Enhancing Immersion in Virtual Spaces

PhytualBlend - a real-time interaction system for seamless physical feedback

Tiantian Lo [1], Yuhong Wu [2], Gerhard Bruyns [3], Daniel K Elkin [4]
[1,2,3,4] The Hong Kong Polytechnic University
[1,2,3,4] {tt-sky.lo|yuhong.wu|gerhard.bruyns|daniel.k.elkin}@polyu.edu.hk

As an extension of physical space, VR and MR technologies offer convenient solutions for spatial and product design by providing immersive user experiences. Nevertheless, these technologies are limited in their ability to provide physical feedback, which can lead to a perceived disconnection between visual, auditory, and bodily sensations. This paper introduces PhytualBlend, an innovative real-time interaction system designed to enhance the physical feedback experience within virtual environments. The system employs perceptual and executive hardware driven by development boards as its hardware components. User's operation on physical entities can be synchronized seamlessly to server-based virtual world through a local information hub, including position, orientation, and haptic interaction. Diverse interaction modes within the virtual world trigger corresponding feedback in the physical space, encompassing tactile vibrations, thermal sensations, visual illumination, and object deformations. Our prototypical demonstrates remarkable performance, achieving a frame rate exceeding 60 frames per second with imperceptible network latency. The modular design of PhytualBlend enables efficient and scalable expansion of various physical feedback, interactive modes, and new virtual environments. PhytualBlend bridges the gap between the virtual and physical worlds, enabling remote collaboration participants to experience and interact with virtual contents in a more tangible and realistic manner.

Keywords: *Virtual Reality, IoT, Physical Feedback, Embedded hardware, Interaction System*

INTRODUCTION

Immersive and interactive technologies such as Virtual Reality (VR) represent a significant milestone in our engagement with the environment and the evolution of our perception of reality (Portman, Natapov and Fisher-Gewirtzman, 2015). Since the 1990s, VR technologies and their expressive capabilities have facilitated the representation of abstract or non-figurative concepts, such as data and information. Originally utilized by architects for conceptual design presentations, virtual environments (VEs) have enabled designers to more easily articulate and explore their imaginations. When VR achieves immersion, designers naturally gravitate towards three-dimensional interaction and work within their media (Rubio-Tamayo, Gertrudix and García, 2017). Consequently, in fields like industrial and environmental design, practitioners seek to leverage VR's three-dimensional attributes to enhance their understanding of spatial characteristics within VEs. Moreover, the advent of multiplayer VEs has facilitated remote collaboration among designers, transcending geographical barriers. In essence, VR-generated VEs have introduced a transformative platform to the design industry. Nevertheless, challenges persist in the application of VR within design contexts.

This paper introduces PhytualBlend, a real-time interaction system designed to enhance physical feedback for VR. PhytualBlend enables virtual content to be bound to corresponding physical entities. Employing embedded hardware arrays, PhytualBlend can accurately senses the position and orientation of physical entities and delivers physical feedback. Users' interactions with physical entities are instantly reflected in the VE, with the VE's interactive feedback enhancing sensory stimulation through the physical entities, thereby bridging the virtual and real worlds.. Leveraging IoT principles, PhytualBlend utilizes a distributed network to support simultaneous visit by users across different regions, making it suitable for multi-user collaborative VEs.

The primary objective of PhytualBlend is to address the sensory disparities between VR and the physical world by providing multi-sensory physical feedback. This affords users a comprehensive perception spanning the virtual and physical realms, allowing their attention to be immersed in the virtual while their bodies perceive changes in the physical world. Consequently, PhytualBlend endeavors to establish a physical-virtual-physical sensory loop to enrich the user's immersive VR experience with a broader range of sensory inputs.

