Digital Innovations in Architecture,
Engineering and Construction

Andrea Giordano
Michele Russo
Roberta Spallone *Editors*

Beyond Digital Representation

Advanced Experiences in AR and AI for Cultural Heritage and Innovative Design

Springer

Digital Innovations in Architecture, Engineering and Construction

The Architecture, Engineering and Construction (AEC) industry is experiencing an unprecedented transformation from conventional labor-intensive activities to automation using innovative digital technologies and processes. This new paradigm also requires systemic changes focused on social, economic and sustainability aspects. Within the scope of Industry 4.0, digital technologies are a key factor in interconnecting information between the physical built environment and the digital virtual ecosystem. The most advanced virtual ecosystems allow to simulate the built to enable a real-time data-driven decision-making. This Book Series promotes and expedites the dissemination of recent research, advances, and applications in the field of digital innovations in the AEC industry. Topics of interest include but are not limited to:

- Industrialization: digital fabrication, modularization, cobotics, lean.
- Material innovations: bio-inspired, nano and recycled materials.
- Reality capture: computer vision, photogrammetry, laser scanning, drones.
- Extended reality: augmented, virtual and mixed reality.
- Sustainability and circular building economy.
- Interoperability: building/city information modeling.
- Interactive and adaptive architecture.
- Computational design: data-driven, generative and performance-based design.
- Simulation and analysis: digital twins, virtual cities.
- Data analytics: artificial intelligence, machine/deep learning.
- Health and safety: mobile and wearable devices, QR codes, RFID.
- Big data: GIS, IoT, sensors, cloud computing.
- Smart transactions, cybersecurity, gamification, blockchain.
- Quality and project management, business models, legal prospective.
- Risk and disaster management.

Andrea Giordano · Michele Russo ·
Roberta Spallone
Editors

Beyond Digital Representation

Advanced Experiences in AR and AI for Cultural Heritage and Innovative Design

Springer

Editors
Andrea Giordano
DICEA
Università di Padova
Padua, Italy

Michele Russo
DSDRA
Sapienza Università di Roma
Rome, Italy

Roberta Spallone
DAD
Politecnico di Torino
Turin, Italy

ISSN 2731-7269 ISSN 2731-7277 (electronic)
Digital Innovations in Architecture, Engineering and Construction
ISBN 978-3-031-36154-8 ISBN 978-3-031-36155-5 (eBook)
https://doi.org/10.1007/978-3-031-36155-5

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

AR&AI and Historical Sources

AR&AI and Museum Heritage

AR&AI and Heritage Routes

AR&AI and Classification/3D Analysis

AR&AI and Education/Shape Representation

AR&AI and Building Monitoring

Monitoring Systems Design with Real Time Interactive 3D and Artificial Intelligence

Valeria Cera and Antonio Origlia

1 Introduction

The paper presents the topic of Environmental Artificial Intelligence, a naming used to indicate Artificial Intelligence approaches, based on the use of natural language, applied to architecture to support the design and operation of systems to control the progress of degenerative states through simulations in a digital environment i.e., employing real-time interactive 3D models.

This is a field of research that the group of the Department of Architecture of the University of Naples Federico II, coordinated by Prof. M. Campi and A. di Luggo, in collaboration with the group of the Department of Electrical Engineering and Information Technology, coordinated by Prof. F. Cutugno, is developing in several ways.

The issue of monitoring the manifestations of decay affecting the built environment, in its most superficial to structural components, is now one of the main topics of experimentation in the scientific community. In fact, the concept of Preventive Conservation, i.e., the tendency to study processes that are able to inform on the state of health of the heritage and monitor it over time, acquiring—through the use of various types of sensors—useful data to guide the diagnostic investigation in a non-invasive manner [1–4], has been affirmed in the last five years. In this sense, interesting are the potentials that, through some research, are emerging with respect

---

V. Cera (✉)
Department of Architecture, University of Naples Federico II, Naples, Italy
e-mail: valeria.cera@unina.it

A. Origlia
Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy
e-mail: antonio.origlia@unina.it

A. Giordano et al. (eds.), *Beyond Digital Representation*, Digital Innovations in Architecture, Engineering and Construction,
https://doi.org/10.1007/978-3-031-36155-5_46

to the use of AI approaches in tracking the prediction of future damage so as to anticipate interventions [5–7].

This is the context for the research presented, which is distinguished by 2 specific aspects: (1) the use of semantic maps to prioritize conservation actions and thus return information on the severity of the damage detected, weighted against the real urgency of intervention; (2) the use of 3D, interactive real-time applications integrated with natural language-based AI systems to, on the one hand, optimize the installation of the monitoring system through digital simulations of its operation; and on the other hand, inform users of the detection of a potentially dangerous change by interacting with them through verbal communication. To this end, the study is organized into 3 macro-actions: (i) Multiscalar digitization and hetero-informative characterization of the semantically annotated cultural heritage artifact; (ii) Design of the remote monitoring system and digital simulation of its operation through integration with AI modules; and (iii) Testing of the infrastructure and scenario simulations for in situ implementation and to guide preventive conservation actions (Fig. 1).

The first and second phases of the project will be explicated here: the objective is the design of the installation of sensors (in this case, RGB chambers) for the monitoring and verification of an AI system that signals, by dialoguing with an expert user, the progress of degenerative states that are evaluated as potentially dangerous and automatically detected. The actions were conducted on the case study of the Cathedral of Padula, a church datable around the ninth-tenth centuries, affected by phenomena of both plaster detachment and surface deposition of frescoes at the intrados of the vaulted systems, for which cognitive actions have been initiated as early as 2019.

