From Frescoes to XR: A Digital Human Pipeline for Saint Neophytos

Abstract

Cultural Heritage (CH) sites such as Byzantine hermitages preserve historical figures primarily through frescoes, manuscripts and architectural traces. While these sources transmit iconographic and theological meaning, they leave the embodied presence, voice and gesture of the depicted figure inaccessible to contemporary audiences. Extended Reality (XR) technologies offer an opportunity to augment such representations into spatial and embodied experiences in which a digital human acts as a mediator between fresco iconography and present-day visitors. This paper presents a pipeline that transforms fresco-based references of Saint Neophytos the Recluse, a 12th-century Byzantine monk in Cyprus, into a historically grounded virtual character deployable across both immersive VR and browser-based environments. The pipeline integrates expert-validated historical research, fresco-driven character modelling, animation aligned with monastic tone and behaviour, and platform-specific deployment from a single shared character asset. The case study illustrates how fresco iconography can be translated into a coherent virtual human performance and disseminated across XR modalities without re-authoring, supporting both on-site visitors of the hermitage and remote audiences accessing the experience through standard web browsers.

Keywords: Extended Reality (XR); Digital Humans; Cultural Heritage; Byzantine Frescoes; Saint Neophytos; Multi-Platform Deployment; WebXR.

1. Introduction

Frescoes are among the principal visual sources through which medieval and Byzantine figures are remembered. They preserve iconographic conventions, garments, postures and theological symbolism, yet they remain static, two-dimensional and bound to the physical surface of a wall. For visitors of religious heritage sites such as the Hermitage (Enkleistra) of Saint Neophytos in Cyprus, these depictions provide essential interpretative context, but they only partially convey the lived presence of the historical figure they represent. Extended Reality (XR) technologies provide a way to extend fresco representation into embodied and spatial experiences in which the depicted figure can be encountered as a speaking, moving virtual human, rather than as a fixed iconographic image [1][2][3].

Significant progress has been achieved in the digitisation of CH sites and artefacts, with particular attention to high-fidelity environments and architectural reconstruction [4][5][7]. Comparative analyses of immersive Virtual Reality (VR) and WebXR pipelines further demonstrate how multi-platform delivery can balance visual quality, interactivity and accessibility while mitigating hardware constraints [1]. Recent web-based experiences have begun to integrate animated characters and storytelling mechanisms within browser environments, broadening dissemination beyond headset-equipped audiences [2].

Despite these advances, two limitations remain particularly visible in the context of fresco-based heritage. First, most XR workflows continue to be environment-centric, treating reconstructed spaces as the primary deliverable and underrepresenting the human figures that give those spaces their cultural meaning [4][7].

Second, when virtual characters are integrated, the pipelines are frequently coupled to specific hardware ecosystems or project-dependent tools, which limits the reuse of the same character performance across immersive and browser-based deployments [1][6]. As a result, fresco iconography rarely reaches the embodied, narrative form that XR can in principle support.

A further difficulty concerns the design process itself. The translation of a fresco into a virtual human is not a purely technical task: it involves iconographic interpretation, theological sensitivity and respect for the conventions through which a figure is traditionally depicted. Without an explicit, expert-validated workflow, it is possible to produce visually convincing characters that nevertheless misrepresent identity, garments or gestures, with consequences for both interpretative accuracy and audience trust [6].

To address these limitations, this paper proposes a digital human pipeline that takes fresco iconography as a primary historical reference and produces a single, reusable virtual character deployable across XR platforms (Section 3). The pipeline is demonstrated through Saint Neophytos the Recluse, a 12th-century Byzantine monk whose figure survives mainly through frescoes inside his rock-carved hermitage and through his own theological writings. Working in close collaboration with CH experts, the workflow translates fresco-based visual references into a stylised-realistic digital human, animates the figure with monastic restraint, and prepares the asset for both immersive VR (Meta Quest 3) and browser-based visualisation through a custom WebXR viewer. The same animated performance is reused across both modalities without re-authoring.

The contributions of this work can be summarised as follows:

- A fresco-to-XR digital human pipeline that incorporates expert validation, iconographic reference handling and theological grounding into the technical production workflow.
- An interoperable, modular production framework that unifies parametric character authoring, facial animation, and game-engine and browser deployment around a single shared character asset, enabling reuse across VR and WebXR without re-authoring.
- A focused case study on Saint Neophytos the Recluse that demonstrates how fresco iconography can be translated into a coherent virtual human performance and deployed across immersive and browser-based platforms for both on-site and remote visitors.