Although IoT devices have established extensive application in the smart home sector, their integration within the VR and design domains remains nascent. This study contends that the fusion of IoT with VR is still in its exploratory phase. Hence, this paper represents one of the few endeavors to bridge the virtual and real worlds through embedded hardware. The research posits that PhytualBlend holds significant potential for advancement in areas such as VR education, exhibitions, and interaction design.

BACKGROUND

With its capacity for simulating and presenting immersive virtual environments, VR technology has showcased its potential applications across various sectors such as education, training, and gaming. Within the realm of design, VR has emerged as a widely embraced visualization tool. Panya et al. (2023) developed a collaborative BIM system, allowing users to experience architectural models within VEs and conveniently access and modify architectural data. The integration of VR and BIM facilitates designers in gaining immersive insights into spatial information regarding architectural models. Stouffs et al. (2013), in their investigation of over 200 papers on VR in design, noted a main focus on tool applications, visualization, and theoretical discussions. These studies leverage VR's visualization capabilities to expand spatial visualization beyond what traditional computer screens offer, albeit confining users' senses to the virtual realm. Consequently, users become mere observers rather than active participants in the VE.

Slater et al. (2010) employed multisensory interference to induce a body transference illusion, leading male subjects to perceive their bodies as being replaced by virtual female bodies. This underscores the pivotal role of bodily senses in VR immersion. Realistic and diverse sensory inputs foster participants' belief in the authenticity of the VE. However, VR's world-building is constrained by the systematic loss of sensory information from the physical world, prompting users to seek additional information from the physical world while engaging with the virtual one. Nevertheless, current VR technology lacks sufficient means to fully replicate sensory experiences in VEs, resulting in a disconnect between VE presentation and physical sensations, thereby contributing to a sense of unreality in certain scenarios.

To enhance the sensory immersion of the VR experience, researchers have developed wearable devices to augment users' physical feedback in VEs, encompassing touch, smell (Serrano, Baños, and Botella, 2016), heat (Lee, 2020), and more. Ke et al.

(2022) introduced PropelWalker, calf-worn haptic devices designed to simulate buoyancy and resistance when users' lower limbs interact with various fluids and materials in VR. User surveys have indicated significant improvements in users' sense of presence in VR. However, these devices necessitate users to carry wearable equipment, imposing constraints on mobility and popularity. Moreover, existing studies predominantly design with a user-centric approach. Essentially, users still only interact with the VE, and the existence of physical space is overlooked.

The new-developed AR technology enables the embedding of virtual content into physical environments, enabling users to interact in both physical and virtual realms. In design area, AR-assisted construction has made strides, exemplified by Blahut and Harnoncourt-Fuchs (2023)'s series of MR systems facilitating interactive representations in the assembly process of custom timber towers. These systems allow users to interact with virtual and real objects simultaneously, overcoming the sensory limitations of traditional VR. However, the virtual content primarily serves as a guide to physical objects, resulting in a singular interaction mode.

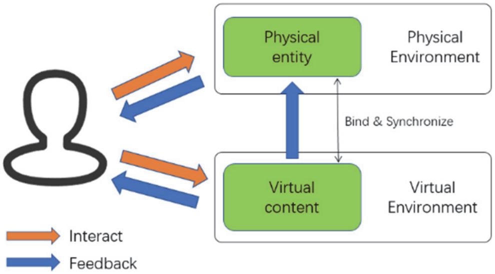

Figure 1
Interaction mechanism of PhytualBlend

Furthermore, physical feedback in most AR experiences remains limited, as current AR devices lack robust support for rich physical sensory experiences.

To address these limitations, this study aims to enable users to interact in both virtual and real spaces, whether through active engagement with physical entities or passive reception of physical feedback. Figure 1 shows the interaction mechanism of PhytualBlend. PhytualBlend revolves around physical entities, synchronizing users' actions on physical entities with virtual content, thereby facilitating interactions
observable in the VE and providing authentic physical feedback through physical entities.