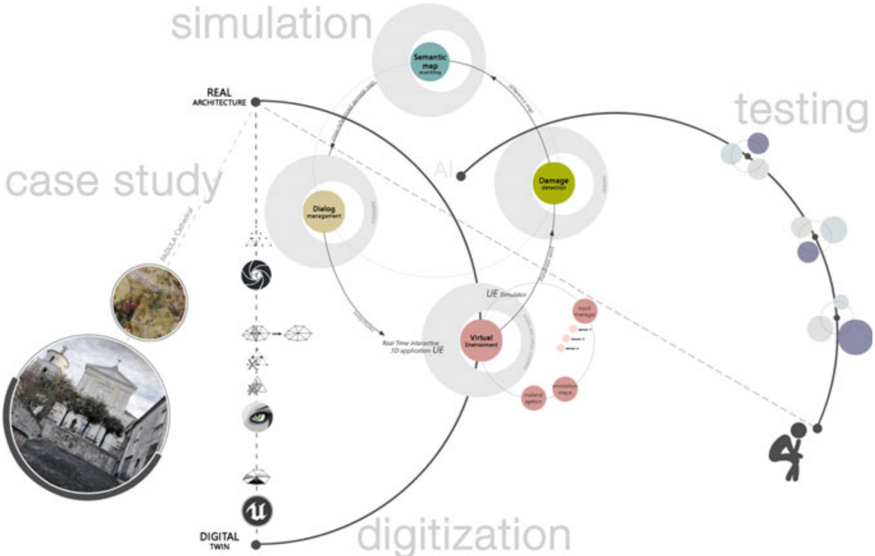


Fig. 1 Research workflow. *Image* V. Cera, A. Origlia

2 Modeling and Characterization of the Digital Environment

To pursue the research objective, it was decided to take advantage of the potential offered by 3D modeling and digital environments to conduct simulations by exploiting real-time interactive 3D models. To be able to test the infrastructure of the control system, the digital environment must be characterized from an informational point of view so as to provide the system with the necessary data to determine the state of preservation of the investigated artifact at a time T0, the initial time of the observation process, and a comparison term for the detection of anomalies. Finally, to support the detection of any progress of phenomena judged to be damaging, semantic annotation of the three-dimensional information model is essential for the reporting of problems that have been evaluated and indicated as such to the user interfacing with the system, based on a hierarchical order of importance.

2.1 Multiscalar Digitization

The first action of the research involved the digitization of the case study.

Evidently, in order to set up a digital environment in which to plan the architecture of a remote control system of the variables and related parameters that influence the state of preservation of the examined artifact, the digitization actions were oriented to the construction of its multiscalar representation. In fact, by articulating the acquisition processes from the macro to the micro scale, it is possible to achieve the construction of a restitutive digital replica of the real architectural configuration of the studied asset, in its most detailed characteristics. This condition is necessary for the arrangement of monitoring systems that, aspiring to inform on the negative evolution of degenerative states, must be based on a particularly large and specified body of information. To meet these objectives, the survey campaign was declined into 3 operational phases: (i) range-based survey with a phase-modulation sensor to acquire a general point cloud of the church; (ii) range-based survey with an optical triangulation system to refine the geometric datum for specific portions; (iii) detailed image-based survey to refine the colorimetric datum.

(i) A TLS Faro Focus3D X330 was employed to survey the entire religious complex by making an orderly and constant acquisition network evenly distributed in the space of the cathedral. Therefore, with a maximum controlled distance between range maps of about 10 m, 37 scans characterized by an average point discretization of 6 mm/10 m, considered suitable for digitizing an interior full of carved decorations and ornaments, were made (Fig. 2a). The individual point clouds were aligned in the proprietary FAROScene software, with the well-known best-fitting procedures of geometric primitives—such as planes and spheres—corresponding to the specific targets used in the capture phase. The tension recorded at the end of the procedure was on the order of a millimeter, with no alignment errors. The final registration

Fig. 2 Data acquisition schemes with TLS (**a**) and hand-held scanners (**b**). *Image* V. Cera, A. Origlia

returned an overall cloud of 240,000,000 points with origin expressed in a local reference system, coincident with that of station No. 1, assumed as the basis for roto-translation of the range maps.

(ii) Having set up a general restitutive model of the morpho-metric specificities of the cathedral, the information base was deepened—in terms of accuracy and metric-formal precision—for those elements particularly significant for its architectural characterization such as: the pulpit, the stoup, the tabernacle and the sculptural collections. Therefore, the previous model was integrated with acquisitions using a portable optical triangulation scanner, the FARO Freestyle3D. Given the dimensions of the elements involved in the detail digitization, it was possible to manage the data recording in a single scan returning a single, complete point cloud for each object. Acquisition was conducted by following a nearly helical trajectory with the sensor, with circular movements around the individual artifact, maintaining a distance from it of about 0.50 m (Fig. 2b). In the trajectory, the hand-held scanner was oriented perpendicular to the lie of the dominant planes (for objects distinguished by flat facades) by integrating the capture with acquisitions at different angles of incidence. The goal was to compose point clouds as void-free as possible.

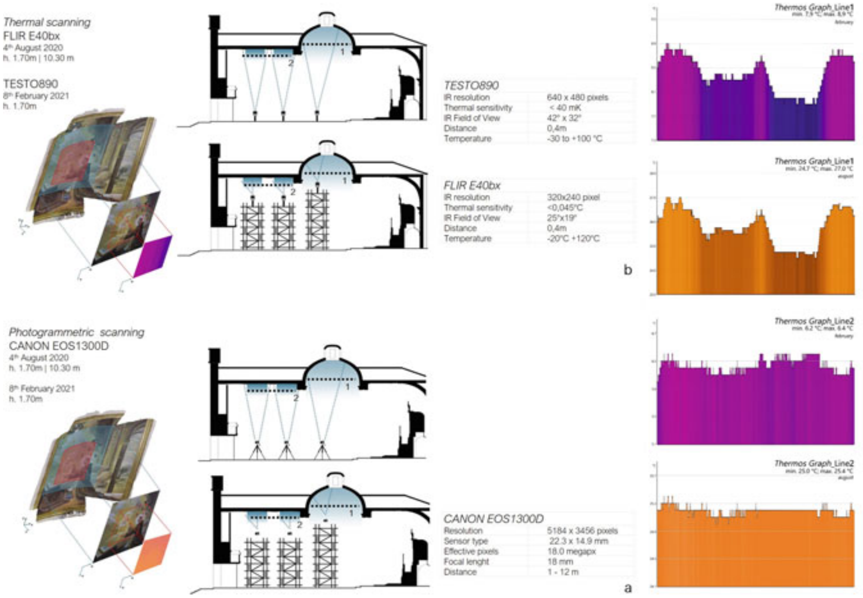
Due to the colorimetric characteristics of the digitized artifacts, which are connoted by non-homogeneous chromatics, it was not necessary to use targets during the scans. In fact, the variability of colors easily allowed the acquisition system to maintain stable tracking by taking advantage of texture diversity. All data acquisition and processing were performed with the proprietary applications: Scene Capture (for acquisition only) and Scene Process (for post-processing). As is well known, point cloud reconstruction is done in real-time and is based on the detection of common points used for the correlation of successive images. No reconstruction errors or gaps were recorded during acquisition but, before saving and exporting the recorded cloud, the raw data were post-processed to improve the quality of the result by filtering the point cloud so as to reduce noise as well as optimizing the scan trajectory.

