods and archival imagery.

Workflow: from 3D surveying to data elaboration and spatialization

The data acquisition campaign for the Chapel of St. Agata was conducted back in the years 2016 and 2017, in the framework of a joint research project [2] aiming at the metric and graphical documentation of the monument. The architectural surveying, involving both laser scanning and photogrammetric techniques, was performed to collect aesthetic and formal connotations of the object.
As expressed by Bevilacqua et al. [2017] and Tenchini [2016] – to which the reader can refer for further details on the surveying process –, the results of the acquisition campaign were provided in the form of graphical documents at scale 1:25, and a first exploration on the integration of the surveying outputs with data derived from historic archival imagery was presented, towards the comprehension of actual/past conditions of the inner wall paintings of the Chapel.
Starting from these survey data, and more specifically leveraging the photogrammetric survey, a semantic classification is performed for the Chapel under study, for a more automated description of both:

i) the current level of advanced degradation;
ii) the alterations, in terms of material mapping and decay, that the interior walls of the Chapel have underwent in the period between the 1960s (restoration works) and today (current, existing state).

The different phases of the workflow are summarized in fig. 03 and the related results are illustrated in the next sections. At first, the semantic classification is performed on UV maps or orthophotos obtained from the photographic campaign of years 2016-2017. The classes of degradation or material in which the photogrammetric model of the actual state is to be subdivided are identified on the digital support, by annotating a small portion of the ortho-photo. Then, a suitable set of features is chosen as additional stack of images that help the classification. Based on the provided data samples and on the extracted features, a supervised ML algorithm, the RF, is trained to classify the remaining part of the dataset.

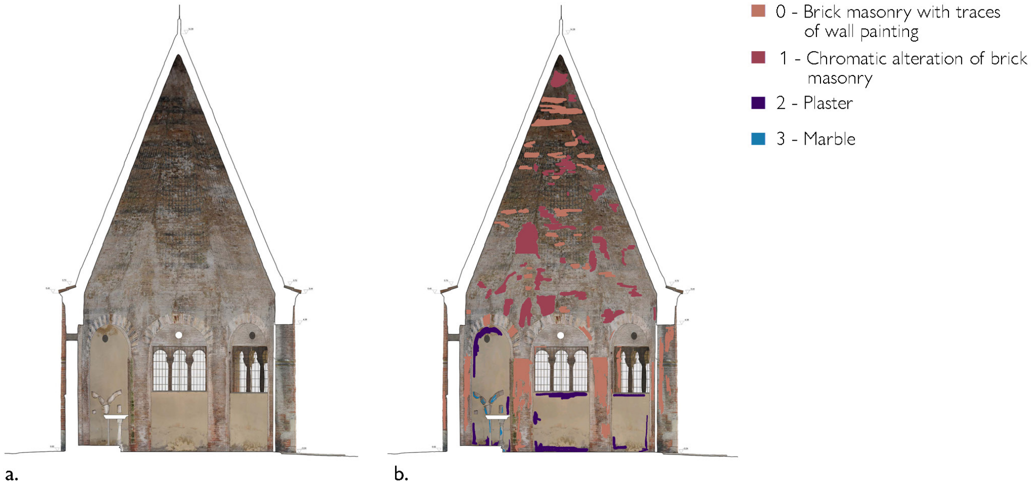


Fig. 04. Section of the chapel (a, drawing by L. Tenchini) and manually-annotated training set with related legend (b).

To assess the classification result obtained, a confusion matrix and common performance metrics used in the AI domain are extracted from a validation set (accuracy, F-measure, precision and recall) [Matrone et al. 2020]. In a second phase, archival images (related to the wall paintings of the interior of the church found in the '60s) are in turn classified, considering once again a series of appropri- ate features and a suitable training set in order to distinguish, over the interior surface of the Chapel, the areas that previously exhibited traces of mural painting.
The semantic segmentation is run in this case on the archival image, and the related classification results (i.e., the classification information for the previous state) are finally projected back onto the photogrammetric model, by exploiting 2D/3D projective relationships.
A comparison of the frescoes at the time they were found in the 1960s (archival and historic imagery for the previous state) and in the actual condition (photogrammetric model and images of the current state), respectively, can be derived in consequence.

