TangibleMoments: Embedding XR Memories onto Physical Objects

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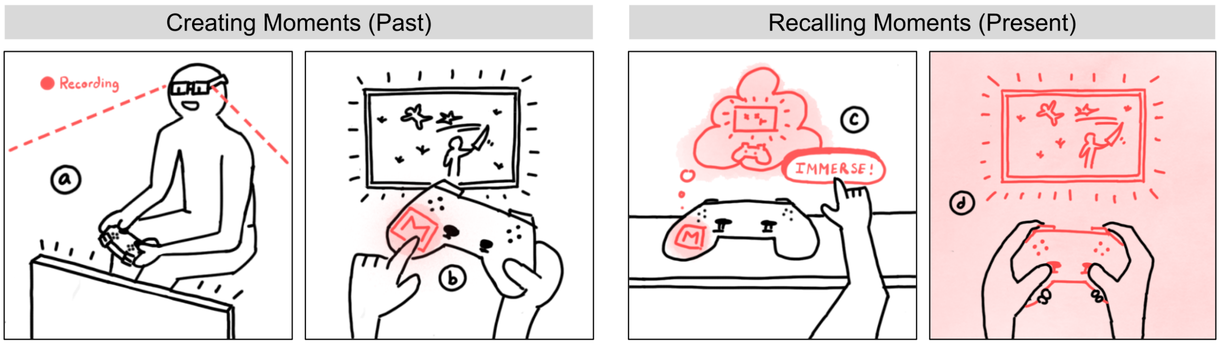

Figure 1: An example scenario depicting the TangibleMoments framework: **(a)** in the past, the user captured an XR memory of a gaming session using their HMD; **(b)** the user attached a virtual sticker to the game controller; **(c)** in the present, the user presses a virtual button hovering over the controller; **(d)** the user is immersed in the XR memory, reliving the past gaming session.

Abstract

The increasing prevalence of Extended Reality (XR) and head-mounted displays (HMDs), alongside rapid advancements in 3D reality capture technology, unlocks a new paradigm for capturing and reliving past memories/experiences through XR. Current methods for accessing and interacting with these *"XR Memories"* still lack the ability to fully leverage the range of capabilities afforded by XR and HMDs. We introduce *TangibleMoments*, a novel framework that enables users to embed XR memories onto physical objects, transforming those objects into *"Moments"*—tangible user interfaces for accessing and interacting with XR memories. We describe and illustrate five interaction methods as part of this framework: Creating Moments, Recalling Moments, Sharing Moments, Copying Moments, and Clearing Moments. We showcase an initial prototype and discuss possible extensions.

Index Terms: Mixed reality, virtual reality, tangible user interfaces, gaussian splatting, spatial memory.

1 Introduction

The act of preserving and reliving memories has long been central to human experience. Traditional methods, such as photographs and videos, serve as powerful tools to recall the past, allowing individuals to revisit significant moments. With the emergence of Extended Reality (XR), which embraces Virtual, Augmented, and Mixed Reality (VR/AR/MR), and head-mounted displays (HMDs), new opportunities have arisen for capturing, replaying, interacting with, and sharing memories in immersive and dynamic ways [48]. In parallel, Tangible User Interfaces (TUIs), which link digital information with physical objects, have demonstrated great potential for embedding digital memories into everyday items [29]. Coupling XR technologies with tangible objects such as personal keepsakes or household items enables more intuitive and engaging ways to interact with memories.

This paper introduces the concept of *TangibleMoments*, a framework that enables users to embed, recall, share, copy, and remove immersive XR memories through interactions with tangible objects. By associating XR memories, such as 3D reconstructions, 360° media, or mesh-based environments—with physical items, TangibleMoments allows users to create meaningful connections between the digital and physical worlds. Users can seamlessly relive past experiences by previewing and immersing themselves in stored memories, share memories by exchanging associated objects, and manage them intuitively through physical gestures, such as attaching, detaching, or duplicating virtual stickers. This novel approach redefines memory preservation and interaction, making it more intuitive, engaging, and accessible.

Through this work, we particularly aim to make the following contributions:

C1. An exploration and summary of current memory-related technologies and user interactions.

