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Survey Data Integration for Enhanced Cultural Heritage Dissemination and Analysis through Virtual Reality

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Abstract

The preservation and dissemination of Cultural Heritage (CH) in the digital era demand innovative approaches that transcend traditional documentation. This article presents a complete workflow for creating semantically enriched and immersive digital experiences of CH artifacts. We detail a methodology that integrates multi-modal survey data—specifically, high-resolution photogrammetry, laser scanning, and diagnostic thermography—to generate a comprehensive 3D digital twin of historical objects. The process addresses key challenges in data acquisition, such as environmental constraints and object fragility, through a robust data fusion pipeline. A critical component of this pipeline is a score-based point cloud denoising algorithm that significantly improves the geometric accuracy of the final model. The integrated and processed 3D model is then deployed within a Virtual Reality (VR) environment developed in Unreal Engine. This VR application allows users to engage with the artifact in an interactive, immersive, and informative manner, offering access to its geometry, texture, and underlying diagnostic data. Using wooden furniture from the Royal Palace of Caserta as a case study, we demonstrate that this integrated approach not only enhances public engagement and educational value but also provides a powerful analytical tool for conservators and researchers.

1. Introduction

Since the inception of the digitally inclined world, the preservation of cultural heritage should include innovative ways that allow for sustained interest in past narratives and artifacts. With the growing need for cultural heritage digital twins, the integration of diverse sources of data is significant in maximizing heritage management, especially where traditional methods are not as precise. No single survey technique can capture all the necessary attributes of a complex historical artifact. For instance, while photogrammetry excels at capturing photorealistic textures, it can struggle with geometrically complex or poorly lit surfaces. Conversely, laser scanning provides high geometric accuracy but often lacks colour information and can be hindered by reflective materials. For this reason, our research uses advanced 3D survey techniques to create an accurate and semantically enriched digital model, specifically designed for the unique needs of each given environment (Balletti et al., 2019; Morena et al., 2021). In addition, techniques like virtual and augmented reality allow immersive, interactive experiences that capture the interest of modern society, particularly young generations accustomed to digital environments.
By enhancing content accessibility and interactive engagement, this study aims to bridge the gap between traditional heritage preservation and the evolving expectations of contemporary audiences, particularly younger generations accustomed to interactive digital media (Srdanović et al., 2025; Teruggi et al., 2021). Virtual Reality (VR) offers a compelling solution, enabling immersive and interactive experiences that can bridge the gap between historical artifacts and modern viewers. VR allows users to explore objects from impossible angles, manipulate virtual models, and access layers of information not visible to the naked eye, thereby fostering a deeper connection and understanding.
This work provides a complete workflow for VR application on 3D objects obtained from different sources, integrating terrestrial photogrammetry and laser scanning, then processed to construct a structured mesh. The obtained objects are then built in a gaming environment using Unreal Engine to obtain an immersive experience, enriched with various types of data that can be consulted via the game functions.
Our case study focuses on ornate pieces of wooden furniture located within the Royal Apartments of the Royal Palace of Caserta, a UNESCO World Heritage site, as part of the 2022 PNRR Call for Proposals SINERGY project[1], aiming to develop tools for predicting mechanical decay in heritage wood, making the integration of diagnostic data like thermography particularly relevant.

1.1 From digital survey to dissemination

The digitization of cultural heritage has been an active field of research for decades, when early efforts focused on the application of individual technologies. Photogrammetry has been widely adopted due to its low cost and ability to capture high-resolution textures, with Structure-from-Motion (SfM) algorithms automating the 3D reconstruction process. Laser scanning, particularly Time-of-Flight (ToF) and phase-shift systems, became the standard for high-accuracy geometric documentation of large-scale sites and complex artifacts (Acke et al., 2021).
More recently, research has shifted towards the fusion of these data sources. The combination of the geometric precision of laser scanning with the textural fidelity of photogrammetry has been shown to produce superior 3D models. The primary challenge in

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this process is accurate registration - aligning the different datasets into a single coordinate system, which is often accomplished using shared targets or feature-based algorithms.
Point cloud processing is another critical area. Raw data from any sensor is inevitably corrupted by noise and may contain holes due to occlusions or reflective surfaces, so it is necessary to adjust this data to be able to obtain structured and textured 3D meshes.
On the other hand, the aim of the research is based on the dissemination of knowledge, focusing on architectural cultural heritage (Pavelka Jr. & Pacina, 2023). For this reason, new digital technologies have been considered, and serious games have been pointed out among the main means of communication above all because their spread among individuals raised with digital media (Yun, 2023). The development of computer graphics has made it possible the digitization of priceless artworks, supporting historical learning and teaching or for enriching museum visitation (Ali, 2024). Simulating real artefacts through Virtual or Augmented Reality allows people not only to discover places far away, but also to interact with them exploring further data enhanced into the digital world (Antuono et al., 2024). In recent years numerous studies have underlined the advantages of the growing impact of immersive technologies on cultural heritage, highlighting their ability to increase educational value and audience reach (Zhang et al., 2024).
Our work builds on these foundations by integrating not just visual and geometric data, but also analytical data (thermography) into a user-friendly VR experience, directly linking dissemination with conservation science (Sanfilippo et al., 2025).

