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Designing Prototype XRI Workspaces with Mixed Reality and IoT Devices for Immersive Adaptive Environments

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Abstract

Mixed Reality (XR) and Internet-of-Things (IoT) are converging paradigms which are evolving into the metaverse. The XRI research domain addresses these hybrid IoT and XR ecosystems with a focus on embodied environmental objects and avatars. This work contributes the results of an XRI design rapid prototype process. Specifically, it presents i) an XRI system architecture, ii) a context-driven workspace prototype, and iii) an early design-science evaluation, toward new immersive adaptive spaces.

Index Terms: Mixed reality, Internet of things, Smart spaces, Adaptive systems

1 Introduction

The collection of emerging technologies that comprise the metaverse is evolving rapidly and includes fields such as Mixed Reality, the Internet of Things, Artificial Intelligence, Blockchain among many others [9]. This interdisciplinary domain has potential impact on multiple industries as it becomes mainstream. As the metaverse ecosystem advances, there is a growing need for approaches that examine how to merge mixed reality and the Internet of Things into new forms of immersive environments. This is being advanced by technology for approaches in both industry as well as academic research [7], and is expected to impact the humans in the loop. How humans can benefit from life within such metaverse immersive environments is still a vast open question which involves considering multiple use cases. For instance, in this work, the focus is on work, leisure, and rest scenarios.

Among many research opportunities in this space, one is how such systems can be designed to support users in context. Figure 1 presents this information related to the challenges of acquiring user context and applying it for immersive adaptation. This would involve understanding the user situation, and reflecting it in the immersive environment within the metaverse applications. The hybrid exploration of Extended Reality (XR), and the Internet of Things (IoT), are described as XRI in this research. XRI refers to an approach which merges these two disciplines to create hybrid immersive environments. This has been explored in research such as, [11], [6] and [2]. For example, a user's everyday workstation can be envisioned as an XRI smart-workstation where the workspace can not only understand the user's context but can also express itself to the user in ways that fit this context, such as dynamically adapting the lighting in the user's visual field, or highlighting of objects around the user, or even presenting IoT-avatars to the user [17] [11]. However, there remains a need for exploring these techniques further for the design of multiple XRI systems, and for testing how these system implementations meet the needs of the users in context. There is an opportunity for researchers to examine approaches for the development of immersive smart spaces.

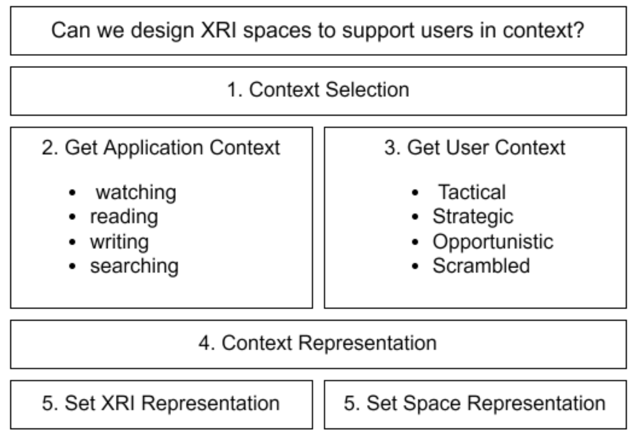

Figure 1: How to Approach the Development of an XRI Smart Workspace.

In this work, the authors recognize the benefits of XR-IoT hybrid systems, as explored in previous research on multiple XRI systems, frameworks for context-aware mixed reality and other forms of virtual physical IoT [17] [11] [12]. A domain that remains for exploration involves XRI testbeds for interaction and exploration. This work explores the design process for a prototype of an XRI Smart Workspace that adapts to the user context. The core contributions are: i) a rapid prototype architectural framework for XRI system development for a smart workspace testbed, ii) the implementation of the architectural framework via a proof-of-concept XRI workspace prototype that transitions based on user-context, and iii) an early comparative discussion and design-science evaluation of such systems.

