KnitworkVR: Dual-reality Experience through Distributed Sensor-Actuator Networks in the Living Knitwork Pavilion

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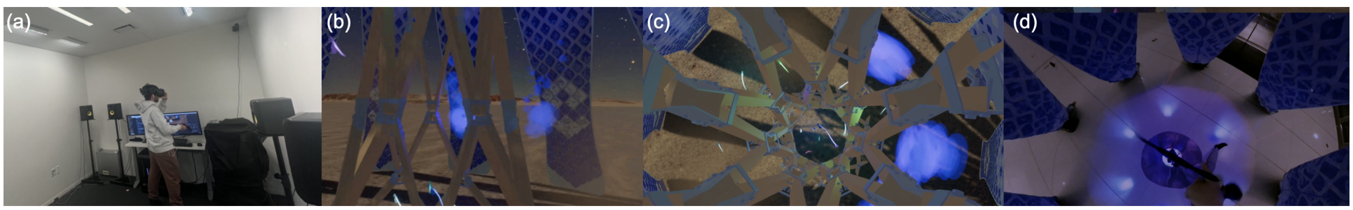

Figure 1: a) A user interacting in KnitworkVR and experiencing its rich b-c) immersive audiovisual landscape driven by d) interactive performance in real-time in the physical Living Knitwork Pavilion at another location.

Abstract

KnitworkVR integrates dual-reality and digital twin platforms to simulate the Living Knitwork Pavilion in a desert landscape, using real-time sensor data. The sensor network captures movements, interactions, and spatial positioning of occupants, linking electric field sensor data with VR positioning. This creates a sensor-driven immersive experience with dynamic lighting, live animations, and adaptive soundscapes, enabling telepresence and collaborative interaction in both digital and physical environments. This paper explores the functional textile design, sensing hardware, audiovisual system, and VR framework, highlighting the applications of immersive spaces with knitted electronic textiles and distributed physical-digital systems.

CCS Concepts

• **Human-centered computing** → **Interaction design**; • **Computing methodologies** → *Virtual reality*; • **Hardware** → Sensors and actuators.

Keywords

electronic textiles, distributed sensing, digital twin, virtual reality, immersive environments, telepresence, AI-generated music

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1 Introduction

Textiles have long been integral to cultural expression and social experience, playing key roles in rituals, gatherings, and dances. Serving as artistic canvas, body armors, and architectural skins, textiles protect and shelter while also acting as mediums for storytelling, immersion, and collective expression. Recent technological advancements have expanded the capabilities and our understanding of textiles, transforming them from passive materials into interactive and responsive substrates [Wicaksono et al. 2021]. By intrinsically embedding sensors within textile structures and integrating computational elements, these smart fabrics can now sense and respond to environmental stimuli and human presence, facilitating seamless integration of imperceptible technologies for physical-digital experiences.

KnitworkVR is an extended digital twin version of the Living Knitwork Pavilion, an architectural interactive textile structure installed in the desert environment of Black Rock City, Nevada [Wicaksono et al. 2024]. The Pavilion was built for Burning Man, a weeklong large-scale event focused on community, art, and expression. After its installation in Black Rock City, we installed it in a building lobby for a longer period of time. The installation offers audiences the opportunity to witness the intricacy of the textile as well as the immersive experience provided by the spatial audiovisual systems, while the virtual reality correspondence offers an immersion into the Living Knitwork Pavilion's original state in the Black Rock Desert landscape.

Since the design is modular, in the lobby installation, we installed eight of the textile panels (total textile area of 44 m², with active radius of 3 m and sensing area of around 28 m²) instead of the original 12 panels (66 m²) due to space constraints. Finally, we have also developed a dual reality pipeline and environment where the sensors, audio, and visual experience of the Living Knitwork Pavilion in the physical reality interacts in real-time with the position trackers of the user, as well as the audio and animation of the virtual representation of the Living Knitwork Pavilion in Knitwork VR (Figure 1). We aim to demonstrate how contemporary technologies and materials, inspired by cultural wisdom and heritage, can enhance our experiences, deepen our connections with one another, and enrich our immersion in built environments.

1.1 Electronic Textiles and Interactive Space

Electronic textiles (e-textiles) have paved the way for innovative human-computer interaction and musical expression, exemplified by early projects like the Musical Jacket [Marrin and Picard 1998], MiMu Glove [May and Larsson 2021], and FabricKeyboard [Wicaksono and Paradiso 2017]. With advancements in fiber and yarn functionalities, digital knitting now enables the integration of sensing and computation within fabrics [Luo et al. 2021]. Researchers have developed knitted fabrics with functional yarns capable of tactile sensing and musical feedback from wearable to room-scale installations [Wicaksono et al. 2022; Wicaksono and Paradiso 2020].

