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RESEARCH ARTICLE

Exploring the Application of RFID for Designing Augmented Virtual Reality Experience

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ABSTRACT Recent technical advancement has driven the boundary between the physical reality and digital virtuality to diminish significantly. As part of the emerging trend, existing research leverages a synergized use of Radio Frequency IDentification (RFID) and virtual reality (VR) to create compelling hybrid user experience. However, current state-of-the-art literature indicates a lack of coherent architecture for seamlessly integrating these two siloed technology stacks, thus hindering full-fledged mixed and extended reality applications. In this article, we first conducted a comprehensive literature review and identified key design themes and different technical affordances of RFID within VR context; in reflection of our findings, we hence proposed an overarching architecture to facilitate swift and flexible composition of RFID and VR; Three use cases were further established using the proposed architecture to both demonstrate its technical feasibility and qualitatively assess RFID's augmentation over conventional VR applications. This exploratory research intends to offer some preliminary design knowledge and insights for designing and developing RFID-augmented VR applications, open up opportunities for further discussion and research interest in this area, thus ultimately contributing to more immersive, interactive and informative user experience.

INDEX TERMS RFID, virtual reality, mixed reality, extended reality, augmented virtuality, user experience design.

I. INTRODUCTION

In the mid-1990s, Milgram and Kishino first brought up the concept of the "Reality-Virtuality (RV) Continuum" [1], with its two extremes consisted of solely real and virtual (computer simulated) objects and a mixture of both inbetween (namely the "augmented reality" and the "augmented virtuality"). More than two decades passed, the original theory has been dramatically expanded by, for example, introducing multisensory modalities rather than relying exclusively on the visual ones [2], [3], or bringing in the discussions about the real and possible constructs [4] etc. While the definitions of "virtuality" and "reality" continuously evolve and remain multivariate, emerging technical trends and memes ranging from cyber-physical systems [5], digital twins [6] all the way towards the most recently buzzed "metaverse" [7], commonly manifested an ever blurry boundary between the physical reality and the digital virtuality.

Embedded and ambient sensing technologies have further accelerated the trend, among which, Radio Frequency IDentification (RFID) is gaining research community's attention. Explicitly, the passive Ultra High Frequency (UHF) RFID, being low cost, battery free, capable of non-line-of-sight (NLOS) detection and easy to be embedded in all kinds of physical objects, renders itself an ideal medium for creating non-obtrusive, holistic user experience across the physical and virtual realities. So far, RFID has already been widely adopted in a variety of industrial and commercial applications, such as warehouse and inventory management, security systems, logistics tracking etc. [8]. However, its application in virtual reality is yet in a preliminary stage, most of which are no more than an extension of, if not identical to, its

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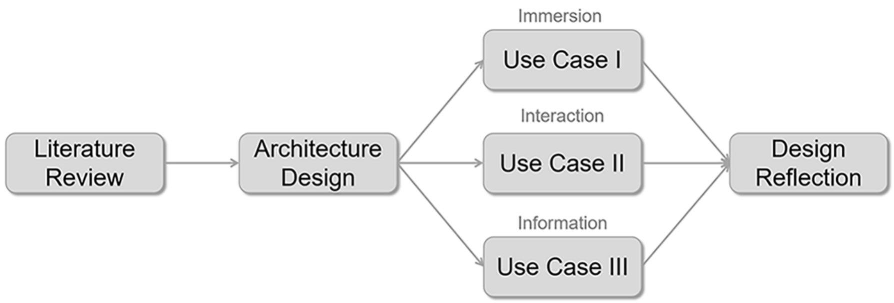

FIGURE 1. Research structure and workflow overview.

known uses. Although sparse domain-specific solutions can be identified from current literature, there lacks a coherent architecture and knowledge base that seamlessly incorporates both RFID and VR for designing and developing full-fledged hybrid user experience.

In this article, we intends to investigate how to leverage RFID, specifically its technical affordances of introducing physical reality into virtuality, to further enhance the overall user experience of virtual/mixed reality. Although current state-of-the-art research has witnessed an ever-growing interest from varied domains including education, tourism, game and entertainment etc., yet, several fundamental questions remain unanswered: *What similarities and differences are there between RFID's uses in VR and non-VR applications? What possible technical affordances as well as limitations should the designers and the developers be aware of, when integrating RFID into virtual reality? By what means can we leverage RFID to improve hybrid user experience and how to assess it?...* Through the initial exploration of the answers to these intriguing questions, we aim to delineate the design space of RFID-augmented virtual reality, reveal novel design possibilities, thus eventually leading to more interests and opening up new discussions in this emerging field.

Overall, our research followed the above structure as presented in Fig. 1. First, a comprehensive literature review was conducted to systematically analyze RFID-integrated virtual/mixed reality systems over currently available application domains. As reported in Section II, we identified RFID's different uses in VR/MR context and related design themes from the state-of-the-art research, which were further used for guiding the following system and use cases design. Second, based on the findings of the literature review, an overarching technology architecture for easy and flexible integration of RFID into virtual reality was proposed in Section III. Compared with traditional development approaches, it provides a full-stack solution with loose couplingness, higher adaptability to varied development and deployment requirements, as well as better mobility covering both indoor and outdoor use scenarios. Followed by Section IV, three use cases were designed and deployed to demonstrate how the proposed technology stacks can be utilized to augment the *immersion*, *interaction* and *information* dimensions of hybrid user experience [9] respectively. Last but not least, we reflected on the design lessons learned from each use case, and in Section V, we summarized our limitations, contributions and further speculated some future design opportunities and trends.