This prototyping framework and development of an XRI testbed is presented as follows: Section 1 provided the motivation; Section 2 presents a background on XR, IoT, context awareness, XRI systems, and Immersive Smart Workspaces; Section 3 presents a system design and implementation for an XRI prototype framework; Section 4 provides a discussion of the key results and directions for future work; and Section 5 summarizes the paper.

2 Background

The exploration of XRI prototyping requires a focus on the multidimensional themes of XR, IoT, context awareness, XRI hybrids, and immersive explorations of smart workspaces. These are presented in the following sections.

2.1 XR Background

XR is defined as "a group of emerging technologies such as virtual reality (VR), augmented reality (AR), and virtual worlds (VWs) that involve the use of 3D models/simulations across physical, virtual,

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and immersive platforms" [20]. XR is a bridge connecting our physical and virtual worlds. With the expansion and adoption of the metaverse, we are moving towards a more connected world through XR. VR Headsets like Meta Quest 2 provide a low-cost, affordable device to experience Virtual and Augmented Reality. On the software side, there are various gaming engines like Unity and Unreal, and SDKs like the Presence Platform by Meta, which allow developers to create XR experiences. Interactions play a major role in any XR environment. The conventions one should use while defining these various interactions in mixed reality like Eye Gaze Detection, Virtual Controls Handling, Hand Gesture Recognition, etc. are highlighted in [13]. The type of animal embodiment and interactions with it can have a major effect on the way humans-in-the-loop treat wildlife. This has been presented in [15] and it raises an important question about the design choices we make for various interactions and embodiments in XRI Smart Environments that can have a positive effect, maximize immersiveness and also support users in context.

2.2 IoT Background

IoT is defined as a "Group of infrastructures interconnecting connected objects and allowing their management, data mining and the access to the data they generate" [3]. Today, we are moving towards a more connected world, and even the most basic objects that we use in our everyday life are turning into smart, IoT objects. We are headed to a future where every object in our environment would be a connected object. Therefore, it is essential to discuss the role of IoT in XRI smart spaces. These IoT objects provide important contextual information about the user and the environment that they are present in. Mixed Reality can represent this information acquired from IoT objects within immersive interfaces to represent this information. For example, an easy-to-understand XR interface has been presented in [16] which allows users to connect their various IoT devices.

2.3 Context Awareness

Context is defined as "any information that can be used to characterise the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves" [1]. In order to create a smart, adaptive and immersive environment, we need to gather context from the environment and from the user, and process this contextual information to understand the state of the user. A system that automatically uses this context to support the user is called a context aware system. The term context-awareness has been defined in [1] as a system which "uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task". The XRI Smart Immersive Workspace will also be a context aware system which will adapt its environment according to the user's context within the XRI space. Along with having a context aware system, we also need to manage this contextual information. This can be done through a context management life cycle as proposed in [14]. The context life cycle consists of four phases: first, context acquisition from various physical and virtual sensors. Second, modelling the contextual data and representing it into meaningful information. Third, processing the modelled data to derive high-level context information, and fourth, dissemination of the context to the end-users.

2.4 XRI Background

XRI refers to the convergence of XR and IoT, and there have been multiple research efforts that have explored hybrid designs to combine XR and IoT. For instance, an open-source framework for XR-IoT applications has been proposed in [2], using technologies like Node-RED for the communication between the edge devices and the game engine. A scalable XR-IoT framework called "ARIoT" has also been proposed in [6]. In previous work, [12] the authors have presented hybrid mixed reality based IoT-enabled objects in the form of a Smart Plant avatar. In [11] the authors also presented a system design architectural framework for XRI smart environment development. The XRI Smart Workstation system design in this work extends the research in this direction. On the connectivity side, a simplified end-user oriented process flow model has been provided in [16] which would allow users to connect their IoT objects in a no-code manner.

