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Design of an XR-based AI-augmented Content Framework for Frescoes (focusing on Raphael's School of Athens)

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Abstract

Recent advancements in Artificial Intelligence (AI) have significantly enhanced the cognitive abilities of digital humans, making them increasingly human-like not only in appearance but also in behavior. Although AI has been actively applied across various industries, its integration into cultural heritage and museum-based eXtended Reality (XR) experiences remains relatively underexplored. This study aims to develop an interactive XR experience by recreating 57 philosophers, mathematicians, and scientists depicted in Raphael’s fresco (1510–1511) as AI-driven digital humans. To achieve this, we integrate technologies such as ChatGPT, domain-specific AI models, and AI Augmentation (AIA) to enable these historical figures to engage in intelligent and dynamic conversations with visitors. The ultimate objective of this research is to design a framework that combines static cultural heritage assets, such as paintings, with immersive XR technologies to establish an AI-based digital human platform. Through this system, users can move beyond passive observation to engage in personalized and interactive dialogues with historical figures, deepening their understanding and exploration of cultural heritage. By enhancing intuitive interaction and immersive presence, this framework paves the way for next-generation digital cultural heritage exhibitions.

1. Introduction

Museums have long played a role in preserving and exhibiting historical artifacts and cultural heritage. With the advent of the digital age, museums are actively utilizing cutting-edge technologies to change the way they communicate with visitors (Yang and Guo., 2024). Projects such as the Google Art Project have improved accessibility to artworks by utilizing high-resolution digital images. In addition, virtual reality (VR), augmented reality (AR), and extended reality (XR) technologies are reproducing museum spaces and historical sites to provide immersive exhibition experiences.

In addition, the rapid development of artificial intelligence (AI) technology has brought about changes to the entire museum industry. AI-based systems provide visitors with more immersive and interactive museum experiences. Beyond simply providing exhibition information, AI enables personalized curation, visitor data analysis, and the introduction of AI digital humans that act as interactive guides.

Accordingly, the British Museum has introduced an AI-based chatbot designed to allow visitors to interact with virtual guides and receive real-time information about the exhibition. (Mensa and Damiano., 2024) There are also research cases that apply AI technology to analyze visitor data and create customized content by utilizing mixed reality technology that combines reality and digital.

Museums are also introducing AI technology to understand individual tendencies through five-sensory experiences and emotional storytelling, and to provide new experiences with immersion and authenticity (Pietroni, E., 2025).

This new form of exhibition combining AI-based digital humans and XR technology goes beyond simple viewing to provide vivid historical experiences, and shows how museums are changing from simple information providers to spaces for visitor participation. In addition, recent studies have shown that the National Museum of Rome is piloting a system that introduces AI-based virtual docents to provide customized explanations to visitors' questions (Pegolo, G., 2023), and the Cairo Museum in Egypt is using VR technology to increase visitor participation and provide personalized experiences through interaction to promote understanding of history and culture (Hassan et al., 2025).

XR also enhances the interaction between cultural heritage educational materials and users by showing users real historical sites and artifacts. AR helps to increase understanding by digitally overlaying information to provide contextual visual understanding (Boboc et al., 2022). Existing cultural heritage exhibitions have mainly relied on passive viewing, and visitors often acquire information unilaterally through set routes and explanatory texts. Various studies have been attempted to supplement this, but limitations still exist. (1) Digital humans are limited to delivering standardized information, making natural conversation difficult, (2) spatial reproduction is excellent, but thematic narrative structure is insufficient, and (3) real-time response and immersion induction systems according to the choices and actions of visitors are lacking. To overcome these limitations of existing studies, this study designed an immersive interactive content framework that combines XR and AI technologies targeting Raphael's <The School of Athens>. In particular, the goal is to implement an immersive environment in which AI-based digital humans provide natural language conversations that reflect the philosopher's thought system and have a thematic exploration structure that unfolds according to the user's movements and choices. Through this, we aim to propose a new form of cultural heritage experience model that goes beyond simple information delivery and allows visitors to experience in-depth conversations with ancient philosophers and actively explore the journey of philosophical thought.

