UDC 7.025.3:004.946:930.85
DOI https://doi.org/10.32782/uad.2025.6.24

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EUROPEAN EXPERIENCE IN USING VIRTUAL REALITY TO AID IN CONSERVATION AND RESTORATION OF CULTURAL HERITAGE ITEMS

The introduction of Virtual Reality (VR) and Augmented Reality (AR) technologies has fundamentally transformed the methodology and ethics of cultural heritage conservation in European countries. While not as widespread as could be expected, both of them have proven practical usage examples. The goal for this paper therefore is to examine the critical role such immersive technologies play in the work of modern historians, restorers and art researchers. Of particular interest are the projects aimed at restoration of fine arts artifacts such as paintings, frescoes, and sculptures. For example, by creating high-fidelity digital copies, European institutions and initiatives utilize VR/AR for non-destructive analysis, pre-visualization of interventions, and collaborative decision-making, significantly reducing risk to irreplaceable originals. Our analysis draws on key papers highlighting how virtual restoration serves as a crucial planning phase of the project, allowing conservators to test hypotheses, simulate reintegration of broken or missing pieces, and virtually reassemble fragmented objects before any physical action is taken. Previous sources are augmented by several EU initiatives aimed at providing a common base for VR/AR use in research of European cultural heritage. In some cases we found, digital restoration may be the only option left for a successful completion of now ruined artifacts, be it frescoes, sculptures or entire parts of an architectural complex. The paper concludes that as of now the European approach to preservation, restoration and study of cultural artifacts demonstrates a slow but steady shift towards integrating digital tools as a standard practice, thus ensuring that conservation efforts are informed, reversible, and follow ethical standards of minimal needed intervention.

Key words: *augmented reality, conservation, cultural heritage, digitalization, immersive experiences, preservation, virtual reality.*

Сосік Ольга. ЄВРОПЕЙСЬКИЙ ДОСВІД ВИКОРИСТАННЯ ВІРТУАЛЬНОЇ РЕАЛЬНОСТІ ДЛЯ ПІДТРИМКИ ЗБЕРЕЖЕННЯ ТА ВІДНОВЛЕННЯ ОБ'ЄКТІВ КУЛЬТУРНОЇ СПАДЩИНИ

Впровадження технологій віртуальної реальності (VR) та доповненої реальності (AR) кардинально змінило методологію та етику збереження культурної спадщини в європейських країнах. Хоча ці технології не набули очікуваного розповсюдження, вони вже мають практичні приклади застосування. У цій статті розглядається важлива роль, яку ці імерсивні технології відіграють у роботі істориків, реставраторів та дослідників мистецтва, особливо в проєктах, спрямованих на реставрацію творів образотворчого мистецтва, таких як картини, фрески та скульптури. Створюючи високоякісні цифрові копії, європейські інституції та ініціативи використовують VR/AR для недеструктивного аналізу, попередньої візуалізації втручань та спільного прийняття рішень, що значно зменшує ризик для незамінних оригіналів. Наш аналіз базується на ключових статтях, в яких підкреслюється, що віртуальна реставрація є важливою фазою планування, яка дозволяє фахівцям перевіряти гіпотези, моделювати реінтеграцію пошкоджених або втрачених частин та віртуально збирати фрагментовані об'єкти перед тим, як проводити будь-які фізичні дії. Попередні джерела доповнюються кількома ініціативами ЄС, спрямованими на створення спільної бази для використання VR/AR у дослідженні європейської культурної спадщини. У деяких випадках, як ми виявили, цифрова реставрація може бути єдиним варіантом для успішного відновлення зруйнованих артефактів, будь то фрески, скульптури або цілих частин архітектурного комплексу. У публікації ми також доходимо висновку, що наразі європейський підхід до збереження, реставрації та вивчення культурних артефактів демонструє повільний, але стабільний перехід до інтеграції цифрових інструментів як стандартної

практики, що забезпечує усвідомлений, оборотний характер реставраційних заходів та їх відповідність етичним стандартам мінімально необхідного втручання.