(iii) Referring to the quality of the colorimetric datum of the surface texture, the collection of survey data was refined with an image-based activity conducted both for the sculptural and architectural elements mentioned in the previous point, and for the fresco cycle of the vaulted systems. Wanting to set up a control system referring to the progress of decay phenomena that, at present, affect the surface layer of the frescoed walls, as previously reported, the color data becomes a key component to be recorded. Any changes in its parameters can, in fact, be indicative of the presence of ongoing events that need attention. Employing a CanonEos1300D SLR camera set with a focal length of 18 mm, the photographic dataset related to the pulpit, stoup, tabernacle, some minor altars, and sculptural collections was collected. Adopting parallel axis shooting techniques combined with that of converging axes, shots were recorded using a telescopic pole for the taller architectural elements. As will be clarified in the next subsection, the collection of frames for the pictorial cycle at the intrados of the vaulted systems was conducted, however, at the same time as the recording of thermal images. In this way, it was possible to collect digital documentation that was already partially integrated and overlaid for subsequent interrogation and manipulation. Once again, the SLR was used with which the shots were acquired at different heights: for an initial collection of data, the camera was placed on a tripod at approximately 1.70 m above the floor level of the church, with a distance of about 11 m from the frescoes of the vault and about 15.50 m for those of the dome; the subsequent shooting was carried out with the help of a scaffold on which it was possible to take acquisitions with a height from the ground of 10.30 m and, therefore, closer to the deteriorated surfaces, with a distance of about 2.80 m from the walls (Fig. 3a). The choice of focal length was commensurate with the characteristics of the field of view of the sensors used for the subsequent capture of information on the thermal state of the surfaces. Therefore, respecting the usual overlap percentage between successive images of 60%, the following were captured: 35 photos for each fresco of the nave vault and 25 for the dome, from the height of the scaffold; 23 photos for the paintings of the vault and 14 for those decorating the dome, from the ground.

The datasets collected in the 3 operational phases described so far were integrated with each other to obtain a single 3-dimensional model, through processing in the RealityCapture application.

Specifically, the range maps of the TLS, previously aligned and registered in the proprietary software, were imported into RC in.ptx format, setting as 'Draft' the relationship between the scans to be imported so as to employ, in subsequent steps, the initial registration as a starting point to be refined. Information on the intensity of the scans was acquired at the same time as the colorimetric indications. A similar procedure was performed for the clouds from the triangulation scanner. Next, the frames captured with the passive sensor were imported.

Next, all datasets were subjected to an initial joint alignment process for automatic computation of their position and orientation in the scene. The integrated point cloud thus obtained was, then, subjected to triangulation for the generation of a polygonal



TESTO890	
IR resolution	640 x 480 pixels
Thermal sensitivity	< 40 mK
IR Field of View	42° x 32°
Distance	0,4m
Temperature	-30 to +100 °C

FLIR E40bx	
IR resolution	320x240 pixel
Thermal sensitivity	<0,045°C
IR Field of View	25°x19°
Distance	0,4m
Temperature	-20°C +120°C

CANON EOS1300D	
Resolution	5184 x 3456 pixels
Sensor type	22.3 x 14.9 mm
Effective pixels	18.0 megapx
Focal lenght	18 mm
Distance	1 - 12 m

Fig. 3 Data acquisition with photogrammetric technique (**a**) and with thermal cameras (**b**). Diagrams related to the thermal state of the frescoes (**c**). *Image* V. Cera, A. Origlia

mesh model. Having defined the spatial reconstruction region by excluding some spurious points near the church windows from the calculation, the computational parameters were specified. Considering the huge amount of data collected, a slightly undersampled point cloud was chosen to be triangulated. The density of the cloud was filtered by establishing a minimum distance between two successive points of 0.002 m and requiring that points with an intensity below 0.03 be discarded because they were considered inaccurate. From the streamlined data, the polygonal surface was generated, choosing laser scans as the information to be considered for reconstruction and instructing the application to take into account in the process only those images taken covering areas not recorded with the active optical sensors. This choice was motivated by the desire to obtain a triangular mesh distinguished by as accurate and precise a geometry as possible.

Once edited, the mesh was textured by setting the texture information calculation method to 'multi-band' for the highest quality output. In order to achieve an effective representation of the visual qualities of the architecture, both images acquired from the camera embedded in the laser scanner and photos taken with the external camera were specified as input resources, with priority given to the latter for areas of greatest interest for research purposes. The downscale of the images for the coloring process was set to 2, to speed up the process, but without enabling the intuitive fill function for the parts not perfectly covered by a camera or scan so as not to alter the colorimetric data. For texturing, the maximum texture resolution was set at 16,384 × 16,384, and an image reduction before texturing of 2. At the conclusion of the whole process, the model was imported into Unreal Engine 5 software, which was chosen for the simulation of the monitoring system and integration with AI modules, as will be discussed below.