2. Related Works

2.1 AI-based Digital Human

AI-powered digital humans are being actively studied in the fields of cultural heritage, museums, and education, and are attracting attention as a key technology to deepen the interaction between visitors and systems. At the museum exhibition, Silaiu presented the possibility of utilizing AI digital humans to

increase the immersion and learning effectiveness of visitors (Sillaiu et al., 2022). In this study, digital humans are designed to provide a personalized experience by responding to visitors' questions in real time beyond the description of exhibits (Sillaiu et al., 2022).

Rosemary analyzed the effectiveness of interactive information services provided by AI-powered virtual guides through the case of the British Museum. They reported that AI chatbots' ability to suggest recommended exhibitions or answer in-depth questions based on visitor preferences beyond just text provision leads to improved quality of museum visits (Rosemary, 2024).

Nah, K., studied that the expansion of the digital environment, the metaverse, and the intervention of artificial intelligence will further activate interaction in the virtual world, and will develop more comfortably and intimately in the future to allow digital humans to immerse themselves in user experiences in virtual spaces (Nah, K. et al., 2022).

Pegolo, G. focuses on the applications of artificial intelligence in the Rome National Museum segment, and the system provides an interactive experience where AI analyzes and provides feedback once visitors mimic the poses of famous artworks (Pegolo, G., 2023).

Existing research has shown that AI digital humans can be utilized in a variety of ways beyond the role of information providers in cultural heritage exhibitions, such as interaction with visitors, personalized curation, and immersive narrative design. However, until now, most digital human systems have shown limitations in understanding fragmentary reactions or limited contexts, and emotional recognition, complex interactions, and in-depth subject-specific conversations remain areas that need to be developed.

Reflecting the achievements of these prior studies, this study aims to overcome the limitations of existing studies, develop an in-depth interactive AI digital human tailored to historical characteristics based on Raphael's <Athens School>, and design immersive XR content that organically changes dialogue and exploration according to real-time behavioral responses of visitors.

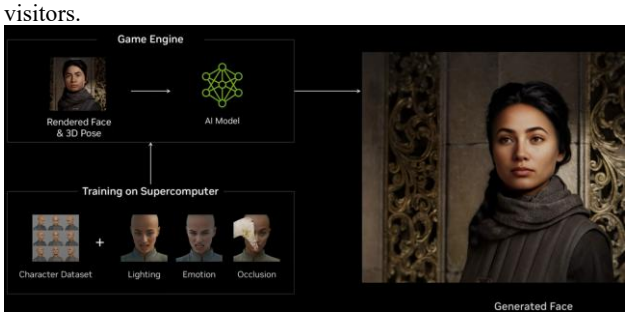

Figure 1. Speech Language Model Digital Human

2.2 Digital Cultural Heritage Using Based XR

XR (eXtended Reality) technology is in the spotlight as a key means of maximizing immersion and interactivity in the field of digital cultural heritage (Digital Cultural Heritage). Innocente et al. analyzed the possibility of using XR technology in the preservation and exhibition of digital cultural heritage and suggested that VR and AR provide visitors with an opportunity to experience the ruins in a unique temporal and spatial context (Innocente et al., 2023).

Benardou et al. proposed a methodology for designing sites that have been destroyed or difficult to access in an immersive environment through virtual archae-ology cases using XR technology (Benardou and Drumpouki, 2022).

These studies emphasized the educational and experiential value of digital cultural heritage restoration and contributed to significantly expanding access to cultural heritage.

Banfi et al. presented an example of vividly recreating past living conditions through XR-based simulations and designing for visitors to actively explore the environment at the time at the 3D heritage restoration project of the Caitelia Metella Tomb and Caetani Castle in ancient Rome (Banfi et al., 2022). This study demonstrated that historical understanding is greatly improved when historical evidence-based 3D modeling and immersive navigation are combined.

