

Acting On The Edge: Developing Mixed Reality Heritage Performance Through Real-Time 3D And Virtual Production Technologies

Acting On the Edge

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The past few years have seen a surge of interest for in-situ Mixed Reality (MR) in the field of cultural heritage with engaging and entertaining experiences that enable and enrich learning while augmenting the historical context. This paper contributes to this body of work by introducing a novel application of MR in heritage sites that fuses see-through Augmented Reality (AR) smart glasses with live theatre. We developed two artistic-educational experiences for two heritage sites in the US and the UK exploring the fusion of theatre with historical research as a tool for decolonisation. Our design approach introduces a new interaction design and production model for developing shared location-based MR experiences that is based on dynamic, real-time 3D rendering akin to virtual production processes. Our world-as-a-stage metaphor further draws on the theatricality of the MR medium. The system design consists of a timeline system, an IoT infrastructure and a cross-platform network communication protocol to enable real time interactions between actors, audiences and holographic content. We carried out empirical evaluation studies on both sites that demonstrated the success of the application in engaging participants with the presented histories of the historic sites and its usefulness as a learning tool. Based on the evaluation insights, we discuss interaction design considerations and analyse the proposed model's added value in establishing a real-time virtual production development and performance environment that can streamline XR prototyping for shared in-situ MR experiences.

CCS CONCEPTS

• Computing methodologies ~ Computer graphics ~ Graphics systems and interfaces ~ Mixed / augmented reality • Human-centered computing ~ Human computer interaction (HCI) ~ Interaction paradigms ~ Mixed / augmented reality • Human-centered computing ~ Human computer interaction (HCI) • Interactive systems and tools • Applied computing ~ Arts and humanities ~ Performing arts

Additional Keywords and Phrases: Heritage, Theatre, Mixed Reality Heritage Performance, Real time 3D, Virtual Production.

1 INTRODUCTION

Mixed Reality (MR) applications in cultural heritage have seen significant growth in recent years, combining technological innovations with artistic and design processes to create engaging educational experiences. The use of immersive technology in heritage is found primarily in Virtual Reality (VR) applications with only a handful of projects using MR [3]. Our use of the term MR describes mediated

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hybrid, augmented, experiences in physical spaces that involve audio and visual projections, e.g. projection mapping, pass-through AR, see-through holographic projections through high-end smart glasses such as Microsoft's HoloLens or Magic Leap, IoT devices, and distributed computing architectures. The creation of MR experiences in cultural heritage contexts establishes a multifaceted design environment that requires collaboration across various disciplines. As a design space it is uniquely characterized by the integration of the physical environment, tangible and intangible artifacts, Internet of Things (IoT) devices, smart sensors and peripherals, AR visors, users and other actors, narrative and the audiovisual augmented content that enhances the physical space. This complex real-time interplay between the physical and digital, coupled with human interaction, and diverse requirements from each discipline and stakeholder benefits from a structured and holistic design approach.

In this paper, we introduce and discuss a novel application of MR in heritage and our design approach, which regards the MR augmented space as a living hybrid-architecture environment driven by cyber-physical systems. This environment needs advanced design and infrastructure that facilitate the exploratory development of meaningful MR interactions. Transforming the living environment into a hybrid space requires an equally dynamic system that can respond swiftly and in real time to any changes under the complexities and uncertainties of real-life conditions. Following an anticipatory design approach, we have developed a system with dynamic properties similar to those used in virtual production. The theatre practice is well-acquainted with performing in unpredictable environments and has established mechanisms to respond to unanticipated changes in real time. Given the inherent theatricality of the MR medium, we can view the hybrid cyber-physical environment it creates as a performance space and use theatrical metaphors to develop a system that is conceptually designed, implemented, and performed as yet another actor.

'Jin's Dream' and 'Sancho's Journey' are two MR experiences that engage audiences by utilizing smart AR glasses, allowing participants to immerse themselves in a theatrical performance set within a heritage site. We term this new class of audience experiences as MR Heritage Performances (MRHP). The primary aim of the project was to explore how MR-enabled spaces, their systems, and their capabilities can serve the needs of cultural heritage under an artistic-educational investigation in a museum context. Through a fusion of MR and live acting, these two performances illuminated the challenging histories of the 18th century transatlantic slave trade in two distinct historic sites on both sides of the Atlantic. The project examined the effectiveness of performances in terms of audience engagement, usability, learning, and the challenges and opportunities that MR technology-supported experiences present to the heritage sector. Although developed in a performative theatrical context, we argue that the proposed interaction design and systems architecture approach can be applied to the design of MR experiences across various domains, including entertainment, education, training, healthcare, and several industrial and enterprise applications. This paper is structured as follows: Section 2 presents related work; Section 3 discusses the design philosophy, implementation approach, and decisions. Section 4 presents and discusses the evaluation results. Finally, Section 5 identifies the main findings, contributions, and limitations of this work and suggests further directions.

2 RELATED WORK

This section presents related work on our interaction design approach for developing MR experiences in cultural heritage fusing MR and theatre, and outlines previous approaches to the technical implementation we propose.

2.1 Mixed Reality and Theatre

The concept of Mixed Reality in Theatre has a long history of interplay even before the emergence of VR or Augmented Reality (AR) or digital technology when theatre makers used the Pepper's Ghost technique to create projection of pseudo-holograms onto the theatre stage. Non-immersive digital technologies have been thoroughly investigated as a way to transform the traditional theatrical experience enriching the

acting and storytelling, scenography, and lighting design [8]. Early works blending live theatre and MR used video projections and motion capture of hidden actors to simulate actor-avatar interactions [1, 17]. These works are also an excellent example of interdisciplinary collaborations between professionals from many different fields such as theatre, HCI, animation, educational psychology, and music. Steve Benford and Gabriela Giannachi have documented several projects from the artistic perspective including the work of prominent immersive theatre companies in their seminal book *Performing Mixed Reality* [5]. For the past few years, VR has been at the forefront of immersive theatre spearheading discussions on scenography, dramaturgy and interdisciplinary collaboration, especially with non-theatre disciplines [7, 37, 38, 39]. A few experimental theatrical works have employed mobile AR [2, 30] and pass-through AR [10], whereas smart AR glasses appear in only a handful of experimental performance projects using interactive narrative without real actors, e.g. [14, 18]. Dima and Maples [2021] have discussed how the fusion of smart glass AR and theatre can create participatory and engaging sensorial experiences unfolding a theory for Affectual Dramaturgy within (the context of) a cultural heritage site.