The remainder of the paper is structured as follows. Section 2 reviews related work on XR pipelines for CH, virtual humans for heritage interpretation, interaction design, and multi-platform deployment. Section 3 details the proposed pipeline. Section 4 presents the Saint Neophytos case study. Section 5 discusses the outcomes, limitations and future directions of the work.

2. Related Work

2.1 XR Pipelines for Cultural Heritage

VR, Augmented Reality (AR) and Mixed Reality (MR) are increasingly employed in CH applications to support immersive visualisation, interpretation and dissemination of historical sites and narratives. Prior studies and systematic reviews consistently report extensive use of reconstructed architectural environments and spatial exploration techniques, with an emphasis on geometric fidelity and visual immersion in the representation of monuments, archaeological sites and museum spaces [4][5][7]. These approaches have significantly expanded the accessibility and visual richness of digital heritage experiences. They also reveal a clear environment-centric orientation, with comparatively limited attention given to the preservation and reuse of animated narrative assets or character-driven content across contexts and platforms.

Complementary work has investigated structured XR workflows that combine immersive VR and browser-based WebXR tools, demonstrating how multi-platform

cultural experiences can be produced and distributed across devices [1][2]. Such efforts highlight the growing importance of interoperability and accessibility in heritage dissemination. Compared to these existing pipelines, which are typically organised around environment reconstruction or HBIM-derived assets, the workflow proposed in this paper places the digital human at the centre of the production process and treats the fresco itself as the principal historical reference. Existing pipelines also tend to remain closely coupled to specific hardware ecosystems or project-dependent tools, which can constrain long-term reuse and scalability when the goal is character-driven storytelling rather than spatial visualisation.

Overall, existing XR pipeline research has advanced the technical production and visualisation capabilities of CH applications. Nevertheless, challenges persist in achieving content interoperability, narrative continuity and the integration of culturally grounded design considerations within unified workflows. These observations motivate methodologies that support multi-platform deployment while treating expert validation and iconographic coherence as structural elements of XR creation, an aspect addressed by this work.

2.2 Virtual Humans and Historical Character Representation

Virtual humans are increasingly incorporated into CH XR applications as narrators, guides and mediators of historical content, with the potential to enhance engagement, emotional connection and narrative comprehension beyond environment-centric experiences [21][22]. Empirical and design studies show that hyper-realistic character modelling, dynamic animation and audiovisual fidelity can significantly influence user engagement and cultural mediation [8]. Research in museum contexts indicates that information richness, aesthetic quality and flow experience contribute to user immersion when interacting with digital agents [9]. Thematic reviews further highlight how animated characters and narrative sequences foster presence and emotional resonance [10].

Practical workflows for the creation and integration of realistic virtual humans illustrate technical practices such as motion capture, lip-sync and animation retargeting that are used to bring virtual narrators to life in AR and VR heritage applications [6][23]. Surveys of digital humans in CH underscore the role of avatars and agents as mediators of cultural content and facilitators of interactive experiences in both on-site and online contexts [3][24]. However, these workflows rarely position iconographic sources, in particular frescoes, as the primary anchor for character design, and they seldom integrate explicit expert validation steps as structural elements of the pipeline. The present work targets this gap by treating fresco-based references as the entry point of the workflow and embedding iconographic and theological review at each production stage.

2.3 Interaction Design and Narrative Control in XR Characters

Interaction design plays a central role in shaping how users engage with virtual characters in immersive environments. Surveys on 3D virtual human interaction highlight the importance of multimodal modalities, such as speech, gesture and facial expression, in fostering responsive behaviour and more engaging user experiences [11]. Research on VR interface design further emphasises principles such as feedback mechanisms and multimodal triggers as key elements for immersive and narrative-driven interaction [12]. In the context of XR storytelling, authoring tools based on trigger–action logic demonstrate how character behaviours and narrative sequences can be dynamically linked to user input, moving beyond static or purely scripted performances [13]. Recent research on interactive narratives driven by Generative AI has also shown increasing potential for behaviour control systems that adapt the plot in response to user input [12]. Many CH applications, however, still rely on predefined character animations and sequences, which suggests the need for pipelines that support both expressive control logic and platform reuse [13].

