DIGITAL HERITAGE (2025)
S. Campana, D. Ferdani, H. Graf, G. Guidi, Z. Hegarty, S. Pescarin, and F. Remondino (Editors)

Immersive RockArt: When rock carvings meet photogrammetry and computer graphics

D. De Luca[1], M. C. Liguori[1], A. Guidazzoli[1], E. M. Farella[2], F. Remondino[2], T. Cittadini[3] and M. Loeffler[4]

[1]CINECA, Italy
[2]Bruno Kessler Foundation (FBK), Italy
[3]Centro Camuno di Studi Preistorici, Italy
[4]Kunstkraftwerk Leipzig, Germany

Abstract

Rock Art Immersive is an interdisciplinary project for the 3D documentation, valorisation, communication, and tourist promotion of the UNESCO site of the Pitoti rock carvings in Val Camonica (Italy). Photogrammetry and Computer Graphics are coupled to create reality-based interactive and communicative material to safeguard and valorize a heritage site.

CCS Concepts

• ***Applied computing*** → ***Arts and humanities;*** • ***Computing methodologies*** → ***Computer graphics;***

1. Introduction

With its 12,000-year history of stone carving and more than 140,000 prehistoric rock engravings, spread over more than 180 sites in 24 municipalities. the Val Camonica in Italy offers the world's largest collection of this heritage. In 1979, it is declared the first UNESCO World Heritage Site in Italy [San22]. The carved scenes depict various scenes and activities of daily life, from hunting and farming to rituals or other social experiences. The environmental condition of the site poses significant challenges to its preservation, as the fast-growing vegetation on the stones requires constant maintenance. Moreover, the effects of time and centuries of weathering exposure have, in some cases, worn their visibility down.

The evolution of digital technologies is offering unprecedented opportunities for documenting and valorising such cultural heritage sites, both in terms of data collection and fruition [CB12, Rem11, RMK*13]. While reality-based 3D surveying techniques are nowadays well-established solutions for the accurate 3D documentation of heritage contexts, the significant advancements of computer graphics are offering new possibilities for data fruition, visualization, and valorization [Sco21].

Aware of these possibilities, RockArt Immersive is an ongoing interdisciplinary project, launched to bring together several research institutions and no-profit cultural associations involved in the realization of an engaging, interactive, and immersive experience to boost knowledge and awareness of the Val Camonica rock site. This paper presents the 3D surveying and modeling activities carried out to create 3D assets of the carved rocks and the successive computer graphics methods. The project involves the Centro Camuno di Studi Preistorici (CCSP), Italy; Kunstkraftwerk of Leipzig, Germany; Fondazione Bruno Kessler (FBK), Italy, and CINECA, Italy. All 3D digitized engravings are animated, colored, and set into an audiovisual narrative that will be showcased in several locations across Italy and abroad. So far, a video trailer (https://youtu.be/uC0CtvxBB1s) is available as a proof of concept of the final immersive installation.

Figure 1: *A rock art detail*

While many heritage-oriented valorization products for large audiences prioritise accurate visual representation, focusing on didactics, the workflow hereafter presented integrate and handle very high-resolution and precise scientific data into a computer graphic pipeline, delivering 3D animations and visual effects in a truly spectacular and artistic outcome. Furthermore, the development of a transportable immersive show has the potential to enhance portability to different locations, reaching an even wider audience. The

DOI: 10.2312/dh.20253071

inspiration is drawn from prior successful experiences in museum installations [FGI*15, MNR*16]. The increased challenge in this work is to manage, optimize and transform large-scale 3D scientific data to achieve immersive experiences, mixing science, technology and art in a "POP" cultural production.

