

Advanced Technologies in Cultural Heritage

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1. Introduction

Cultural heritage consists of material and immaterial traces of human history, identity, creativity, and collective memory; its preservation is a major scientific, social, and technological challenge.

Within the context of the growing process of digitalization, virtual reality, and artificial intelligence, cultural heritage research is increasingly called upon to integrate the study of physical artifacts with digital, diagnostic, and computational approaches that support their documentation, conservation, interpretation, and dissemination [1–5]. In light of this background, this Special Issue brings together scientific contributions on advanced technologies for cultural heritage, ranging from artificial intelligence, image processing, 3D documentation, virtual, augmented, and mixed reality, and decision support tools to archaeometric investigations, materials characterization, and recent applications of advanced materials, protective films, and nanomaterials in the conservation of cultural and historical heritage artifacts. With regard to the latter aspects, the materials studied were obtained through tailored syntheses, while others were investigated to improve our understanding of their potential in the valorization of historical artifacts. These modern technologies are based on synergistic, conservation-compatible processes and operations, restoration, and display interventions, thereby enhancing the presentation and valorization of artifacts within museum contexts.

As a whole, the papers brought together for this Special Issue highlight how technological innovation can enhance the analysis, preservation, authentication, presentation, and valorization of both tangible and intangible heritage, while remaining compatible with the material, historical, and cultural values of heritage objects, sites, and practices. The volume comprises 14 papers (11 research articles and 3 reviews) presenting recent advances in the field in a manner accessible to a broad audience. Overall, the 14 papers bring together 59 individual authors affiliated with 31 different institutions across 10 countries or territories. These contributions collectively address five major subject areas, including chemical engineering, computer science, engineering, materials science, and physics and astronomy, reflecting the multidisciplinary nature of the research (data is from Scopus).



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2. Published Articles

The article by Go et al. (Contribution 1) focuses on a particularly significant question in conservation science: how can image-based computational methods assist in the identification of production techniques and, in turn, support a more rigorous understanding of historical artifacts? From this perspective, four convolutional neural network (CNN) architectures—AlexNet, GoogLeNet, ResNet, and VGG—together with a vision transformer (ViT), were evaluated by the researchers using micrograph datasets derived from a range of pigments. The authors considered the classification metrics, receiver-operating characteristic curves, precision–recall curves, and interpretability analyses as the primary evaluation measures. Concerning the findings, the CNN-based models achieved accuracy rates ranging from 97% to 99%, whereas the ViT attained 100% accuracy, thereby emerging as the top-performing architecture. These results suggest that ViT is particularly effective in capturing complex patterns and processing data with a high degree of accuracy. However, the authors emphasize that interpretability analyses based on guided backpropagation revealed limitations in the ViT's ability to generate class activation maps, making its internal decision-making process more difficult to interpret. By contrast, the CNN architecture yielded more detailed and informative interpretations, providing meaningful insight into learned feature representations and hierarchical processing mechanisms. Despite its interpretability challenges, ViT consistently surpassed the CNN-based models across all evaluation criteria. Taken together, the research findings underscore the promise of deep learning for the classification of pigment manufacturing processes and make a valuable contribution to cultural property conservation science by reinforcing the scientific basis that supports the preservation and restoration of historical artifacts.

The second article (Contribution 2) authored by Kabassi et al. presents the design and implementation of an intelligent system that applies multi-criteria decision-making methods to assess olive trees and determine whether they should be classified as monumental. The methodology is implemented in a multiplatform application called “Olea App”. The system assesses individual olive trees as well as entire orchards in order to identify those most suitable for promotion. To achieve this, it combines three multi-criteria decision-making approaches: the Analytic Hierarchy Process (AHP), Simple Additive Weighting (SAW), and the Multi-Criteria Optimization and Trade-Off Solution (VIKOR). Through these methods, olive trees are evaluated using both tangible and intangible criteria. The proposed approach was applied to trees in the Ionian Islands and proved to be highly effective. With regard to the transferability of the research outcomes, the cross-platform application can support other researchers in evaluating olive trees and groves, particularly when tree age cannot be estimated using methods such as luminescence dating techniques. Overall, this article presents an innovative technological solution for identifying, evaluating, and preserving monumental olive trees. By integrating scientific, cultural, and technological aspects, the platform provides a sustainable, accessible, and scalable method for protecting these trees, while also promoting sustainable tourism and economic incentives for their conservation.