Traces of decorative paintings of the internal walls

At first, the semi-automatic annotation method exploiting AI is performed solely considering the photogrammetric model of the current state of the Chapel. As for the example of fig. 04, the annotation of decorated and non-decorated parts is performed over a section of the building, derived from the elaboration of the ortho-mosaic of the photogrammetric model (fig. 04a).
In the training phase, four annotation classes are manually identified on a portion of the ortho-photo and associated to dedicated colours and labels (fig. 04b): brick masonry still presenting traces of wall painting (class 0), chromatic alteration of brick masonry (1), plaster (2) and marble (3). The white background of the ortho-photo is excluded from the classification.

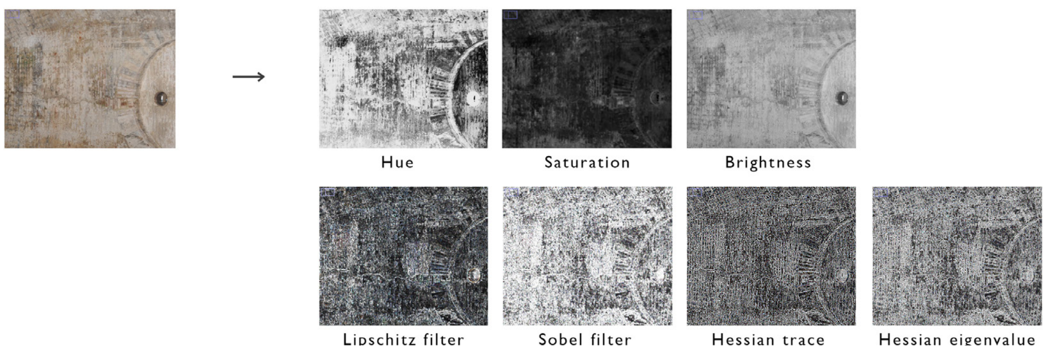


Fig. 05. Image adjustments, edge-detection and noise-reduction filters extracted from the input image.

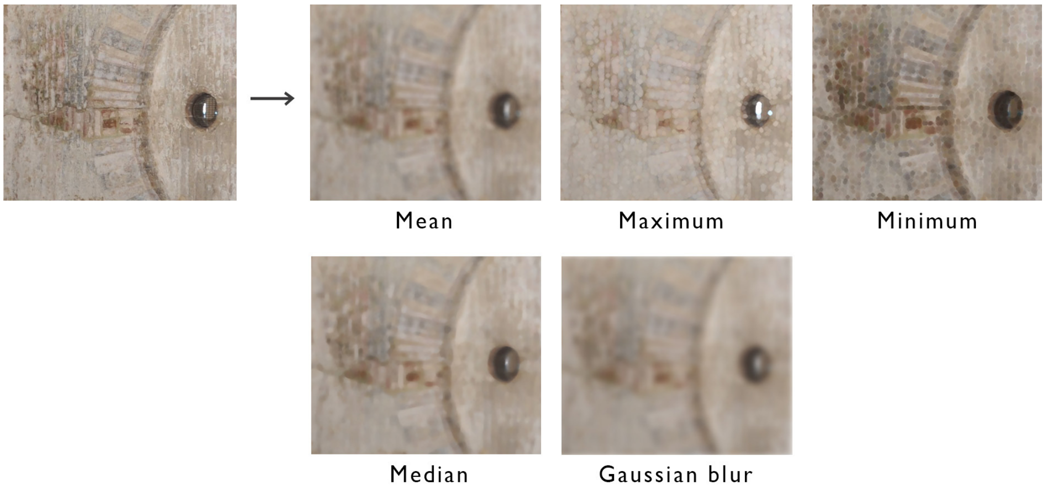


Fig. 06. Texture filters extracted from the input image.