2. Related works

Studies in the field of the 3D digital documentation of heritage rock engravings over the last decade have highlighted some of the complexities of working in this context. The main challenges are related to the environmental conditions, uneven surfaces, and variable lighting situations which can complicate the data acquisition process and affect the quality of the results [HP15].
To address the need of capturing and reconstructing larger scene contexts together with the small-size rock engravings, some multi-scalar 3D documentation solutions have been proposed [APR15, BVTB*24]. From the technological perspective, both range and image-based techniques have been exploited for the 3D modelling task [Jal21, GBECRMP24] Digitized 3D assets have been further leveraged in some works mainly for image classification [HIL*22], segmentation [ZPS*15], and skeletonization tasks [WSZ17]. Leveraging such digitized assets for immersive fruition, interaction, and animation represents a key direction in digital cultural heritage, with recent reviews analyzing the state-of-the-art, potential, and grand challenges of these technologies [WDL*25].

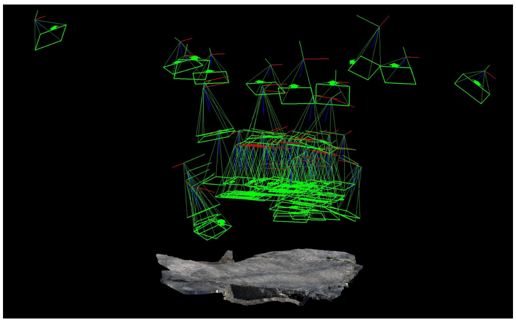

Figure 2: *Example of a photogrammetric camera network.*

3. RockArt Immersive: project implementation

3.1. 3D rock engravings digitization and modelling

All project outcomes are based on image-based 3D models. The image acquisition campaign poses several challenges, related to the uneven rocks surface, the limited dimension and depth of most of the engravings (< 1 cm), and the variable lighting conditions. In such environments, to minimize the risk of detail loss and harsh shadows, image capturing should ideally be conducted when the light is more diffuse and uniform, such as early mornings and late afternoons. However, due to the timeline constraints of the field campaign, images were acquired under more variable lighting conditions. This variability necessitated additional adjustments and pre-processing, including image equalization and shadow correction, to ensure a more consistent appearance across the images, preserve the fine details of the engravings, and improve the overall quality of the final render. Photogrammetry, coupled with metrological targets properly distributed around the engravings, is used to generate 3D models with high geometric precision and color fidelity, to ensure a realistic and consistent representation of the rock surfaces. A multi-scale approach is leveraged for capturing the individual engraving and the surrounding rocks (Figure 2, Figure 3). Several focal lengths (28 mm, 50 mm, 105 mm) and diverse acquisition distances are used to yield a final sub-millimetric Ground Sample Distance (GSD) for the digitized engravings (0.1 mm) and a portion of the surrounding rocks (0.5 mm). The derived dense point clouds of the engravings feature an average resolution of 0.1 mm and are leveraged for the meshing process.

Figure 3: *Example of photogrammetric dense point cloud, without/with color information.*

3.2. Data editing and optimization

The large datasets required intensive pre-processing before animation and rendering. This involved (i) data cleaning for removing unnecessary elements and artefacts; (ii) remeshing for achieving a more manageable datasets; (iii) creation of Levels of Detail (LoD) and multiple versions of the same assets with different levels of geometric complexity.
Blender (`https://www.blender.org/`) is used for the creation of the scene, animation, and the final rendering of the trailer. The visualization of point clouds with millions of vertices poses significant challenges both in terms of interactivity in the viewport and rendering times. Therefore, it was decided not to implement a classic Level of Detail (LOD) system based on the distance, as this would have caused pop-in errors and inconsistencies during camera movement; instead, optimization techniques using Blender Geometry Nodes (Figure 4) are implemented:
Decimation: Viewport - To ensure fluidity during animation (target 24-30 fps), the point cloud displayed in the viewport underwent aggressive decimation, reducing the displayed points by a factor of approximately 1/100 compared to the optimised original. Rendering - For the final rendering, decimation is less aggressive and varied between 50% and 90% of the points depending on the shots.
Frustum Culling: To further reduce the computational load, a frustum culling and back culling techniques (implicit in frustum) are implemented using Geometry Nodes. This system identifies points that fall outside the volume of view (frustum) of the virtual camera and excludes them from calculation and visualisation. Technically, this is achieved by projecting rays from the camera origin through a proxy plane (a 20:10 rectangle positioned in front of the camera) to the point cloud. Points not intersected by these rays are