2. Materials and methods

2.1 Data acquisition and integration

The chosen case study it the Royal Palace of Caserta, which, being a UNESCO World Heritage site, has strict rules concerning spaces usage. Every type of in-depth study of the objects within the Palace has thus limitation, leading to the necessity of Non-destructive analysis and the impossibility of moving the pieces of furniture. Specifically, for the context the survey campaign was carried out with two techniques: terrestrial photogrammetry and laser scanning (Ebolese et al., 2019). Both were initially applied in the Royal Apartments along the southern façade, with the intention of extending the experiment to the entire complex.
Regarding photogrammetry, three types of Canon cameras were used: EOS 5D Mark IV with focal length 20mm, EOS 60D with focal length 18mm, EOS R6m2 with focal length 24mm. A systematic orbit shooting pattern was employed, ensuring a high degree of overlap (approximately 80-90%) between consecutive images to facilitate robust SfM reconstruction. It was necessary to take several hundred high resolution images of each room to return not only the architectural value but the single pieces of furniture even in the back parts. These objects presented significant challenges, including intricate carvings, gilded surfaces, and difficult lighting conditions. These data were then processed in Agisoft Metashape obtaining a high-resolution dense cloud. Simultaneously, a range-based survey was conducted using a Leica BLK360 laser scanner, registering the individual scans with the external markers to create a unified, high-accuracy geometric point cloud.
The subsequent registration of both outcomes in a common coordinate system was achieved by manually identifying several homologous points present in each dataset, obtaining a metrically correct 3D model (Figure 1), but still suffering from noise due to ambient light variations, reflective gilded surfaces, and inherent sensor noise. Over the last few years, several algorithms have been suggested for the cleaning of 3D point clouds to make them more geometrically descriptive of real-world objects. Specifically, in this experimentation it was used the denoising algorithm described by Gonizzi Barsanti et al. (2025).

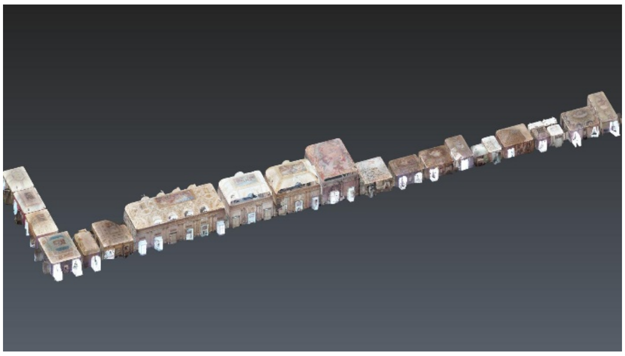

Figure 1. Complete point cloud from integrated digital survey carried out in the Royal Apartments of the Royal Palace of Caserta.

The cleaned, fused point cloud was used to generate a polygonal mesh model using a Poisson surface reconstruction algorithm. Finally, the high-resolution textures derived from the photogrammetric process were re-projected onto this optimized mesh, resulting in a geometrically accurate and photorealistic 3D model.
Context restitution is enriched by the detailed survey carried out with a handheld metrology-grade 3D scanner, Shining 3D FreeScan UE Pro, to capture the precise geometry of the artifacts. This was crucial for obtaining accurate measurements and defining the true shape where photogrammetry might fail. Due to the fragility and historical value of the furniture, adhesive markers could not be placed directly on the objects. Instead, a strategy was adopted where coded markers were placed on stands and the floor around the object, creating a stable reference frame for automatic scan alignment (Figure 2).

Figure 2. The strategy adopted to place markers for detailed survey of the artefacts in the Royal Palace of Caserta, using a handheld metrology-grade 3D scanner, Shining 3D FreeScan UE Pro.