II. THE USE OF RFID IN VIRTUAL REALITY: AN STATE-OF-THE-ART REVIEW

In this paper, we use the term ''virtual reality (VR)'' to refer to immersive environments that are fully computer synthesized. While this definition has much overlap with Milgram and Kishino's RV continuum [1], the major difference lies in that we do NOT further distinguish if it relies exclusively on visual displays, or whether the synthesized environment actually exists or not. Applications integrating VR along with RFID (or RFID-tagged physical objects), according to another work by Milgram *et al.* [10], are generally ''(partially) immersive augmented virtual systems, which allow additional real-object interactions''. According to this definition, most RFID-integrated VR systems fall into the genre of ''augmented virtuality'' on the RV continuum, which can also be deemed as a subcategory of ''mix reality (MR)'' systems. Moreover, VR, MR together with augmented reality (AR) sometimes are also collectively described using the term ''eXtended reality (XR)'' [11].

Bearing this equivocalness in mind, we first performed a literature review on research involving both RFID and virtual reality. A literature retrieval was done on April 13th, 2022 per *IEEE Xplore*, *ACM digital library* and *snowballing*, with the query string specifying that both the keywords ''radio frequency identification'' and ''virtual reality'' (or their abbreviations) must be contained in the metadata. In total, 408 publications were acquired. In the first round of title and abstract screening, we excluded mishit results, such as papers using ''vr'' as a symbol in mathematical formulae rather than ''virtual reality'', and irrelevant publications, for instance, literature review papers and conference summary notes where VR and RFID actually were quoted from two or more independent papers. Consequently, 25 papers remained for full-text examination. In the second round of screening, we further ruled out less relevant results, such as papers where RFID or VR was only mentioned in a general background.

Other excluded papers, although considered relevant, did not provide enough descriptions for analyzing the system design and/or user experience outcome. As a result, we identified 11 publications as both relevant and with adequate details for investigation purposes, which also indicated a rarity in this research area.

After carefully scrutinizing each paper's content, four different themes have emerged and specifically piqued the authors' interests, namely the *Application Domain*, the *Types of used VR*, the *Mobility of used RFID Reader/Tag* and the *Utility of RFID in VR context.*

Current literature was found scattered over several different domains, including industry [12], property management [13], [14], education/vocational training [15], [16], museum/exhibition [17], [18] and entertainment/recreation [19], [20], [21], [22]. We also found that the most adopted VR type was head-mounted devices [14], [15], [21], followed by hand-held devices [17], [18] and immersive virtual environments [16], [22]. For example, [17] proposed a stethoscope-like hand-held mediation device, by which users can view VR contents through a monocular attached to the device; while in [22], a tent-shape projection screen was used to create an immersive virtual environment.

Meanwhile, four different combinations of RFID reader and tag mobility could also be identified, respectively: 1) Mobile tags with non-mobile readers [12], [13], [14], [15], [16], [19], [22]. It has accounted for a predominant use, where one or more RFID readers are launched at specific location(s), and RFID tags are used to identify and track a variety of moveable objects, vehicles and of course, human beings. Minor use cases include: 2) Mobile readers with non-mobile tags [17], [18]. In this case, users usually move along with mobile devices (e.g. notebook computer, PDA etc.) with an RFID reader, while the tags are embedded with static objects-of-interest (e.g. an exhibit at museum), or simply deployed throughout the space for localization purposes. 3) Both readers and tags are mobile, and an example was provided in [21], where a pair of RFID reader/tag was combined with a Vive tracker to form an inductive tray. The tray detected if the items placed in it were picked up. Although the relative position between the RFID reader and the tag remained mostly unchanged, the tray as a whole was portable and could be placed in different locations. 4) Both readers and tags are non-mobile, such as in [20], where a 5 × 7 RFID tag array with a fixed reader 10 cm behind was proposed for gesture detection purpose. It envisioned mostly stationary scenarios such as users performing gestures in front of a large, fixed display.

To note that, most papers either reported to adopt passive RFID tags or did not clearly specify which type of RFID tags was used. Only one study [18] reported to have utilized active RFID tags, and the tags were deployed and distributed statically in the environment. In this case, the tag type appeared to have no significant impact on user experience, as they had no direct contact with users. In this paper, we don't specifically distinguish between different RFID power sources because it is more of a technical parameter. Instead, the device mobility was emphasized as an important aspect of the overall user experience.

As for the RFID's uses within VR context, we roughly categorized them into five different uses:

- **Use 1 (U1)**: *Motion Tracking*, including both gesture and body posture detection. Examples include [12], [19], [20]. However, most of these studies were highly algorithm specific and/or relying on specific RFID array configuration, thus inducing extra device requirement or restrictions on mobility. Although all three papers claimed that their systems were designed for or applicable to VR environment, none of them was tested in actual VR applications.
- **U2**: *Localization*, where RFID is used to detect and monitor a target's physical position, examples like [18], [22]. This includes both *precise position tracking* and *approximate location checking*. The former, similar to U1, is generally done by measuring the characteristics of received backscattered radio wave signals. For instance, Wang *et al.* proposed to use a hand-held RFID reader for tracking the holder's real-time position within an indoor area, where dense RFID tags were deployed and distributed throughout the space [18]. While more applications belong to the latter and utilized RFID to, for example, check if tagged users or items enter/exit a certain area [22], or if they are within a certain physical proximity [13].
- **U3**: *Identification*, referring to RFID's ability to distinguish between different tagged objects. For instance, Fiore *et al.* presented an MR education application that supported gamified collaborative learning between real-world learners and virtual learners participating remotely [16]. Two groups of learners cooperated to accomplish learning tasks in such a way that real-world participants submitted their answers to quizzes by choosing and reading the corresponding RFID tags; if the correct tag was read, some hidden objects in the virtual world would be unlocked, and then the remote participants took their turn to process the tasks. This application revealed RFID's potential to mark both physical and virtual entities and further bridge the two.
- **U4**: *Information Exhibition*, referring to RFID's ability to either present the information contained in the tags or direct users to external information sources. The exhibited information could be inserted and displayed in a virtual environment in the form of images, audios, videos etc. [17]. RFID was also witnessed acting as an information container to carry data-to-be-exhibited, e.g. trainee information, task progress etc., from a virtual environment, e.g. a VR manufacture training system, to physical touchpoints, e.g. a machine terminal, as demonstrated in [15].
- **U5**: *Access Control*. RFID can also be used to determine whether a specific user is authorized to access certain resources, which can either be physical entities or digital