2.2 Informative Characterization of the Digital Environment: State of Conservation at Time T0

In order to simulate and subsequently validate the operation of the control system, prior to its installation in situ, the reconstructed digital environment must be characterized from an informational point of view. That is, it is necessary to collect a body of data that allows to establish the state of preservation of the investigated artifact at a time that can be defined as T0, or the initial time of observation, which will be referred to for the evaluation of the progress of decay phenomena. It is evident that in the multiplicity of factors, elements, aspects, resources that characterize an architecture (consider the technological, structural, energetic as well as historical and engineering aspects), only a few have been considered here (surface thermal state, microclimate humidity value, material, and color components) functional to the type of investigation hypothesized and related to the alteration phenomena that motivated the study. Therefore, the extension of the information base was divided into 4 actions, performed for the areas that at the beginning of the research showed the presence of pathological states (cover frescoes): (i) acquisition and analysis of infrared images using a thermal imaging camera to determine the thermal state of the deteriorated surfaces; (ii) cataloguing and mapping of materials by visual survey and manipulation of reflectance maps; (iii) cataloguing of color parameters associated with the materials; (iv) cataloguing and mapping of the degradation phenomena already in progress, characterized both qualitatively and quantitatively with the study of geometric deviation and direct investigation.

(i) The determination of the thermal state of the deteriorated surfaces was carried out from the recording of infrared images by thermal imaging camera, collected at 2 different times, summer and winter seasons. This was used to get initial information on the thermal distribution of the surface layers related to the variation of the cycle of seasons.

The first thermal survey campaign took place in summer, in August 2020. Using a FLIR MR77 hygrometer, ambient temperature, and relative humidity values of 24.3 °C and 66%, respectively, were recorded. Using a FLIR E40bx thermal imaging camera, thermograms were acquired with a resolution of 320 × 240 pixels, taking into account the tabular value of the emissivity coded for the material of the dome frescoes i.e. ochre lime plaster, average between dark and light colors, $e = 0.97$.

The second thermal data collection was carried out in the winter period, in February 2021, using a TESTO890 thermal imaging camera to capture images with a resolution—extended—of 1280 × 960 pixels. As anticipated in the previous subsection, for each thermal shot, a photograph was also recorded in the visible field with the reflex camera in order to have a single discrete 3D model in which for each point at the position in space results aggregated also the temperature value. To do this, thermograms were acquired at the station points and at the same elevation as described for the photogrammetric survey (Fig. 3b). Their integrated processing was carried out, as extensively discussed in [8], within the 3DF Zephyr software, taking advantage of the coincidence of the optical centers of the two sensors in the data capture phase.

Based on the analysis of the thermal imaging data, basically 2 differentiated physical conditions were noted: one related to the frescoes of the nave vault, and the other related to the paintings of the dome. The thermography of the vault paintings revealed a substantial homogeneity of the thermal state between the points affected by the plaster detachment and those still intact (homogeneous thermal distribution around 25.3 °C for the August shot and 6.3 °C for the February shot). This data suggested that although moisture infiltration had been there and had caused plaster detachment in the past, at the time of the two shoots the area was dry showing no change in temperature.

Because of the time interval between the two acquisitions and the unchanged qualitative situation of the thermal behavior, the degradation phenomenon could therefore be considered arrested, at the current situation.

Opposite was the thermal condition of the dome frescoes: in both summer and winter periods, the thermographic analysis made clear the presence of cold areas, with a temperature 1° or 2° lower, depending on the season considered, than the surrounding areas. In this case, the insistence of a pathological condition of high humidity emerged in 4 segments descending toward the drum starting from the lantern.

In August, the coldest areas recorded a temperature of 24.7 °C, despite the surrounding temperature distribution attested to 27.0 °C. In winter, the temperatures recorded for the areas mentioned earlier were 7.9 °C and 8.9 °C, respectively (Fig. 3c).

Such thermally characterized areas, cross-referenced with images in the visible range, appeared to overlap with the visually damaged portions. What is more, a further significant fact is that these 4 cooler portions were, at the time of analysis, found to be much more extensive than the diseased areas. Therefore, thanks to the data from the thermal imaging camera, the presence of moisture was highlighted that was not visible on the surface and, therefore, to be monitored to obviate the manifestation of further deterioration phenomena involving plaster detachments in larger areas. For that matter, the persistence of this thermal behavior in the two different recordings in different seasons of the year showed the persistence of the conditions triggering the manifestations of degradation.

(ii) The cataloguing and mapping of the main materials that constitute the facies of the studied artifact followed the indications contained in the Italian standard UNI 3972:1981 for the graphic representation of architectural materials. Through direct

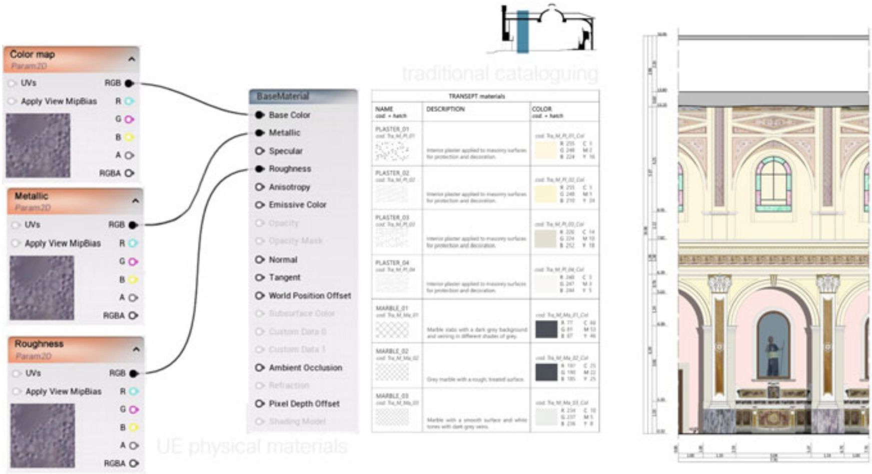


Fig. 4 Example of the scheduling and mapping of materials and colors and their use in Unreal Engine 5. *Image* V. Cera, A. Origlia

observation and comparison with historical archival sources, the materials were catalogued in traditional type paper sheets that, at the same time, were used for the definition of the specific Physical Materials parameters applied to the model in UE5 (Fig. 4).

These were mostly polychrome marbles, stucco, plasters with different finishes, walnut wood for some prominent elements such as the inlaid choir, and glass in various colors.

In order to accomplish the most accurate material scheduling possible at this stage of the research, the reflectance maps recorded with the TLS were also manipulated, so as to extract additional descriptors useful for the material composition of the artifact. It should be noted that this type of activity was possible where the TLS stations were planned taking into account from the beginning the variables most influential on the reflectance data.