2.2 VR application

The final 3D model was imported into Unreal Engine 5 to create the immersive experience. The design of the immersive digital environment was based on the adoption of a first-person perspective (Figure 3), considered optimal for Virtual Reality

(VR) use as it enhances the user's sense of presence and agency. This configuration empowers the effortless inclusion of three-dimensional objects, files, and data that users may wish to utilize while moving within the virtual environment (Iacono et al., 2024). Users can navigate the virtual space using their VR controllers, allowing for both free roam "walking" and point-to-point "teleportation" for comfortable exploration. This freedom of movement offers a significant advantage over pre-rendered 360° virtual tours.

Figure 3. Construction of the VR environment within Unreal Engine 5, starting from the first-person template.

User interaction with the data within the VR environment is primarily done and made possible with the help of VR controllers (Figure 4). These devices are fundamental to the experience as they allow the users to navigate the virtual space, interact with the objects, and data (D’Agostino et al., 2022). In this context, the workflow created offers in-depth video game-like possibilities as well as a simplified desktop application that allows people from different parts of the world to virtually visit and move around the Royal Palace. By allowing free movement and interaction, this approach adds value over traditional virtual tours by giving users more control and a greater sense of immersion in the historic sites they visit.

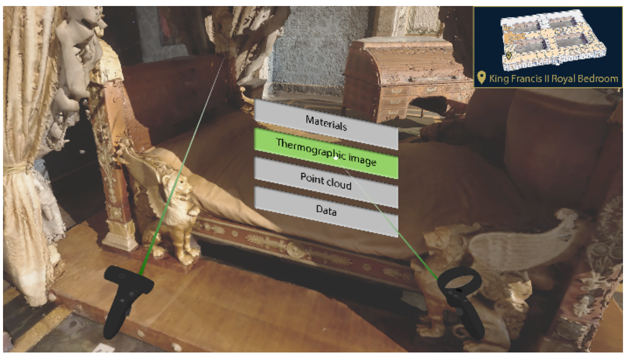

Figure 4. Interactable menu in the scene driven by VR controllers.

The user-model interaction is mediated by a system of customised widgets, i.e. user interface (UI) elements developed specifically for this application. This UI was developed using Unreal Engine's Blueprint visual scripting system, allowing for rapid prototyping of interactions without complex coding (Figure 5). These widgets act as gateways for querying the model, allowing contextual data to be extracted and visualised. The orchestration of the user experience is centralised in buttons integrated into the scene and linked, through event-driven programming scripts, to specific functions that activate the display of additional information layers. These call up the content implemented in the information architecture to offer a balanced and multifunctional experience.

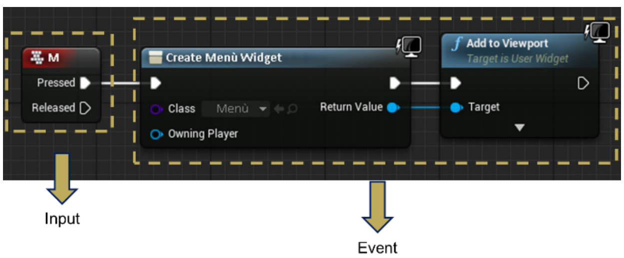

Figure 5. Unreal Engine’s Blueprint algorithm to let the menu appear in the digital world.

As part of the experimentation, different categories of information were defined and implemented, each characterised by a specific design approach in relation to the cognitive objectives pursued. Among these, three significant implementations stand out.
The outcomes of targeted thermographic surveys (IRT) conducted on the wooden objects, using a FLIR A700 thermal

imaging camera, microbolometric with 24° lens, can be consulted (Figure 6). This information is displayed through pop-up panels that are activated within the digital scene. By selecting specific hotspots or areas of interest, the user can call up the corresponding thermographic image showing the distribution of surface temperatures. This approach allows a qualitative and immediate analysis of thermal phenomena.

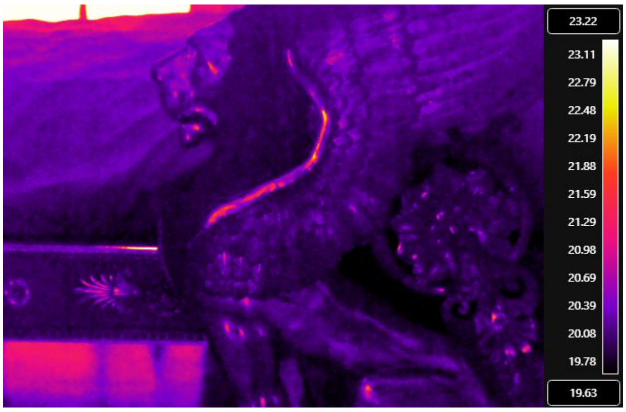

Figure 6. A sample of the thermographic survey conducted on the wooden lions on the left side of the bed. Images taken with a FLIR A700 thermal imaging camera, microbolometric with 24° lens.