The portion of annotated data of fig. 04b constitutes a set of data samples used for learning. It is associated with the extraction of pertinent features, including image adjustments, edge-detection, and noise-reduction filters (fig. 05) as well as texture filters (fig. 06).
The results of the automatic annotation by RF training are provided in fig. 07 and may be displayed in transparency over the input data. The distinction between parts of brick altered by the presence of plaster (chromatic alteration) and parts of brick where traces of the original frescoes are still recognizable is graphically highlighted by colour maps. In order to validate the classification results, the automatic annotation is compared to the manual annotation on a portion of the data (validation set of fig. 08a-08c). The graphical comparison between true and predicted labels, resulting from the juxtaposition of the two images, is provided in fig. 09: the false colours denote the difference between true and predicted classes. From the comparison between these data, the confusion matrix and related performance measures are also extracted. The rows and columns of the confusion matrix provide, for each class, the number of correctly and incorrectly classified pixels, respectively (fig. 09). The results show optimal values of accuracy and precision, on the order of 90%.
In addition, compared to the manual approach, the supervised automatic classification allows to describe more details and differences in the material composition of the surfaces, and it requires a remarkably low amount of time (almost 30 minutes for the training and classification time against the manual annotation time of the whole orthophoto, which would require, to an estimate, from 6 to 9 hours).

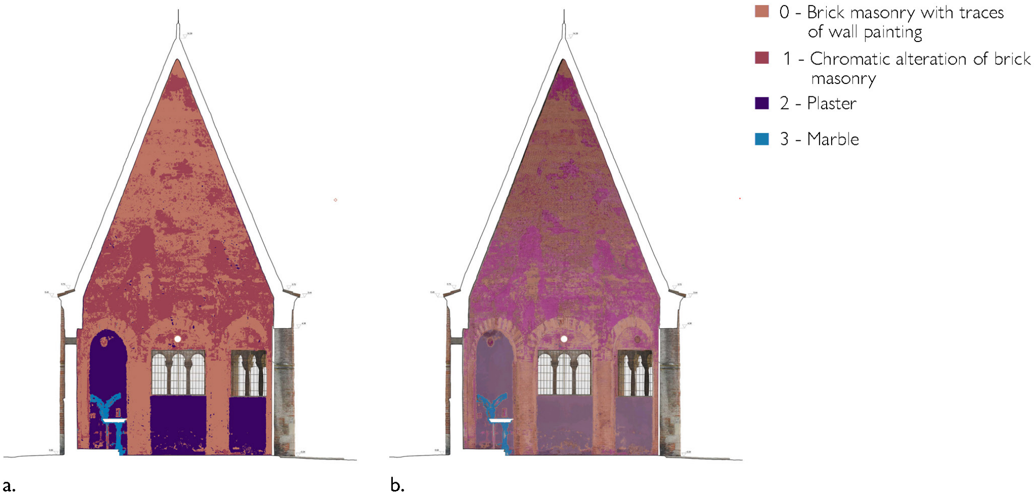
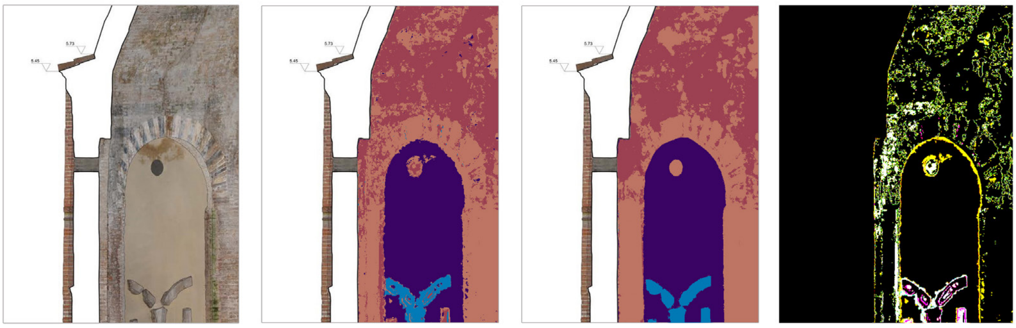


Fig. 07. Semantic segmentation results for a section of the Cappella di Sant'Agata in Pisa, in opacity (a) and in transparency (b).



a. b. c. d.