Ключові слова: *віртуальна реальність, доповнена реальність, культурна спадщина, оцифрування, імерсивні враження, консервація.*

Introduction. Europe, owing much to its immense cultural heritage and historically significant collections, has become a global center for further integration of digital technologies into the field of conservation and restoration. The basic idea behind such initiatives is to preserve millennia of history, from monumental architectural pieces to delicate fine arts or jewellery. This has driven a need for tools that could offer precision, non-invasiveness, and ability to document the item while preserving its appearance in more ways than traditional photography allows. Virtual Reality (VR) and Augmented Reality (AR) systems have emerged as powerful instruments capable of addressing this need.

VR, which provides a fully immersive, computer-generated environment, and AR, which overlays digital information onto the real world, albeit in ways less sophisticated than Extended or Mixed Reality would (XR and MR respectively). All of the above technologies steadily gain acceptance in fields other than gaming, with what by many would be described as "more purposeful" and "worthy" use cases. Potential applications are to be considered on a case-by-case basis, most notably in regards to architectural and archaeological sites where VR/AR can prove to be most useful on a large scale. We in turn will place particular emphasis on their utility in the specialized domain of fine arts conservation, including paintings, frescoes, and sculptures.

Rule of minimal intervention. The primary idea of any competent conservation and/or restoration effort is to keep the original item in as good a condition as possible. Sometimes these goals may conflict with each other simply because many restorers, their clients and audience would want to see the piece as it once was. Bringing the item back to its original state, however successfully, would not allow us to keep it in the state it is in right now. Gentle compromise is needed, particularly when we would also like to inspect and study original items. In such cases so-called "digital twins" or "digital copies" may allow us to satisfy all three goals, common point in which is minimization of human intervention in the state of the artefact, un;lless full rebuild (restoration) is indeed necessary, for example, to preserve ancient architectural ensembles.

Various types of augmented realities (we use this as a generalised name for AR/VR/MR/XR) are the expression and end result. Before that however, there is usually a lengthy process in which the piece in question is scanned and photographed. Work on establishing certain baseline processes and best practices has been underway since 2007 (Akça et al., 2007) if not earlier.

In the almost 20 years following that, the general workflow has not changed, in many cases because it did not need to. Most of the art pieces were either drawings, paintings or other media that could be scanned using constantly advancing 3D or 2D scanners. Teams working on architectural sites could use photogrammetry coupled with LIDAR (light detection and ranging) tools. Even items made from glass, one of the few materials which presented a significant amount of challenge in regards to non-invasive digitization, is now not as much of an issue to create a digital copy of (Karami et al., 2022). Worth noting that powdering (coating objects by a thin layer of fine opaque dust) is still suboptimal and most likely requires cleaning artifacts afterwards, this time from powder used for scanning rather than naturally occurring dust and grime. It is expected to be an issue only when working with significantly intricate objects however. Technique is wholly not applicable to works like stained glass windows and similarly sized installations, therefore a new approach may be needed if the goal is to recreate such a stained glass composition in its entirety, including lead came, in full detail.

Obviously, if such endeavours were to be scaled to national or international levels, there

emerges a need for standardized workflows. This is caused in large part by the large number of teams with different equipment and internal working processes expected to be working on similar projects or sometimes on the same one. The primary idea behind adoption of standardized protocols is to facilitate easier communication, set expected quality standards and codify the idea of non-intervention (not harming the artifact's state) as one of the main rules. One such idea was proposed in 2022 by a team of Spanish researchers (Cruz Franco et al., 2022) as part of their research of larger "metaverse" projects. However, the same idea can be applied to management of other, non-metaverse, initiatives relatively successfully.

Digital recomposition. Practical application of digital tools being used as a pre-visualization aid is already outlined in several papers. For paintings and frescoes, a critical step in restoration is a reintegration of their elements – a complex process of filling missing areas of the image. This is highly subjective and depends entirely on the conservator's interpretation of the available data. In many cases it is of great benefit to have access to images, drawings, paintings, scans or full catalogue of the original (ideally, fully intact and perfectly preserved) work.