Consequently, PhytualBlend offers several advantages:

- Sensory Enhancement: Users can interact with virtual and real objects simultaneously, receiving real-world physical sensory feedback while experiencing the audiovisual aspects of the VE.
- Spatial Interaction: The incorporation of physical entities bridges physical and virtual spaces, expanding the scope of spatial interaction and design possibilities.
- Richness: Depending on the scenario, physical entities can be mapped to diverse virtual content, with ample ability for the expansion of physical feedback variety if hardware capabilities permit.
- Modulization and Extensibility: PhytualBlend ensures the functional independency of system components, facilitating large-scale replication and deployment in collaborative systems. It offers high degrees of flexibility with configurable interactions tailored to diverse scenarios.

METHODOLOGY

The main thrust of PhytualBlend's design is to utilize embedded hardware to help expand the effects of the virtual and physical worlds on each other. According to the different human senses, these effects include form (sight), temperature (warmth), vibration (touch), sound (hearing), and so on. In order to realize simultaneous access in multiple places, PhytualBlend composes various hardware into a distributed IoT network. As shown in figure 2, PhytualBlend's framework consists of remote servers and several distributed local hardware networks.

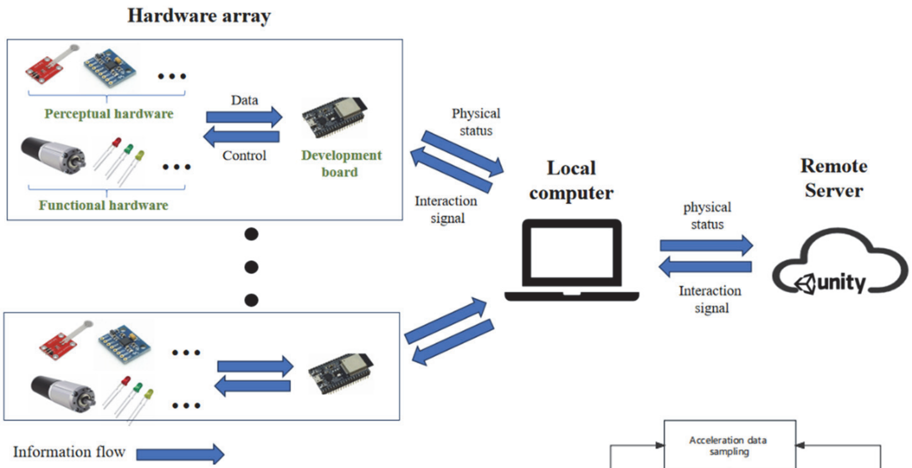

Figure 2
Overall structure

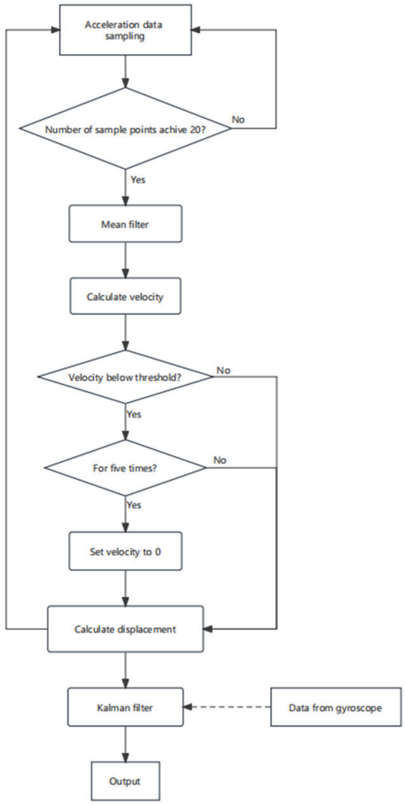

Figure 3
Flow chart of position sensing

The remote servers run the VE runtime, which is built upon the Unity engine. Users can access it through the Unity program as well as ported webGL pages. The local hardware network consists of a local server and several expandable hardware arrays. The hardware arrays are responsible for sensing the position of objects and performing physical feedback. The local server acts as a relay station for data transfer from the hardware arrays to the remote server and communicates interaction commands to the individual hardware.