2.4 Web-Based XR and Multi-Platform Deployment

Web-based 3D visualisation and WebXR technologies have emerged as important channels for CH dissemination, enabling access to immersive content without specialised hardware or software installation [4][5]. Browser-based platforms enable remote exploration of reconstructed sites and artefacts, significantly expanding public reach and inclusiveness. Most web-based CH applications, however, remain focused on static geometry or environment-centric visualisation, while animated virtual characters are rarely integrated, due to performance constraints and the complexity of real-time skeletal and facial animation in web environments [17].

In parallel, multi-platform XR deployment strategies aim to reuse digital assets across VR, desktop and web-based applications [1][2][4]. Although asset reuse for static geometry and textures is well documented in CH pipelines, fewer studies address the preservation and dissemination of animated character performances, including body motion and facial animation, across platforms [6]. Limited attention has also been given to the structured storage, documentation and sharing of XR assets in ways that support long-term reuse and collaboration [1]. Recent reviews of XR workflows identify animation interoperability and narrative consistency as persistent challenges, particularly for character-driven experiences spanning immersive and web-based deployments [1][10]. These observations motivate XR pipelines that combine multi-platform deployment with shared data structures and design-oriented workflows that facilitate accessibility, metadata organisation and sustainable reuse [1][4], an objective that the present work addresses through a single shared character asset reused across VR and WebXR.

3. Methodology

The proposed XR pipeline (Figure 1) supports the creation, animation and multi-platform deployment of a historical virtual human grounded in fresco iconography. The workflow is organised around an expert-validated production process in which CH partners (historians, archivists and museum professionals) take part in defined review steps, rather than being limited to an initial consultation.

The process begins with data acquisition. Fresco images, manuscript references and textual sources are collected and analysed in collaboration with CH experts. This material informs both the representational constraints of the character (face, garments, posture, attributes) and the definition of the narrative scenario. Based on this analysis, a scenario is co-defined with CH stakeholders, specifying character actions, gestures, narrative flow and intended visualisation outputs, ensuring iconographic and historical alignment from the start.

Virtual characters are then created from fresco-based references, following a shared humanoid topology and rig. Modelling and animation are produced using parametric character authoring and animation environments that support standardised humanoid rigs, facial animation and lip synchronisation [18][19]. The resulting animated character is exported in multiple interoperable formats to support different deployment targets.

For web-based visualisation, the character asset is prepared in GLB format, embedding body and facial animations for real-time playback in a browser-based rendering environment. To support this deployment type, we have developed a custom web-viewer. For immersive VR visualisation, the same asset is exported in FBX and integrated into a game-engine framework (Unity) where narrative sequencing and interaction logic are implemented. This structure enables the reuse of the same virtual-human performance across VR, MR and Web platforms without re-authoring, minimising content duplication and supporting scalable dissemination.

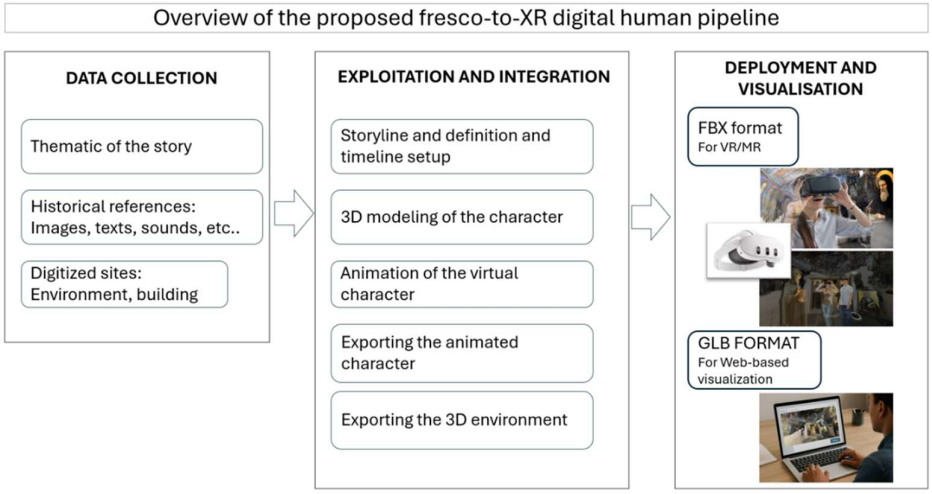

Figure 1: Overview of the proposed fresco-to-XR digital human pipeline.