C2. Presentation of potential interaction mechanisms using tangible objects and XR technologies for capturing, replaying, interacting with, and sharing memories.

C3. Development and showcase of a prototype, including potential extensions.

Our approach highlights the transformative potential of blending tangible objects with XR to enhance memory interactions. This work paves the way for innovative applications in personal storytelling, education, and digital heritage preservation.

2 Literature Reviews: Memory-related Tangible User Interfaces and Extended Reality

In this section, to explore and capture current memory-related technologies and user interactions, we review previous research on reality capture techniques, TUIs for memory recollection, and immersive playback for 3D spatial memories.

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2.1 3D Reality Capture Techniques

Technologies for capturing and digitally reconstructing real-world experiences are crucial for storing, replaying, and interacting with XR memories. Photogrammetry, the process of approximating a 3D structure using 2D images, has been developed for over a century [24]. A newer method for 3D reality capture is Light Detection and Ranging (LiDAR), which involves lasers being transmitted and received to generate a high-resolution 3D point cloud [47]. Bui et al. [8] developed methods to fuse videos and images with LiDAR scans to generate dynamic virtual objects and natural lighting for VR. LiDAR sensors, however, have limitations when used on their own—such as an inability to perceive windows and a limited vertical field of view [19].

Remondino et al. [37] discussed an approach for 3D reconstruction from image datasets using Neural Radiance Fields (NeRF). NeRF-based methods work by training a fully connected network called a neural radiance field to replicate the input views of a scene. NeRF approaches can realistically depict complex scenes from multiple perspectives, but require significant training and inference time [54]. Qiu et al. [36] identified NeRF-based methods as often facing performance issues in real-time, citing computational complexity, and proposed 3D Gaussian Splatting (3DGS) as a promising alternative for effective 3D representations. 3DGS uses parameterized 3D Gaussian symmetry to efficiently represent and render complex three-dimensional scenes. However, there are still limitations associated, such as higher performance requirements driven by the demand for greater accuracy and difficulty integrating with other rendering techniques [10].

3D reality capture has been applied to a variety of industries and use cases, such as archaeology [7, 11, 34], aerospace [35, 41, 55], mining [2, 20, 52], rescue operations [30, 44, 45], navigation and wayfinding [14, 21], forestry [23, 53], agriculture [40, 51], and civil engineering [13, 25]. These applications demonstrate the value of 3D reality capture techniques, not only for personal recollection of past experiences, but also for serious purposes. They underpin the importance of designing intuitive interfaces for users to access and interact with XR memories captured in 3D.

2.2 Tangible User Interfaces for Memory Recollection

TUIs were introduced by Ishii and Ullmer [18], who defined them as interfaces which "augment the real physical world by coupling digital information to everyday physical objects and environments". Since then, many researchers have explored the potential of TUIs for memory recollection and sharing. For instance, van den Hoven and Eggen [42] showed that physical objects such as personal souvenirs are effective for usage as TUIs for memory recollection, because users already have a mental model associating those objects to related digital information. In another paper, van den Hoven et al. [43] recommended that augmented memory systems should include physical artifacts to act as powerful memory triggers, and use tangible interaction to bridge the gap between physical and digital memories.

Mugellini et al. [28, 29] put this tangibility concept into practice by developing the "Memodules" Framework, a platform for transforming personal objects into TUIs linked to digital memories. Users could turn physical objects to Memodules by attaching an RFID tag to it, then configuring it with a lay&play device. The user could define custom interaction scenarios using an action builder. The interactions were facilitated by a console, which reads the RFID tag on the Memodule, retrieves the associated scenario, then begins execution of the memory on an output device (e.g. slideshows on a TV screen, or audio recordings from a speaker). In a similar vein, Nunes et al [31] introduced "Souvenirs", a system for linking digital photo sets to physical objects to facilitate in-home photo sharing and storytelling. Users would attach RFID tags to their physical items (e.g. rocks, postcards, souvenirs), then scan it with an RFID reader embedded into a platform near a TV. The TV would then show digital photos associated with the physical item.