Hardware array

A Hardware array include a development board, perceptual hardware, and executive hardware. They are the direct providers of physical functionality and installed in physical entities that need to perform interactions or in designated locations where spatial interactions need to be realized. The development board is the brain of the hardware array, which is responsible for receiving the information collected by the sensing hardware and controlling the behavior of the executing hardware. The ESP32 was chosen as the hardware platform and was developed using the Arduino language. Both of them have a well-developed ecology and good cost-effectiveness.

In order to fully bind the physical entity to the virtual content, PhytualBlend uses piezo resistors, touch screens, and Inertial Measurement Units (IMUs) as the perceptual hardware to get the user's interactive input to the system. The first two can receive touch input from the user. The IMU consists of an accelerometer and a gyroscope that senses the user's displacement and rotation to the physical entities. Figure 3 shows the flowchart of the perception algorithm. Dual integration is performed on acceleration $a = (a_x, a_y, a_z)$ to compute the positional information of the object

$$position(x, y, z) = \iint_t (a_x, a_y, a_z) \qquad (1)$$

Due to the high sampling rate of the sensors, the study used a mean filtering algorithm to reduce the sampling rate and avoid drastic fluctuations. A stationary detection algorithm was also used to eliminate the accumulation of systematic errors and Kalman filtering was used to increase the reliability of the data. Kalman filtering is a common signal processing algorithm that can be used to extrapolate more accurate predictions using multiple data.

The study configured a rich variety of executive hardware including motors, LEDs, heating pads and speakers to present different physical feedback functions. Some of them can be directly connected to the development board, while others need to be controlled with PWM waves. The executive hardware provides the basis for rich physical interaction and can be rationally matched according to the needs of different scenarios, which is highly flexible and expandable.

Local Server

The local server is the information hub that connects the hardware arrays to the remote server. It accepts the status information of the hardware array from the development board. After parsing the information, the local server will processes them and sends to the remote server.

This procedure includes translating the position information with coordinate system mapper (CSM) module. This is to ensure that the displacement and rotation directions of the physical entity and the virtual content are the same. Since the local coordinate system of the physical entity is determined by the mounting direction of the IMU, the CSM is scheduled to correspond the local coordinate system of the physical and virtual worlds by computing with rotation matrixes. Figure 4 shows the mathematical relationship between the local coordinate systems in the physical and virtual worlds.

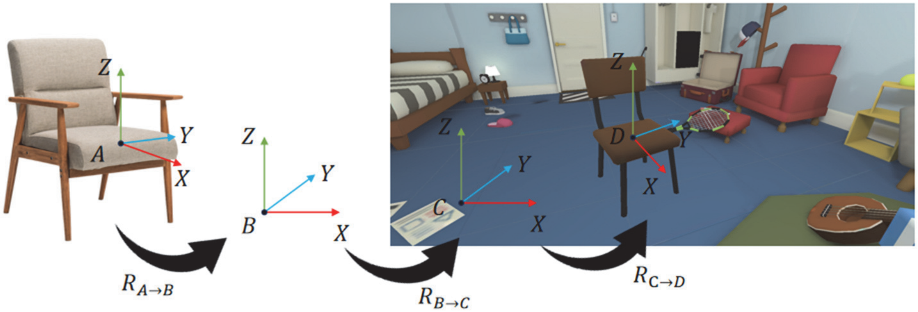

Figure 4
Rotation relationships

Assuming that the local coordinate system of the physical entity is $A \in \mathbb{R}^3$, the world coordinate system of the physical world is $B \in \mathbb{R}^3$, the world coordinate system of the virtual world is $C \in \mathbb{R}^3$ and the local coordinate system of the virtual content is $D \in \mathbb{R}^3$, then the correspondence between the coordinate system of the physical entity and the virtual content is