The few prior theatrical experiences that use smart AR glasses mostly include pre-compiled content developed in a game engine that is viewed during the experience, a common approach that is opposite to our real-time design and content display approach. Some research projects have taken a few steps towards a more dynamic MR experience design. Chen et al. [2020] created a framework for live MR theatre which considers the shared viewing space for multiple viewers, synchronisation of effects with actors, and device-agnostic implementation. Although the holographic content, which included virtual props positioned on a specific place in the 3D space, was pre-baked in a visual app installed on the smart AR glasses, the appearance and disappearance of the props was controlled through a mobile app by a stage manager during the play. At the system level, our work shares a similar setup including a separate app for controlling the timeline that we used only for monitoring and debugging. However, our system is more automatic, complex and dynamic as it introduces the additional layer of the sensor infrastructure for the coordination of events between the real actors and the displayed augmentations.

Our primary inspiration for designing an MR authoring and performance system, which provides the flexibility and utility necessary for creating a rich MR theatrical experience, revolves around the notion of the actor. Actors adjust their timing and performance during rehearsals and on stage based on cues and instructions they receive on the fly from other actors and the theatre director. Therefore, our system's goal was to function as another actor capable of adjusting its performance in response to ad hoc instructions and synchronizing with cues from a highly dynamic environment. To achieve this, we created a sensor-based Internet of Things (IoT) orchestration and synchronization network for all our digital devices.

A fundamental part of distributed and ubiquitous computing, IoT refers to the network of interconnected objects, embedded with sensors, and software that allows them to exchange data with other objects, devices, and systems over the internet. Home automation has been the primary application context for IoT, however, there is an emerging body of work that explores its use in combination with MR [20, 24, 28, 31]. In the theatre context, O'Flynn et al. [2007] describe a wearable sensor system for dance theatre, and Feng et al. [2007] introduce one of the first wearable sensor networks for light control in a theatrical performance.

2.2 Mixed Reality in Heritage

Notably, cultural heritage has been a fruitful application domain for MR [4, 6]. Mobile Augmented Reality applications have been used in heritage sites extensively [35] and several projects have explored mixed reality technologies that, although not what would be now commonly termed 'immersive', create an augmented cyber physical space such as projection mapping [25], tangible media [34] and haptics [12]. Head-worn MR technology using head mounted displays has been used for preservation and architectural visualisations [18, 29]. Increasingly, museums employ wearable MR for visitor engagement. Museums and heritage sites function as rich narrative environments designed to connect visitors with both the unique and the special aspects of human history and culture, fostering a deeper, more personal engagement with the content. [23]. Papagiannakis et al. [2024] have conducted a systematic survey of MR use to enhance

storytelling, Yi and Kim [2021] discuss User Experience design and evaluation methods, while Sterling [2022] offers a heritage perspective of how immersive experience design might shape critical heritage thinking and practice. Example projects created for wearable AR glasses, such as the ones used in our work, that have harnessed the narrative potential of heritage sites for enriched and engaging visitor experience include educational walkthroughs [11, 21], and games [19].

3 MRHP DESIGN AND IMPLEMENTATION

3.1 Our Design Philosophy: World as a stage with live coding

MR is set to seamlessly blend the virtual and physical worlds, creating a unified experience. A physical world is dynamic, exhibiting high complexity and indeterminacy. Every application that interacts with the unpredictable nature of the physical world in bi-directional ways must also be able to change and adapt on the fly. Our design philosophy is grounded in the understanding that addressing the complex and unpredictable nature of the real world cannot be achieved through a static, pre-compiled software development paradigm. While game engines provide a rich open-ended MR development environment, the deployment of compiled software on MR headsets often results in rigidity that contradicts the dynamic nature of real life. Additionally, modifying the behaviours and characteristics of virtual objects, agents, and overall content within a predefined MR application is a cumbersome and extremely slow process that lacks the flexibility for real-time adjustments. Therefore, from a design standpoint, we adopted an anticipatory design approach in order to develop a system that escapes the notion of a pre-compiled application and introduces a dynamic, live rendering environment. This approach is also found in virtual production settings for cinema where the director is able to alter every aspect of the virtual world on the fly to meet their creative intent. Similarly, most virtual production environments escape the limitations of compiled code by running on the game engine's runtime environment. To establish the foundation of our work, we separated our content (3D and graphical assets, sounds, and animations) from rules and behaviours, utilizing a live programming environment to develop and orchestrate the final application with network, live coding, and IoT technologies. The Theater of Things®, a proprietary programming environment developed by Enosis, served as the foundation for our initial explorations and set the stage for developing additional systems and capabilities that enabled us to seamlessly integrate MR within the theatrical performance context. This empowered our actors, directors, and audiences to engage with a system that was transparent and adaptable to any dynamic input, new behaviour, and adjustments on the fly. Our system enabled us to rapidly prototype and test the experiences we were developing during the production and development phases, allowing us to adjust the content, events, synchrony, and behaviours during rehearsals. We were able to rapidly explore and evaluate ideas from actors, directors, and designers, and integrate them into the final performance without needing to return to our development environment, recompile code, and upload it to our devices.

To further inspire our design and development philosophy for real-time computing in MR (RT3D), we drew parallels from virtual production systems used in the film industry. Many of these systems also utilize game engines like Unreal or Unity, but they operate in runtime mode rather than as fully compiled software. This enables rapid development and seamless integration with the dynamic environment of the production set and the director's creative vision. Another important element of our approach was the ability to craft moments of synchrony into the MR theatrical experience. In performance work, synchrony refers to the coordinated and harmonious alignment of various elements in order to create a cohesive and impactful experiential narrative with emotional resonance for the audience. In theatre, synchrony encompasses the coordination of actors, their dialogue delivery, stage movement, lighting, and set changes. All scenographic and dramaturgical material is carefully combined to make this happen. In order to allow synchrony to emerge seamlessly in the hybrid cyber-physical environment of our performances we concluded as previously discussed that the system had to be conceptually designed, implemented and performed as yet another actor. Sha Xin Wei [2016] described how synchrony is supported by creating a

responsive environment in which computationally augmented media respond to the activity of their inhabitants in his influential paper 'Theatre Without Organs'. Extending the notion of responsive digitally-mediated environments according to Xin Wei, we can consider that all hybrid cyber physical environments constitute performative spaces whose media -- sound, visual field, acoustics and lighting, objects and furnishings -- can be reproducibly conditioned, and in which actions can be rehearsed or improvised' [36, p.276]. Using an IoT communication and orchestration network and the RT3D interaction design philosophy, our system responds to cues and sends cues to other actors and devices, adheres to the shared script and timeline, and co-performs through a series of synchrony moments.