Fig. 08. Validation set (a). Comparison between predicted (b) and true (manually-annotated, c) labels, and false colors map highlighting the differences between one class and another (d).

	0	1	2	3	Recall	Precision	Accuracy	F1-score
0 - Brick masonry with traces of wall painting	76161	7413	559	25	90,50%	89,04%	93,01%	89,76%
1 - Chromatic alteration of brick masonry	6381	73752	16	3	92,02%	90,17%	94,19%	91,08%
2 - Plaster	2652	199	74555	1020	95,06%	99,03%	98,15%	97,01%
3 - Marble	346	428	157	4905	84,05%	82,40%	99,20%	83,21%
Average					90,41%	90,16%	96,14%	90,27%

Fig. 09. Confusion matrix and related performance measures extracted based on the validation set.

The control, by the operator, of the annotated data, and the eventual refinement, if needed, of some not correctly classified parts, could be further considered to optimize both results and classification times, still in the perspective of a supervised approach.

Comparison of conservation states over time

In this phase, the extra images are sub-aligned to the set of already aligned images, and the orientation parameters and shooting geometry of the cameras are consequently derived by appropriate insertion of control points, identified both in the added image as well as in the original ones (fig. 10). If the spatialization of the archival image is feasible, then the semantic information can be propagated from the newly added image to the rest of the (existing) image set, as well as to the 3D model. For the example of the Chapel of St. Agata, the insertion of additional images [Burresi, Caleca 2003], dating back to the 1960s, allows to characterize the original frescoes found on the inside cusp, as well as to compare them with the current situation of the walls, affected by advanced degradation patterns [Bevilacqua et al. 2017]. By evaluating the actual and previous states of the wall and by generating an orthophoto of the 3D model in the two respective conditions, a classification approach is applied to compare the mural traces of the 1960s and of today, respectively. The results are provided in fig. 11, and the segmentation of the archival image reveals the lost wall traces over the ortho-photo (fig. 11 c).

Conclusions

This work presented a classification-based methodology for the comparison between actual and previous states of a building. The comparison is derived by making use of AI- based semantic segmentation methods and by leveraging incremental photogrammetry for the spatialization of archival images on an already existing set of images.

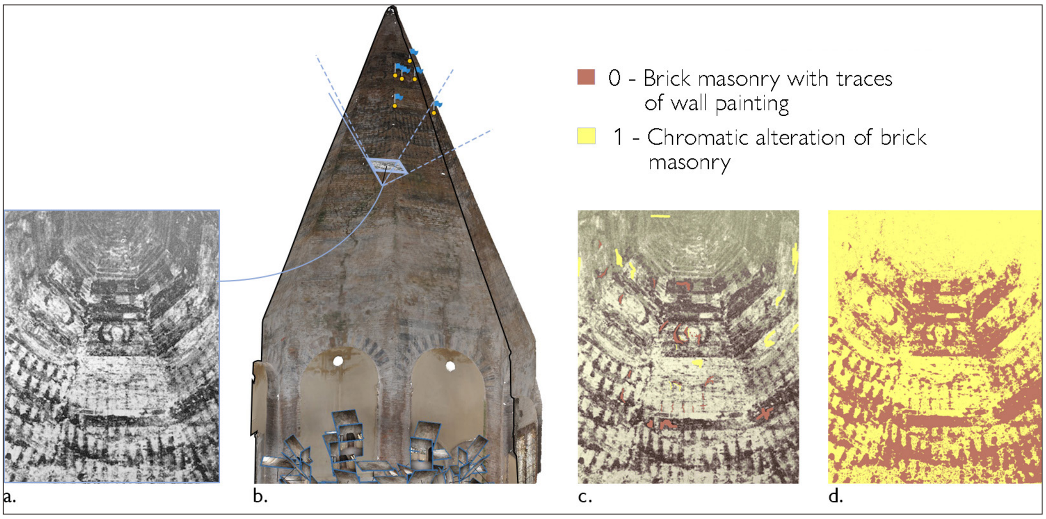


Fig. 10. Spatialization of archival images. The input archival image (a) is suitably inserted within the existing -actual- photogrammetric model (b). The archival image is then trained (c) and classified (d).