Although specific software tools were employed in this work, the pipeline is not dependent on proprietary solutions; equivalent tools may be substituted, provided they support humanoid rig consistency, animation export and multi-format interoperability.

3.1 The Pipeline Stages

This section details the technical workflow that enables character creation and multi-platform deployment. The proposed pipeline shifts focus from site-centric digitisation to fresco-driven heritage interpretation, in which the digital human acts as the primary mediator of cultural meaning. The pipeline consists of six stages:

1) Historical and cultural research grounded in fresco iconography
2) Interpretation and scenario design
3) Virtual character modelling
4) Animation and behavioural simulation
5) Multi-platform narrative and interaction design
6) Multi-platform deployment (VR, MR, Web)

This six-stage structure emerged from an iterative production process conducted in close collaboration with CH experts. Through successive consultations and scenario refinements, the stages were progressively defined to reflect practical needs related to iconographic accuracy, narrative coherence, character expressiveness and multi-platform dissemination. Structuring the workflow in this manner ensures that cultural knowledge, interpretative reasoning and technical production decisions remain explicitly linked at each step.

3.1.1 Historical and cultural research grounded in fresco iconography

This stage establishes the foundation of the virtual character by grounding its representation in validated historical and iconographic knowledge through close collaboration with CH experts. The collaboration consists of structured meetings, exchange of reference documents and archival material, iterative discussions on visual and narrative interpretations, and refinement cycles based on expert feedback, including the testing of early visual prototypes. Contextual narratives, textual descriptions and selected visual references (icons, illustrations and manuscript materials, with frescoes as a primary anchor) are gathered to guide both appearance and behavioural interpretation.

Because the depiction of historical figures may involve sensitive religious or symbolic elements, as in the case of Saint Neophytos (Section 4), proposed visual interpretations are reviewed and approved by CH partners to ensure respectful and accurate representation. An analytical phase then examines the collected sources to identify representational constraints, inconsistencies and areas of uncertainty. These are explicitly documented to maintain

transparency in the interpretative process and to inform subsequent design and animation decisions within the pipeline.

3.1.2 Interpretation and scenario design

The interpretation and scenario design stage is also carried out in collaboration with CH experts, who define the intended audiences, age ranges, educational goals and thematic priorities of the experience. Their input ensures that the narrative content remains historically grounded and aligned with the expectations of specific user groups. Based on these requirements, the technical team translates the narrative intent into concrete XR design elements, including proposed character actions, gestures, camera framing, lighting approaches and graphical user interface components.

Scenario design also considers platform-specific interaction models from the start. While the core narrative structure and character behaviour remain consistent, the modality and level of interactivity may vary between immersive VR and web-based visualisation. VR deployments typically emphasise embodied and spatial interaction, whereas web viewers favour observational or simplified controls. These distinctions are addressed early to maintain coherence across platforms while preserving the original narrative intent and guiding both interaction design and technical implementation.

3.1.3 Virtual character modelling

The virtual character modelling stage focuses on producing a reusable, animation-ready digital human while preserving historical authenticity. Using Character Creator 4 (CC4), a parametric modelling approach is adopted that enables precise adjustment of body structure, facial features and proportions based on validated fresco references. Throughout the process, geometry topology is carefully managed to satisfy the technical constraints of real-time engines and cross-platform visualisation environments. At this stage it is important to define specific facial components (eyes, teeth and tongue) to ensure compatibility with lip-syncing and expressive animation.

Costumes, textures and contextual attributes are customised to reflect the iconographic conventions of the figure (Figure 2), followed by an optimisation step prior to export to maintain performance across immersive XR and web-based platforms. Maintaining a standardised rig and consistent topology across deliverables supports workflow efficiency, multi-platform reuse and the ability to deploy the same asset in diverse narrative scenarios and interaction settings.