The third article, authored by Fracasetti et al. (Contribution 3), focuses on the use of Raman spectroscopy and imaging techniques to investigate Neolithic artifacts from Piacentine sites (Emilia-Romagna, Italy). Here, specialists in the field participated in interdisciplinary projects aimed at in-depth analysis of artifacts and solving new archeological problems, exceeding the common limits of mesoscopic observation. In detail, the authors performed multidisciplinary research combining advanced imaging techniques (Reflectance Transformation Imaging—RTI—and 3D photogrammetry) with Raman spectroscopy to investigate and valorize the Neolithic archeological remains. From a results perspective, RTI images enable the identification of a wide range of human-made and natural marks on artifact

surfaces, helping researchers better interpret how these objects may have been used. When combined with both qualitative and quantitative Raman spectral analysis, this approach allows each fragment to be characterized more precisely from a lithological perspective, improving our understanding of its likely geographic origin. This, in turn, supports the recognition of the External Ligurian Units as a possible main source area for the rocks, alongside the already documented outcrops of the Mont Viso Massif and the Voltri Group. At the same time, the authors emphasize the usefulness of 3D models that show strong potential as tools for both conservation and public engagement. These models can enhance museum displays by creating more interactive and immersive experiences for visitors, while also allowing specialists in the sector to examine artifacts online. This reduces the need for transport and repeated handling, thereby helping to protect the objects while making them more widely accessible.

The following article (Contribution 4) by Pavelka et al. explores modern ways of documenting and visualizing historic artifacts comparing digital photogrammetry and terrestrial laser scanning (TLS), two methods that have become increasingly important in cultural heritage documentation in recent years. The research also examines how current 3D computer graphics technologies can be used for visualization and present an optimized workflow for converting documented objects into virtual reality (VR) and augmented reality (AR). For research purposes, the proposed methods were tested during the rebuilding of the shrine of the Prophet Nahum in Alqosh, northern Iraq, where photogrammetry, drones, and TLS were used. Photogrammetry-based textured 3D models were validated against TLS data for accuracy and used to track reconstruction changes, as well as to estimate the volumes of removed rubble and added materials.

Concerning the findings, the 3D models exposed inaccuracies in the construction logs, which underestimated removed and added materials. Heat maps and volumetric analysis also highlighted the main areas of change, aiding reconstruction and investor reporting. The authors emphasize that these results are valuable not only for restoration at historic sites, but also for future research on VR and AR visualization. The project also made important progress in converting existing 3D models into VR and AR environments, an area that continues to develop rapidly. Unreal Engine 5 was used for this purpose. Although the newer version of the engine offers much better performance, the models still needed to be decimated to reduce data size before being used in VR and AR. Their visual quality was then preserved through the use of textures. A key result of the study was an improved workflow for optimizing 3D models for VR, which enabled the creation of an accessible and engaging virtual museum of the restoration process.

The article by Kim (Contribution 5) aims to discuss an artificial intelligence-based prototype to recognize traditional Korean dance movements using a metadata-enriched dataset. The research followed three main steps. First, the researchers developed a classification framework that captured the distinct features of traditional Korean dance. Second, they gathered video data from both existing materials and newly recorded footage, then created a metadata set by labeling five core movements for training purposes. Third, they used the BlazePose model to extract real-time skeletal key points, which were combined with the metadata-enhanced dataset and processed through a customized method to identify dance movements in real time. The resulting prototype was able to successfully recognize five basic Korean traditional dance movements, highlighting the potential of AI for analyzing complex motion patterns. By combining established AI models with a domain-specific dataset, the authors offer a structured method for the digital preservation and contemporary reinterpretation of traditional arts, while also providing an approach that can be adapted and applied to recognize dance movement expressions from other

cultures, thereby opening up new opportunities for preserving and transmitting intangible cultural heritage through digital technology.