3.2 Performance Design

Decolonisation in the cultural context is a process that challenges colonial power structures embedded in heritage sites. Within this domain, artistic practice, such as theatrical reconstructions and installations including technologically mediated performances, like ours, offer an excellent way to revisit traditional Western historical narratives and challenge their dominance, allowing more nuanced and informed approaches to those perspectives based on revisiting historical evidence.

Our performance design involved two key elements: creating a theatrical script that presented a decolonial narrative with the help of expert historians and creative writers among other stakeholders and designing MR content that supported it. The building blocks of our MR content design approach were set during the Jin's Dream design as it was the first performance we designed and exhibited. In Jin's Dream the script was written first and the MR content was created using the script. Following an alternative method in Sancho's Journey, after the selection of the main characters we created a first draft of the MR content first which was then used to build the theatrical script and the two evolved in parallel. We found both methods to be valid with each one of them offering advantages and disadvantages that were often unrelated to the method itself but the complexities of the broader context and the nature of each heritage site and organization we worked with.

In order to serve the concept of decolonisation, we tried to wave the MR content seamlessly into a unified experience and the theatrical script in multiple different ways. We set to analyse and organise the different ways of experiencing mixed reality content with regards to the elements' position and function in the hybrid space and whether they are acknowledged by the physical actors or not. Borrowing some terminology from narrative theory (diegesis) we propose the below 4 classes of categorising MR Spatio-Temporal Audio Visual Augmentations (Table 1). In the following section we discuss these through examples from both performances.

3.2.1 Jin's Dream Creative Performance Design

'Jin's Dream' was performed at the Ashley House in the village of Historic Deerfield, MA, US. Ashley House was built in 1734 and served as the home of Deerfield's 18th-century Reverend, Jonathan Ashley. The visitors, in groups of 2-3, went through onboarding in a room at the back of the house with access to the garden where they fit the MR device, and were shown what a hologram would look like. We fused onboarding as part of the performance and soon after the fitting they were met by one of the actors (Cato) outside who set the scene for them whilst guiding them to walk at the main entrance of the house. Cato would appear later as voice over the headset which subverted the narrative by offering the enslaved Africans' perspective. This walk of approximately 5 minutes helped participants to ease into feeling comfortable wearing the headset and provided context and instructions all embedded in the theatrical script. Within the unfolding narrative Cato then rings the bell of the main entrance and 'sends' participants back to a day in his childhood. As he instructs them, he is not leaving them as he will reappear later at certain moments as a narrator in the headset. At the entrance they are greeted by Jin, Cato's mother and an enslaved African in the household, who takes them to the parlour where Dorothy (the lady of the house) and Abigail (a friend of the family) receive them. The route of the performance will take them from the parlour to the main corridor, the Reverend's office, and finally the kitchen. Figure 1 shows the house on top view, which was scanned using Lidar scanners on an iPad device. The image also shows some

annotation as the scans were used as visual aids to prototype the performance on the Miro online design tool. Ca is Cato, Abi is for Abigail, Dor is for Dorothy and Rev for Reverend.

Table 1. Classes of MR Spatio-Temporal Audio-Visual Augmentations

CLASS	DESCRIPTION
Non-Diegetic	Non-Diegetic elements in MRHP are not part of the story and are not acknowledged by the physical actors in the experience. They can add to the transformation of the space through the projection of embedded holograms in the user's field of view, such as a virtual fire in the physical fireplace.
Diegetic	Diegetic elements in Mixed Reality Heritage Performance exist in the current space as if they are real, can be acknowledged by physical actors, and have an active purpose in the story. They increase the guest's immersion into the story and its context, taking advantage of the narrative world implemented around the historic site, its characters, the socio-economic, cultural, and religious context, the narrative's era, and the contemporary lenses of the diegesis. An example is a virtual window superimposed on a real one where action takes place.
Liminal	Liminal MR elements are presented as part of the physical space but are not part of the current world although they can greatly contribute to the narrative and the user's experience. They can have physical, metaphysical or illusionary properties and augment real objects that act as mediums for their existence. Physical actors are entirely unaware of the existence of these elements and they exist only in the user's perception. They exist in common time but transcend spaces, such as paintings or statues coming alive.
Cross Over	Cross Over MR elements are not part of the current physical world, they can greatly contribute to the narrative and the user's experience and are acknowledged by the physical actors. They can have physical, metaphysical or illusionary properties and augment real objects that act as mediums for their existence, share common spatial characteristics but transcend time. An example is a vision or a portal shared by both actors and participants.

In the parlour the ladies' conversation includes aspects of everyday life chosen for their references to items around the room connected to the triangular trade that describes the economic and commercial routes and product trades related to slavery. During these scenes we applied Non-Diegetic augmentations in the form of an animated 3D infographic vividly illustrating the complex web of the triangular trade (Figure 2). We also applied Liminal augmentations as a set of three pairs of 2D images that, depicted side by side, juxtaposed the enslaved labour of producing rum and sugar, mahogany and tea and their enjoyment in the New World. The augmentations appeared on top of physical objects in the room: a punch bowl, a mahogany desk, and a tea set. These elements and all others that will be referred to were triggered by the actors at certain times to provide synchrony and seamlessly blend with the acting and narration that unfolds. At the end of the scene, Jin comes back and takes the visitors to meet Reverend Ashley in the study room. Whilst waiting for the Reverend to allow them in, Jin talks to them about her life and duties which is augmented with the auditory elements of footsteps and children playing upstairs, an application of Cross Over augmentation.