VR/AR offer a solution by enabling virtual retouching that goes slightly beyond traditional ässembly of puzzle pieces" and filling in missing details. High-resolution images and 3D scans of the painting are loaded into a VR environment, where the conservator can:

• Analyze the damage up-close. This is an augmentation and not a replacement for current image analysis techniques used to classify the size and pattern of cracks or other defects.

• Test material and color choices. Current VR editors allow application of different colors (paints), textures, and remodeling of 3D shapes in an interactive way closely resembling real restorative processes. Simulation should be performed in a fully controlled virtual environment that accurately represents the lighting conditions of the artwork's final display location along with any other environmental factors potentially influencing restorative works.

• Collaborate with other team members locally or remotely. Multiple experts (conservators, art historians, engineers etc) can review the simulated restoration in a shared VR space, providing feedback without requiring travel or proximity to the fragile original. Essentially, this is a step above current video conferences and file sharing used in similar collaborative projects.

A notable European example is the restoration of Giotto's and Cimabue's frescoes in the Upper Basilica of Assisi, which were heavily damaged by two earthquakes in 1997 (Paquet et al., 2008). Actual work on physical recomposition of fragments was preceded by digitization and computer simulation of end result using inner regions of broken pieces as a guide Classic approach of matching surface, color and contours of pieces proved to be unreliable at best and impossible at worst, due to extensive damage to the basilica roof (seen in an image appendix or the mentioned paper).

Restoring 3D objects has its own set of challenges associated with the task. One such example, sadly relatively common, are sculptures, especially those recovered from archaeological sites or damaged by natural or man-made disasters. They often exist in hundreds of fragmented pieces which may not even form a complete set, further complicating restorative efforts. Traditionally, reassembly is a long, tedious, trial-and-error process that risks further damaging fragments themselves.

Digitization techniques and VR can be used to create a virtual puzzle that is assembled before real pieces. For example, in the restoration of a fragmented terracotta statue damaged in the 2009 Italian earthquake (Arbace et al., 2012), researchers simulated the recombination of 3D-digitized fragments in a virtual environment. This process drastically reduced the physical manipulation of fragile artifacts and allowed conservators to evaluate multiple reassembly options digitally. The resulting digital model was later used to accurately design and 3D print a physical supporting structure.

Recreating interiors. VR recreations of interiors and sometimes whole buildings

(interior and exterior parts together) is another, more appealing, use of virtual reality technologies. In a way, this area is more important than previous examples, because it has hardly any 2D analogues capable of fulfilling the same objective of placing large-scale fine arts (altarpieces, statues, tombs) back into their original spatial context in the same way as they are now or were long ago. Most notably, we can also evaluate the visual impact of restorative efforts in regards to broader architectural space, ensuring that our intervention remains as harmonious with the overall design as possible.

At least several good examples are known:

• Project "Florence As It Was", an initiative that "aims to reconstruct the city the way it appeared at the end of the fifteenth century" (*Florence as It Was – Florence as It Was*, n.d.). An incredibly detailed VR reconstruction augmented by informative "profiles" and history of the Florentine buildings (not architecture in general but specific historic sites). Of course, praiseworthy is the inclusion of photogrammetry models and old maps.

• Digital recreation of (thankfully existing) interiors of a church in Florence, Italy called Orsanmichele (Bent et al., 2022). This project is a part of "Florence as it was" but deserves its own mention on the merits of describing the entirety of the digitization process in great detail.

• VR environment recreation of St Augustine Church and its murals (Soto-Martin et al., 2020). A United Nations Educational, Scientific and Cultural Organisation (UNESCO) World Heritage Site in La Laguna, Tenerife (Canary Islands, Spain) site was recreated as a 3D model, its visible murals scanned, assembled as a part of a digital environment. Works that are faded so much as to be rendered totally invisible, were scanned, repainted (only in digital form) and included along with any other data deemed as necessary for the full experience.