The sixth paper by Azimi et al. (Contribution 6) aims to discuss an automated method for recognizing forgeries in oil paintings. The author's premise is that authenticating paintings requires in-depth expertise and knowledge of the painter's work. In this regard, recent computer vision algorithms have shown promise in image processing tasks; however, the authors emphasize that creating an automated model for authenticating paintings remains a challenge in art preservation and art history. The challenge is further compounded by the ability of forgers to create artworks that imitate an original artist's unique brushstroke signature while introducing new content. The authors propose a conditional Generative Adversarial Network (GAN)-based model to analyze an artist's brushstroke style and detect forgeries. Their approach uses two detection methods, frequency-based forgery scoring and discriminator models, and relies on Reflectance Transformation Imaging to capture the depth and texture of brushstrokes. The study tests oil painting authentication on works by a contemporary Korean artist for two cases: distinguishing originals from direct counterfeits and detecting creative forgeries that mimic the artist's brushstroke style. The findings suggest that GAN-based analysis of brushstroke details can support traditional authentication methods and assist connoisseurs.

The next paper in the collection is authored by Fan et al. (Contribution 7). The authors aim to develop a reliable digital restoration method for reconstructing the damaged faces of Tang Dynasty female terracotta figurines, helping to preserve them as cultural heritage. Tang Dynasty female terracotta figurines, which are important examples of ceramic art, have often been damaged by both natural causes and human activity, with facial damage being one of the most serious and common problems. The authors underline that although image inpainting has been widely used in the restoration of other forms of cultural heritage, such as murals and paintings, where large datasets are usually available, its use in the restoration of Tang Dynasty terracotta figurines is still relatively limited. The study began by assessing the degree of facial damage found in Tang Dynasty female terracotta figurines and then used the Global and Local Consistency Image Completion (GLCIC) algorithm to reconstruct their original appearance, ensuring that the restored areas remained consistent with the image as a whole as well as with its local details. To deal with the limited amount of data and the blurred facial features of the figurines, the researchers improved the algorithm through data augmentation, guided filtering, and local enhancement methods. The experimental findings indicate that the refined algorithm achieves greater accuracy in restoring the facial shape of the figurines, although further improvements are still needed in the reproduction of color and texture. Overall, the study offers a new technical approach for the protection and inpainting of Tang Dynasty terracotta figurines and proposes an effective strategy for image inpainting in contexts where data are scarce.

The following paper by Lin et al. (Contribution 8) proposes a generative adversarial network (GAN)-based method for restoring damaged ancient paintings more effectively by improving style consistency, semantic coherence, and fine detail reconstruction in missing areas. Ancient paintings are an important part of cultural heritage and carry deep cultural value, but over time they often deteriorate because of various forms of damage, making restoration especially difficult when parts of the image are missing. The authors proceed from the observation that existing inpainting methods often produce semantic inconsistencies, blurred textures, and poor recovery of fine details in damaged regions. To address these limitations, the researchers propose a GAN-based method called RG GAN, designed specifically for ancient painting restoration. One of its key components is the Regional Attention Style Transfer Module, which helps to align the style of restored areas with the undamaged parts of the painting while preserving the authenticity of the

original content. The method also includes a Multi-Scale Fusion Generator to capture and integrate features at different scales, improving both global structure and local detail reconstruction. In addition, the Multi-Scale Cross-Layer Perception Module strengthens the representation of filled regions, while the Global Context Perception Discriminator enhances detail recognition and spatial awareness. Tests on ancient painting datasets show that the method achieves strong performance, with higher PSNR and lower LPIPS values than competing approaches.