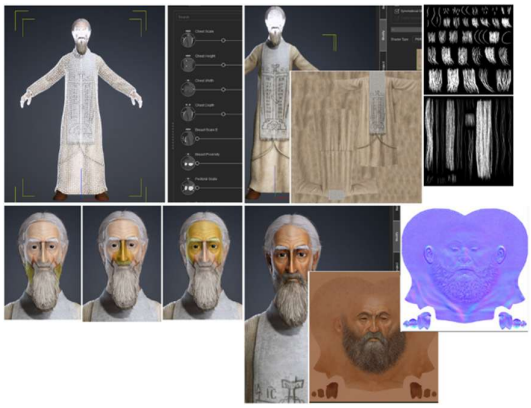

Figure 2: Character modelling and texturing – Saint Neophytos case study.

3.1.4 Animation and behavioural simulation

Once the virtual character is created, the animation stage defines movement, gestures and expressive behaviours in alignment with the scenario established with CH experts. Full-body animations are produced according to narrative events, while facial expressions and lip-sync are generated in iClone 8 to match speech and emotional cues. Two lip-sync approaches are adopted: either CH experts provide an audio recording that is transcribed into text, or they provide a written script that is converted into audio through an AI text-to-speech generator (Figure 3). In both cases, the correspondence between audio and text guides accurate speech animation and preserves narrative fidelity.

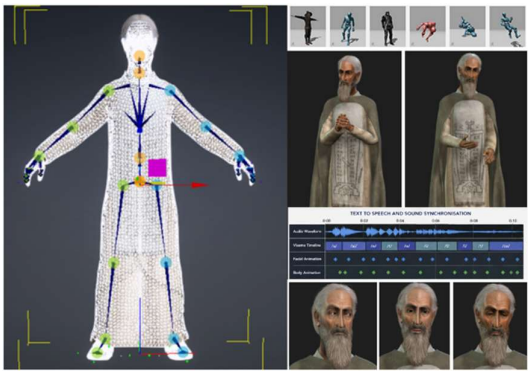

Figure 3: Character facial animation.

3.1.5 Multi-platform narrative and interaction design

The experience is conceived differently for immersive VR and web-based visualisation rather than being directly replicated across contexts. In VR, the user is fully immersed in a three-dimensional environment, where the sense of presence itself constitutes a primary form of interaction. The experience is driven by narrated content, background soundscapes, well-planned camera framing and a graphical user interface that allows users to move between story scenes with comfort and immersion (Figure 4).

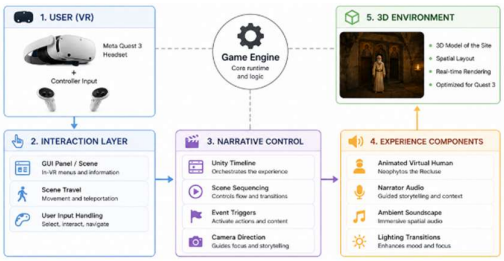

Figure 4: The layered architecture of the immersive VR experience developed in Unity for Meta Quest 3.

The web-based experience, by contrast, is intended for informational and exploratory engagement rather than full immersion. Scenes can be selected, background settings can be changed, and contextual text about the historical story can be accessed. In this context, interaction prioritises interpretative clarity, user control and accessibility. By applying a common narrative structure while adjusting interaction strategies for each platform, the pipeline guarantees consistent storytelling across XR modalities while preserving the unique experiential characteristics of immersive and browser-based environments.

3.1.6 Multi-platform deployment

The platform-specific deployment phase adapts shared character assets and animations to distinct visualisation contexts while preserving narrative coherence (Figure 5). For immersive VR deployment, character geometry and animations are exported in FBX format and integrated directly into Unity, where narrative sequencing, camera choreography, lighting and interaction logic are coordinated through Unity Timeline. The final application is built and optimised for Meta Quest 3 (Android).

For web-based visualisation, FBX assets are imported into Blender and converted to the GLB format required by our custom web-viewer, which enables browser compatibility and additional optimisation of geometry and animation data. The resulting GLB files support timeline-driven animation playback within standard web browsers, complemented by lightweight interactions and informational overlays oriented towards accessibility and educational use.

By maintaining distinct asset preparation paths for web and VR while reusing the same core character data, the pipeline enables consistent storytelling across platforms with interaction models tailored to each deployment context.