Some researchers have applied this concept for more specific use cases. For instance, Behllini et al. [4] linked physical artifacts with digital audio recordings to create "fragments"—TUIs that represent critical moments in the lives of domestic violence perpetrators in their journey away from violence. This enabled the physical artifacts to embody lasting reminders of positive change in a peer support system. A user study with male perpetrators of domestic violence found fragments to be motivational, authentic, and supportive. De Jode et al. [12] applied this technology to enhance second-hand retail, allowing users to access audio or video stories about pre-owned items.

TUIs may also be used as a means to not only store digital memories, but also interact with those memories through functions such as adding, deleting, and sharing. Bexheti et al. [5] developed "MemStone", a TUI enabling real-time control over capturing and sharing personal memories via gestures like shaking and double-tapping. The gestures perform various functions, such as recording, sharing, or deleting of data recorded through body-worn cameras and smartglasses. A user study demonstrated higher efficiency and lower error rates compared to a smartphone-based control app. Likewise, Barthel et al. [3] developed a system for users to add, retrieve, and share multimedia stories about objects. They highlighted the system's potential to enhance inter-generational communication and community memory.

2.3 Tangible Extended Reality

Research on TUI in XR has highlighted their potential to create intuitive and seamless interactions by combining XR's enhanced visualization capabilities with TUI's natural interaction techniques. Hong et al. [16] explored the integration of TUIs with ubiquitous VR/AR environments, emphasizing the importance of physical interaction in enhancing user experience. They discussed the challenges of designing intuitive systems that blend digital and physical elements, such as large interactive tabletops, walls, and mobile AR platforms. Also, they highlighted how TUIs can encourage collaboration, improve usability, and create richer interaction possibilities by enabling users to manipulate physical objects as part of the digital experience.

Billinghurst et al. [6] introduced the Tangible AR metaphor, demonstrating how the integration of AR and TUI facilitates intuitive interaction between the real and virtual worlds. For more realistic interactions, Lee et al. [22] previously introduced an occlusion-based interaction method in the context of Tangible AR, using visual occlusion of physical markers to facilitate intuitive interactions. Similarly, Henderson et al. [15] proposed Opportunistic Controls, which utilize existing environmental affordances to provide passive haptic feedback, simplify gesture input, and enhance task efficiency, as validated through user studies. Chan et al. [9] developed the MagicPad, a TUI framework for spatial AR, enabling interactive 3D visualization and manipulation with applications in immersive environments like CAVE systems and artistic installations. Rodrigues et al. [39] extended the scope by integrating mobile AR with tabletop TUI to address spatial limitations, blending real and virtual components for richer, more seamless interactions.

Applications of TUI-based AR have been explored across diverse fields, demonstrating its ability to enhance both user experience and learning outcomes. Huang et al. [17] examined TUI-based AR in fire education, showing that it improves cognitive learning performance and reduces mental load due to its object-linked characteristics. Park et al. [33] developed a tabletop AR system using ARToolKit markers and Kalman filter-based tracking, which supports storytelling applications and intuitive interaction. In the context of modeling, Park et al. [32] introduced the Tangible Aug-

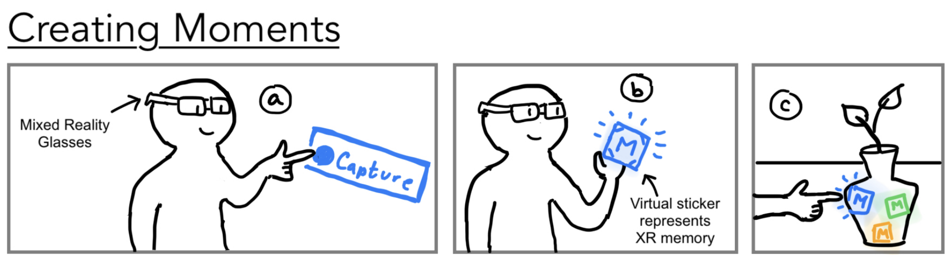

Figure 2: The method by which users embed XR memories into physical objects: **(a)** the user captures an XR memory from their HMD; **(b)** a virtual sticker, associated with the XR memory, appears in the user's hand; **(c)** the user attaches the virtual sticker to a physical vase to embed the XR memory onto the vase, hence creating a Moment.