2.5 Related Work: Immersive Smart Workspaces

Multiple researchers are already working to create mixed reality smart workspaces, as seen in Table 1. A prototype for an immersive mixed reality workspace for software development teams has been presented in [18] with a focus on visual analytics, which would help the team manager and other team members to get a better idea of the progress of the work in their team. A needs framework has been proposed in [4] which acts as a guide for the design of Mixed Reality systems for long-term immersion. They have used a classical office space scenario for their prototype and transformed it using Mixed Reality in line with their needs framework. When thinking of the design of the proposed XRI Smart Workspace, some of the needs mentioned in their work align with our User Goals of Productivity and Wellness. The authors of [8] have shown how we can transform office workspaces and overcome the restraints of a physical workspace like limited space and screens through mixed reality displays.

To sum up, the XR background gives us frameworks to be used to create immersive spaces. The IoT background helps us to understand and select the possible edge devices for our Smart Workstation design. The context awareness background gives us a way to use the contextual information obtained from the IoT edge devices to make smart spaces which adapt the environment according to user context. Finally, the background on XRI provides us with an opportunity to transform the Smart Workspaces indicated in the background into XRI Smart Workspaces.

3 Towards an XRI Immersive Smart Workspace

This work presents an early prototype of an XRI Immersive Smart Workspace, implemented using a passthrough mixed reality headset, and components available in the Meta Quest 2 HMD using the Presence Platform [1], and MQTT [2] channels and brokers for communication between the virtual and physical world components. This section highlights this design and development process, including a general discussion of User Goals in a workspace and a System Design Architecture of the prototype.

3.1 User Goals in a Workspace

The goals we consider for a user in a smart workspace can be seen in Figure 2. Among these, our prototype centers on an XR-IoT Smart Workstation for fostering Wellness and Productivity. There are several factors that can affect the productivity of the user. To help the user in increasing their productivity, we propose a design which adapts to the work context of the user by acquiring the application context of their current tasks, and change the environment accordingly. While performing a work task, users may feel demotivated or tired. If the user is given certain motivators while they are immersed in their Smart Workspace, it can have a positive impact on their productivity. The Workspace design should also be such as to minimize the distractions that may hinder the productivity of the user. Another user goal is Wellness. Wellness has a direct impact on the productivity of the user. Drinking water regularly and in adequate

[1] https://www.oculus.com/blog/building-mixed-reality-with-presence-platform-a-new-dimension-for-work-and-fun/

[2] https://mqtt.org/

Paper	Main Contribution	Virtuality	Agency	Embodiment	Interaction	Communication	Relationship with our research
K. Varno et al. (2019) [19]	Digital workstation for assembly	Handheld AR (Tablet)	No agency	No embodiment	Feedback through tablet vibration	No communication	Need of virtual tours for user task navigation, Hybrid objects for training
V. S. Sharma et al. (2019) [18]	Immersive dashboards for software development teams workspace	Mixed Reality (Hololens)	Displays contextually relevant information for users	No embodiment	No interaction with the generated 3D visualizations	3D visualizations generated via JSON data	Immersive dashboards to support users in context
J. Guo et al. (2019) [4]	Virtual office space and Needs Framework for long term immersion	Mixed Reality (HTC Vive)	Sub-systems for monitoring and response to user needs	No embodiment	Interactions with the virtual and physical objects in the workspace	Camera-based image communication (on-entry to VE)	Needs/effects during long-term immersion in XRI spaces
P. Knierim et al. (2021) [8]	Hybrid multi-screen environment in nomadic office space	Mixed Reality (Smart Phone)	Hand tracking for typing in Mixed Reality	No embodiment	Interaction with virtual keyboard	Virtual/XR desktop/laptop screen	Keyboard interactions in XRI spaces
XRI Smart Workspace (Current Paper) (2022)	Immersive workspace, context-adaptations to virtual environment based on user/environment objects	Mixed Reality (Quest)	Adapts virtual environment via user application context and mug water level	Hybrid Mug Avatar signals hydration level; potential motivator behavior	Virtual and physical object interactions in workspace	Application and IoT Context shared via MQTT for immersive environment	N/A

Table 1: Related Work Table of XRI Smart Workspaces and a comparison with the proposed prototype in this work.