Keeping the focus on the painted representations of coverage, the related hue intensity images were examined by evaluating the changes in reflectance in relation to the wavelength of the emitted pulse type. As argued in [9], by varying the percentage range of the observation from a full 1–100 range to smaller, detailed ranges with 5–10 percentage point shots, the following resources were extracted:—for the dome, the recorded reflectance variations, ranging from 30–35% to 62–75%, were completely consistent with the behavior of the lime plaster with chromatics of blue (30%), natural (60%), yellow ochre (70%), and red ochre (65%);—for the vault frescoes, similar reflections were made in relation to the reflectance values with a variation between 33 and 60% (Fig. 5).

(iii) As indirectly emerged from the description of the manipulation of reflectance maps, the cataloged materials were also associated with a sampling of their respective colors. The color survey, at this cognitive stage, was carried out by the computer

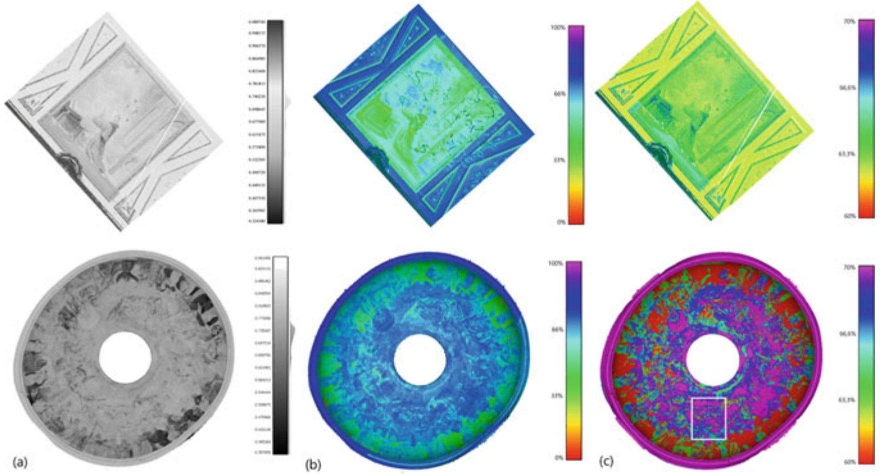


Fig. 5 Manipulation of the reflectance maps obtained with the TLS survey (**a**, **b**). By varying the range of the percentage value **c**. *Image* V. Cera, A. Origlia

method, employing a recognition system based on the comparison of images in the visible range with a computerized color catalog. The sampling covered both the general materials of the architecture examined as a whole and the colors proper to the frescoes. Hence, by way of example, we report a great chromatic variety of the marbles used in a variety of shades, from red to ochre, blue to black. Each color was expressed in both the additive RGB and subtractive CMY color models (Fig. 4).

(iv) By cross-referencing, finally, the materials cataloguing, the results of reflectance mapping, and the study of thermal states, it was possible to set up a map of the phenomena of alteration and degradation that punctually affect the investigated pictorial layers. Using the normative indications of UNI11182:2006 as a reference for cataloguing, the perceived phenomena were traced back to: the lacuna (subtractive phenomenon of material) for the vault, affected only by the loss of surface coloration; and the efflorescence (additive phenomenon of material) for the dome, affected by the manifestation of overlapping patinas. For each of them, an initial quantitative estimate of the surface extent of the affected areas was provided, to get an idea of the relevance and scale of the ongoing phenomena. Regarding, on the other hand, the quantification of the volume of material lost or deposited, an attempt was made to obtain values by exploiting some mathematical algorithms, such as RANSAC in Cloud Compare, and by computing the maximum displacement, positive and negative, of the 3D model with respect to primitive geometric solids. However, it was not possible to arrive at a noteworthy result where portions with millesimal thickness variations are involved.

Hence, at this stage, we stopped at calculating only the surface extent of damage.

2.3 Semantic Annotation of the Digital Environment for a Hierarchy of Phenomena to be Monitored

All the resources collected so far have been associated with the model constituting the digital setting of the research experiment using a semantic labeling approach. Specifically, the model was segmented into semantically relevant macro- and micro-elements by employing an annotation system using 2D maps related to 3D space, already codified in [10]. For the identification of concepts in the domain of interest, we referred to the Art and Architecture Thesaurus, implemented in the semantic tree with historical treatises and specific manuals on sacred architecture. The architecture was then segmented through the annotation maps with respect to both its components considered in the horizontal development of the architectural space and in the vertical one. The following were then identified: facade, hall, triumphal arch, transept, triumphal arch, chancel, apse (horizontal decomposition); I order, II order, roof (vertical decomposition). Proceeding from the most general to the most detailed components, the most significant elements of the artifact were progressively annotated, taking advantage of the potential offered by the thesaurus in terms of inference between concepts (Fig. 6).

Finally, the macro- and micro-elements were hierarchized, again through the use of semantic maps, according to the state of degradation found. In this way, it is possible to have an initial indication of the most sensitive areas and therefore to be monitored with greater attention and priority interest.