The actor who plays the Reverend, an imposing character with strong beliefs about the social structure of the time, welcomes the guests and the dialogue evolves mostly around social hierarchy and the place of the enslaved Africans in it. A look outside a virtual window superimposed on the actual window showing the town's landscape as it was at the time accompanies this scene as Diegetic augmentation (Figure 3). We designed a moment of synchrony where, as the guests are all looking outside of the window, the Reverend triggers the animation of a walking character, a freed slave, passing by while talking about him. The Reverend's scene culminates with him sharing excerpts from a sermon intended for the enslaved Africans. This moment is augmented with Non-Diegetic animated content of enslaved Africans that reveal the true, unspoken responses of the enslaved population to his words. Cato who appears as a narrator on the headset provides additional counterpoints and context to the Reverend's perspective including an interactive map indicating all houses in Historic Deerfield that had slaves. At the same time the names of all slaves appear illuminated on the wall above the fireplace and key figures of the abolition of slavery replace the portraits of kings and generals that were hanging around the room, both Non-diegetic augmentations that enforced a counter narrative.

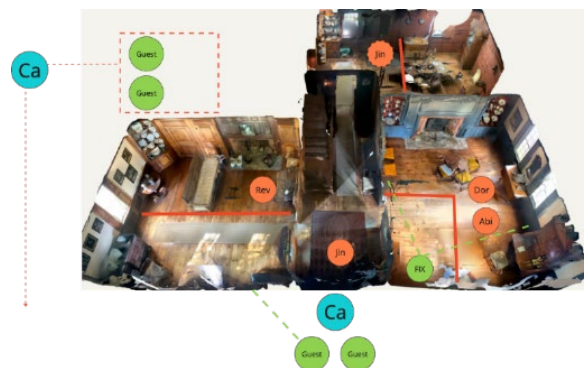


Figure 1: A top view scan of Ashley House, Historic Deerfield. The dotted square indicates the small room (unscanned) with access to the garden where device fitting took place.



Figure 2: An animated hologram on the floor showing the complex web of the triangular trade. Actor portraying Abigail in the background, Jin's Dream.



Figure 3: The actor portraying the Reverend and two members of the audience looking outside the virtual window, Jin's Dream.

In the final scene at the kitchen, Jin's story is enriched by a portal to her village in Africa opening on one of the kitchen's walls with a lion walking up to the portal and stopping just before the audience, a Cross

Over augmentation as it was designed to appear as Jin’s dream of her home. At the end of the scene, Jin is called away at which point the actor portraying Cato who walked them to the front door at the start comes in from the door that leads to the garden.

In our design we sought to create a smooth offboarding as we did with the onboarding. As the immersive experience concludes, the audience is gently guided back to the present. Cato invites participants to remove their headsets while continuing to engage with his closing remarks. In a poignant gesture, Cato offers each audience member a tangible memento - a physical object of personal significance to him. The offering of a physical memento contrasts with the digital nature of the preceding experience, highlighting the enduring power of tangible objects in creating lasting memories. Cato emphasizes the importance of preserving and sharing these stories, encouraging the audience to become active participants in the ongoing narrative of history.

3.2.2 *Sancho’s Journey Creative Performance Design*

Sancho’s journey was performed at Marble Hill House, a grand eighteenth-century villa in southwest London, UK. Our goal with this heritage performance was to subvert the traditional narrative of the house by refocusing it on the connections of the villa’s material culture to the transatlantic slave trade and the forced labour of enslaved Africans and other workers in the Jamaica and British Honduras. The performance uses Western African mythology and imagery to take the protagonist, Charles Ignatius Sancho, a nobleman who was born enslaved, and the audience to a journey of self-realisation.

The visitors start the experience in the onboarding room where they meet Anansi, a West African mythical folklore character, played by a physical actor. Following our design approach to fuse onboarding into the performance, Anansi sets the scene for the audience by telling them a story. During the story, as in Jin’s Dream, the audience has some time to get familiar with wearing the headset and experiencing the holograms. Anansi introduces them to an augmentation of the Sankofa bird, a powerful symbol which emerges from a virtual logo on the wall and flies towards them, sitting on their hand - an example of Cross Over augmentation. Then Anansi takes the visitors outside and to the main entrance, ‘sending’ them back to the 18th century. The audience assumes the role of friends of the house’s owner at the time, Lady Henrietta Howard, who is absent that evening, and arrives to be shown around the house by her friend, Betty Germain, and Sancho. The performance starts from the Entrance Hall and moves to the Tetra Hall, then to the Dining Room and back again to the Entrance Hall, room by room (Figure 4). The Sankofa bird follows them in each room, sometimes making its presence known and other times visible only if the audience looks towards its direction.

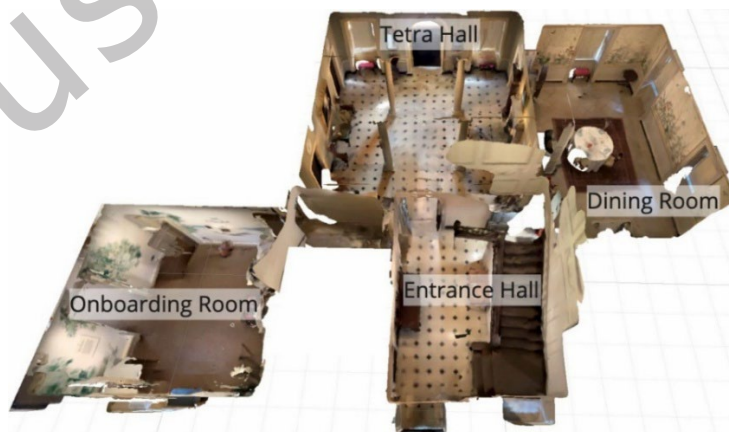


Figure 4: Top view of the rooms in Marble Hill House that were used in the performance, scanned using Lidar sensors

At the entrance, during Sancho’s description of the house and its objects, such as a grand mahogany staircase in the Entrance Hall, a virtual portal opens on the west wall right above the staircase landing. The

portal connects to a forest and an African tiger steps out of it and lies on the landing looking at the visitors, following their gaze as they move around the space (Figure 5). The event marks the beginning of a series of connections to West African natural environments and culture curiously disrupting each time Sancho's narrative of the magnificent house and its history. Sancho senses these augmentations lightly at the beginning but clearly sees them towards the end marking a move from Liminal to Cross-Over augmentations as he comes to realisations over his heritage and the society he lives in.