Moreover, environmental microclimate monitoring was performed using data loggers, positioned close to the sample objects, continuously recording the environmental temperature (°C) and relative humidity (%) from February 2024 to April 2025, with a sampling frequency of 5 minutes to capture even short-term environmental dynamics. The temperature time series were then processed using statistical models or machine learning algorithms. These data can thus be called up in the scene via interactive panels (Figure 7). The aim is twofold: to identify trends and anomalies not visible to the naked eye and to develop predictive models capable of estimating future thermal trends under certain operating or environmental conditions.

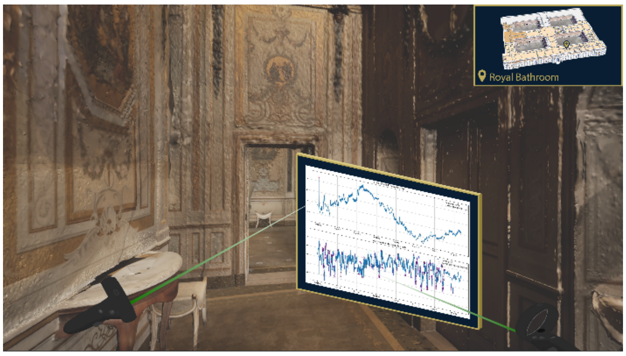

Figure 7. Interactable table showing the changing of temperature and humidity in a long period.

For single objects, the generation of a solid model through automatic segmentation of the point cloud is also being tested. Starting from the raw point cloud, acquired by laser scanning or photogrammetry, semi-automatic segmentation algorithms have been implemented that identify and classify the different geometric components of the object (e.g. walls, floors, structural elements). The result is the creation of a solid model (B-Rep or closed polygonal mesh), no longer just a set of points, but an intelligent and structured geometric model to which information regarding material composition can be associated so that it can be ready for subsequent analyses such as engineering simulations (e.g. FEM). These models are made available online via cloud platforms and can be consulted directly in the digital scene on panels connected to these platforms via links (Figure 8).
This multi-layered approach empowers users to explore the artifact not just as a visual object, but as a complex subject of scientific study. The ability to access the extensive metadata of each 3D object and model as they navigate through the volumetric space increases the cultural and educational value for a wider audience (Holloway-Attaway & Vipsjö, 2020; Wen et al., 2025).

3. Results and conclusions

3.1 Discussion

The results demonstrate the significant value of an integrated, multi-modal workflow for the digital preservation of cultural heritage. The primary contribution of this work lies in the successful implementation of a complete pipeline, from challenging in-situ data acquisition to an engaging and analytically useful VR dissemination platform. The application of our integrated workflow yielded significant improvements at each stage.
As for model fidelity and accuracy, the fusion of photogrammetry and laser scanning resulted in a 3D model superior to what could be achieved with either method alone. The laser scanner data corrected for geometric distortions present in the photogrammetry-only model, particularly in areas with uniform texture or complex shadows. The photogrammetry provided the rich colour and texture that the laser scanner could not capture. The denoising algorithm was highly effective, producing a smoother and more coherent surface topology. Quantitative analysis showed an improvement in surface accuracy, achieving a local precision of 0.02 mm in cleaned areas, which is critical for detailed conservation analysis.
Regarding the immersive and interactive experience, the final VR application provides a highly immersive and stable outcome. Users can get arbitrarily close to the virtual artifact, examining details of the wood grain, carvings, and gilding at a scale impossible in a physical museum setting. The multi-modal visualization successfully transformed a static digital object into a dynamic tool for exploration and learning. The inclusion of thermographic data, in particular, provided a unique insight into the "unseen" condition of the artifact, making the abstract concept of material decay tangible to a general audience.
This workflow is not without its challenges. The data acquisition and processing stages are computationally intensive and require significant expertise. The need for specialized hardware such as laser scanners, high-end PCs, VR headsets, as well as proprietary software, presents a cost barrier. Furthermore, while our VR application is highly functional, formal user experience studies are needed to quantitatively assess its impact on user engagement, knowledge retention, and its utility for conservation professionals.