Other initiatives. EU has been funding some initiatives on its own, in particular projects like ECHOES (European Cloud for Heritage OpEn Science) (ECHOES, n.d.) and GREENART (GREen ENdeavor in Art ResToration) (GREENART, 2024) are examples of this collective effort. The former of the two aims to create the collaborative "cloud" in a form of unified shared platform which offers "access to data, cutting-edge scientific and training resources, and advanced digital tools, all developed collaboratively by the heritage community to meet their specific requirements". In other words: their goal is to help create unified processes touched upon earlier in this paper, however it remains to be seen how successful this project will be. The latter initiative is aimed at creating "green" and environmentally friendly ways for conservation of cultural heritage objects. This is rather interesting, since many old materials, including concrete, are environmentally friendly by their nature. The same can be said about the majority of old building techniques, so if restoration is carried out in accordance with original approaches, it may have relatively low impact on the environment, which can hardly be said about many modern sites. VR is by itself a way to bridge a gap between plan and implementation in ways not involving trial and error, which are frequently considered and are wasteful from economic and material points of view. We create digital versions, ensure our restorative, corrective or maintenance plans are sufficient for the goal and produce correct results in as few attempts as possible and only then start actual work. As with ECHOES it remains to be seen what the actual impact of GREENART will be, nonetheless both initiatives are helpful to the cause and may help with refining uses and role of virtual and augmented realities in the conservation and restoration of cultural heritage items.

Discussion. VR/AR software is still relatively inefficient as a tool for collaborative art editing or research, hardware on the other hand has reached levels when it is fully capable of completing the same tasks. Current shift towards cheaper and more powerful head-mounted displays (devices we usually call "VR goggles") and mobile AR devices, has made these tools practical for everyday use as a professional tool. The integration of 3D models into game engines like Unity or Godot allows for quick development

of custom interactive VR environments tailored for specific conservation tasks. Matter of factly, as of now it is the only efficient way of creating large-scale detailed VR environments. New AI and machine learning tools (machine learning being less sophisticated software), often layered on top of digitized art pieces, may be of use in automatic detection of defects, prediction of material degradation, or simply streamlining workflows of art restoration teams.

Quality of digital model and especially, one made for VR interaction, is entirely dependent on the fidelity of initial scans, in the absence of which, second best option is to use handmade digital 3D models. When it comes to paintings or drawings, we have an added challenge of achieving the highest degree of accuracy in rendition of color and material texture. Such a high standard is needed in part due to the discussed use of such models – restoration, conservation and non-invasive research. Thankfully, already present standards allow for interoperability and mostly issue-free collaboration between different teams. Long-term preservation of digital assets themselves is of higher concern in our opinion. Unlike physical artifacts that can last centuries and in some cases several millenia, digital models are at the mercy of technological and economic progress or lack thereof.

Conclusions. European experience with using virtual and augmented realities in the conservation and restoration of cultural heritage shows a practical and actionable guide of how to proceed further with such approaches. Cultural heritage specialists working with fine arts are offered a unique path to non-destructive analysis and risk mitigation, allowing them to, among other things, prepare interventions beforehand using digital copy before touching the original item. In some cases (like with Basilica of Assisi) creating virtual copy is quite literally the only possible way to successfully finish restorative projects in a reasonable timespan. Unlike more traditional digital research tools, VR/AR provide us with the interactive way to pre-visualize results of such conservation efforts, view previously unnoticed aspects of the art piece in question, visit no longer accessible areas or view digitally recreated pieces that were lost to time. As a result, VR and to some extent AR gained their status as a prerequisite for responsible conservation, unless their use would be more of a hindrance than benefit. As European collaborative projects continue efforts in establishing open standards and shared project databases, every reasonable effort should be directed towards ensuring that new technologies are not used solely for the sake of using them. Thankfully, this is understood by artists, historians, conservators, restorers and other specialists involved in preservation of their culture. The goal of any such endeavour is and should always be to ensure that past and present are preserved not just for the current generation, but for as many of the future generations as possible. If done right, and here Europe makes good progress as well, virtual reality applications can make European art and culture accessible, understandable, and enduring for a rather long time. Simultaneously, success of similar initiatives within and without the EU can provide a blueprint of how the global community can proceed further with similar matters.

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Стаття надійшла: 21.11.2025
Прийнято: 05.12.2025
Опубліковано: 30.12.2025