$$D = R_{A \to B} R_{B \to C} R_{C \to D} A \tag{2}$$

where $R_{A \to B} \in \mathbb{R}^3$ is a rotation matrix to rotate the coordinate system A to correspond the coordinate system B, and so on for the other symbols. In practice, for convenience, the world coordinate system of the physical world is often aligned to the world coordinate system of the virtual world, so the relationship becomes

$$D = CSM(A) = R_{A \to B} R_{C \to D} A \tag{3}$$

The CSM module stores the local coordinate system correspondences between physical and virtual objects.

Remote Server

Remote servers holds a Unity runtime that runs the VE. The user's actions in the real world will affect the VE through information transfer, and when these actions trigger the set interaction

patterns, the VE will send interaction information back to the local server. Finally, interactions in the VE can also respond to the user's real world as physical feedback. These interaction triggers were written in C# and combined with various physical features of Unity to make it work satisfactorily in the VE. Thus, the user exists and interacts in two realms at the same time - the physical world and the virtual world, which means that the user's body is in the real space manipulating physical objects and sensing the physical feedback provided by PhytualBlend, while the user's attention is in the VE experiencing the virtual content and receiving the visual feedback from the VE. This experience provides the user with a physical-virtual-physical sensory loop, which is conducive to enhancing the user's experience in multiple spaces.

Message transmission

Message transmission is a very important part of the PytualBlend system. Figure 5 shows the information recording and transfer mode the development board and various types of hardware to ensure prompt and reliable information transmission. The communication between the development board and the local server used UDP network for

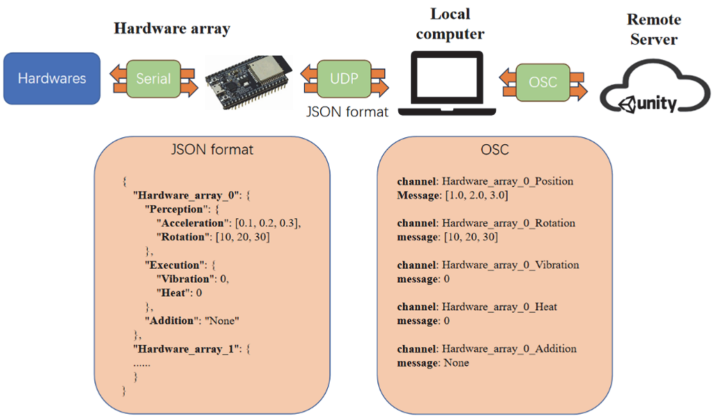

Figure 5
Data transmission mechanism of PhytualBlend

convenience and wire-free benefits. Due to the diversity of devices in the hardware array, the research adopted the JSON format to record the status information of the hardware and used the OSC protocol to interact with the remote server. JSON is a syntax for storing and exchanging textual information that topologically has tree structures. OSC is a communication protocol with a high degree of freedom to use customized rules to transfer the information over the network from one device to another. The advantages of JSON and OSC fit well with the rich variety and variable number of hardware arrays, and they have plenty of freedom to be upgraded and optimized.

Real-time performance, robustness and scalability were also a key focus of this study. The entire system can continuously serve for hours at a frame rate of no less than 60 FPS, with only occasional delays due to network fluctuations. The development is based on the principle of modularization to ensure that each component can operate independently without functional dependencies and coupling from upstream or downstream modules. Information from the physical and virtual worlds is also strictly, which facilitates the categorization of data for storage and statistics. Due to the distributed design, PhytualBlend can be easily expanded to any location and added to any possible hardware with minor changes. This is very conducive to field deployments based on project requirements, giving users possibilities beyond their imagination.