In addition, Bruni et al. presented a cultural heritage exhibition model that combines narrative-based interaction with XR technology within a virtual space so that visitors can become subjects of stories rather than just audiences (Bruni, L. et al., 2022).

These preceding studies have shown the possibility that XR technology can go beyond the representation of digital cultural heritage and build an immersive narrative environment based on visitor participation. However, the existing cases tended to focus mainly on visual representation and spatial experience, and the content structure that induces interactive interaction or in-depth thinking with characters was relatively insufficient.

2.3 Virtual Production Technology

Virtual production is an innovative production method that integrates physical shooting and digital simulation to create a real-time immersive environment and is increasingly being used in the field of cultural heritage digitization. Guo et al. organized the concept of virtual production that integrated physical and virtual spaces using LED wall and real-time rendering technology, and specifically presented the possibility of creating immersive narratives and interactive experiences (Guo et al., 2024).

Margetis et al. introduced examples of free movement and experience between real artifacts and virtual representations by applying them similarly to existing virtual production technology, which provides an X-Reality experience that integrates museum and cultural heritage exhibitions into virtual museums, and allows for an interactive experience that naturally fuses the physical and virtual worlds through virtual agents showing natural behavior (Margetis et al., 2020).

This study emphasized the distinction from existing VR exhibitions in terms of real-time reactivity and natural immersion within virtual environments. In addition, by applying virtual production technology to ancient Chinese cultural heritage restoration projects, the method of maximizing the sense of realism of visitors by combining immersive digital background through LED large screens and exhibition of real relics is being used in festivals and tourist attractions these days. In particular, real-time lighting and camera tracking technology enhance the immersion and presence of the visitor experience.

Helzle emphasized that virtual production technology is an effective methodology that can simultaneously satisfy interactivity, real-time, and spatial immersion in developing XR experience content. The existing VFX production process is being innovated by installing LED screens, and holographic display technology is making the boundary between real and virtual content more ambiguous. It is used as visual story-oriented content that pursues a new level of immersion beyond the existing two-dimensional screen (Helzle, 2024).

In addition, the technological foundation for integrating digital humans, interactive objects, and immersive environments into one real-time production flow is increasing in the future.

Xu applied real-time virtual set production technology to museum education programs to design an immersive experience

as if students were exploring ancient civilization directly (Xu, D. 2025). This study empirically showed that by integrating LED wall-based environments and interactive objects, learning effects and immersion can be improved at the same time.

These studies show that virtual production can play an important role in cultural heritage exhibition and experience design beyond just video production technology. In particular, real-time rendering, LED-based virtual sets, and digital human integration are combined with XR and AI technologies to enable more immersive and interactive digital heritage experiences

This study aims to overcome the limitations of existing virtual production technology and to build an immersive interactive space where visitors can have real-time conversations with historical figures and experience philosophical discourses by incorporating AI-based digital humans into a virtual production environment. To this end, we planned a design that realistically reproduces Raphael's <School of Athens> using an LED media wall and digitally implements 57 figures and an architectural environment based on 3D modeling. In addition, each figure is equipped with an AI-based conversation function so that it can answer visitors' questions and explain the historical context and philosophical position of the figure. In addition to visual elements, we provide visitors with a more immersive audiovisual experience by combining a soundscape that recreates the atmosphere of the School of Athens and real-time lighting and shadow effects.

This integrated approach is differentiated from existing studies in that it suggests a new form of cultural heritage experience model where visitors 'participate and converse' rather than simply 'viewing' a virtual environment.

Figure 2. Fresco XR Virtual Production Environment

3. Methodology

This study designed an XR-based AI augmented content framework targeting Raphael's fresco <The School of Athens>. The design process was conducted through three main stages: digital human interface, spatial structure analysis, and XR content flow design. Each stage was systematically designed based on related literature analysis, case studies, and multi-faceted analysis of user experience flow, and will be utilized in the technical design for implementing future XR artificial augmented digital content prototypes.