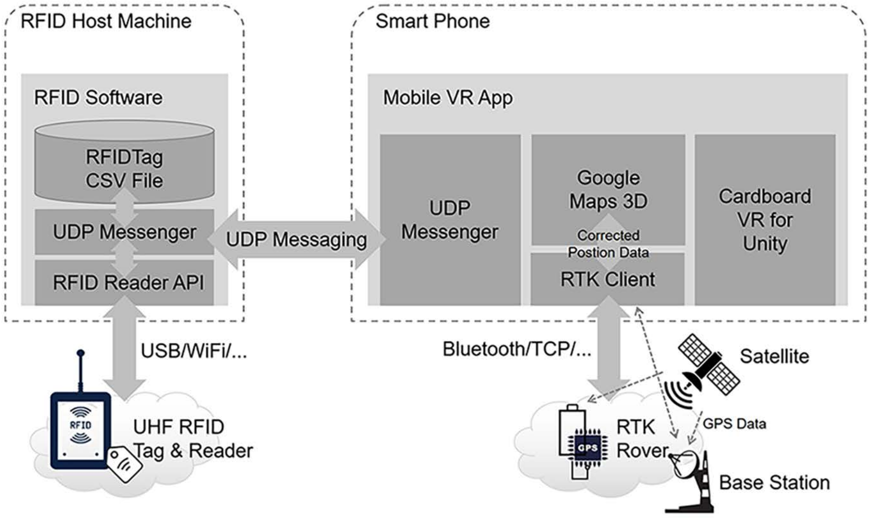

FIGURE 2. **Overall architecture for proposed RFID-Enhanced virtual reality system: RFID messenger stack (Left) and mobile VR application stack (Right).**

properties, examples including [14], [15]. For access control, there was no particular difference identified with regard to VR/MR context when compared to its non-VR/MR uses.

Meanwhile, a few studies like [13], [14], [17] showcased a synergized use of different RFID utilities. For example, Yi *et al.* [17] used RFID tags to identify different exhibits at museums (U3) and present associated contents and information to visitors in virtual reality (U4), the combined use of which can be typically found in many education, cultural heritage and exhibition application settings. To precisely overlay the virtual content layer over physical objects, the same research additionally combined displacement sensors and infrared proximity sensors to estimate the distance from a reference RFID tag, which also reflected a variation of the localization utility (U2). Dindar *et al.* [13] based on a real library and set up a virtual library in the *Second Life*, a Web-based 3D virtual platform. The RFID sensing infrastructure deployed in the physical library streamed real-time data for further processing and extracting higher-level events to create a synchronization in the virtual world, e.g. if a specific book is leaving the entrance without checking out, there will also be an alarm in the virtual library (U2, U3, U5).

To briefly summarize our findings from the literature survey, on one hand, there has been an uptake of RFID technology in VR/MR applications across various domains due to an appealing set of its particularities and technical affordances; on the other hand, current state-of-the-art research relies mostly, if not exclusively, on isolated domain-specific solutions. It reflects the absence of a coherent architecture that seamlessly incorporates both RFID and VR application technology stacks. However, the design and development requirements varied greatly from one another in this area, e.g. different levels of device mobility (completely stationary, partially mobile, highly mobile), different VR deployment (hand-held devices, head-mounted devices, immersive virtual environments and maybe more) etc. Therefore, it entails: 1) a loose-coupled, flexible architecture that well encapsulates the lower-layer diversity from the upper-layer construct; 2) inter-stack independence, meaning that RFID works unaffectedly despite the variation of VR hardware, and vice versa; 3) easy adaptability to domain-specific contents and implementation, because aside from VR designers and developers, there will also be on-the-fly adjustment and fine tuning from domain experts working in the field, which then further implies a need for end-user-oriented development.

III. RFID-VR TECHNOLOGY STACKS: ARCHITECTURAL DESIGN

Grounded in the findings of our literature review, we hereby propose an RFID-VR development architecture consisting of two independent technology stacks, as shown in Fig. 2. The RFID messenger stack takes care of all RFID-related tasks, including reading/writing RFID tags from an RFID scanner, defining and associating user-defined information with RFID tags, and most importantly, transmitting the RFID data to the VR side. While the mobile VR application stack is responsible for measuring a user's precise position and head movement, loading and rendering virtual environment based on 3D geographical maps, and on receiving RFID data, triggering corresponding behaviors within the virtual space. To cover as wide application scenarios across both outdoor and indoor uses as possible, we have adopted a set of light-weighted, compact mobile devices for the implementation. The data exchange between the two stacks is done via standard UDP messaging. More technical details can be found in the following subsections.

FIGURE 3. ThingMagic M5EC RFID reader and non-modified commercial UHF RFID tags.

FIGURE 4. Cardboard VR Goggles, Android Smartphone, SparkFun GPS-RTK2 rover with bluetooth module and patch antenna.

A. RFID MESSENGER STACK

In general, the RFID messenger handles the detection of activated RFID tags, which can either be automatically sensed by entering an RFID scanner's range or proactively triggered by users, and further communicates the RFID data with the mobile VR application. Usually, the messenger software relies on manufacturer-specific driver or compatible API to connect to and configure RFID scanners. As shown in fig. 3, we leveraged a ThingMagic M5EC RFID scanner and hence its compatible Mercury API provided by the same manufacturer. Designers and developers may need to follow the development manuals of their RFID device accordingly.