Figure 2: A selection of goals of a user in a Workspace and three potential factors that can impact productivity as targets for design.

amounts is one of the factors that contribute to the wellness of a person [4]. But many times it happens that when a person is stressed or engrossed in a work task, they often forget to drink water. If there was a mechanism that could monitor the amount and frequency of water intake, the system could give regular reminders to the user to drink water, which may lead to a positive impact on the user's wellness, and in turn, increase their productivity. Hence our designs reflect this situation, as presented in the following sections.

3.2 Design Architecture

Figure 3 gives an overview of the system design for the XRI Smart Workstation prototype. Figure 4 presents the prototyping process for the design and implementation of the system. The system is divided into 5 components: 1) Mixed Reality Scenes- We are changing the virtual environment of the user based on the 3 states of work, leisure, and rest. These states are represented respectively using 3 separate Unity scenes. 2) User Interaction Components- The various interactable objects in the workspace are managed by the Object Placement Instantiator, which has an interaction manager with interactions like Controller and Hand Controller associated with it. The Object Embodiment Manager is used to control the embodiments [3] of the Water Mug avatar, based on the inputs received from the Agent Controller. 3) Scene Adaptation Logic- The Agent Controller itself acts as a separate component. It contains the controller logic for all the changes that need to take place in the scene. 4) Communication Channel- We used MQTT as our communication channel. MQTT uses a Publish-Subscribe model to send and receive messages. The contextual information from our various edge devices and applications are sent to the Agent Controller through the MQTT channel. 5) Physical Objects, Controller, Edge Devices and Web Application - These include the Meta Quest 2 controllers, the physical hands of the user, the application controller, and our IoT object. The hands act as hand gesture controllers in the workspace. The application controller is an MQTT channel which sends information about the current active website (work, leisure or rest) of the user to the MQTT broker. The IoT object is the Smart Water mug which has sensors attached to it, and the state of water intake, i.e. frequency and amount are sent to the MQTT broker through the microcontroller attached to the mug.

[3] Note that in this work we consider embodiment to refer to the representation of the avatar object as it becomes the embodied agent expression of a hybrid virtual-physical XR and IoT object within the user's environment.

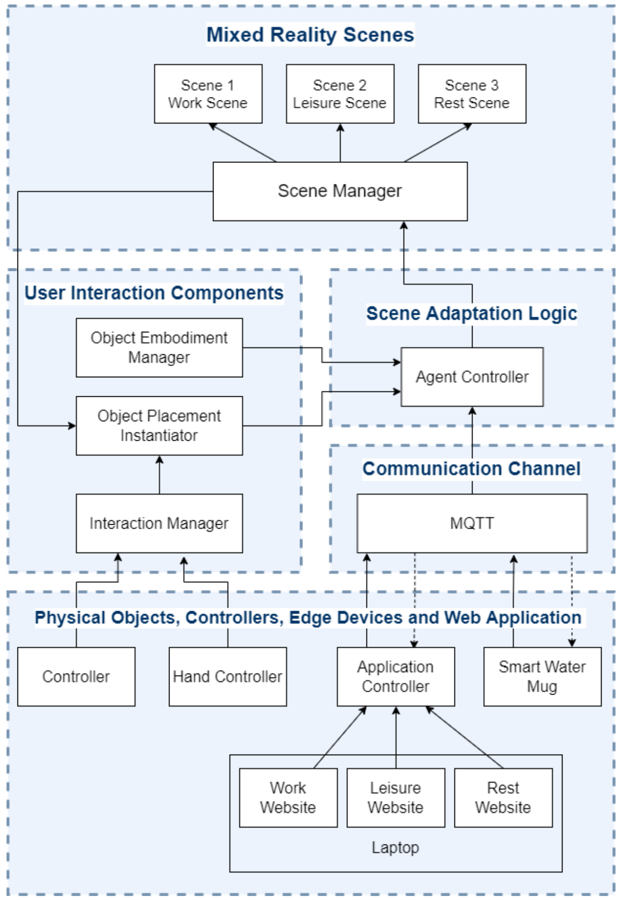

Figure 3: System design architecture and components for an XRI prototype application that can be extended to future designs. The dashed lines show the general architecture, with specific sub-components within the implementation framework. This general structure can be applied to future prototypes.