3.1 AI Augmentation, Digital Human Design

This study designed a digital human framework utilizing the latest AI technology that enables real-time conversations with classic characters in an XR-based immersive content environment. The design process was centered on four core axes: natural language processing based on a large-scale language model (LLM), emotion recognition and response generation, situational context understanding, and real-time interaction optimization. To build the natural language conversational ability of the digital human, we established a strategy utilizing a large-scale language model based on GPT-4. In order to reflect the philosophical thought system and language style of the main characters of <The School of Athens> such as Plato, Aristotle, and Pythagoras, we analyzed classical literature and major philosophical topics, and designed customized prompt engineering and fine-tuning methods for each character.

In addition, we built a dialogue data set for each character and designed a scenario tree to enable natural questions and answers according to the context. In addition, we reflected the latest multimodal AI technology in the design to support emotion recognition and emotional response generation. In addition to the user's linguistic input (text, voice), we developed a method to link an emotional response generation model so that the digital human can recognize nonverbal cues such as facial expressions, gaze, and gestures to express appropriate emotional states (empathy, curiosity, excitement, etc.). To this end, we integrated a deep learning-based facial expression recognition model (FER) and a voice emotion recognition model to provide real-time emotional feedback.

We enhanced the context understanding function to increase the naturalness of the conversation. In addition, we designed it so that the character can provide answers that fit his or her philosophical background or historical context by analyzing the audience's questions and conversation flow in real time. To this end, we enhanced the context memory function and applied a conversation history-based response generation technique.

We induced a deep conversation flow by considering the relevance to the audience's previous questions. We designed a lightweight model and a streaming conversation management technique to minimize the conversation generation delay (latency) for real-time interaction in an immersive XR environment. We considered a lightweight transformer model optimized for smooth operation in an edge device environment, and designed a websocket-based communication protocol for real-time linkage with the XR system.

The AI digital human framework design in this paper goes beyond the simple script-style character implementation of the past and aims for deep interaction based on intelligent thinking, emotional responses, and contextual understanding similar to real humans.