Our RFID messenger software was developed using C# and ran on a Surface Book 2 laptop with Windows 11 x64 operating system as host machine, which was connected to the RFID scanner via USB serial port. It is the user's option to adopt, for example a mobile scanner with built-in OS instead of an external host machine (e.g. the laptop in our case) for higher mobility, or a stationary scanner with larger antenna for a wider read range, depending on practical in-situ needs. The proposed architecture can be adapted to a wide range of different devices and technical solutions, and be deployed exclusively using commercial ready-made UHF RFID tags and off-the-shelf scanners.

Currently, we leverage a flat-file database in the form of comma-separated values (CSV) to register and store the information of RFID tags. It is also possible to replace with other types of databases that support more intensive and sophisticated data operations, otherwise the CSV file will be a light-weighted option. End users are allowed to associate any specific tag with customized information or Web resources, e.g. a pair of geographic coordinates, or a URL of downloadable 3D assets by simply editing the CSV file. Once a registered RFID tag is read, the software will first look up for a matched data record in the CSV file according to each tag's unique Electronic Product Code (EPC). The returned query result (if not null), including associated user-defined data, will be sent to the mobile VR app via UDP messaging handled by the UDP messenger component for further processing. The design rationale of adding a flat-file database here as an intermediate interface is twofold: first, it decouples the RFID-related tasks from the VR side and avoid handling all the functions in one single application like in traditional tight-coupled, monolithic architecture, so that any internal modification that takes place within the RFID stack will not affect the VR side, and vice versa; second, it exposes a standard-formatted, unified interface to other services and human users alike, allows on-the-fly accessing, managing and testing the data/operations associated with each RFID tag, while all the underlying implementation and internal mechanism are encapsulated and concealed from end users and upper-layer applications.

In addition to commercial passive UHF RFID tags, we also incorporated the method presented in our previous study [27] to apply structural modification on antennas and antenna-IC interconnections of RFID tags, so that they can only be activated when being pressed or held down like a button. These modified RFID tags are also applicable to other gestures like hovering, swiping and such, thus switching RFID's interaction paradigm from passive sensing towards active triggering. It is supposed to further extend the design spectrum through capturing richer user behaviors and contextual dynamics within the virtual environment.

B. MOBILE VR APPLICATION STACK

The mobile VR application provides a highly portable virtual reality environment based on real geographic 3D maps, which was implemented using the Unity platform (version 2019.4.23f). Its possible application covers both indoor and outdoor use scenarios. To this end, we purposely adopted Google Cardboard VR goggles along with an Android smartphone (a Samsung Galaxy S9 with Android 10 OS was used for actual tests, as shown in Fig. 4) as our major platform. While existing outdoor VR solutions frequently entail bulky backpack devices with heavy PCs inside, our proposed line-up instead underlines portability, mobility and relatively cheaper cost. However, to note that the proposed

RFID-VR technology stacks stay independent from any specific hardware, and it is also technically feasible to run the same VR application on more specialized VR devices, such as HTC Vive, Meta Quest etc., for possibly higher system performance and graphic quality.

To increase the safety when using the mobile VR application in the outdoor, we introduced a Real-Time Kinematic (RTK) positioning module into the proposed system to obtain a precise spatial mapping between users' actual physical locations and their corresponding coordinates in the virtual world. Compared with ordinary GPS, whose precision is around 10 meters, our previous study has proved that the proposed RTK positioning module was able to achieve an average positioning precision at sub-meter level inside a dense urban environment [23]. We adopted a set of commercial off-the-shelf products for implementing the RTK positioning module, including a SparkFun GPS-RTK2 rover (with u-blox ZED-F9P on board), a SparkFun Bluetooth Mate Silver for communicating the RTK rover with Android phone via bluetooth, a Taoglas MagmaX AA.171 patch antenna as well as an ordinary 5000 mA USB power bank. Refer to [23] for more system performance and technical details.

The RTK-refined position data is then transmitted by an RTK client to the Google 3D Maps[1] component to further render and update the 3D virtual landscape in a real time manner. Tasks like head movement tracking and magnetic button events etc., are handled by Google Cardboard VR SDK.

Meanwhile, the mobile VR application relies on a symmetrical UDP messenger component as in the RFID software side to establish data communication and keep listening for real-time RFID data. In the coming subsection, we will explain in details how data is handled and processed in RFID messenger and mobile VR application respectively, and how it is exchanged between both sides as well.

C. DATA FLOW VIA UDP MESSAGING

An asynchronous UDP messaging paradigm is adopted for data communication between the RFID messenger and mobile VR application, as shown in Fig. 5. Because UDP communication does not require maintaining a stable connection, it thus results in more light-weighted data packages and swifter transmission, and is considered less demanding on both computational resources and network conditions.

As described earlier, users can associate an RFID tag with bespoke information by editing the CSV flat-file database provided by the RFID messenger (Step 1 in Fig. 5). For example, a URL that directs to an external Web resource, may it be a 3D asset bundle located in a remote server or other multimedia contents to be loaded into the VR environment. The VR mobile app will initialize the transaction with the RFID messenger by first sending a “Start Reading” message via UDP (2). On receiving the message, the RFID software launches a loop to keep reading from the RFID scanner (3), and once a registered RFID tag is detected, the related data will be sent to the VR mobile app also through UDP (4).