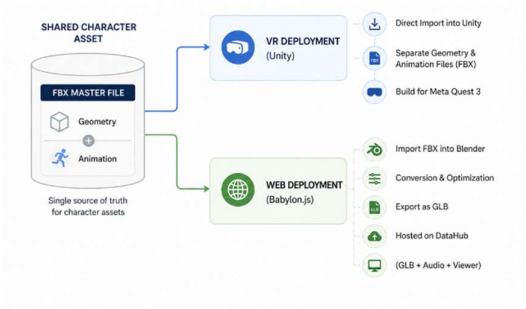

Figure 5: Platform-specific asset preparation workflow.

4. Case Study: Saint Neophytos the Recluse

The proposed pipeline is examined through a focused case study developed in collaboration with CH experts. The case study demonstrates how the workflow described in Section 3 supports the translation of fresco-based references into a coherent virtual human performance and its deployment across both immersive VR and browser-based platforms.

4.1 Historical context and motivation

The case study focuses on Saint Neophytos of Cyprus, a 12th-century medieval religious figure known for his hermitic life and lasting theological and cultural influence in the Eastern Mediterranean region. Historical records describe his withdrawal from society in pursuit of solitude and his settlement in a rock-carved hermitage that later became a site of religious and cultural importance (Figure 6). Although written manuscripts authored by Saint Neophytos provide valuable theological reflections and autobiographical insights, textual sources alone do not fully convey presence, tone or spatial context. The figure is also depicted within the hermitage itself through a series of frescoes, which constitute the principal visual reference for his appearance, garments and iconographic conventions.

In this setting, the creation of a virtual character enables the transformation of fresco depictions and written testimony into a situated and embodied narrative, allowing visitors to encounter the figure as a speaking subject within the reconstructed environment [20]. A stylised-realistic digital human was therefore developed to retain historical credibility while remaining suitable for real-time XR rendering. The character was fully rigged for both body and facial animation, with restrained expressiveness intentionally reflecting an ascetic monastic lifestyle. Garments, textures and material properties were modelled on Byzantine monastic references and on the frescoes inside the hermitage, while overall geometric and visual complexity was optimised to ensure compatibility with both immersive XR applications and browser-based visualisation platforms (Figures 7 and 8).

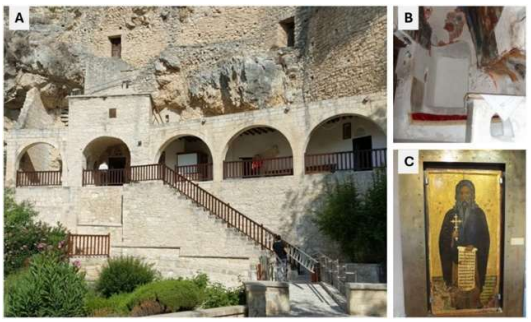

Figure 6: A) The Hermitage (Enkleistra) of Saint Neophytos, B) Cell and office of Saint Neophytos, and C) Fresco depiction of Saint Neophytos.

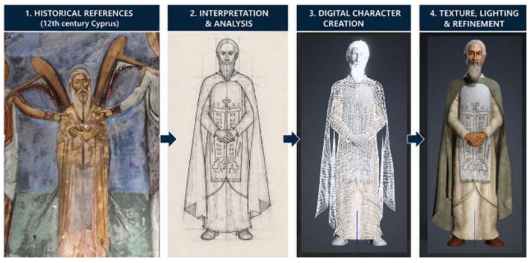

Figure 7: Virtual Saint Neophytos – from fresco-based historical references to 3D representation.

Figure 8: Stylised-realistic digital human of Saint Neophytos.

4.2 Scenario and audience

The scenario is set in Paphos, where visitors of the historic monastery encounter a digital representation of Saint Neophytos within the Enkleistra. The virtual character appears within a reconstructed environment and delivers a predefined narrated script, guiding users through the hermitage, its historical purpose, and the figures and spaces represented within

the site. The interaction is structured around short visual sequences and spoken narration.
The experience is primarily designed for general visitors seeking an introductory and visually supported interpretation of the site. The scenario therefore prioritises sequential presentation, controlled camera framing and synchronised narration, in order to communicate historical information in an accessible and coherent manner across both immersive and web-based formats.