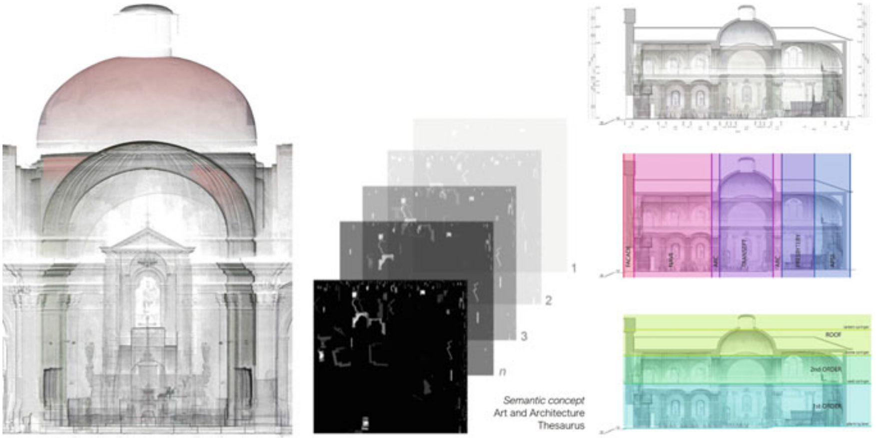


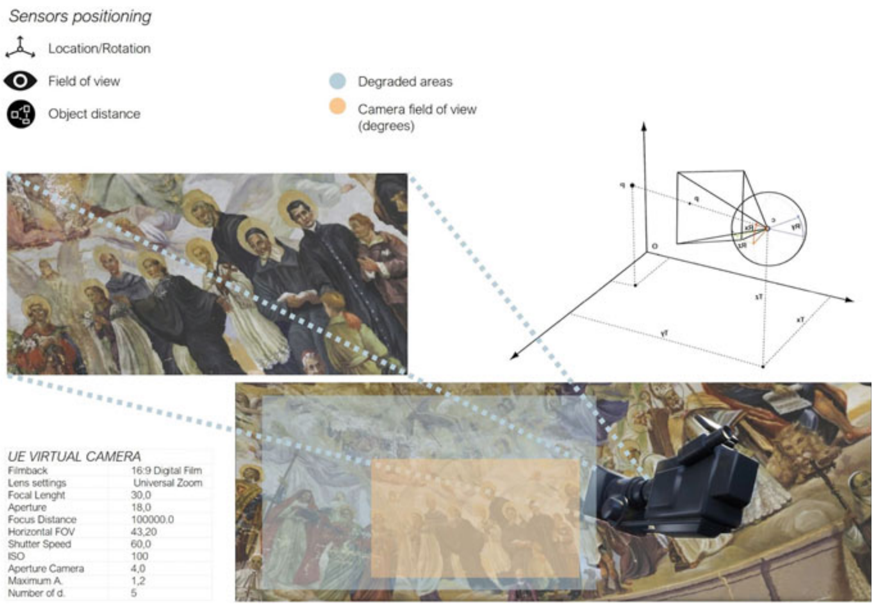
Fig. 6 Example of the semantic annotation using maps. *Image* V. Cera, A. Origlia

3 Design and Simulation of the Integrated Monitoring System with AI

The Unreal Engine 5 has introduced, with respect to its previous version, a number of improvements that further push its applications in the architecture field. First of all, the introduction of the Nanite engine for geometry virtualization allows the use of extremely detailed meshes without the need of introducing approximations through the use of Normal Maps or Ambient Occlusion. Also, the introduction of the Lumen Global Illumination system makes the technology for photorealistic rendering in real time accessible in many different situations. This is ideal for the field of architectural survey, where the output of photogrammetric and/or laser scanning procedures produces 3D models characterized by a high degree of polygons. In this work, we take advantage of these new technologies to generate a stream of video data from the engine and inform a monitoring system during its development phase. This has the advantage of avoiding time consuming and costly tests on-site and allows testing the basic technology in the lab using realistic data. An example of the rendered architecture in Unreal is shown in Fig. 7.

First of all, the Unreal Engine supports complex simulations of a wide range of camera lenses for image rendering, so that the behavior of RBG monitoring sensors can be approximated this way. Figure 8 shows a Cinematic Camera placed in the 3D environment to simulate a monitoring sensor pointed towards a fresco together with a selection of the parameters allowing to change the effect of lenses, ISO, aperture, etc.…

Fig. 7 A view of the imported 3D model of the considered case. No decimation approach was used but the rendering speed keeps running at 60 FPS using Nanite virtualized geometry. *Image* V. Cera, A. Origlia



UE VIRTUAL CAMERA

Filmback	16:9 Digital Film
Lens settings	Universal Zoom
Focal Lenght	30,0
Aperture	18,0
Focus Distance	100000,0
Horizontal FOV	43,20
Shutter Speed	60,0
ISO	100
Aperture Camera	4,0
Maximum A.	1,2
Number of d.	5

Fig. 8 A Cinematic Camera in the Unreal Engine 5. *Image* V. Cera, A. Origlia

The Unreal Engine 5 has also consolidated the production-ready version of the Pixel Streaming technology, which allows remote clients (e.g., browsers) to connect to a server running the Unreal Engine application and receive a rendered stream of frames. While this technology also supports interaction between the remote user and the application, in this case we will focus on Unreal acting as an environmental simulator for remote Artificial Intelligence systems for architectural monitoring. The architecture of a Pixel Streaming application is shown in Fig. 9.

The 3D environment equipped with simulated camera sensors can be used to stream images containing simulated damage localized on different areas of the model.

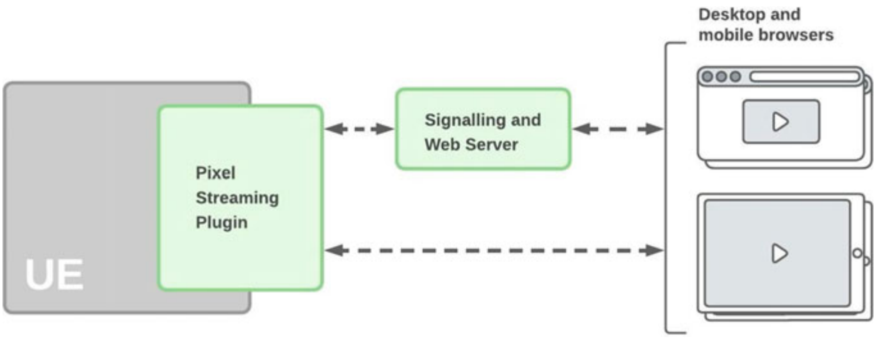


Fig. 9 The pixel streaming architecture provided by the unreal engine. *Image* V. Cera, A. Origlia

This is achieved, in this work, using Decals, which are designed to project patterns over textured surfaces to add details and dynamic changes guided by the application state. We consider a library of Decals containing a wide variety of damage patterns and we focus on the stains subset, consisting of 62 stain patterns including, for example, paint, moss, and grunges, of which some examples are shown in Figs. 10 and 11.

A dedicated shader has, then, be used to control the amount of damage projected by each Decal actor in terms of strength (transparency) and extension. To simulate stain extensions, the corresponding parameter is linked to a Gaussian mask filtering the projection over the scanned texture. The control panel of the Decal material is shown in Fig. 12a while the effect of a Decal projecting a damage pattern over a scanned surface is shown in Fig. 12b. Different levels of damage extension, controlled with the corresponding slider, are shown in Fig. 13.