Figure 3. Characters from Raphael's School of Athens

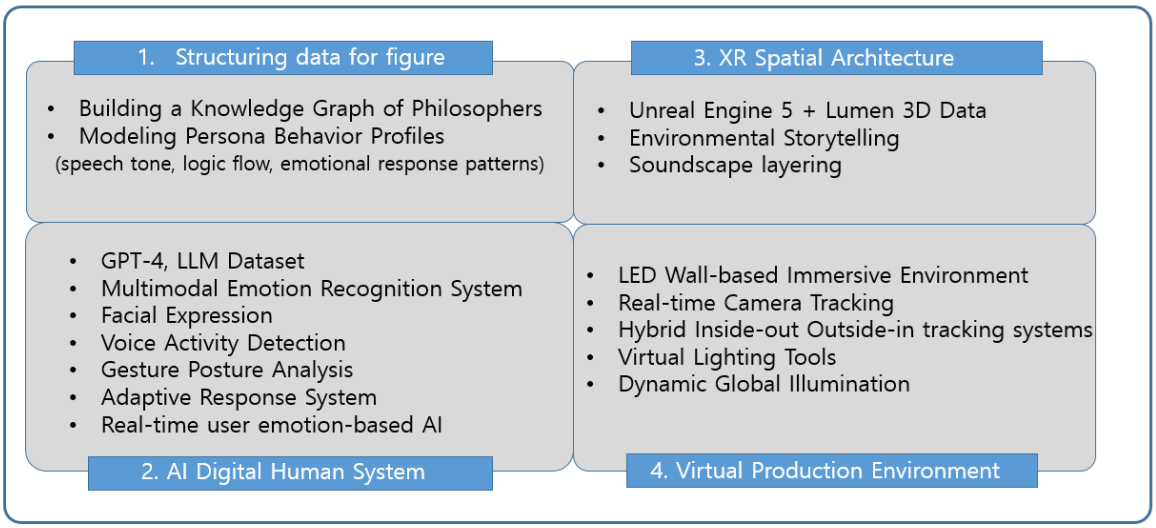

Figure 5. XR-AI Augmentation Technology Research Methodology Framework

3.2 Spatial structure analysis

This study designed a spatial structure based on Raphael's fresco, The School of Athens, to allow users to experience the flow of philosophical thought within an immersive XR environment. The design process focused on three key elements: visual immersion, user movement path optimization, and thematic experience segmentation. To maximize visual immersion, the original composition and Renaissance architecture of The School of Athens were analyzed to design a 3D virtual space. Lumen lighting technology, which implements marble columns, vaulted ceilings, and natural lighting using Unreal Engine 5, was applied, and high-resolution PBR (Materials) was used to implement realistic textures.

To induce a natural movement flow for users, the main movement paths were set by analyzing the placement and interaction relationships of characters in the work. The navigation structure was designed for each area divided into the philosophy area in the center, the science and mathematics area on the left, and the art and literature area on the right.

A system was built to encourage free movement within the space and conversations with main characters in designated interaction areas. NavMesh was applied to naturally guide the user's movement path, and camera transitions and visual effects were utilized to maintain immersion when transitioning between zones.

To segment the immersive theme experience, each zone was composed of detailed spaces based on narratives and scenarios that reflect the thoughts and themes of the corresponding characters. Background music (BGM) and environmental soundscapes were set for each zone, and lighting changes and sound transitions were used to allow visitors to intuitively perceive the change in theme. In addition, trigger-based events were inserted at each interaction point to actively expand the user experience.

This XR space structure design enabled visitors to actively explore each zone and participate in philosophical conversations beyond simple visual appreciation, creating an immersive experience.

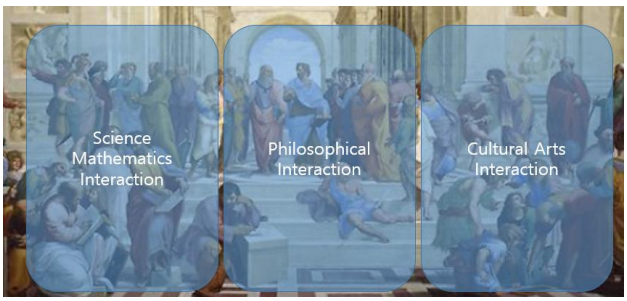

Figure 4. Fresco XR-AI Augmented Space Structure Design

3.3 Configuring XR content flow structure

This study designed a step-by-step content structure and real-time interaction system to optimize the user experience flow and interaction method within immersive XR content.

The entire experience flow consists of four stages: initial entry, topic exploration, character conversation, and free exploration. In the initial entry stage, the welcome sequence and intro video were used to guide users to naturally immerse themselves in the XR environment, and in the topic exploration stage, the user was designed to explore topics of interest through the first conversation with the representative character of each zone.

In the character conversation stage, the user was able to have an in-depth conversation with a digital human and experience the philosophical thoughts of each character. The recommended conversation trigger was set based on the topic connectivity between characters, and the conversation topic was branched according to the user's choice to allow the user to experience various exploration paths.

In the free exploration stage, the user was allowed to freely move throughout the entire space and interact with additional characters. At this time, a recommendation system was designed to suggest new conversation opportunities based on the user's topic interest even during free exploration, thereby improving the user's immersion and motivation to explore.

A real-time event system was applied throughout the content flow to generate situational responsive events based on the user's movement, gaze direction, and dwell time.

This was designed to allow the user to interact more actively with the environment and maintain immersion. This XR content flow and interaction design aims to encourage viewers to experience the philosophical world as active explorers rather than passive observers.

4. Results

This study closely analyzed the technical achievements and limitations of previous studies and designed an XR-based AI digital human exhibition framework based on this. The research results are largely composed of three axes: digital human design, XR space structure design, and real-time immersive environment construction based on virtual production.