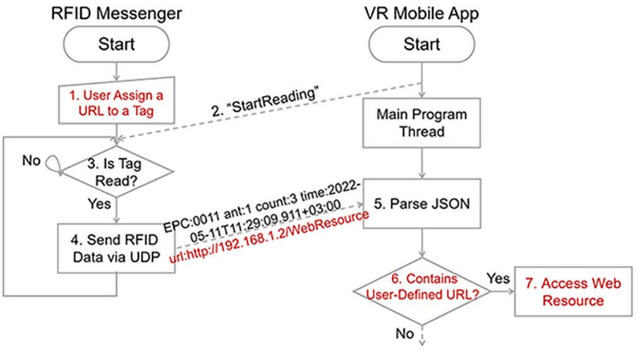

FIGURE 5. Example of data flow between the RFID software and VR mobile application, with case-specific steps highlighted in red.

Currently, we handle the RFID data using JSON-formatted string, which looks like: `“EPC”:“0011”, “ant”:“1”, “count”:“3”, “timestamp”:“2022-06-11T11:29:09.911+03:00”, “url”:“http://192.168.1.2/WebResource”`, among which, the EPC is the unique identifier for each tag and the url is the user-specified resource address. When the data arrives at the VR mobile app, it will be further parsed into different key-value pairs for the program to handle respectively (5). In this case, once the parsed RFID data is confirmed that it contains a url (6), a resource loader will then take over to access the specified external resource and load it into the current virtual reality environment at runtime (7).

To specifically note that, due to UDP's connectionless nature, it is difficult to restore lost data. Therefore, we followed a “stateless” interface design paradigm [28], where the VR mobile app needs not to store or retain any transaction details or request states, but relies exclusively on the data delivered from RFID messenger to complete the transaction. Therefore, the overall architecture is able to maintain a relatively loose coupling and inter-stack independence, thus reducing the re-programming and re-adaption efforts in case that any modification needs to be made to any of the system components.

IV. RFID-AUGMENTED VR VERSUS CONVENTIONAL VR: DEMONSTRATIONS AND DISCUSSIONS

Based on the proposed RFID-VR technology stacks, we further designed and deployed three different use cases, with the aim of reflecting the aforementioned RFID utilities and their combined uses, as well as demonstrating how RFID technology affects and augments VR experience as a whole. As we stated in Section II, while dedicated RFID-VR/MR applications and systems do exist, these systems, however, greatly varied from one application domain to another and were not targeted on a general, multi-purpose

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[1] Google Maps SDK for Unity is deprecated as of October 18, 2021. The service transition can be done via several methods, including developing one's own back end and map service server using the resources provided by the provider.

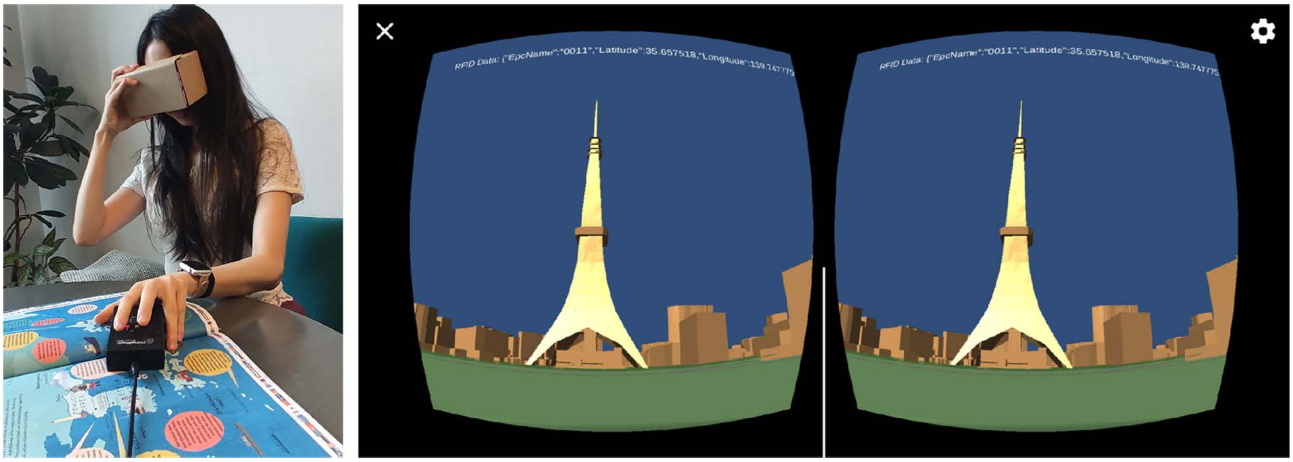

FIGURE 6. Use Case I: RFID-enabled VR scenic spots cruising.

framework/guideline/toolkit as in our case. As a result, there's not much we could find for a parallel comparison. We hence grounded our evaluation approach by referring to different toolkit evaluation strategies in a more general HCI field [24]. According to Ledo *et al.*, demonstration was the most adopted evaluation method to exhibit a toolkit's purpose and design principles by using and combining its components into examples. It highly aligns with our attempt to explore the design space of RFID-augmented VR/MR, which "(design spaces)…often consist of dimensions with properties (categorical or spectrum variables)" and thus making design space exploration "a systematic way of trying to map out possible design boundaries." Reference [24] While it is usually difficult, if not impossible, to explore the full design space, demonstrating application examples that reflects different dimensions of the design space is proved a strong evaluation strategy to showcase the breadth of designs and the transferability of an idea to neighbouring problem spaces.

Therefore, our established use cases each emphasized a general dimension of extended reality user experience, i.e. *immersion*, *interaction* and *information*, which are in line with the classification proposed by Parveau *et al.* [9]. The above indicators have been adopted by other studies such as [25] for gauging AR, VR and MR user experience. By leveraging the same criteria, we further provided a qualitative assessment by comparing RFID-augmented VR and its conventional VR counterpart. The results were concluded in Table 1 at the end of this section. We provide a detailed account of each use case and its underlying design rationale, followed by discussions about speculative design concepts and possible design space.