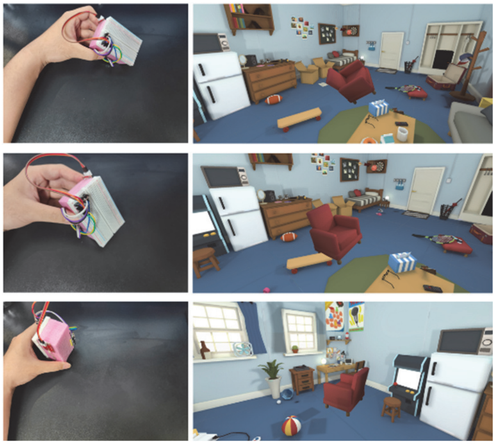

Figure 6a
Sofa rotated as rotating the physical entity

Figure 6b
Vibration occurred when sofa collided with something

Figure 6c
Heat triggered when sofa was placed in unproper area

PROTOTYPE TEST

In testing the prototype of the system, the research created a digital twin for a room in Unity. In this scenario, a physical entity was mapped to a sofa in the VE. Any movement of this physical entity by the participant caused the sofa model in the VE to move in the same way. The resulting interactions might trigger enhanced physical feedback on the physical entity.

The physical entity was fitted with an IMU and a pressure sensor as perceptual hardware to detect the position and orientation in real time and sense the user's pressing action in a specific area. In terms of executive hardware, a vibration motor and heating pads were used to provide tactile and thermal feedback.

In the experiment, participants were asked to arrange the room in the VE as they like. This can be achieved by moving the physical entity bound to the sofa model (Figure 6a). When the sofa in the VE collided with some specific models, the physical entities in their hands would vibrate to indicate that they could not be placed here (Figure 6b). In addition, the experiment set up interesting interactions in areas where sofa was not suitable for placement. When the sofa entered these areas, activated heating pads gave the participants thermal feedback (Figure 6c). PhytualBlend managed to work at no less than 60 FPS. The changes in the VE could be observed in real time, and the set physical feedbacks were triggered properly.

The participants consisted of 14 undergraduate and master's students in architecture and design, all of whom had some experience with VR and were familiar with utilizing Unity and other virtual spaces to express their ideas. Some participants had extensive experience of playing video games. Post-test feedback centered on surprise at the real-time physical feedback and curiosity about linking physical entities with virtual content.

The participants felt that PhytualBlend provided a more interesting solution than the traditional modification of 3D models on screen or in BIM. In questionnaires and online interviews, they reported that compared with interacting with virtual content, physical entities offered them a more reassuring tactile experience. The physical feedback delivered by PhytualBlend enabled them to perceive more distinctly the consequence of their actions within the VE. In general, multi-sensory physical feedback could actually heightened their sense of immersion. This likewise helped to get more inspiration for spatial design and spatial interaction.

We conducted time-delay and computing resources analysis according to the experiment. The results showed that the communication burden among hardware arrays, local server and remote server was typically small as the messages contained only strings. For the computational burden of VE, usual manipulations like translation, rotation, scaling and collision detection required minimal cost. Thus, PhytualBlend can theoretically support dozens of physical entities working simultaneously if network permits.

DISCUSSION

The PhytualBlend system is designed to enhance the sensory experience and provide realistic physical feedback to users in virtual environments (VE) by leveraging hardware and information technology. Following hours of prototype testing and demonstrations at workshops, the PhytualBlend system has effectively showcased its reliability and comprehensive sensory support. The study yielded the following findings:

Effective binding of physical entities and Virtual Content. The perceptual hardware accurately captures the position, orientation, and touch inputs of physical entities, synchronizing real-time responses with bound virtual content. This binding relationship is easily interchangeable and removable based on different scenarios.

Accurate and low-latency messaging. Each component maintains workstream through information transmission. A well-functioning system denotes the reliability of messaging. PhytualBlend is capable of work with a frame rate of 60 FPS or higher, meeting the requirements of most applications.