3.3 Implementation Framework

3.3.1 XR Design

The design looks toward an immersive adaptive environment for the user where their workspace transitions depending on operating context, which may include new virtual object presentations in the scene, and also embodied agents. The mixed reality scene of the Workspace comprises of a chair, a desk and a window. The embodiment of these objects change according to the state of work, leisure or rest. The Work Scene has a simple desk and a revolving chair, like we have in a typical workspace. Along with that, the window object in the virtual environment is covered with blinds, to minimize distractions from the outside world while the user is working, and can help them to fully focus on their Work Task. The Leisure Scene has a colourful table and a hanging chair as shown in Figure 5 so that the user feels as if they are immersed in an environment where they can enjoy themselves and get entertained. The Rest Scene has wooden furniture and windows, and a comfortable couch embodiment for the chair, giving the experience of being immersed in a rustic cabin where the user can rest and relax themselves.

3.3.2 IoT (Smart Water Mug) Design

For our IoT object, we have selected a Smart Water Mug, which acts a Hydration Monitor for the user. As health and wellness are directly related to an increased productivity, the Smart Workspace is designed to have an avatar agent which reminds the users to regularly drink water, and to also keep a track of their water intake. We monitor the quantity and frequency of water intake by the user via a water level sensor and an ESP32 Microcontroller. We use MQTT to send the sensor information to Unity, as done in the author's previous work [12] [17] with a Smart Plant. The mixed reality counterpart of the Hydration Monitor is the Smart Mug IoT Avatar, which is an embodied mug agent. The Mug Avatar sits on the desk of the users and changes its colour, as shown in Figure 6, according to the water level of the mug. When a user is engaged in a work task, and if they have not consumed water for a certain period of time, the mug avatar can be designed to give them a visual reminder to drink water by expressions, such as jumping up and down on their table. Similarly, if the water level in the mug becomes low or empty, the mug avatar could then express sadness and stand with its head low; additionally the colour of the avatar could change to red, indicating to the user that they need to refill it and re-hydrate.

3.3.3 Application Context

To acquire the Application Context of the user, we are using 3 separate websites for each state (work, leisure, and rest). Whenever the user switches to any one of these websites, the scene changes according to the type of website the user is on. When the user opens the Work Application Tracker website, the scene around them changes to Work Scene. The Work Application Tracker has some embedded documents in it. When the user switches to the leisure website, the scene changes to Leisure Scene. Similarly, when the user switches to the Rest Website, the Mixed Reality scene changes to Rest Scene with the rustic cabin furniture.

3.3.4 Connectivity Design

Since the XRI Smart Workstation consists of various heterogenous components, we need a mechanism to allow message passing among these components. We are using MQTT for this purpose. MQTT allows the components to communicate with each other by publishing the messages about their states on various MQTT channels. The other components can then simply subscribe to these channels and listen on messages being published on the channel. These messages are then processed into useful information by the various agent controllers which finally decide the behaviour of the mixed reality environment based on the inputs from these components.

This section provided the main components of our research. We looked at the goals of a user in a smart workspace. We also looked at the system design architecture which was divided into various components based on their functions. Finally, we presented the implementation framework of our prototype with the various heterogeneous components and explained how we brought them together in a single system.

4 Discussion and Future Work

To evaluate this early prototyping work, we consider the Design-Science Research Guidelines as proposed by [5]. Design-science methodology centers on research relevance to operating needs and the rigorous application of the knowledge base toward creating design and prototype artifacts. These artifacts would be evaluated according to standard approaches, which may consider observational, analytical, experimental (including user studies), testing, and descriptive methods. As an early prototype, this work briefly applies descriptive evaluation techniques; and experimental methods are left as a direction for future research.