The scenes in the next room involve Sancho and Betty getting into a heated argument over the human cost of the growing British Empire when a portrait of King George II on the wall comes to life morphing into a Liminal animated 3D model of the King, who goes on to speak about the financial gains and power given to the British Empire through the triangular trade. Sancho, distressed, asks for guidance from Asase Ya, the Earth goddess of fertility, love, and truth in West African mythology. As he does so, the goddess appears as a Cross Over augmentation and speaks to him, startling him. Even though he can't really hear her, only the audience does, he senses her and her words. The argument between Betty and Sancho finds a new dimension in the next room where Betty wonders where to hang a painting, Agostino Brunias' *Dancing Scene in the Caribbean*, appearing as Diegetic augmentation. The painting depicts a scene of apparently free and independent leisure activity among the Black population, an example of paintings of that time which served to hide the true conditions and distort the European perspective on the slave plantations [33].



Figure 5: Tiger coming out of the wall portal seemingly stepping on the staircase landing, Sancho's Journey

As Sancho and Betty argue over the subject of the painting, with Betty insisting that the painting shows nothing offensive but happy people dancing, the main character of the painting, a Caribbean woman wearing white, emerges from the painting as a Cross Over augmentation and berates Betty for her comments (Figure 6). She points to the window in the room where Sancho and the visitors see it opening to a forest with mahogany trees, another Cross Over augmentation. The roots of the trees grow into the room and lead everyone back to the Tetra Hall where they find three traditional West African instruments as Cross Over augmentations and hear a base rhythmic sound playing. This part acts as a mini game. The visitors can add each instrument's sound to the base rhythm by standing close and in front of them. Once all three instruments are played, the melodies merge into a song which transforms from traditional folk song to modern afro beats.

Back in the entrance hall, when the hidden stories behind the material culture of the house have been revealed, Anansi joins Sancho. A Cross Over mahogany tree appears on the mahogany staircase accompanied by West African music, the Sankofa bird and the tiger are also present. Anansi guides Sancho and the audience on a short ritual to pay respect to the Africans enslaved in the West Indies, across the Americas, and in Europe. A leaf falling from the tree ends up on a physical card on the desk below the tree which depicts the Sankofa bird on the one side and a poem on the other side which the audience takes as a

memento. In this closing scene, Anansi invites the audience to gather this gift from the mahogany tree and share its legacy with others.

3.3 Performance setup

In both performances, groups of two to three audience members walk through the site wearing a Microsoft HoloLens 2 headset, which enables them to view the physical environment enhanced by holographic elements. This immersive experience transforms spectators into active participants in an on-site narrative guided by live actors. Participants assume character roles within the story without the need for active performance, although we encourage them to participate by giving them era-appropriate expressions for greeting, casual conversing, agreeing, and disagreeing. The actors, who are not wearing headsets, lead the performance and interact with the audience, using the holographic content that the audience sees through an embedded system linked to the IoT sensor network and timeline system (Figure 7). The embedded system consists of an M5Core2 IoT prototyping device, worn under their costumes, through which they can trigger content in each audience member's headset. The actors also receive a haptic signal, buzz, a cue to continue acting or make a performative gesture or acknowledgment when specific triggered events emerge, or sections conclude, allowing for precise synchronization between live performances and augmented content. The devices are connected to a timeline system that controls what is rendered in the headsets based on predefined scenes and actions implemented following the narrative. Our timeline intersects with dynamic non-linear sections where the system performs a set of interactions while expecting external cues to move the needle. Sometimes, the event cues were based on linear time and sometimes on external triggers through the IoT. The system is designed to make the interchange seamless and to enable the occurrence of 'magical moments' where the virtual and physical content is in synchrony, blurring what is perceived as 'real', such as when the Reverend comments to the passer-by the virtual window which the actor triggered to coincide. In *Sancho's Journey*, we additionally used the affordances of the cyber-physical space for the musical instrument interactions. We used virtual environmental sensing, such as spatial colliders, to control the interaction (e.g., activate, play, animate, follow, move, deactivate) with virtual content by both actors and the audience without using the IoT network. For both MRHPs, we created a new kind of script that on top of the dialogues incorporates all elements of the performance such as the technical notes for the performers and all the spatial and audio augmentations happening through the MR device.



Figure 6: The painting's central figure talking to the actor portraying Betty as an audience member watches, *Sancho's Journey*. Snapshot taken from video recording on the HoloLens worn by another audience member.



Figure 7: An audience member and actor interacting with the holographic content.

3.4 System design

In both developed systems, the augmentations are handled and rendered through Unity3D in real-time. Inspired by distributed computing architectures and based on the foundation of the MR rapid prototyping platform at Enosis, we developed a system architecture that was primarily based on robust networking. The robust network was fundamental to creating an interactive distributed computing system that references qualities of an actor, and to implement our approach of MR as theatre. Enosis' Theater of Things proprietary rapid prototyping platform is based on the 25 year long development of Open Sound Control [16] a format for organising and transmitting data originally proposed in the context of interactive electronic musical instruments. OSC is used to add dynamic behaviour to a system, in various contexts, allowing for the remote sensing and triggering of events as dispatched by an OSC server and its clients. Based on the fundamentals of the protocol, Theater of Things extends these capabilities beyond local networks using a sophisticated stateless programming language called odot to perform more complex operations of incoming data OSC bundle feeds in real time [22]. These advanced operations offer an even more flexible and highly sophisticated framework for authoring individual and group behaviours on the fly as well as monitoring the state of a complex system. Both OSC and odot libraries are Open Source frameworks that are free to use. Inspired by the proposed architecture anyone interested in exploring and extending the potential of this approach can develop similar developing environments. Our design system for MRHP can be seen in Figure 8. The hybrid cyber physical environment affects and is affected by the actions of the actors through the dynamic timeline system and the IoT network. The physical environment serves as a canvas where the media assets are being arranged and displayed. Controlling the physical lighting is crucial for best viewing the holograms but also adjusting the virtual lights on the game engine to match the physical light direction and other qualities. The virtual augmentations are arranged around the selected rooms, objects of interest, walls, floors, windows and other places of the historic site and controlled in real-time by the timeline and the actors via OSC. That allows the creative and performative flows to constantly interact with the dramaturgy following the developed script while adjusting to the dynamic nature of the theatrical performance.