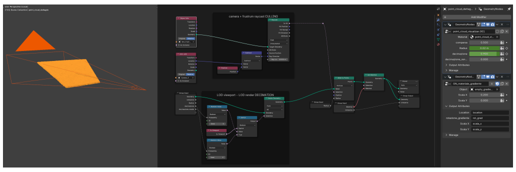

Figure 4: *Blender Geometry Nodes point cloud optimization.*

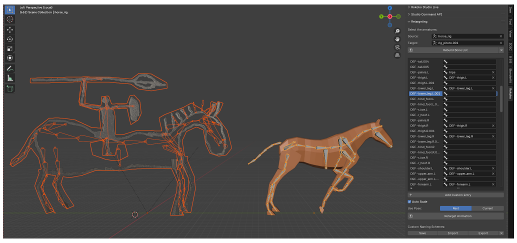

Figure 5: *Rigging, animation and retargeting of a "pitoto" warrior.*

discarded. This method naturally identifies two cones (frustrum): in front of the camera (the one of interest) and a specular one behind the camera. The node system was configured to also explicitly discard points belonging to the rear frustum, further optimising performance.

Animated apparition control: To simulate the point cloud "generation" resembling a laser scan, an empty object is animated (location and rotation). Its changing properties are read by Shader Nodes to dynamically control point visibility and transitioning (e.g., changing colour), creating a progressive appearance effect.

3.3. Animation workflow

The trailer narratively follows the photogrammetric process. From point cloud generation and transformation into a mesh, through texture mapping, to the final model render. To give greater emotional impact and demonstrate the potential of the technique, it is decided to animate one of the acquired figures, the Pitoto depicting a warrior on horseback. The animation process comprises:

Mesh extraction and preparation: The high-resolution mesh of the Pitoto on horseback is isolated from the rest of the rock scan. It is then optimised, contoured, and solidified. The key challenge was the 3D interpretation of an inherently 2D stylised figure, seeking a compromise between fidelity to the original engraving and animation requirements to avoid artefacts or unnatural movements.

Rigging: A Rigify rig is built within Blender, consisting of virtual bones to control the movement of the horse (legs, head, tail), custom tailored in order to add the controls for the Pitoto rider.

Animation and Retargeting: To achieve a credible animation of the horse, we started from a pre-existing animation of a galloping horse that has a standard rig (based on Rigify). To transfer this animation to the custom Pitoto rig, a Blender add-on "Rokoko Studio Live" is used to retarget the rigs, by mapping from a source armature (the horse) to a target (the Pitoto custom rig), by using a bone correspondence list (Figure 5).

Manual Finishing: While retargeting provided a solid basis, extensive manual keyframing is essential to adapt the animation to the Pitoto specific stylized morphology, to correct any interpenetrations and add specific details like the spear and shield movement and emphasizing the transition from rock to free animation. A manually animated horse wheelie is integrated into the ride sequence. Finally, visual effects (smoke, particles, dust) are added to seamlessly blend the static carving with the dynamic animation.

Figure 6: *Applied NPR shaders and compositing for stylizing effects.*

3.4. Data presentation: Non-Photorealistic Rendering

Parallel to the technical development for data management, extensive stylistic research defined the project's visual aesthetics. Given the scarcity of detailed historical references for the Val Camonica populations, a Non-Photorealistic Rendering (NPR) approach is adopted (Figure 6). The goal is a level of abstraction respecting the rock engravings' essence and mystery, avoiding any claim of strict historical accuracy.