A. AUGMENTED IMMERSION

Traditional VR applications are generally considered as fully immersive environments that will cut users off from their actual surroundings. While in our proposed mobile VR technology stack, it is possible to create an immersive experience while still being able to maintain users' perception of the outside world. In an outdoor environment, this can be achieved by utilizing the Google 3D Maps SDK along with the RTK high positioning to create a precise and consistent spatial mapping between users' actual physical locations and their 3D coordinates in the virtual space. By further integrating the RFID messenger, we hence designed and implemented the first use case. As shown in Fig. 6, different RFID tags were associated with latitudes and longitudes of famous landmarks and scenic spots on the map (**U3+U4**), for example, an RFID tag representing one of Japan's landmark constructions, the Tokyo Tower was defined as "`EPC:0011, Latitude:35.657518, Longitude:139.747775...`"

The use case works in a way that when no RFID tag is read, the VR app obtains users' current locations through real-time GPS readings from the RTK module, according to which the users' coordinates inside the virtual world will be set to the same place. When the user walks or turns around, the VR view will be updated correspondingly based on a conformal mapping. Once an RFID tag with valid latitude and longitude is scanned, an immediate offset will be calculated and continuously applied to any further read GPS position. Thus, users will find themselves teleported to the specified location in the VR space and able to freely explore the new surroundings around them (**U2**).

As for indoor scenarios, users are allowed to import pre-constructed models or 3D scanned indoor environment,[2] and indoor positioning is also a well exploited area with a variety of ready-built solutions like beacon-based positioning, magnetic positioning, dead reckoning and such. To this end, RFID has been widely applied in indoor positioning systems as shown in [18] and [22], which provides

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[2] Recent commercial VR headsets like Microsoft Hololens 2 are equipped with computer vision based algorithms to obtain 3D meshes of the surroundings. See https://www.microsoft.com/en-us/research/blog/microsoft-hololens-2-improved-research-mode-to-facilitate-computer-vision-research

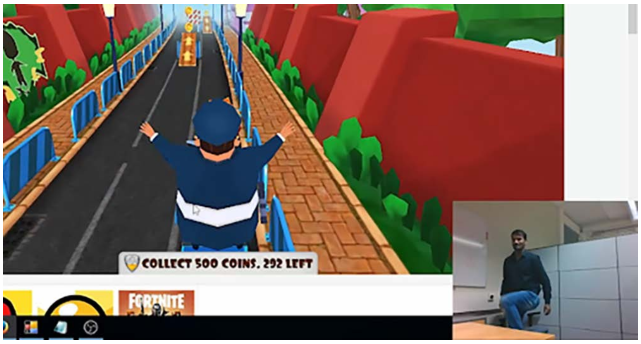

FIGURE 7. Exemplar somatosensory game play by mapping RFID-tagged limb motion to keyboard input.

users an economical and consistent option with the proposed RFID-VR architecture.

Discussion: Spatial perception is always an integral constituent of the sense of immersion. As shown in Section II, the existing VR/MR applications have exploited mostly, if not exclusively, RFID's passive sensing utility of physical locations. Via Use Case I, we intend to prompt designers and developers to be aware of RFID's potential of being an proactive interface between physical and virtual locations.

However, when testing the proposed VR application in actual outdoor environment, we noticed that safety issue still remained the biggest concern. This is due to the reason that the static 3D map lacks dynamic real-time representations of moving objects like vehicles and pedestrians. But if we consider applicable situations, e.g. inside a sightseeing bus where users stay statically in their seats during the whole trip, or a specific zone with predefined geofencing, along with carefully-designed applications, a safe as well as fully immersive outdoor VR experience thus can be expected. Moreover, complementary tracking systems can be further implemented for making people aware of their surroundings.

B. AUGMENTED INTERACTION

Previous study suggested that *immediate interactions*, namely nature interfaces like gesture, voice, gaze etc., render better user experience compared with those *mediate* ones, such as via controllers [9]. Most current VR solutions suffer from bulky and/or costly equipment or constrained activity ranges for tracking user's motion. Even among immediate interactions, however, which modality will be the most proper one is highly context dependent and task specific. For example, voice commands may be efficient when a user wants to search for a specific virtual asset among many others using keywords, otherwise gesture control will be more preferable and intuitive to accomplish tasks like tweaking detailed product design in VR or calibrating the orientation of a 3D map.

Distinguished from existing studies that leverage RFID for finger or full-body movement tracking (see Section II), our previous use case [26] has proved that structurally modified RFID tags stand as input modality. This use case was designed to examine the use of RFID tags, which were attached to different body parts, for triggering corresponding keyboard events and controlling an ordinary video game. The mapping between an RFID tag and a specific keyboard input was defined in the CSV file as "`EPC:0011, keyboard:SPACE...`", and when the user lifted his leg to the position which the tag could be activated by the RFID reader, it immediately created a system event identical to a key press on the space bar. Our preliminary evaluation proved that the resulting precision and latency were adequate for completing tasks like playing musical instrument sound [26] or full-body somatosensory games, as shown in Fig. 7.

Similarly, the input from VR controllers or other devices can be mapped to various body posture and gesture combinations by leveraging the same flat-file database interface (**U1**). Compared with traditional programming-intensive methods, it entails no users' acquaintance with programming knowledge such as system event processing and hardware-specific APIs etc., resulting in significantly less development efforts. In reflection on the needs we identified in Section II, this sort of end-user development (EUD) scheme allows designers and developers to better concentrate on exploring and experiencing interactions itself, and quickly switch among different interaction possibilities. This use case showcased a design alternative other than relying on dedicated algorithms and/or specialized RFID array configurations like many current studies. Instead, it takes advantages of existing VR input modality, built contents and resources. These features, to the best of the authors' empirical knowledge, are of great value specifically in an early design stage.