In terms of AI-based digital human design, we referenced the study of museum exhibition real-time interactive virtual guide system presented by Sylaiou et al. (2022) and Mensa and Damiano (2024) to build an in-depth interactive digital human model that reflects the individual thought systems and language styles of classical philosophers. Beyond the simple information guidance provided by previous studies, we designed a customized dialogue tree and emotional response system for each character so that users can deeply experience actual philosophical discussions with Plato, Aristotle, etc.

In the XR space structure design, we applied the immersive 3D reproduction and historical verification-based narrative structure emphasized by Bekele et al. (2018) and Bruno et al. (2019). We reflected the study of (2010).

This study reconstructed Raphael's <School of Athens> painting into a high-resolution XR environment and designed the space by dividing it into thematic zones (philosophy zone, science zone, art zone) so that visitors can actively experience thematic exploration and philosophical thinking. In terms of utilizing virtual production technology, based on the studies of Smith et al. (2022), Müller et al. (2023), and Feng et al. (2023), we integrated real-time virtual set construction using virtual production LED walls and viewer-responsive content production techniques based on camera tracking.

This study designed an immersive experience environment content framework that breaks down the boundaries between physical and virtual spaces and dynamically changes the responses of XR spaces and digital humans according to the location, gaze, and behavior of visitors.

In addition, referring to the study of Wang et al. (2023), we planned interactive objects and a real-time event trigger system to increase the immersion of visitors. In addition, reflecting the storytelling-based empathy technology emphasized by Chen and Zhao (2024), we designed an experience in which the audience directly participates in the discourse of ancient Seowon philosophy rather than being a simple information recipient. Through this, we synthesized the results of existing research and studied the next-generation digital cultural heritage exhibition framework that satisfies immersion, interaction, and emotional immersion by incorporating XR, AI, and virtual production technologies.

Through this, we overcame the limitations of passive appreciation of existing cultural heritage exhibitions and suggested the possibility of transitioning to an active experience model led by the audience.

5. Conclusion

This study proposed a new exhibition model that enables immersive interactive experiences by designing an XR-based AI augmented content framework centered on Raphael's <School of Athens>. Unlike existing cultural heritage exhibitions that were limited to simple information delivery and visual appreciation, this study built a system that supports subjective exploration and deep thinking of visitors by integrating AI-based interactive digital humans, immersive XR space design, and active content experience flow.

In particular, by applying the latest LLM-based natural language processing technology and multimodal emotion recognition technology, the digital humans were able to flexibly respond to user input while reflecting each individual's unique philosophical worldview. In addition, high-resolution spatial