4.3 Pipeline application to Saint Neophytos

In addition to the six general stages of the pipeline, case-specific design adaptations were introduced to reflect the contemplative identity of Saint Neophytos. Gesture animations were intentionally softened and reduced in amplitude to convey monastic restraint, while facial expressiveness was kept subtle to avoid theatrical exaggeration. These adjustments ensured that the technical pipeline remained consistent while the character's behaviour and presentation aligned with the historical tone and narrative atmosphere defined together with CH experts.
Iconographic decisions, including the cut and colour of the monastic mantle, the placement of the cross-bearing tablet and the proportions of the face and beard, were validated against the frescoes preserved inside the Enkleistra. Where fresco evidence was incomplete or stylised, the corresponding decisions were documented as interpretative choices rather than fixed reconstructions, in line with the transparency principles introduced in Section 3.1.1.

4.4 Outcome

The resulting scenario was deployed in two complementary modes: an immersive VR application for headset-based use (Figure 9) and a web-based version (Figure 10) accessible through a custom browser viewer integrated into a digital heritage data hub for broader dissemination on Europeana [20]. Upon entering the reconstructed Enkleistra, visitors are greeted by a virtual human representation of Saint Neophytos that visually transitions from the fresco into three-dimensional space. The virtual human introduces himself through narrated speech and explains the iconographic and historical significance of the surrounding frescoes, guiding the viewer through the visual elements of the environment.

Figure 9: Headset-based VR representation of Neophytos the Recluse within the cave environment with interactive GUI.

Figure 10: Web-based visualisation – browser-accessible presentation with simplified assets, narrated sequences and contextual information.

Across both deployments, the same character asset, animations and narration are reused without re-authoring. The two outputs differ in the modality of interaction (embodied and spatial in VR, observational and exploratory on the web) but share a single underlying performance. From a production standpoint, this confirms the feasibility of a fresco-to-XR pipeline organised around a single shared digital human and supports the broader goal of disseminating Byzantine fresco heritage through both on-site and remote channels.

5. Discussion and Conclusion

This paper presented a fresco-to-XR digital human pipeline for the creation and deployment of Saint Neophytos the Recluse within both immersive VR and browser-based environments. The pipeline integrates fresco-based historical research, expert validation, character modelling and animation, and platform-specific deployment around a single shared character asset. The case study demonstrates how Byzantine fresco iconography can be translated into a coherent virtual human performance and disseminated through complementary XR modalities, supporting both on-site visitors of the Enkleistra and remote audiences accessing the experience via standard web browsers.

The key characteristics of the proposed approach can be summarised as follows: a workflow anchored in fresco iconography and validated by CH experts at each production stage; a single shared character asset reused across VR (Meta Quest 3) and a custom WebXR viewer; and a structure that maintains a consistent technical pipeline while allowing scenario-level adjustments to gesture, pacing and interaction strategy in line with the contemplative identity of the figure.

More broadly, the preservation of the same pipeline stages, asset structure and deployment logic across both immersive and browser-based outputs demonstrates the workflow's reusability, internal consistency and potential scalability to additional fresco-grounded characters and heritage contexts. The required adaptations can be applied directly at the scenario level, through adjustments in narrative pacing, gesture expressiveness and interaction strategies, without modifications to the underlying technical pipeline. By combining methodological transparency, iterative collaboration with CH experts and multi-platform deployment, the approach establishes a practical and extensible foundation for the continued evolution of fresco-driven digital storytelling.

5.1 Limitations and Future Work

Several directions emerge naturally from the current implementation. First, the experience relies on guided narration with a predefined script. Future developments may explore open conversational interaction, adaptive AI-driven dialogue and context-aware behavioural systems built on top of the same character asset. Second, the present validation is qualitative and based on expert review, on-site testing of intermediate prototypes and informal visitor feedback. Formal user studies, including longitudinal engagement studies and large-scale audience assessments, are planned to evaluate educational impact and usability across demographic groups. Third, the pipeline currently targets a single fresco-grounded figure; extending it to additional Byzantine figures and to other iconographic traditions will allow systematic comparison with existing XR pipelines for CH along measurable axes such as production effort, asset reuse and cross-platform consistency. Finally, addressing damaged or partially documented frescoes remains an open challenge that would benefit from explicit handling of uncertainty within the workflow.

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