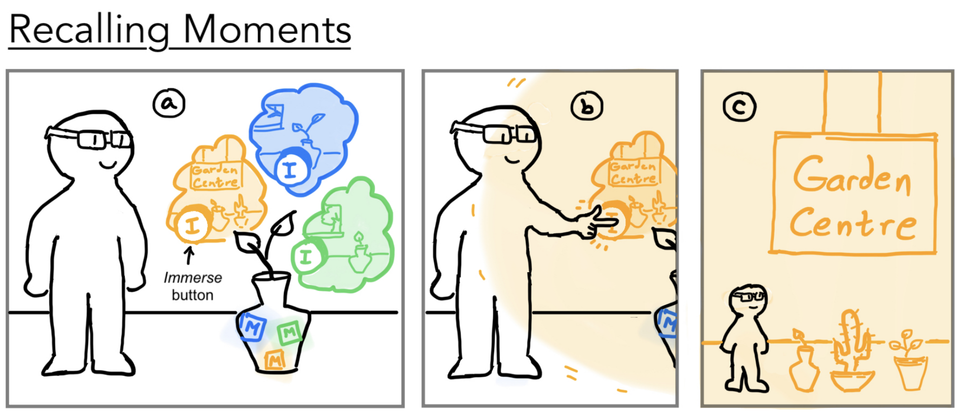

Figure 3: The process of reliving the XR memories embedded onto physical objects: **(a)** previews of each XR memory attached to the vase appear above the vase; **(b)** the user presses an *immerse* button, and their surroundings begin to change; **(c)** the user is immersed in an XR memory from the past (in this case, he is reliving the time he bought the plant from a garden centre).

mented Reality Modeling (TARM) system, which allows users to intuitively create 3D models by manipulating physical blocks and drawing directly on them with a pen. Xu et al. [49] presented Post-card AR and CubeMuseum AR, illustrating how gamified tangible AR interfaces can significantly improve user motivation, engagement, and learning in cultural heritage settings. Monterio et al. [27] proposed Teachable Reality, a prototyping tool that uses everyday objects and vision-based machine teaching to create flexible TUI-based AR applications, validated through user studies and expert feedback. These studies collectively demonstrate the versatility and impact of integrating TUIs with XR, providing insights and frameworks that inform the design and implementation of systems.

3 TangibleMoments: Concept and Interactions

We propose TangibleMoments as a new framework for interacting with XR memories by associating them to physical objects. This concept utilizes MR to bridge virtual content with the physical world, in addition to VR to fully immerse users into past memories. We use the term *"XR memory"* to refer to any snapshot or recording of a past experience, which leverages the heightened immersion of HMDs to elevate the viewing experience beyond that of a traditional photo or video. Examples include 3DGS, NeRFs, 360° photos or videos, and mesh-based environments reconstructed using LiDAR, photogrammatry, or other 3D reality capture techniques. Once a user embeds an XR memory to a physical object, we refer to it as a *"Moment"*—a tangible link between the virtual memory and the physical world. The physicality and omnipresence of Moments enable intuitive ways to interact with XR memories.

Our concept consists of five processes for interacting with XR memories using physical (tangible) objects:

- **Creating Moments:** the method by which users embed XR memories onto physical objects.
- **Recalling Moments:** the process of reliving, or experiencing, XR memories embedded onto physical objects.
- **Sharing Moments:** the means by which the user can make XR memories accessible to other users.
- **Copying Moments:** the process of creating copies of XR memories using physical manipulation of objects.
- **Clearing Moments:** mechanisms to remove (disassociate) XR memories from objects, archive them, and delete them.

We will provide details for each of these processes, alongside descriptive illustrations, in the following paragraphs.