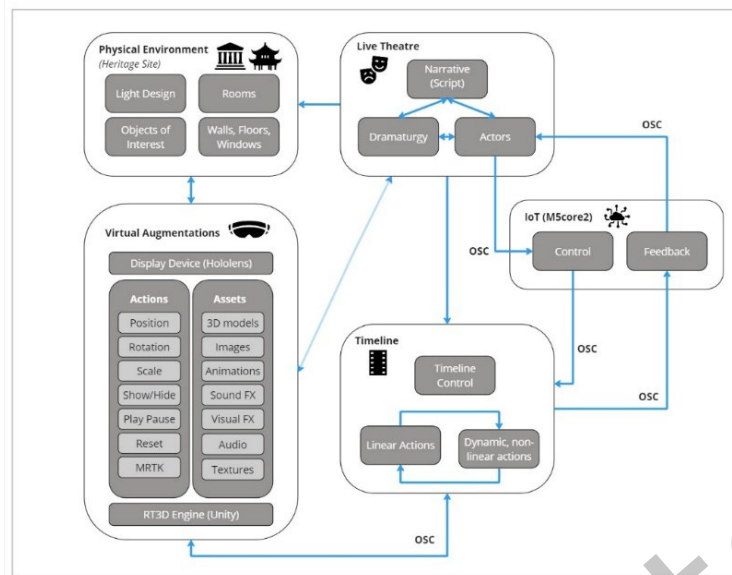


Figure 8: The design architecture of the MRHP

3.5 Implementation

While MR applications are commonly built on game engines and published as compiled applications, in our system design operations and associations between time, actions and digital content can be authored dynamically in real time, offering unparalleled flexibility for rapid prototyping, live coding and sophisticated control of complex heterogeneous cyber physical environments. Multiple instances of the same or different devices (physical or virtual) can be supported by extending the address space to include an identifier for each instance. Rules, pattern matching, direct mapping or complex logic can then be used to address different subsets and combinations of assets and their behaviours in a dynamic environment. The state of all nodes in a single device, a closed system or an environment can be packaged together on a single frame of reference, an OSC bundle, and carries all tags, addresses, values and time tags as a vertical slice of reference.

3.5.1 Jin's Dream

To rapidly assess our approach in 'Jin's Dream', we used MaxMSP and Ableton Live to develop our timeline management and authoring environment. This was due to the software's seamless integration in order to author a system that consisted of a timeline with a cue control database (Enosis Timeline), a control interface (Enosis Timeline Control), a dictionary that contained all interaction design associations (Enosis OSC Dict), an expandable network mapping interface (Enosis Timeline OSC Send) and an IoT configurator (Enosis Timeline IoT). The interface is presented in Figure 9.

On the timeline a user can define regions and mark specific events (cues) that relate to certain scenes and select to either freeze the playhead when it reaches that cue or instruct the playhead to proceed to playback media in a linear way. Every cue is automatically added to a database (Enosis Timeline) and pops up an editor where the user can author all instructions as an OSC bundle. There are two types of commands, internal that can control the playhead and other functions of the timeline, and instructional, that are transmitted to all connected HoloLens display devices within the network through UDP streams.



Figure 9: Ableton control interface incorporating the Enosis Timeline.

Audio files such as a voice over, a music track or sound effects can be directly imported in the timeline and populated by setting cues. Each cue is registered at a local database with a precise timetag and an editor window pops up where the author can describe the interactions and the media instructions at each of the MR headsets. Dynamic interactions at the Unity side included audio playback controls, enabling and disabling 3D scenes, 3D models and other media, playing back animations, scaling, rotating, repositioning an object etc.

Enabling persistent anchoring for the HoloLens and using hands interactions we could then adjust media around the rooms and place them at the required positions. During rehearsals the director of the play, the producer and other subject matter experts, museum curators and historians could request adjustments in placement, performance, timing and type of events, which could be implemented directly on the timeline without involving Unity or requiring recompilation of the application hosted at each HoloLens. Adding and removing audience members became as simple as powering on another HoloLens, adding the IP address for the OSC streaming on the timeline and directly receiving the instructions for the immersive media display.

3.5.2 Sancho's Journey

In 'Sancho's Journey', we took a slightly different approach where we considered time a dependent variable. In this approach, the experience was broken down to a series of isolated scenes (states). The experience would transition from scene to scene based on events (exit events). This approach enabled a more dynamic flow compared to a timeline, considering the experience as a series of scenes and events regardless of how long they would take. This also enabled the experience to be more flexible to change, especially at a rehearsal/live show. In this approach new scenes could be inserted between two existing scenes without affecting the future or past scenes. Hence, the control was done through a state-machine which broke down the script into smaller scenes which would start and end with an event such as an interaction by audience, cue from actors, ending an animation, or when an object in the scene reaches a destination. We used the same OSC communication approach and network infrastructure as in 'Jin's Dream'. For this purpose, a bespoke Control Interface was developed with C# and Maui .NET to be ubiquitous and executable on PC, iOS and Android. The control interface allowed for adding, removing and updating states, changing their orders and setting entry and exit conditions in real time. The state data was saved in JSON format, allowing for reloading previous versions. A sample flow of states and the snippet of the JSON files can be seen in Figure 10. This approach allowed for higher controllability and error recovery during performance, as it allowed for rules to be applied to replaying a previous state, adding new audience members, new HoloLens device, mid-experience through a late join algorithm which executed all OSC commands up to the current state whilst skipping all signals send to actors and all play commands for audio and animation.

In Editor mode, using hands interaction, the director could adjust placement of holographic assets for better alignment and finetuning of virtual elements. The new spatial and positional information were sent to the control interface and saved as part of the initialisation state. This allowed for efficient adjustments during rehearsals.



Figure 10: States flow and snippet of states in JSON.