The application to the case study of the Chapel of Sant'Agata in Pisa is representative of the methodology, as the integration between archival imagery, 3D surveying, and AI classification approaches allows to better describe and characterize the state of conservations of the building's interiors over time. The reality-based model of the Chapel is considered to compare the actual condition of the interior frescoes with the situation that existed at the time the frescoes were discovered, in the late 1960s. The temporal evolution of the frescoes is depicted by providing the evidence of previous wall traces, and by leveraging a semantic segmentation process. Considering the importance of the integration of such techniques, future work on this topic goes in the direction of a deeper fusion between 3D models, images, temporal states and classification techniques. In detail, the author is currently working on the construction of a dedicated application in which the reality-based model derived from surveying and the classification information derived from the study of archival documentation can be directly accessed, integrated and visualized. In such immersive experience, the integration and dissemination of reality-based models and classification results may be achieved by considering advanced real-time visualization tools as Unreal Engine (fig. 12).

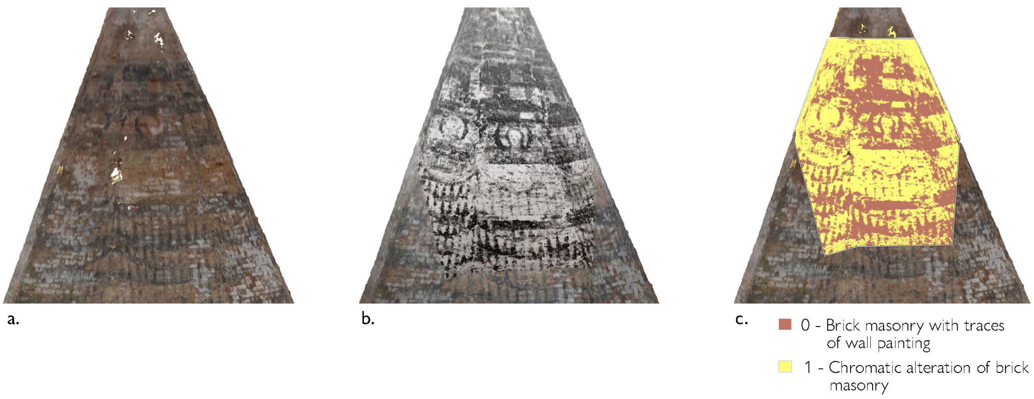


Fig. 11. Portion of the ortho-photo of the interior walls of the chapel: actual condition (a); spatialization of the archival image (b); evidence of previous wall traces highlighted by segmentation and projection of the archival image over the ortho-mosaic (c).

Fig. 12. A digital rendering of the reality-based model of the Chapel via Unreal Engine, toward the integration and dissemination of the classification results within Virtual Reality applications.

Notes

[1] This study is part of a larger research project, carried out in the framework of a Ph.D. thesis, on the semantic annotation transfer and retrieval for architectural heritage by combination of Artificial Intelligence, H-BIM and collaborative reality-based annotation platforms. The Ph.D. thesis involves, in the framework of a co-tutelle agreement, the Universities of Pisa and Florence, the Ecole Nationale Supérieure d'Arts et Métiers in Aix-en-Provence, the MAP laboratory (Modèles et Simulations pour l'Architecture et le Patrimoine) of the CNRS in Marseille and the Université Franco-Italienne.
[2] The joint research project involving the Municipality of Pisa and the University of Pisa was documented in the M.Sc. thesis by Lavinia Tenchini [2017].

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