Creating Moments Figure 2 illustrates our concept of embedding XR memories onto physical objects (i.e. creating Moments). The first step is to capture an XR memory (Figure 2a). The memory will be stored as digital data representing a 3DGS, mesh model, 360° media, or some other format aligned with our concept of XR memory. Next, a virtual sticker is created, which is linked to the XR memory (Figure 2b). In an MR environment, users can manipulate the virtual sticker with their hands. The virtual sticker can be thought of as an intermediary representation of the XR memory, given a visual form without association to a physical object. The user can attach the virtual sticker onto any physical object (Figure 2c). Upon doing so, the HMD recognizes the object as associated with that particular memory. This association will persist across sessions, and the virtual sticker will appear attached to the object every time it is visible to the user while they are wearing their HMD. In a sense, the user has permanently embedded the

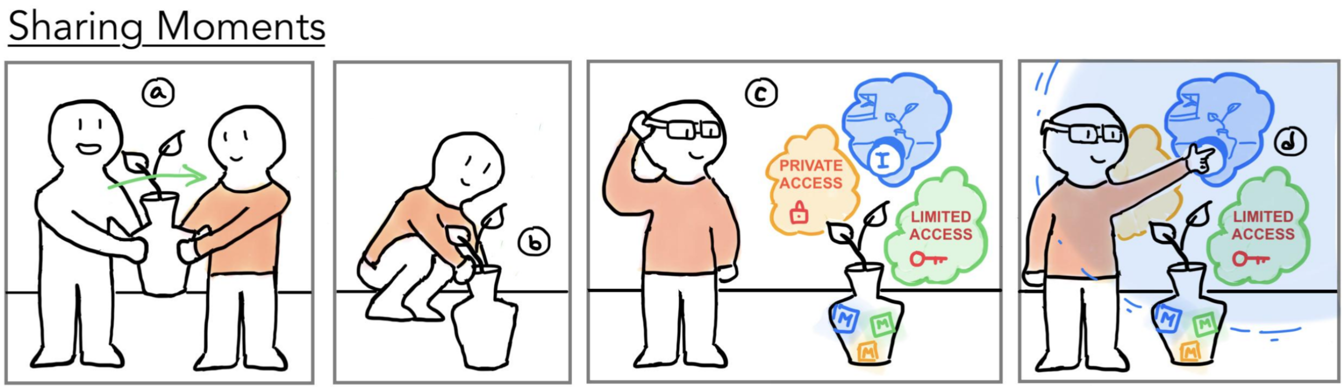

Figure 4: The process of sharing XR memories with others, via transfer of physical objects: **(a)** user 1 transfers the vase to user 2; **(b)** user 2 places the vase down in their home; **(c)** user 2 wears their HMD, providing them an interface to interact with memories embedded onto the vase, with varying levels of visibility (public, limited, private); **(d)** user 2 immerses themselves in a memory they have access to.

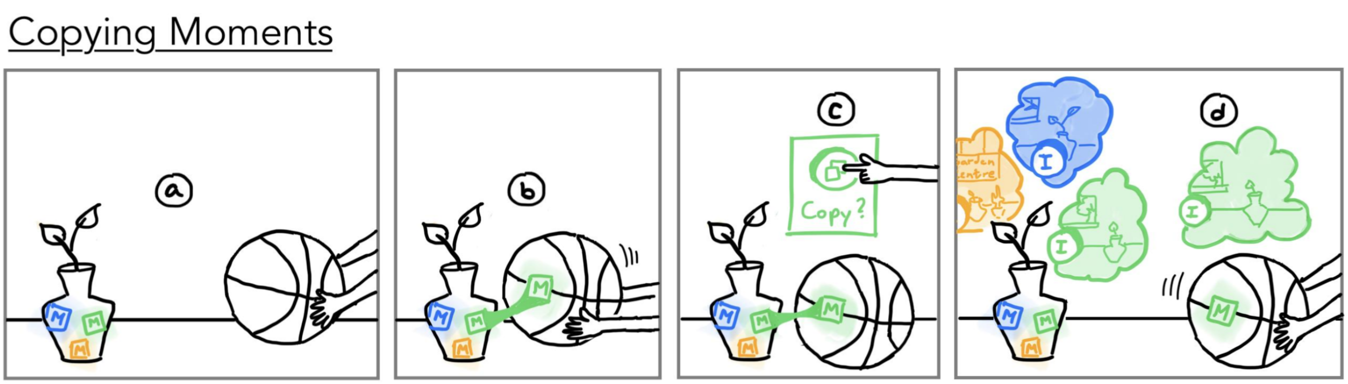

Figure 5: The process of creating copies of XR memories by physically manipulating objects: **(a)** the user retrieves a new object to copy a memory onto—in this case, it's the basketball; **(b)** the user brings the new object close to the original object; **(c)** the user presses a *copy* button; **(d)** the memory will be copied to the new object, effectively creating a new Moment.

memory onto the object, hence creating a Moment. As shown in Figure 2c, multiple XR memories can be embedded onto a single Moment.