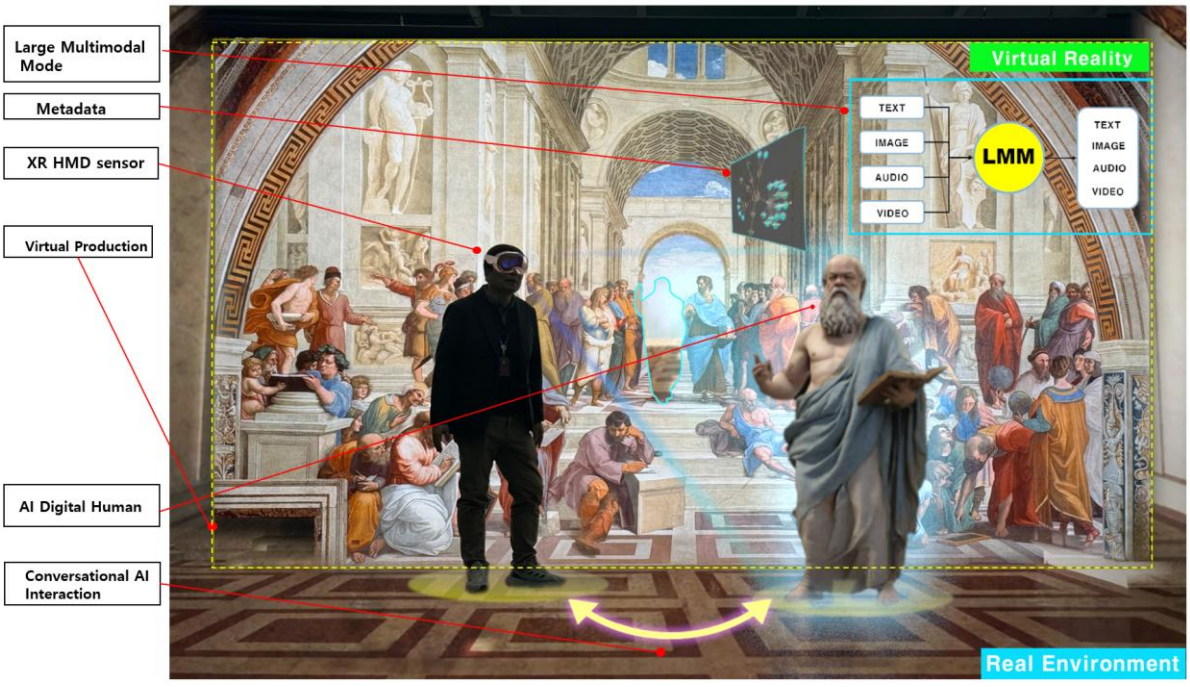

Figure 6. XR-based AI-Augmented content design concept image

reproduction using Unreal Engine 5 and navigation design that considers user experience dramatically improved immersion and realism compared to existing XR exhibition contents.

In future studies, we plan to develop actual prototype contents based on this framework and empirically verify immersion, interactivity, and learning effects through user evaluations. In addition, we plan to explore the possibility of expanding to other cultural heritage works and to enhance the system by adding personalized interaction functions tailored to various user characteristics (age, background knowledge, etc.). This study is significant in that it presents a new approach to integrating AI and XR technologies into the field of cultural heritage exhibitions, and it can be evaluated as basic research that opens up the possibility of expansion to various fields such as culture and arts, education, and tourism by overcoming the limitations of existing research and building an immersive interaction environment.

Through AI-based digital human XR content, global visitors will gain the opportunity to interact and converse directly with the historical figures depicted in The School of Athens, without the need to physically visit the Vatican in Rome.

This initiative reimagines Raphael’s masterpiece not merely as a static work of art, but as a cutting-edge "AI Digital Human Platform" that summons the great minds of human history into the present world through the fusion of digital human technology and artificial intelligence.

The 57 AI humans representing the historical figures of The School of Athens will thus function as an unprecedented form of "AI Time Machine Experience," integrating history, art, technology, and human imagination into an immersive cultural encounter.

Through AI-based digital human XR content, global audiences can now engage in direct interaction and dialogue with the figures depicted in Raphael’s School of Athens, even without physically visiting the Vatican in Rome. This development represents a paradigm shift: The School of Athens is no longer perceived solely as a static masterpiece of Renaissance art, but reimagined as an advanced “AI Digital Human Platform” that summons great thinkers from millennia of human history into the present through the convergence of artificial intelligence and digital human technologies.

The 57 historical figures portrayed in The School of Athens—including Plato, Aristotle, and Socrates—have been recreated as AI-powered digital humans. These virtual beings are not merely visual reconstructions but function as part of an unprecedented fusion of history, art, technology, and human imagination. In doing so, they enable an “AI Time Machine Experience” that transcends temporal and spatial boundaries, allowing users to converse with and reflect alongside the most influential philosophers and artists of antiquity

Ultimately, this project transforms The School of Athens into an immersive AI-interactive platform, blending XR and AI technologies with the humanities and creative arts. It opens up a new mode of cultural and philosophical engagement, positioning the artwork as a living interface between past and future, enabled by the affordances of intelligent, responsive digital human systems.

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