Enhanced interactivity and immersion. With enhanced physical feedback and emphasis on the physical space, users reported significantly improved interactivity when interacting with virtual content. The addition of multisensory elements further enhanced immersion in the VE, fostering a greater desire to explore and engage with the virtual environment.

Rapid expandability of the system. Expansion options include adding execution hardware for additional physical feedback, more hardware arrays in a local network (also means more physical entities), or deploying additional local hardware networks to support multi-user collaboration. These expansions facilitate PhytualBlend's adaptation to a variety of scenarios.

PhytualBlend's utilization of embedded device networks to enhance physical feedback in VR has yielded satisfactory results. However, when confronted with design scenarios requiring larger scale or higher accuracy, the current system falls short of meeting the demands. The study recognizes the need for further improvement in PhytualBlend's functionality and reliability.

The first improvement is improving data presentation for virtual content. Inspired by BIM, metadata for virtual content, a focal point for designers, plays a crucial role in the VR design process. PhytualBlend needs to incorporate user interfaces to display or modify the design data of critical content, such as geometry and color attributes, to meet the requirements of VR design.

Secondly, IMU-based position sensing exists systematic flaws. Due to intrinsic characteristics, IMUs meet decreased accuracy over hours of working and lack stability of acceleration. Refer to the comparison of solutions for indoor positioning by Oguntala et al. (2018), future plans involve leveraging a vision system to enhance the position perception of physical entities. Coupled with markers, this approach holds promise for achieving highly precise position tracking and real-time correction.

Thirdly, specialized network architectures are necessary for potential large-scale multiplayer collaboration scenarios. As the number of accessing devices escalates, network pressure and resource demands increase exponentially. Due et al. (2018) gave an excellent example of data synchronization mechanism in BIM systems. Local hardware networks need to be equipped with gateways to optimize the allocation of network resources. Moreover, retransmission mechanisms should be introduced to mitigate network congestion and prevent information loss.

Numerous studies have focused on enhancing VR immersion through hardware-based physical feedback. The most familiar ones can be vibrable game controllers when people playing VR games. These studies adopt a human-centered approach, where hardware follows the user's movements, primarily interacting with the VE from the perspective of the avatar. However, within the design realm, designers prioritize the objects or interactable environments within virtual spaces. Object-centered approach adopted in PhytualBlend seems more natural for designers. Furthermore, the low-cost, scalable and flexible executive hardware is the key to the promotion of PhytualBlend both in quantity and in customization.

The study concludes that VR technology in the design domain should not only serve as an outstanding visualization tool but also prioritize real-world experiences. The next phase of VR should serve as a bridge between reality and the virtual realm, providing users with a more comprehensive perspective encompassing both virtual and physical domains. Integrating physical and virtual interactions allows creations within the VE to resonate more profoundly with users' actual senses.

CONCLUSION

This article introduces PhytualBlend, an enhanced physical feedback system in VR built upon embedded devices. Aimed at addressing VR's neglect of physical senses, PhytualBlend offers users a more comprehensive perception of both virtual and physical worlds through multi-sensory physical feedback.

The core of PhytualBlend is a physical entity bound to virtual content. User interactions with this physical entity are detected by the embedded hardware installed inside, leading to real-time responses in the virtual environment and triggering multi-sensory physical feedback. To achieve this functionality, distributed structures, robust sensing algorithms and appropriate data transmission mechanisms have been devised. With its modular design and scalability, PhytualBlend can rapidly expand its quantity and variety of functions at a low cost.

Feedback from test participants indicates that compared to conventional methods, PhytualBlend's interactive approach is more engaging, and its multi-sensory physical feedback enhances their sense of immersion. PhytualBlend's emphasis on physical space facilitates their realization of spatial design and interaction.

This research represents an initial exploration into connecting the virtual and real worlds using IoT concepts. PhytualBlend will further develop in areas such as VR education, exhibitions, multi-user collaboration systems, and interactive design to advance the application of VR in the design field.

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