Recalling Moments Figure 3 illustrates our concept of reliving XR memories embedded onto physical objects (i.e. recalling Moments). The first step is to wear an HMD, and face the object on which the memory is embedded. A floating preview of each memory will appear around the object (Figure 3a). In the figure, there are three memories embedded onto the vase. As such, three previews appear around the vase. Each of these previews corresponds to an event in the past involving the object. There is a virtual *immerse* button attached to each floating preview. When pressed (Figure 3b), the preview expands to fill up the user's surroundings and immerse them in the memory associated with the floating preview (Figure 3c). Once immersed, the user may explore the memory with 6 degrees of freedom, analogous to a typical immersive VR simulation. In the figure, the user recalls an XR memory they created when they bought the plant from a garden centre. This allows them to inspect the appearance of the plant from that time, and view other plants which were at the garden centre.

Sharing Moments Figure 4 illustrates our concept of sharing XR memories with others via the transfer of physical objects (Moments). Embedding XR memories onto tangible objects provides users with the means to physically hand memories over to other users (Figure 4a). Exchanging gifts is a tradition which has been deeply ingrained in many cultures as an action that binds people together [50]. As such, the physical act of giving may enhance the emotional and cultural significance of sharing XR memories. Upon receiving an object on which a memory is embedded, users may place them in their own personal space (Figure 4b). They can then wear their own HMD to view and interact with the memories embedded on the object (Figures 4c, 4d). To give users control over their privacy, they can set a level of visibility on each XR memory. We propose three levels of visibility: public, limited, and private. Public memories are immediately available to all users. Limited memories are available only to certain selected people. Private memories are available only to the creator of the memory.

Copying Moments Figure 5 illustrates our concept of creating copies of XR memories, by physically manipulating objects. Through this process, users are able to copy an XR memory from an ”original object” to a ”new object”, effectively duplicating the memory. The first step is to retrieve both objects (Figure 5a). Then, the user moves the new object close to the original object (Figure 5b). To be specific, the new object should be in proximity with the virtual sticker on the original object which corresponds to the memory which the user wants to copy. Once this action is completed, a virtual *copy* button will appear above the objects (Figure 5c). Upon clicking the button, the memory will be embedded onto the new object. The end result is a single XR memory embedded on two separate Moments (Figure 5d).

Clearing Moments Figure 6 illustrates our concept of removing XR memories from objects, archiving them, and deleting