There are 7 fundamental guidelines. First is, design as an artifact. Here, the artifact is the prototype and system design of our XRI Smart Workstation. Second, is problem relevance. The XRI workspace helps to increase the productivity and wellness of the

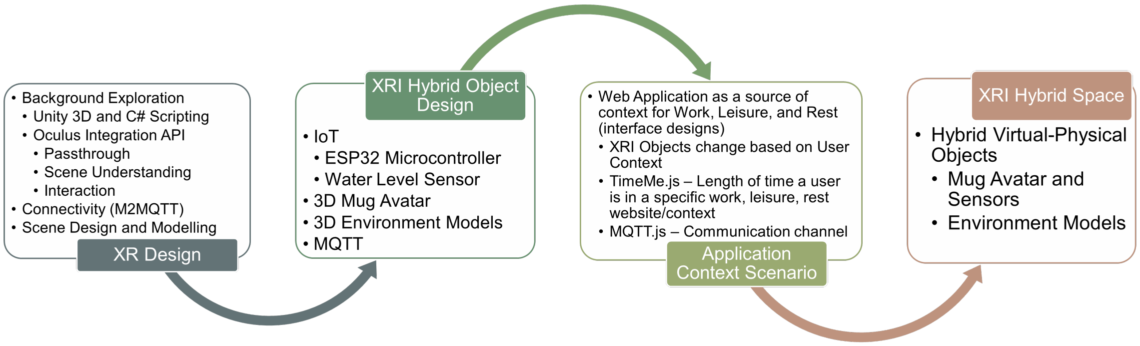

Figure 4: Process Adopted for the Rapid Prototyping of the XRI Smart Workspace

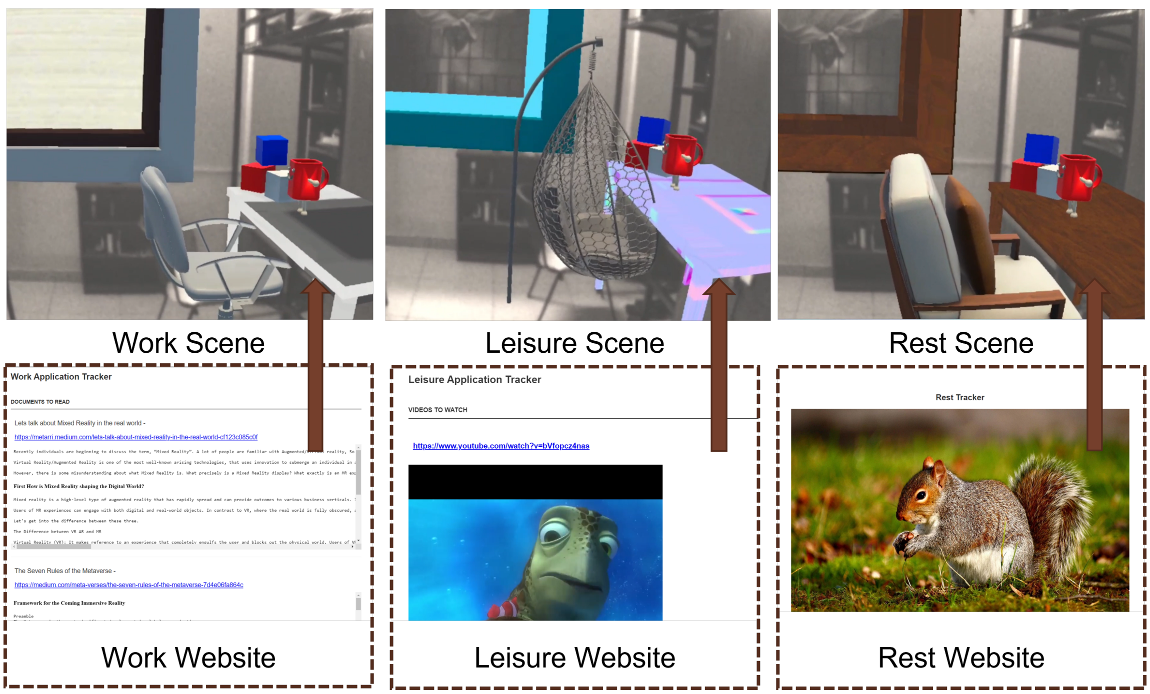

Figure 5: The Mixed Reality environment changes according to the Application Context of Work, Leisure, or Rest.