This research led to a pictorial and abstract rendering style, characterized by jagged edges, uneven textures and "toon" lighting for both characters and environments. Watercolor-like effects are also explored via compositing to diffuse fine details and manage visual complexity in crowded or distant scenes. For preliminary 3D models of figures and animals, open source AI image-to-3D algorithms (`https://github.com/microsoft/TRELLIS`,`https://github.com/Tencent/Hunyuan3D-2`) are used, often based on selected 2D AI images. Upon importing these assets into Blender, we transformed their conventional 3D appearance to align with the abstract style, primarily using shading, compositing, and geometric modifiers.

3.4.1. NPR shading

Pictorial textures are applied to the 3D models using UV mapping. This approach ensures textures to follow model deformations during animation, preserving figure recognition while contributing to the desired NPR style. For the NPR rendering, Blender PBR and emissive shaders are combined to unnaturally manipulate light interaction, emphasizing colors and creating a "toon" effect.

3.4.2. Geometric silhouette modifiers

In order to break up the regularity of the 3D shapes and give the silhouettes a more organic and "uneven" appearance, a modifier stack is applied that included the subdivision of the geometry followed by displacement modifiers. The displacement uses UV coordinates, introducing irregularities and jagged details on the edges of the models, but consistent with their movements.

Proceedings published by Eurographics - The European Association for Computer Graphics.

3.4.3. Post-rendering compositing

The final stylization phase in Blender compositor, applied Kuwahara and Sobel filters (https://docs.blender.org/manual/en/latest/compositing/types/filter/) to blend and enhance the painterly aesthetic. The anisotropic Kuwahara filter is extensively used for a painterly effect, smoothing fine details and creating homogenous color areas resembling brushstrokes, contributing to an undefined, watercolor feel derived from a customized node group (based upon a Royalty Free licensed assed from BlenderKit, https://www.blenderkit.com/). Conversely, the Sobel filter is employed for edge detection, extracting contour lines to create high-contrast effects (e.g. b/w silhouettes) that recall the essentiality and sharp patterns of rock art.

3.5. Data rendering

To create the complete immersive show a vast amount of high-res data is required: ∼45,000 frames at ∼20,000x2,000 pixels of total resolution. Rendering this scale of data using conventional approaches, like the render engine Blender Cycles, would result in prohibitively long render times and demand unsustainable hardware resources. To overcome these challenges, an intensive rendering optimization strategy is developed.

3.5.1. Rendering engine choice and parameter optimisation

Blender real-time engine, Eevee, is chosen over Cycles because, even if less physically accurate, its faster rendering time supports the project feasibility, aiming at an ideal 2-3 minutes/frame. Achieving these target requires specific optimizations, such as (i) optimizing shadow quality (reduced shadow map resolution, limited soft shadow rays), (ii) limiting raytracing usage, (iii) significantly reducing samples per pixel, (iv) avoiding unnecessary expensive techniques like motion blur and (v) optimizing volumetric effects (fog, atmospheric smoke).

3.5.2. Additional effects and compositing

Stock footage, for elements like dense smoke or dust, is integrated to compensate for potential detail loss from aggressive Eevee optimizations and to enhance scene complexity without increasing render times. The footage is applied to simple planes, within the 3D scene, and added directly in the compositor. Blender real-time Compositor was a crucial factor in achieving further time optimization, leveraging GPU power for compositing operations, accelerating filter application (like the kuwahara/sobel node network) and final frame elaboration.

4. Conclusions

The paper reported the ongoing work of valorising an ancient cultural heritage area, often disregarded by tourists, by coupling photogrammetry with advanced computer graphics solutions. The final immersive show relies on 2D/3D animations and non-photorealistic rendering (NPR) techniques, and these choices will be evaluated by surveying the audience reaction and attitude toward the dichotomy: realism vs abstraction. The ultimate goal is to attract visitors to the physical archaeological site, valorise the heritage area and promote tourism.