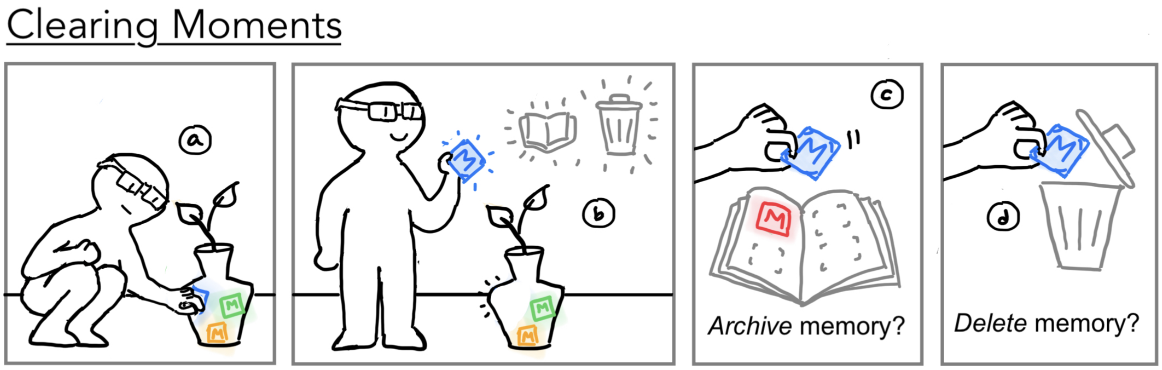

Figure 6: The process of removing XR memories from objects by archiving them and or deleting them: **(a)** users can ”peel” virtual stickers off physical objects to disassociate that particular XR memory from the object; **(b)** once removed, a virtual photo album and a virtual garbage bin appear near the user; **(c)** the user may archive the memory by placing the virtual sticker into the virtual photo album; **(d)** the user may also delete the memory by throwing the virtual sticker into the virtual garbage bin.

them. The first step in this process is to peel the virtual sticker off the object (Figure 6a). This removes the association which existed between the object and the XR memory. Upon removing the virtual sticker, a virtual photo album and a virtual garbage bin appear near the user (Figure 6b). The user may place the virtual sticker in the virtual photo album to archive the XR memory (Figure 6c). In this case, the XR memory is not deleted, and it can be accessible at a later time through a digital interface. The user may also throw the virtual sticker into the virtual garbage bin to permanently delete the XR memory (Figure 6d). The physical gestures associated with these actions may trigger users to be more mindful about managing their XR memories, as opposed to a purely digital interface.

4 Developed Prototype

To demonstrate the potential of TangibleMoments, we developed an initial prototype, which implements our “Recalling Moments” concept, as described in Section 3 and illustrated in Figure 3. It was built on the Unity game engine (v6000.0.24f1) and developed for the Meta Quest 3 HMD. As opposed to the virtual stickers depicted in Figure 3b, we opted to use physical stickers for our prototype to reduce complexity. The stickers display QR codes which represent strings of letters linked to particular memories. We leveraged Google ML Kit’s Barcode scanning (v17.3.0) and the Android MediaProjection API [1] for display access to the HMD. The XR memory included in our prototype is a mesh model which we created using LiDAR scanning with the Polycam application [2], on a 4th generation iPad Pro. We used Blender (v4.3) to reduce artifacts and make other minor modifications to the mesh.

We have included an example scenario for our prototype in Figure 7. In this scenario, the user has embedded an XR memory on a game controller. In turn, the game controller has become a TUI for the user to recall a particular memory. Upon viewing a sticker on the back of the game controller, the user’s HMD scans the QR code and displays a preview of a previously-recorded memory in which the user was playing a video game. The user presses a button below the preview, which immerses them in the memory. The user can move around the memory and re-experience the moment in VR.

5 Discussion and Future Directions

This section discusses the implications of the TangibleMoments concept, reflecting on its current capabilities and opportunities for enhancement. We explore future research directions, including the integration of advanced technologies such as AI, multimodal interaction techniques, and WebXR, to improve accessibility and scalability. These advancements aim to expand the scope and impact of TangibleMoments, transforming how we store, interact with, and share memories.

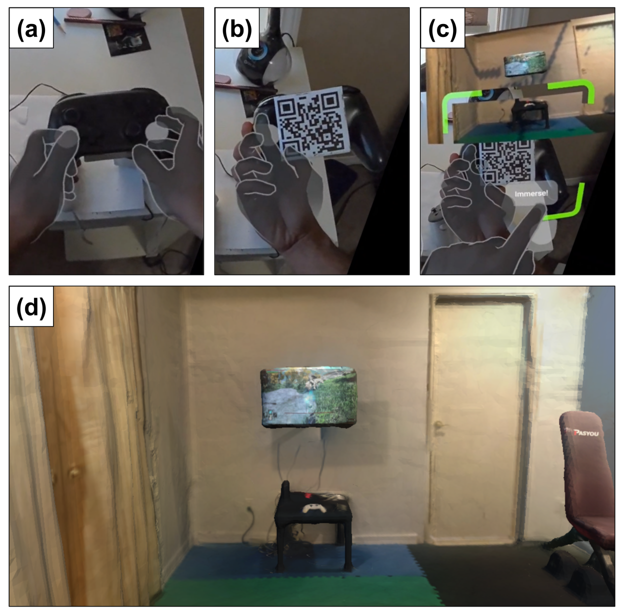

Figure 7: Walkthrough of our prototype: **(a)** the user grabs a game controller; **(b)** they turn it around to reveal a QR code sticker; **(c)** the HMD scans the QR code and displays a preview of the XR memory associated with it; and **(d)** upon pressing the *immerse* button, the user is immersed in an XR memory of playing a video game.