The following paper (Contribution 9) by Marciniak et al. studies the complex structure of the historic wooden church of St. Michael in Domachowo (Poland). This case study demonstrates how historical masonry systems operate under conditions entirely different from those of wooden structures, which have received comparatively less attention to date. Moreover, although fewer in number, wooden religious buildings represent a highly significant group in Poland because of their outstanding architectural, historical, and cultural value. In particular, the church of St. Michael consists of several segments which differ in terms of building material, structural system, and the degree of wear of their structural elements. The authors paid particular attention to examine the multi-branched columns located at the junctions of different segments. The main objective of the analysis was to determine the degree of bonding between the column branches and to evaluate the influence of this bonding on the behavior of the entire structure. To assess the degree of bonding between the column branches, an experimental modal analysis was proposed, as this method is useful in determining the dynamic properties of a given structure. Based on the experimental results, it was determined that the column branches are interconnected; however, their interaction is limited. Several models of the structure were also developed, including models with a different degree of bonding between the column branches. The study also examined the influence of the bonding between column branches on stress levels in the nave columns and on the maximum displacements caused by wind loads. The results suggest that repairing or strengthening some of the short walls would improve the overall spatial stiffness of the church and help reduce the building's response to wind loads. This implies that localized strengthening measures could improve the structural behavior of the system under lateral loading conditions.

In the 10th paper, written by Fornari et al. (Contribution 10), the authors assessed the role of crystalline nanocellulose (CNC) as a bio-based consolidant for degraded ancient wood and compared its performance with two widely used synthetic products, Paraloid B-72 and Regalrez 1126. Scanning electron microscopy (SEM) showed that CNC has a rod-like morphology, with a width ranging from 15 to 30 nm, while FTIR analysis revealed only the characteristic peaks of nanocellulose. The researchers also carried out conductometric, pH, and dry matter analyses, obtaining values consistent with what is reported in the literature. The treated wood samples were then analyzed by reflected-light optical microscopy and SEM to assess xylophagous damage and surface morphology. The results show that wood treated with nanocellulose retains a surface appearance much closer to untreated wood than samples treated with the other consolidants. Finally, colorimetric analyses performed after the first treatment and again after a second treatment three years later indicate that the CNC-treated samples remained highly homogeneous and uniform, with no visible changes in final color compared with those treated with traditional synthetic products.

In the article by De la Rosa et al.—the final paper from the research group (Contribution 11)—the authors explore how flexible polyvinyl alcohol (PVA) fibers affect the mechanical behavior of low-strength hydraulic lime concrete, a material used when compatibility with historic substrates is required in conservation and rehabilitation work. To this end, the authors developed a hydraulic lime concrete matrix following a specific mix design method. The researchers next carried out three-point bending tests on notched prismatic

specimens under both quasi-static loading, with a displacement rate of 4×10^{-4} mm/s, and dynamic loading, at 4 mm/s, using a servo-hydraulic testing machine. The results show that, under both quasi-static and dynamic loading conditions, flexural strength, residual flexural strengths at different crack openings, and fracture energy all increase with increasing fiber content; moreover, the transition from quasi-static to dynamic loading, associated with higher strain rates or loading velocities, leads to a significant enhancement of these mechanical parameters. Overall, the authors conclude that discontinuous PVA fibers make hydraulic lime concrete more suitable for applications exposed to dynamic actions, including heritage restoration and rehabilitation.

The contribution of Sylaiou et al.—the first paper from the review group (Contribution 12)—examines how digital tools are transforming archeological research by reviewing the main technologies used for data acquisition, comparing them with traditional methods, and discussing their applications, advantages, challenges, and integration in archeological fieldwork and cultural heritage documentation. In particular, the authors examine in detail the wide range of digital technologies used for data acquisition in archeology, such as geographic information systems (GISs), global positioning systems (GPSs), remote sensing technologies, 3D scanning, photogrammetry, drones and aerial photography, while also considering mobile applications and digital recording systems. Each of these categories is further explained in terms of their application in archeological studies. Lastly, the authors mention the potential of further developments in digital technologies that could enhance data acquisition capabilities and contribute to an even better understanding of human history.