References

[APR15] ALEXANDER C., PINZ A., REINBACHER C.: Multi-scale 3d rock-art recording. *Digital Applications in Archaeology and Cultural Heritage 2*, 2 (2015), 181–195. Digital imaging techniques for the study of prehistoric rock art. 2

[BVTB*24] BARNETT T., VALDEZ-TULLET J., BJERKETVEDT L., ALEXANDER-REID F., HOOLE M., JEFFREY S., ROBIN G.: A multiscalar methodology for holistic analysis of prehistoric rock carvings in scotland. *Heritage Science 12* (Mar. 2024), 1–35. 2

[CB12] CHIPPINDALE C., BAKER F.: *.P.I.T.O.T.I., Digital rock-art from prehistoric Europe: heritage, film, archaelogy*. Skira Editore S.p.A., Milano, 2012. 1

[FGI*15] FISCHNALLER F., GUIDAZZOLI A., IMBODEN S., DE LUCA D., LIGUORI M. C., RUSSO A., COSENTINO R., DE LUCIA M. A.: Sarcophagus of the spouses installation intersection across archaeology, 3d video mapping, holographic techniques combined with immersive narrative environments and scenography. In *2015 Digital Heritage* (2015), vol. 1, pp. 365–368. 2

[GBECRMP24] GARCÍA-BUSTOS M., EGUILLEOR-CARMONA X., RIVERO O., MATEO-PELLITERO A. M.: 3d recording of palaeolithic rock art through different techniques: a critical comparison and evaluation view supplementary material 3d recording of palaeolithic rock art through different techniques: a critical comparison and evaluation. *Journal of Field Archaeology 49* (08 2024), 1–19. 2

[HIL*22] HORN C., IVARSSON O., LINDHÉ C., POTTER R., GREEN A., LING J.: Artificial intelligence, 3d documentation, and rock art—approaching and reflecting on the automation of identification and classification of rock art images. *Journal of Archaeological Method and Theory 29* (03 2022). 2

[HP15] HÖLL T., PINZ A.: Cultural heritage acquisition: Geometry-based radiometry in the wild. In *2015 International Conference on 3D Vision* (2015), pp. 389–397. 2

[Jal21] JALANDONI A.: An overview of remote sensing deliverables for rock art research. *Quaternary International 572* (2021), 131–138. Impacts of scientific approaches on Rock Art research: global perspectives. 2

[MNR*16] MENNA F., NOCERINO E., REMONDINO F., DELLEPIANE M., CALLIERI M., SCOPIGNO R.: 3d digitization of an heritage masterpiece - a critical analysis on quality assessment. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XLI-B5* (06 2016), 675–683. 2

[Rem11] REMONDINO F.: Heritage recording and 3d modeling with photogrammetry and 3d scanning. *Remote Sensing 3*, 6 (2011), 1104–1138. 1

[RMK*13] REMONDINO F., MENNA F., KOUTSOUDIS A., CHAMZAS C., EL-HAKIM S.: Design and implement a reality-based 3d digitisation and modelling project. In *2013 Digital Heritage International Congress (DigitalHeritage)* (2013), vol. 1, pp. 137–144. 1

[San22] SANSONI U.: *Alle radici d'Europa : dieci millenni d'arte rupestre in Valcamonica e nelle Alpi centrali / Umberto Sansoni ; prefazione di Emmanuel Anati.* 2022. 1

[Sco21] SCOPIGNO R.: Mixing visual media for cultural heritage. In *Digital Transformation of Museums and Heritage Sites* (jun 2021), RISE IMET 2021, Springer, pp. 297–315. 1

[WDL*25] WANG H., DU J., LI Y., ZHANG L., AND X. L.: Grand challenges in immersive technologies for cultural heritage. *International Journal of Human–Computer Interaction 0*, 0 (2025), 1–22. 2

[WSZ17] WIESER E., SEIDL M., ZEPPELZAUER M.: A study on skeletonization of complex petroglyph shapes. *Multimedia Tools and Applications 76* (03 2017). 2

[ZPS*15] ZEPPELZAUER M., POIER G., SEIDL M., REINBACHER C., BREITENEDER C., BISCHOF H., SCHULTER S.: Interactive segmentation of rock-art in high-resolution 3d reconstructions. In *2015 Digital Heritage* (09 2015), pp. 37–44. 2