Data generated using Pixel Streaming from the Unreal simulation can be used to train and test machine learning algorithms aimed at performing anomaly detection

Fig. 10 Grunge maps for stain patterns used in decals (normals included). *Image* V. Cera, A. Origlia

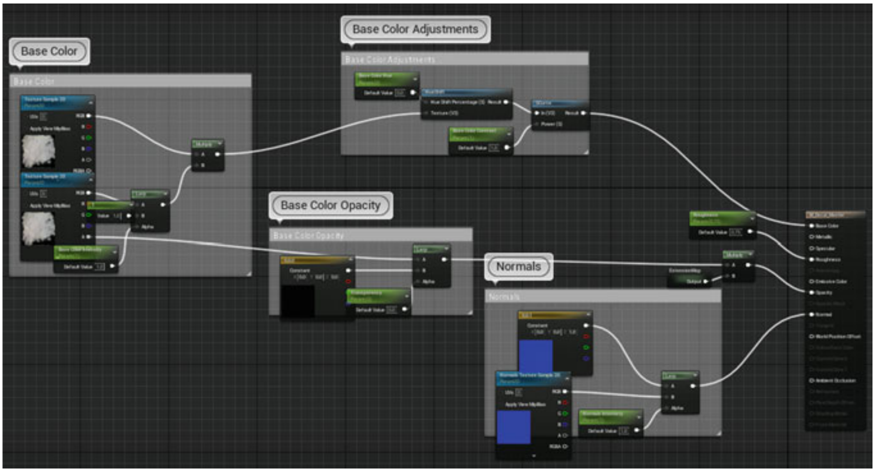


Fig. 11 The master material blueprint controlling the parameterized decals. *Image* V. Cera, A. Origlia

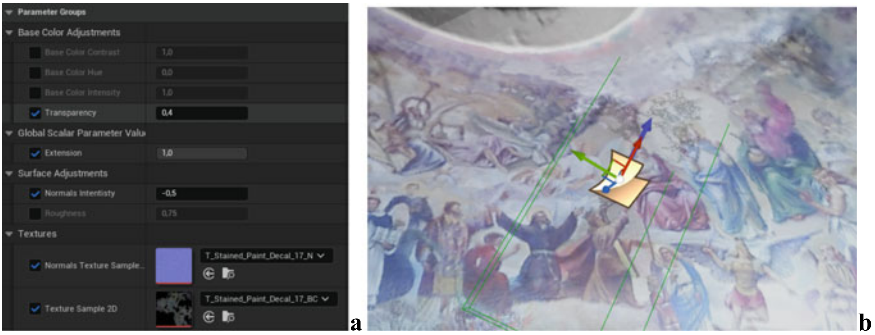

Parameter Groups
Base Color Adjustments
☐ Base Color Contrast 1,0
☐ Base Color Hue 0,0
☐ Base Color Intensity 1,0
☑ Transparency 0,4
Global Scalar Parameter Valu
☑ Extension 1,0
Surface Adjustments
☑ Normals Intentisty -0,5
☐ Roughness 0,75
Textures
☑ Normals Texture Sample… T_Stained_Paint_Decal_17_N
☑ Texture Sample 2D T_Stained_Paint_Decal_17_BC

Fig. 12 The configuration panel of the Decal simulating stains. In particular, the Transparency and the Extension sliders allow to control the amount and the extension of the projected stain (**a**). A damage Decal projecting a stain pattern over the 3D model (**b**). *Image* V. Cera, A. Origlia

Fig. 13 Two levels of stain extension controlling the damage Decal. A Gaussian mask is used to approximate a radial extension of the damage. *Image* V. Cera, A. Origlia

or damage recognition. This effectively implements a simulation in which a remote data processing server using machine learning provides information to a monitoring system designed to cross-reference the position of detected anomalies with the information provided by the semantic maps. Specifically, once an anomaly is detected, a difference operation between reference images of the normal situation and the anomalous image localizes the problem with respect to the 3D model. The proposed strategy represents, in general, a methodological proposal to build synthetic datasets to train machine learning algorithms in the damage recognition task. Since real data representing different kinds of damage and containing pre and post-incident representations of architectural artifacts are not easily collectable and/or accessible, this proposal represents a way to rapidly build damage simulations over existing 3D datasets.

Depending on the extent of the damage and on its position, for example, with respect to works of art or structurally relevant areas, a Real Time Interactive 3D (RTI3D) application can be driven to generate an error message in natural language and report the position of the damage. To implement this kind of application, also including data coming from external sources, typically organized in a graph database, the Framework for Advanced Natural Tools and Applications with Social Interactive Agents (FANTASIA) [11, 12] is used. FANTASIA is an open-source plugin for the Unreal Engine developed to support the creation of Embodied Conversational Agents (ECAs) and, in general, RTI3D applications. FANTASIA aims at supporting the academic community, mainly, in conducting Human–Machine Interaction studies but can also be used for more industrially oriented applications (e.g., automatic kiosks, Virtual Assistants, etc.…). The framework consists of a series of components that, currently, allow Unreal to access (a) the Azure Automatic Speech Recognition service, (b) The Azure Natural Language Understanding Service, (c) The Azure Text-To-Speech service, (d) The Amazon Text-To-Speech service, (e) The Neo4j Graph Database, (f) The AGRuM library for Bayesian Networks. The FANTASIA architecture is shown in Fig. 14.

Being centered around the Unreal Engine, FANTASIA can be directly connected to the outcome of remote analysis processes performed using machine learning techniques to guide the behavior of artificial conversational agents in Unreal. These can either be embodied or not and can make use of Natural Language Processing techniques made available by the connection with services provided, for example, by Amazon and Microsoft. The interaction control systems FANTASIA allows to implement are based on a combination of Behaviour Trees, for task prioritization, Bayesian Networks, for decision making, and Graph queries, for deductive reasoning.