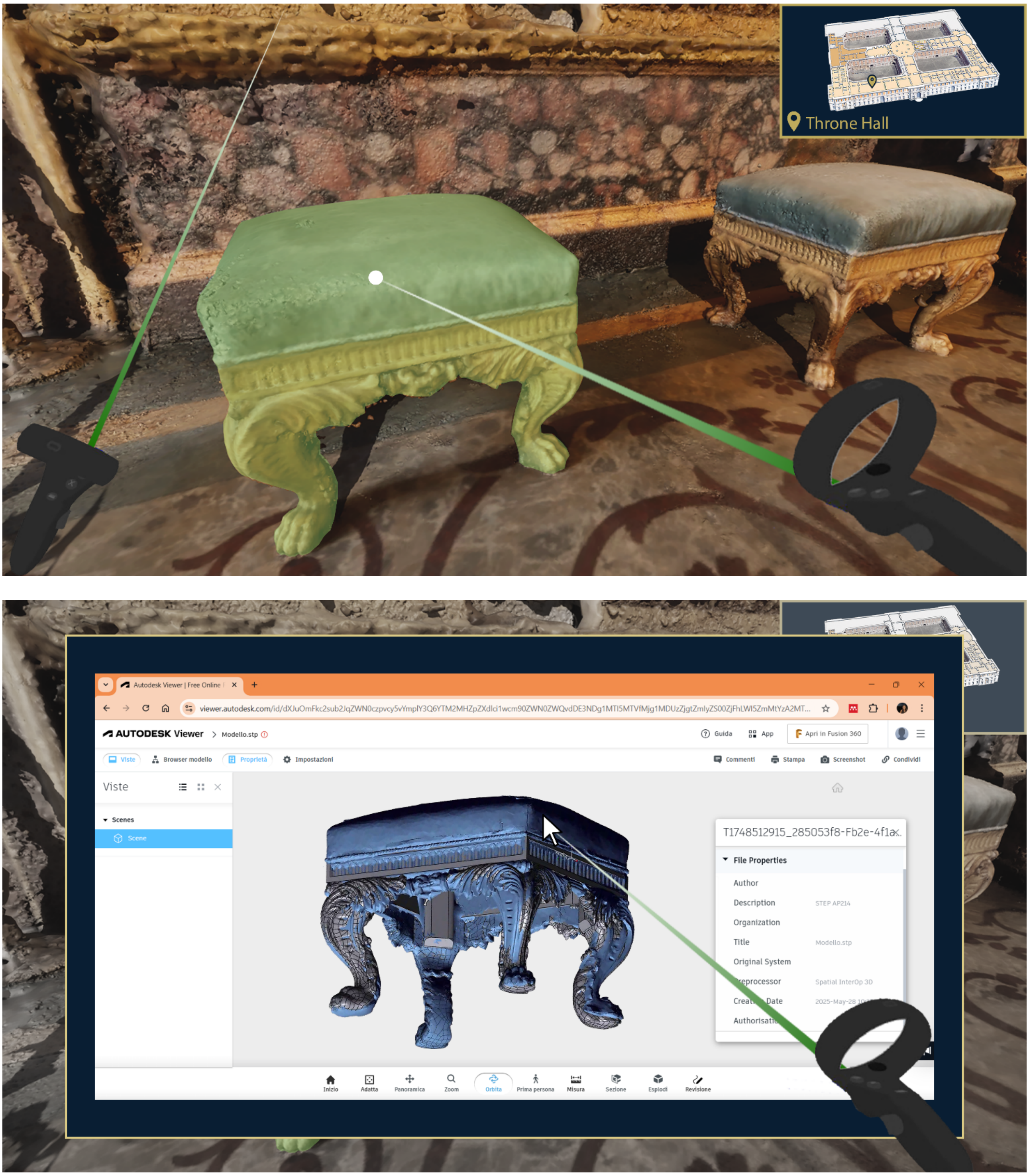

Figure 8. Up: selection of a single element in the scene with VR controllers. Bottom: online browsable 3D model extracted from the point cloud starting from semi-automatic segmentation algorithms.

3.2 Future developments

This paper has presented a comprehensive and validated workflow for the creation of immersive and analytically rich digital twins of cultural heritage artifacts. By integrating photogrammetry, laser scanning, and thermography, and employing advanced point cloud processing techniques, we produced a high-fidelity 3D model that serves as the foundation for an interactive VR experience. The case study of the furniture at the Royal Palace of Caserta demonstrates that this approach can enhance cultural and educational dissemination while simultaneously providing valuable data for conservation efforts. Future work will proceed in several directions. First, we plan to incorporate additional data modalities, such as multispectral or hyperspectral imaging, to provide even deeper insights into material composition and degradation. Second, we aim to expand the application to entire architectural spaces, allowing for a fully immersive exploration of historical rooms. Third, we will develop collaborative, multi-user VR features, enabling guided tours and remote consultation between conservators and researchers. Finally, we will conduct formal user studies with both the general public and heritage experts to rigorously evaluate the effectiveness of the platform as an educational and analytical tool.

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