Discussion: We argue that it deserves specific design considerations from designers and developers to determine both *what interaction modalities to be used*, e.g. full-body movement, hand gesture, touch and voice command etc.; and *how is the sensing granularity*, e.g. if continuous tracking of full-body movement is necessary, or it can be substituted by multiple button-like binary input placed on different body parts. Given RFID's NLOS detection, unlike many other visual markers, it allows multiple RFID tags to be simultaneously detected by one reader as long as they are within the read range. Thus, it facilitates collocated interactions with multiple tags or tagged users involved. *This sort of triangular interaction among user, RFID scanner and tags, depending on different deployment, is able to capture not only users' movement, but also behavior and activity context.*

Designers and developers must be conscious of available system options and combinations, and further make better use of particular features of RFID technology. For example, activation (passive sensing/proactive triggering), read ranges (long/medium/short), mobility (readers and tags can be either mobile or immobile hence four combinations) etc., which offers rich resources for designing a wide range of hybrid user interaction. Moreover, some RFID tags are more durable, stretchable and even washable, thus making them particularly suitable for blending with not only various physical objects, but also textiles. We expect that it is able to deliver both immediate, non-obtrusive user interaction and

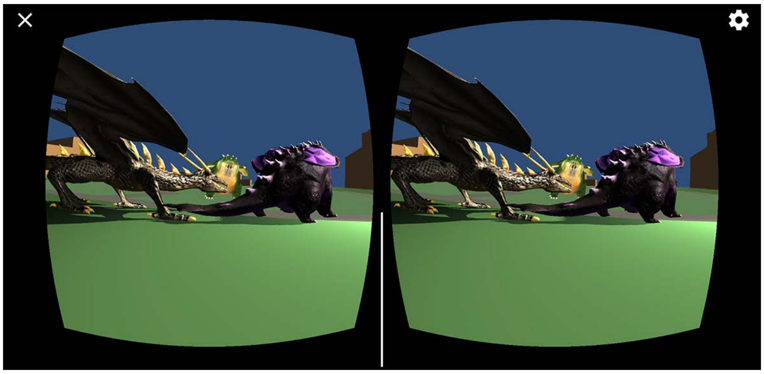

FIGURE 8. Use case III: RFID-enabled dynamic asset loading.

rich virtual/physical expressiveness for augmenting virtual reality experience through varied RFID-embedded clothes, accessories and alike smart wearables.

C. AUGMENTED INFORMATION

It has never been a new idea to draw on the particularity of RFID tags (or RFID-tagged physical objects) to convey contents and information, and further superimpose a virtual representation layer on top of physical or mixed reality, e.g. explanations about the provenance of a museum exhibit, a video tutorial for guiding the use of a laboratory tool etc. By leveraging the proposed architecture, it is also convenient to insert RFID-associated text, images, audio and video into the VR environment. This can simply be done by specifying the corresponding information source in the CSV database without much re-adaptation efforts. This use, however, is somehow technically interchangeable, if we consider that plenty of similar AR applications are already out there.

To explore the unique design alternatives of RFID-enhanced information dimension in VR context, we argue that aside from mapping an extra information layer, it also prompts a different perspective to *contain and convey the information as part of the virtual world*. If we consider that numerous virtual objects, virtual representations of physical objects and/or data, spatio-temporal trajectories, or even the virtual environment itself, they can all interact with us dynamically. Therefore, it is of practical importance, given the continuous scaling up of VR/MR applications, to enable these virtual assets to be retrieved, instantiated and released in real time. Aside from growing computational performance, it also entails a flexible mechanism to identify and launch various virtual assets at runtime and in response to diverse in-situ requirements and user-generated virtual contents. Hence, we designed and implemented the third use case for demonstrating RFID's potential as a physical interface for dynamic asset loading, as shown in Fig. 8.

This use case was designed with an aim of facilitating use scenarios of artefact-focused MR/XR storytelling [29], object-embedded documentation [30] and alike applications. The key idea was to create a consistent and meaningful mapping between the materiality and physical properties, e.g. a 3D-printed figurine with RFID embedded, and the information it contained, e.g. a game character, its background and related narrative etc. Take a virtual asset bundle that contains different 3D dragon models as an example. Each dragon model was associated with a physical RFID tag, by appending a CSV-formatted data via RFID messenger like "`EPC: 0001, Bundle-Url:http://193.**.**.4/assetbundles/dragonbundle, AssetName:Dragon1`", which specified the corresponding web resource address and the asset name. These RFID tags can further be embedded into a hand-crafted dragon figurine, a simple cartoon badge, or any tangible forms pertaining to a meaningful user experience.

Once a user scans the RFID-embedded artefact, the 3D character will then be loaded into virtual space at runtime. Because of the stateless, loose-coupled structure, the mobile VR application needs not to know anything beforehand about the contents to be loaded, or spend any computational resources or storage for pre-compiling and such. Rather, all the virtual assets will only be downloaded, processed and rendered on demand (**U3+U4**). Although it might introduce trade-offs like extra download time, the loose couplingness along with dynamic loading mechanism promise improved scalability and on-the-fly integration of end-user-defined virtual contents. When further combined with the real-time geospatial mapping feature, the loaded virtual characters can further be utilized for MR/VR pervasive gaming or exhibition purposes.

Discussion: RFID technology has long been utilized in warehouse and inventory management, logistics tracking and alike industrial and commercial applications. It seems a natural extension to utilize RFID's technical affordance for both *managing solely virtual properties without corresponding physical entities*, as well as *synchronizing the status between physical properties and their virtual counterparts*, as partially embodied by the concept of "digital twins" [6]. To this end, technical advancement in consumer technologies such as the aforementioned 3D scanning, allows easy creation, transition and synchronization between physical assets and their virtual 3D copies.