AI-Integrated Tangible Objects The integration of AI into TangibleMoments opens new possibilities for enhancing memory-related interactions. To improve the process of capturing memories, advanced 3D reconstruction techniques like 4D Gaussian Splatting can be employed, enabling the storage and correction of dynamic, time-evolving spatial states [46]. Furthermore, emotional analysis models [1] can analyze a user’s emotional state and adapt the content replay accordingly, personalizing the experience based on the emotional context. Additionally, generative AI methods [38] can be utilized to reconstruct incomplete or fragmented memories, trans-

[1] https://github.com/trev3d/QuestDisplayAccessDemo (Accessed 2024-11-28)

[2] https://poly.cam/ (Acessed 2024-12-19)

forming them into interactive, immersive environments that allow users to relive and explore their memories in new, meaningful ways.

Expanding Interaction Modalities Expanding the interaction modalities of TangibleMoments can significantly enrich user engagement and memory exploration. Multimodal interaction support, including voice, gestures, and touch, offers intuitive ways for users to interact with their memories. Coupled with haptic devices, these interactions provide a tactile dimension that enhances the immersive experience. Beyond individual memory exploration, TangibleMoments can enable collaborative memory sharing, where multiple users contribute to shared memories. This collaborative approach fosters the creation of new, collective memories by combining and reassembling individual memories into diverse, interactive units, encouraging social engagement and shared experiences.

Physically-Simulated Virtual Content Another promising avenue for enhancing TangibleMoments involves enabling virtual content from pre-recorded XR memories to physically interact with the real-world environment during replay. This capability would allow elements like virtual characters or objects, recorded in their original context, to dynamically adapt to the physical surroundings in which the XR memory is currently being replayed. For example, a virtual character captured during a previous memory could recognize and navigate around new physical obstacles or interact with real-world objects present in the replay environment. Such physical simulation would enrich the immersive experience by creating a seamless blend of virtual and real elements, fostering deeper engagement and realism.

WebXR Integration for Accessibility and Scalability The incorporation of WebXR technology into TangibleMoments ensures cross-platform accessibility, allowing users to interact with their memories seamlessly across various devices. By leveraging WebXR, memory data can be stored and synchronized in the cloud, making it accessible across various platforms through web browsers, thereby ensuring continuity and broad accessibility [26]. Furthermore, scalable deployment strategies can enable TangibleMoments to reach a broader audience, making the system adaptable to diverse user needs and environments. This approach ensures that the system remains inclusive, versatile, and capable of supporting a growing community of users interested in memory preservation and interaction.

Public Memory Sharing with GPS Integration An intriguing future direction involves integrating GPS-based systems for public memory sharing. These location-anchored memories would allow communities to contribute to a shared digital heritage, enriching the space with layers of personal and collective experiences. Such an approach would encourage users to explore physical locations through XR, creating a dynamic bridge between real-world spaces and digital memories, fostering community engagement and storytelling.

6 Conclusion

This paper introduced "TangibleMoments" for embedding, recalling, and interacting with XR memories by associating them with physical objects. By leveraging tangible user interfaces and XR technologies, the system bridges the gap between physical and digital memory preservation, offering intuitive and engaging interaction methods. Through an initial prototype, we demonstrated the potential of TangibleMoments to redefine how we store and relive experiences. Future directions, such as AI integration, multimodal interactions, and WebXR accessibility, highlight the transformative possibilities of this approach for various application scenarios, such as personal storytelling, education, and cultural heritage. This work lays a foundation for exploring new ways to create meaningful connections between the digital and physical realms, inspiring innovative applications and future research in XR memory interactions.

Acknowledgments

We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) [RGPIN-2022-03294].

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