4 EVALUATION

We ran close to 60 performances across the two sites, including dress rehearsals with members of staff and volunteers that helped us gather useful insights on the setup and our technical system in terms of the functionality, usability and user experience (actors and audience). We interviewed 60 participants on each site using semi-structured interviews and we also interviewed the actors. In Jin's Dream we conducted one to one interviews whereas in Sancho's Journey we interviewed participants together after each performance in focus groups of two to three, depending on the number of audience members that went through the experience each time. Participants in both sites were recruited through the heritage site's mailing lists and there were no exclusion criteria other than age - participants had to be over 18 years old. Participants had to fill in a simple form with basic communication details and select preferred day and time slot. We did not collect any other information. The interviews took place in dedicated spaces close to the end of the experience in each site, lasted between 15 and 20 minutes and were recorded using professional recording devices. We performed thematic analysis in the interview transcripts to identify recurring themes directly linked to the system design that addressed the visitors' experience with the system. Initial coding was conducted with assistance from Google's NoteBookLM, which was used to identify preliminary codes in the transcripts. All AI-generated codes were subsequently reviewed, validated, and refined by the researchers to ensure accuracy and alignment with the research questions. Three themes emerged: multiple levels of emotional engagement impact on in-situ learning, communicating historical information through the virtual material, and unrestricted bodily exploration through the Hololens. We also analysed the actors' perspective on the experience, identifying challenges and opportunities for their role.

4.1 Learning through engagement

The immersive nature of the experience itself, the combination of the live performance, the virtual elements, and the historical setting, contributed to the overall emotional impact for many participants. Several participants remarked on feeling "transported" or "immersed" in the experience. One participant in Jin's Dream stated that the experience "allows a level of immersion that you don't get if you're just in the house even with a guide." Another appreciated the way the technology facilitated a deeper understanding, saying that it "provides a much more intimate look at what life was like for the people who were here". Participants in Sancho's Journey appreciated the way the technology facilitated a deeper understanding, and effectively highlighted lesser-known aspects of history connected to Marble Hill House and its objects. In Jin's Dream, the presence of actors portraying enslaved Africans coupled with immersive storytelling techniques, and the direct audience interaction enriched with holographic content had a heightened emotional impact on the audience. For many, the fact that there were enslaved Africans in the specific geographical area was new information. Sancho's Journey significantly enhanced the audience's awareness of Marble Hill House's connections to the transatlantic slave trade. Both experiences resulted in significant educational outcomes for participants.

Our design in both performances presented diverse viewpoints on historical events acting as a secondary layer of visual proof and historical depth that "reframed" the physical objects, and often virtual events came in contrast with the actors' discussions and portrayals. This was well-received by participants who noted that this approach allowed for a more nuanced understanding of the past. Some participants felt a greater sense of immersion and connection to both the story and the historical setting through the use of the HoloLens. One participant felt that the technology enabled them to closely engage with the actors, creating an authentic feeling of intimacy and immediacy. An interesting point that was raised was that many audience members expressed a desire to actively engage with the actors by conversing with them. However, uncertainty and hesitation arose about the extent to which such interaction was permitted or possible stemming from not knowing when holographic elements would appear during the performance.

4.2 Virtual material's effectiveness

Many participants felt the blend between live acting and the technology was seamless and well-choreographed, with the actors providing successful cues for where to look. The virtual material had a varying impact on participant engagement and immersion. While some found it heightened their connection to the performance and the historical narrative, others felt it created a barrier to their engagement. Several participants expressed concern that the virtual elements, while interesting, sometimes distracted from the live performance and the actors, hindering their ability to fully connect with the emotional core of the story. This suggests a need to carefully consider the balance between live and virtual elements to ensure the technology enhances rather than overshadows the actors' performances and the emotional resonance of the story. Equally, prolonged acting-only scenes can transfer the weight of the attention to traditional theatre and as a result create imbalance in audience expectations.

Some of the holographic content was particularly effective in communicating complex historical information that might be challenging to grasp through traditional methods. Comments were particularly addressing the 3D infographic animation illustrating the triangular trade route which was praised for its ability to visually represent the complexities of the transatlantic slave trade, with one participant saying it 'brought a lot more information...you wouldn't normally have just looking at it'. One participant noted that the technology made learning history "so direct", while another appreciated how it enabled them to "see the invisible". The holographic images attached to physical objects showed the labour behind the objects, such as enslaved people cutting down mahogany trees, linking the finished furniture directly to the source of its material and the human cost involved.

4.3 Usability

Most participants seemed to find the HoloLens relatively easy to use, with little difficulty navigating the virtual elements or interacting with the technology. Many were able to quickly acclimate to the device and found the visual cues and prompts intuitive. They appreciated the ability to walk around freely and engage with the virtual elements without feeling physically restricted. Most participants said that they would have wanted a longer performance. This was fairly surprising as, aware of fatigue issues due to the device's weight, we designed the performances to last for about 35 min which we thought was borderline long.

4.4 Actors perspective

The actors, who were interviewed individually, unanimously recognised the MRHP's effectiveness as an educational tool and innovative approach. Following the traditional theatrical rehearsals, we conducted numerous technical sessions to help the actors acclimate to performing for an audience wearing headsets. These sessions also focused on training the actors to interact naturally with the devices, aiming to create a seamless experience for viewers. Initially, the actors found it somewhat challenging to adjust their performances, but they quickly adapted to the unique requirements. One actor provided insight into this process, stating:

"We were essentially learning to understand what the audience was experiencing without being able to see it ourselves. It was an interesting challenge to master. Once I got the hang of it, though, it felt similar to working with any other technical element in a theatrical production."

The actors observed where the holographic content is positioned through the HoloLens prior to the performances so that they could position themselves, and the audience when needed, accordingly. This strengthened the coupling between the physical actors and the virtual material. When asked how they felt acting in front of an audience that wears a headset, they responded that it didn't change much in their connection with them except when sometimes 'you were looking at people and they'd just be looking off in different directions, and so you just work with that'. Another mentioned that the device would give them a lack of sense of control, which was interesting to work with. As they would also observe the audience during the performances, many actors noticed that the immersive element of the participatory performance, both the live theatre and holographic material, forces them to be present in a certain way so there is a lot of immediacy. As with other technology used in theatrical productions actors had to be at any point ready to respond to potential technical issues. They experienced this in the first technical rehearsals when we were fine tuning technical elements, and they created workarounds e.g. using ad libs in character to include technical glitches into the performance which, as one actor posed it, 'kept us on our toes'.

5 DISCUSSION

The evaluation results demonstrated the potential of MRHP in enriching learning, which is an important objective for cultural heritage institutions especially when it is connected and a result of socially impactful initiatives. Many of the results address the narrative design space of the hybrid environment focussing on how the interactions between actors, including the MR component, and audiences can bring in more synchrony and seamless integration. Our dynamic system supported on-the-fly adjustments and trials so that this process becomes an easy incorporation into technical rehearsals. The virtual production environment enabled rapid and efficient problem-solving during technical rehearsals. Unlike traditional methods that involve time-consuming recompilation processes, issues could be immediately actioned and implemented live with minimal delay.