The second review, written by Doni et al. (Contribution 13), begins with the premise that preserving heritage artifacts involves complex challenges and therefore calls for innovative solutions to prevent deterioration and prolong the life of historical objects. The review underlines that recent advances in materials science are transforming cultural heritage conservation and restoration by introducing innovative techniques and materials that improve the protection, stability, and visual integrity of artifacts. Having this background in mind, the authors reviewed recent materials-science advances for conserving and restoring historic artifacts, with particular attention given to nanomaterials, smart materials, and bio-inspired polymers. Through specific case studies, from ancient manuscripts to architectural heritage, the review discusses how these materials can improve preservation while addressing issues such as compatibility, reversibility, and long-term effects.

The last review—and the last article of the Special Issue—written by Giannuzzi & Fatiguso (Contribution 14) starts from the observation that digital technologies and automated analysis techniques applied to the historic built environment (HBE) constitute effective tools for the collection and interpretation of data in support of building conservation. This role is further enhanced by the use of artificial intelligence in digital image processing, which makes the diagnostic analysis of the built environment simpler and more accurate.

The authors performed a scoping review following the well-established PRISMA protocol to analyze the use of deep learning (DL) architectures for image-based classification of degradation phenomena in historic buildings and to evaluate their potential applications in decision support systems for conservation and management. The literature review focused on the methods used to identify building surface deterioration, cracks, and post-disaster damage. The authors paid particular attention to the innovative DL architectures developed, the accuracy of the results obtained, and the classification methods adopted to highlight their pros and cons. With regard to the findings, the review highlights the growing potential of deep learning to support conservation practice, particularly through improved diagnostic accuracy, more effective data acquisition methods, and the possibility of real-time monitoring. The review also emphasizes the value of integrating these approaches into

interoperable environments, where information can be more easily shared among different stakeholders involved in heritage management. At the same time, it identifies several future directions, including the development of mobile applications, the integration of IoT and sensor-based systems for in situ and long-term monitoring, the use of multimodal non-destructive data, and the connection of diagnostic outputs with intervention planning, timing, and costs.

3. Conclusions

The contributions collected in this Special Issue were reviewed—after the initial check by the Guest Editors—by three independent reviewers who assessed the compliance of the manuscript with the journal's guidelines, the accuracy of the experimental data and their interpretation, and the quality and clarity of the figures and tables. During this process, reviewers also identified possible knowledge gaps, methodological weaknesses, or aspects requiring further clarification, which were subsequently addressed by the authors through appropriate revisions guided by the Guest Editors.

Care was also taken with self-citations from the journals, as well as the self-citations of the authors, which were carefully checked to ensure that they were maintained below a rate of 15% to ensure compliance with the requirements of the scientometric indexing databases. By rigorously selecting the works and rejecting a significant number of manuscripts (Contribution 9), this editorial provides a coherent overview of the available research and aims to attract readers while further stimulating interest in the content published in this Special Issue.

In conclusion, this Special Issue has brought together high-quality works on the documentation, analysis, conservation, restoration, authentication, and enhancement of tangible and intangible cultural heritage and it provides a solid state-of-the-art reference for these research fields. It is also evident that this Special Issue can be particularly useful for a wide range of professional stakeholders. Researchers will find up-to-date contributions on the latest cutting-edge methodologies, while restorers and conservators will benefit from new techniques and materials available in practice. Museums, cultural institutions, and other organizations will also benefit from analyses of tools for the digitization, valorization, and preventative maintenance of heritage assets. Moreover, technology companies and developers may identify opportunities for applying tools such as AI, augmented reality, and sensors. For policymakers and funders, the volume provides a guide to understanding the challenges and opportunities associated with investing in the sector. Finally, the conservation and dissemination of cultural heritage in an increasingly digital world carry important implications for citizens worldwide.

Conflicts of Interest: The authors declare no conflicts of interest.

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