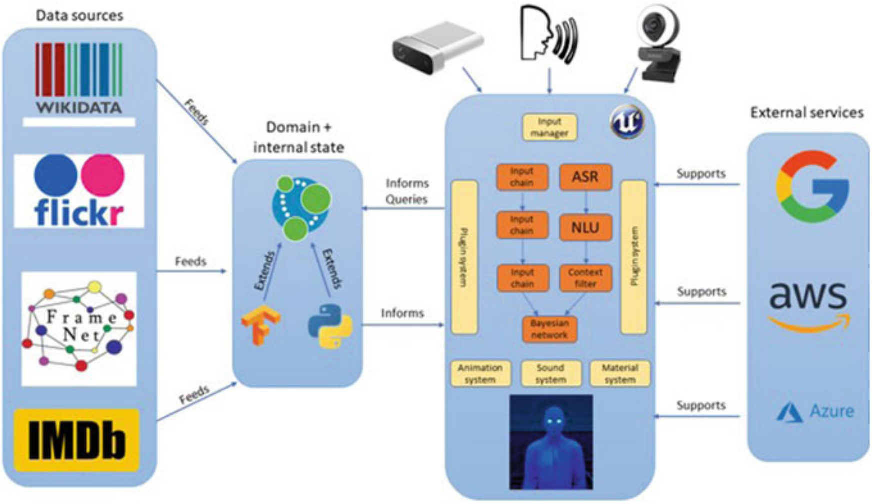


Fig. 14 The FANTASIA architecture. *Image* V. Cera, A. Origlia

4 Conclusions

We have presented a simulation environment for the design and test of monitoring applications leveraging on the novel technologies brought in by the Unreal Engine 5, on our methodology for semantic data annotation and on a framework for the development of interactive applications powered by Artificial Intelligence. We have shown how we imported a large set of data in the engine without the need of decimation procedures and how we simulated damage over the scanned geometry to be captured by virtual cameras configured in such a way as to simulated real lenses. The video stream produced inside the engine can be sent to remote processing applications to perform anomaly detection and, in general, machine learning tasks that inform interactive applications developed using FANTASIA, a module designed to support the development of RTI3D applications integrating AI for Natural Language Processing.

With this infrastructure in place, future work will consist of simulating different kinds of damage and their evolution. Also, using the Unreal Engine photorealistic rendering capabilities, we will explore the possibility to generate synthetic datasets to train monitoring approaches based on machine learning and, in general, on AI.

Acknowledgements Although this contribution is the result of shared work, Valeria Cera is the author of paragraphs 1 and 2, Antonio Origlia is the author of paragraphs 3 and 4. The authors wish to thank all people who contributed to the logistical and data collection phases: don Giuseppe Radesca, Michele Sanseviero, Alessandro Cancellaro, Settimio Rienzo, Michele Cirignano, Marika Falcone, Giovanni Angrisani, Lorenzo Bisceglia.

References

1. Russo, A., Giovampaola, I.D., Spizzichino, D., Leoni, G., Coletta, A., Virelli, M.: The project of Parco Archeologico Del Colosseo and the Italian network of archaeological parks: from satellite monitoring to conservation and preventive maintenance policies. In: El-Qady, G.M., Margottini, C. (eds.) Sustainable Conservation of UNESCO and Other Heritage Sites Through Proactive Geosciences, pp. 659–678. Springer, Cham (2023)
2. Poljak, M., Radoslav, P.: Microclimatic monitoring. The beginning of saving historical sacral buildings in Europe. Energies **16**(3), 1156 (2023)
3. Masciotta, M.G., Morais, M.J., Ramos, L.F., Oliveira, D.V., Sanchez-Aparicio, L.J., González-Aguilera, D.: A digital-based integrated methodology for the preventive conservation of cultural heritage: the experience of HeritageCare project. Int. J. Arch. Heritage **15**(6), 844–863 (2021)
4. Bakalos, N., Doulamis, N., Doulamis, A.: Multispectral monitoring of microclimate conditions for non-destructive preservation of cultural heritage assets. In: Kavoura, A., et al. (eds.) Strategic Innovative Marketing and Tourism, pp. 641–646. Springer, Cham (2020)
5. Moreno, M., Prieto, A.J., Ortiz, R., Cagigas-Muñiz, D., Becerra, J., Garrido-Vizuete, M.A., Segura, D., Macías-Bernal, J.M., Chávez, M.J., Ortiz, P.: Preventive conservation and restoration monitoring of heritage buildings based on fuzzy logic. Int. J. Arch. Heritage, pp 1–18 (2022)
6. Limongiello, M., Lorusso, A., Sanseverino, A., Messina, B.: Conservazione predittiva di edifici storici attraverso un sistema basato sull'IoT. In: Battini C., Bistagnino E. (eds.) Dialoghi. Visioni

e visualità. Testimoniare Comunicare Sperimentare. Atti del 43° Convegno Internazionale dei Docenti delle Discipline della Rappresentazione, pp. 2607–2620. FrancoAngeli, Milano (2022)

7. Falcone, M., Origlia, A., Campi, M., Di Martino, S.: From architectural survey to continuous monitoring: graph-based data management for cultural heritage conservation with digital twins. Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci. **XLIII-B4**, 47–53 (2021)
8. Cera, V.: La manipolazione di modelli discreti per orientare l'indagine diagnostica per il restauro. In: Genovese, R.A. (ed.) Il patrimonio culturale tra la transizione digitale, la sostenibilità ambientale e lo sviluppo umano, pp. 167–190. Giannini Editore, Napoli (2021)
9. Cera, V.: Multisensor Data fusion for cultural heritage assets monitoring and preventive conservation. Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci. **XLVI-2/W1**, 151–157 (2022)
10. Cera, V.: La significazione digitale dell'elemento architettonico. Dal rilievo alla strutturazione semantica dell'architettura. EditoriPaparo, Napoli (2019)
11. Origlia, A., Cutugno, F., Rodà, A., Cosi, P., Zmarich, C.: FANTASIA: a framework for advanced natural tools and applications in social, interactive approaches. Multimedia Tools Appl. **78**, 13613–13648 (2019)
12. Origlia, A., Di Bratto, M., Di Maro, M., Mennella, S.: Developing embodied conversational agents in the unreal engine: the FANTASIA Plugin. In: Proceedings of the 30th ACM International Conference on Multimedia, pp. 6950–6951 (2022)