The MRHP concept introduces a novel element to actors' repertoire of skills, presenting both an exciting challenge and a natural progression in their craft. Actors, who are often required to adapt to various technologies in their profession, found the integration of MR both intriguing and intuitive. They recognized the significance of this new tool, particularly in light of the growing trend towards immersive experiences in both entertainment and educational sectors. They acknowledged that proficiency in working with immersive technologies like MR would likely become increasingly valuable across various performance

settings in the future. This shift not only enhances their current performances but also prepares them for evolving audience expectations and new forms of storytelling.

5.1 Design Challenges and Limitations

The system in both MRHPs worked with minimal errors. Initially, we faced a network signal issue at Marble Hill House due to its thick walls which was solved by using a powerful router. Thick walls are commonly encountered in historic sites. Depending on how far the furthest room used in the performance is, different solutions can be implemented. A mesh network for example may work better for rooms covering a large area horizontally and vertically, i.e. different floors.

A major challenge we had, which is persistent in all MR systems, is the current lack of a sophisticated occlusion mechanism within the dynamic physical environment. Occlusion, in the context of MR, occurs when a virtual object appears to be hidden or blocked by real-world objects or other virtual objects, just as they would be in the physical world. This creates the illusion that virtual objects exist in the same physical space as the user and obey the laws of physics. Realistic occlusion is processor-intensive to achieve and can be implemented easier in static environments. For example, positioning holograms behind static physical objects could be achieved easily through the game engine using virtual blockers superimposed exactly where the physical object was, e.g. a sofa, or by enabling scene understanding that can partially solve the problem but with a considerable cost in performance and battery life. Real-world environments on the other hand are dynamic, with objects and people constantly moving, as in the two MRHPs. Tracking and rendering holographic content accurately in such environments is complex. The challenge was to ensure that the actors and audience would not be at any time in front of virtual objects otherwise the objects might appear to float in front of or behind them, breaking the illusion of coexistence in the same space. To avoid this, we carefully choreographed the movement of the actors and audience in each room. Having the actors' help was crucial to this as it limited the agency of the audience in terms of walking. The actors were trained to guide the audience to specific points in each room which served both to ensure they are viewing the virtual objects appropriately and that no one is in between the virtual objects and the audience's line of sight. This poses already limitations as to where to place the virtual objects so that they can be viewed easily and be in an unobstructed line of sight. The size of the space where the experience takes place, and the number of the audience plays an important role. Our maximum audience size was 3 for each run which for the small size of the rooms in Ashley House was the upper limit. During the trials for *Jin's Dream*, we had to remove a virtual fire positioned inside all fireplaces of the Ashley house. The fire, augmented by real flickering LED lights that added lighting depth, was meant as a decorative environmental element. We realised that having it persistently in the fireplace limited severely the movement of the actors allowing them very little room to move before they would get in the middle of the fire and the line of sight of the viewer. New generation MR devices are expected to have ultrafast and power efficient spatial sensors to assist with holographic rendering with advanced occlusion comprehension.

Another challenge we identified concerned the network configuration and efficiency across the areas and devices in our local network and the pros and cons between the TCP and UDP protocols. While UDP is sufficient for sending and receiving continuous streams of data where dropped packages wouldn't affect the performance of the system achieving its goals, sending important information such as interaction design instructions and associations between the nodes require a guaranteed delivery similar to the TCP protocol. In order to get the best of both worlds we implemented a pseudo-TCP over UDP where a frame of data contained a unique code which, unless it was sent back to the server, the server would continue to reach the node with the same message. It is worth mentioning that this security mechanism was implemented not at the package layer but within the frame of information that was then packaged and transmitted across the network to specific recipients. Depending on the type of data that was sent we then had the option to enable or disable the secured delivery service.

Dynamic virtual object positioning was another challenge. The experiences included virtual moving objects that would interact with physical objects such as the Sankofa bird and the tiger. We therefore needed to track their trajectory in relation to the physical space and objects. We achieved this within the

game engine by assigning virtual elements in the engine as proxies for the physical objects in order to apply relevant motion algorithms. However, this works well only if the physical objects are static. If they are being moved, or in motion, something that is possible by design in a theatrical play, another solution needs to be sought which may impact on the performance.

5.2 Design Opportunities and further directions

Our interaction design philosophy and the system that was designed accordingly were developed in one of the many possible implementation environments using generic open-source protocols as they support various platforms. The versatility of our virtual production live theatre MR environment and the design metaphors we employed make our cultural heritage content and its experience scalable to other hardware devices. As such, the system design can inspire similar implementations in different immersive settings. Considering the system as another actor enabled us to design powerful virtual content, adaptive real-time interaction design and content-actor transitions. The transitions between the live acting and the holographic content were identified by the audience to be contextually and usability-wise very smooth.

As the game engine is primarily seen as an asset handler, future implementations can deliver content that has varying levels of detail, complexity, and interactivity, that can be cloud based to reduce the load on local devices and ensure quick access to it. Our proposed framework enables multi-user interactions easily which are limited only by the size of the space and of the virtual objects with regards to ease of movement and viewing. The design also allows for a variety of sensors and IoT devices to be connected for different input/feedback methods and interactions. A fruitful further area of research within our framework is the use of environmental sensors as an additional layer of interaction, and their integration in the lived experience of the audience.

6 CONCLUSION

We introduced a novel interaction design and development model along with its supporting system for creating MR performances at heritage sites. The model harnesses the theatricality of the MR medium and employs the system-as-actor metaphor to create a compelling hybrid MR theatre experience. To support this metaphor, we developed a distributed computing system that utilises an IoT network worn by the actors and a timeline system that manages the virtual content based on linear time and IoT triggers. Our model is based on a real-time management of the virtual content and its relation to the physical environments and the actors, making the process akin to that of cinematic virtual productions. We chose this path due to the requirements of a live theatrical play and our system-as-actor metaphor. We believe it serves as a valuable lens for approaching MR experience design in general and across various contexts, as it introduces new capabilities and creative processes and simplifies the development process through rapid prototyping, adaptive rehearsals, and scalable deployment that transcends the limitations of solely compiled applications.

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