TABLE 1. Comparison between RFID-Augmented and Conventional VR (adapted from [9], [25]).

	Immersion	Interaction	Information
RFID-Augmented VR	Real-time spatial mapping between physical & virtual realities	Immediate interaction with physical & virtual object	Registered in 3D space, correlation to user space, time persistence
Conventional VR	Fully virtual (computer simulated)	Mediate interaction with virtual object	Registered in 3D space, no correlation to user space, no time persistence

This *reality-virtuality duality* is commonly shared also by other RFID utilities when being used in VR context. Imagine in a pervasive VR/XR games, a player can use RFID tags as physical tokens that are required for accessing some sort of secured resources or information (**U5**), e.g. saved game progress, rare game props or confidential messages. Apparently, the player can have control over who has the physical access to the tag itself, at the same time he or she can also decide to what extent the digital information contained by the tag is exposed to different user groups, e.g. team members, family and friends, strangers or opposing players.

D. SUMMARY

As exemplified by the above use cases, we qualitatively compared the proposed RFID-augmented VR with conventional VR by referring to previous studies that adopted the same criteria [9], [25]. We also briefly mentioned a few takeaway ideas that we learned from the use cases design.

- **Immersion**: Conventional VR usually relies on fully computer synthesized environment that cuts users off their actual surrounding, while the RFID-augmented VR manages to maintain a real-time spatial mapping between physical and virtual realities. It is noteworthy that a ''real-time'' spatial mapping may NOT necessarily equal to a conformal mapping. This means that *virtual space may have varied representation from its physical counterpart in the sense of scale, distance, direction and all the other spatial or even temporal transpose*.
- **Interaction**: Conventional VR mostly leverages either mediate interaction such as controllers, or device-free gesture/posture interaction in compromising of activity range or mobility with only virtual objects. The RFID-augmented VR enables immediate interactions with both physical and virtual object by comparison. We argue that *there is neither "one-size-for-all" solution nor absolutely good or bad method*. While everything can be deemed a sort of design resource, what will be the most suitable interaction is highly task specific and context dependent. Therefore, *Designers and developers must stay informed of available design options, possible technical affordances and restrictions, thus further taking good advantage of them*.
- **Information**: The information in conventional VR is registered in 3D space but with no correlation to users' current space, and usually perishes when the application is terminated. Instead, the RFID-augmented VR registers the information in 3D space with correlation to users' current space. Moreover, it allows physical medium (i.e. the RFID tag) to contain the information over time after the application is terminated, or even across different applications. We suggest that when designing and developing XR and augmented VR user experience, *it deserves specific design attentions for the reality-virtuality duality, which refers to RFID's affordance of being able to contain and convey information between digital and physical space bidirectionally*.

V. CONCLUSION

A. LIMITATION AND FUTURE WORK

This research intends to explore RFID-augmented VR user experience. Unlike many other user-centered studies directly gaining first-hand user opinions and feedback via interviews or user tests etc., instead, we systematically investigated systems and applications in this field, so as to extract ''secondary'' user experience as the foundation of our analysis. However, this is a nascent research area with relatively less evidence-based research, and it further shrank down the sample size as some existing studies did not provide sufficient materials and descriptions for in-depth analysis. With the limited scale of literature review, the result may not be able to fully enclose and evaluate all significant factors that will have an impact on the UX outcomes. Therefore, a thorough evaluation of user experience that incorporates end users directly will be our next step, from which we expect feedback and insights that will validate and further refine the presented work in this article.

Grounded in the findings of our literature review, we have proposed an RFID-VR technology architecture with the aim of enabling easy exploitation and integration of RFID's utility and facilitating the design and development of full-fledged VR and MR applications. The proposed technology stacks have provided a concise, database-like tool for end users to configure and customize their own VR/MR applications by, for example, using RFID as an input method, setting virtual location and inserting external Web resources etc. However, a more sophisticated mechanism needs to be further incorporated for accomplishing complicated programming tasks and business logic, such as procedure calling, event detection and condition handler etc. Following this thread, it is also among our future work to explore the potential uses of RFID as both a sort of medium for data physicalization [31] and a tangible interface for physical programming [32].

B. CONTRIBUTION

This work is among the earliest exploratory endeavors for investigating the utilization of RFID-based sensing in augmenting VR/MR user experience. The novelty and contribution of this article is threefold: 1) From the *theoretical* perspective, we have structurally analyzed RFID's technical affordances and related design themes in augmented VR or MR systems through a comprehensive review of the current state-of-the-art literature. 2) From the *technical* perspective, we have proposed a full-stack technology architecture to facilitate the design and development of RFID-augmented VR/MR applications. Compared with traditional development approaches, the proposed technical stacks have manifested some unique advantages such as loose couplingness, adaptability to various development and deployment requirements, and higher mobility that covers both indoor and outdoor scenarios etc. It also allows end users to easily insert their own 3D contents into VR environments without programming effort and at runtime. 3) From the *practical* perspective, three use cases have been established for demonstrating and assessing RFID's augmentation for the immersion, interaction and information dimensions of conventional VR user experience.

By delineating the design space and speculating possible future directions, we expect this work will be able to inform the design and development practise in this emerging field, raise awareness and interests from the research community and open up opportunities for further discussions, thus ultimately contributing to the creation and innovation of hybrid user experience.

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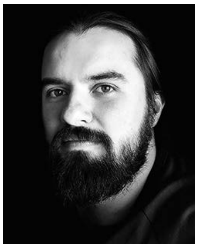

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