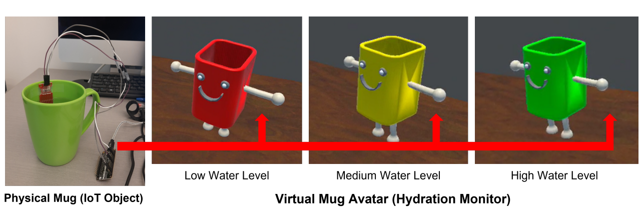

Figure 6: Prototype of an embodied Hybrid virtual-physical XRI Water Mug Object, with the physical (left) component, and the virtual (right) counterpart of the mug. The early work shown expresses water level as color, and can be extended to have behavioral expressions and animations.

users engaged in a task. Third, for design evaluation we will be using the evaluation methods as proposed by Hevner et al., specifically the Informed Arguments and the Scenario based evaluation.

Table 1 shows the comparison of our XRI Smart Workspace prototype with some of the other Smart Workspaces in literature along a certain set of parameters like the level of Virtuality, level of Agency, Embodiment, Interactions and Communications in the prototypes. We also mention the main contributions from their research and the relationship of their research to ours. This table acts as an early comparative evaluation method.

For the scenario-based descriptive method of evaluation, we can elaborate the work, leisure and rest scenarios in terms of utility, quality and efficacy. The utility of these scenarios would be on the lower end as it is still very limited to specific use cases. In terms of quality, our design for the three scenarios has low-medium quality in terms of the models used, the scene adaptation logic and the agent controllers. The potential efficacy of this design lies towards the higher end of the spectrum, as this design research focuses on increasing workspace productivity, wellness and efficiency, and this prototyping research is definitely a step towards future designs for these future immersive adaptive user spaces. This work also applies across the reality-virtuality spectrum [10] without added complexity; as the scene manager would transition the environment details regardless of the user's perspective across the spectrum.

The fourth guideline is the research contributions, which have already been outlined in Section 1. The fifth guideline is the research rigor. We have used a rapid prototyping method, where we engaged in continuous research, development, and functionality testing of the Smart Workspace design. The sixth guideline is Design as a Search Process. This includes research of the application and solution domain. We have considered a subset of the technologies, frameworks, etc. most related for this work, as well as identified the end goals and constraints of our design (see Table 1). The last guideline is communication of the research. Our current prototype acts as a starter testbed for future researchers, and will also be a part of the authors' future work. We hope that the contributions made in this paper will help other researchers take similar steps forward with the research and development of XRI smart immersive spaces.

Future work for this XRI Smart workstation design-approach would be to make the various heterogeneous components more interrelated to each other by using Machine Learning algorithms which can dictate the behavior of objects and the changes in the scene. This work focused more on changes in the virtual world when something in the physical world changes. In the future, we would also add interactions in the virtual space which would alter the states of the physical objects, and more refinement of the immersive mixed reality visualizations and IoT Avatar animations. Some limitations in the prototype were due to the hardware limitations of the Meta Quest 2, like low resolution, black and white Passthrough mixed reality camera-feed, and challenges in anchoring virtual objects to the physical objects dynamically, but these limitations are expected to be overcome within the next generation of mixed reality headsets. Lastly, we also aim to explore different evaluation methodologies to test our XRI Smart Workspace prototype and development process more fully, such as with qualitative and quantitative user studies.

5 Summary

As the fields of mixed reality and the Internet of Things continue to converge toward immersive environments, there is a growing need of core testbed tools and frameworks for designers and developers to consider the important configurations and interactions within these systems. This must account for reusability, flexibility for differing scenarios and even for adaptive context changes. This work presented the results of rapid prototyping for XRI hybrid system designs with a focus on a smart workspace as a testbed. It provides a high level perspective on architectural design components necessary for such systems and a path towards future proof of concept prototype instantiation which can adapt visual configurations of the user environment to match the changes in the user's physical environment, as well as work context information. Although this is an early outcome, it may be evaluated based on design-science methods as a prototype artifact. It is hoped that this work will enable future researchers in XRI design projects to create hybrid immersive smart spaces and the many multimodal interactions within the upcoming metaverse domain.

Acknowledgments

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