Projects like Sensory Playscape [Ahlquist 2016] and Ada [Sabin et al. 2020] delve into the tactile and material properties of knitted textiles and tensile structures, incorporating external systems that respond to human interaction, creating immersive, multi-sensory environments. This work introduces a large-scale e-textile comprising seamlessly-knitted conductive textiles. The Pavilion provides a cohesive, immersive experience that engages the senses of movement, sight, sound, and touch.

1.2 Immersive Experience within the Built Environment

Interactive performances have leveraged various technologies to continuously map motion. Notable early examples include Ballets Russes by Diaghilev and Stravinsky in 1917, and The Odyssey of Variations V by Cage, Cunningham, and collaborators in 1965 [Spieth et al. 2022]. In these performances, dancers played an active role in shaping both the auditory and visual components through sensor-mediated environments. More recently, networked performances like The Mocap Streamer system have showcased how avatars of dancers, equipped with inertial sensor, can interact with each other and collaboratively dance in two distant areas [Strutt 2022].

With the advancement of audio, gesture sensing, and projection technologies, large-scale digital architectural installations have become prominent. Works by artists such as Refik Anadol and TeamLab exemplify this trend, exploring the intersection of immersive technology and art [Özdamar 2023]. These installations push the boundaries of perception, creating a seamless blend between the physical and virtual worlds. Projects like DoppelMarsh and DoppelLab feature virtual environments generated from extensive sensor networks within buildings or environments [Haddad et al. 2017]. The rich information captured by these systems allows designers, musicians, and visual artists to animate sensor data in virtual environments through direct, artistic, or metaphorical mappings. Motivated by the concept of Dual Reality—where real and virtual worlds are distinct yet enhanced by their ability to reflect, influence, and merge via embedded sensor/actuator networks— both KnitworkVR and the Living Knitwork Pavilion transform real-time sensor data streams from each other into shared spatial and immersive audiovisual experiences through animations and interactive systems [Lifton and Paradiso 2010].

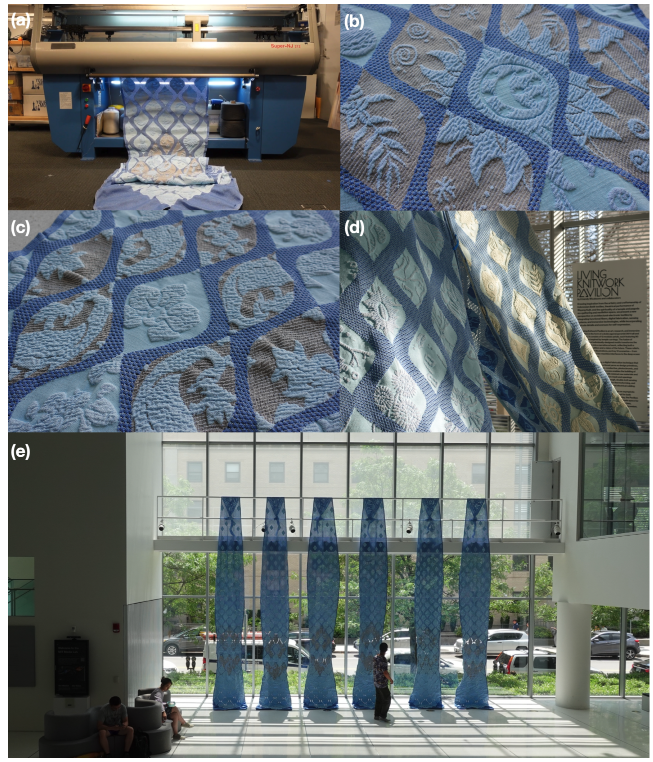

Figure 2: a) Digital knitting process of the Knitwork panels (each panel requires 12 hours of constant knitting). b-d) Detailed tactile, intricate popped-up patterns of the Living Knitwork petals with silver showing where the antennas are.e) Knitwork petals as tapestries, with each panel measuring 1 x 7.2m and weighing 5.5 kg.

2 The Living Knitwork Pavilion

Our structural design is driven by several constraints, primarily the need for the structure to function as a shade with distributed textile sensor networks. A conical shape is deemed most suitable as it allows the central meeting point at the top of the Pavilion connecting all integrated sensors within each textile panel to the main processor, as well as spatial audio and robotic lighting system. Additionally, the stainless steel ornament at the center functions as a field transmitter (Figure 3).

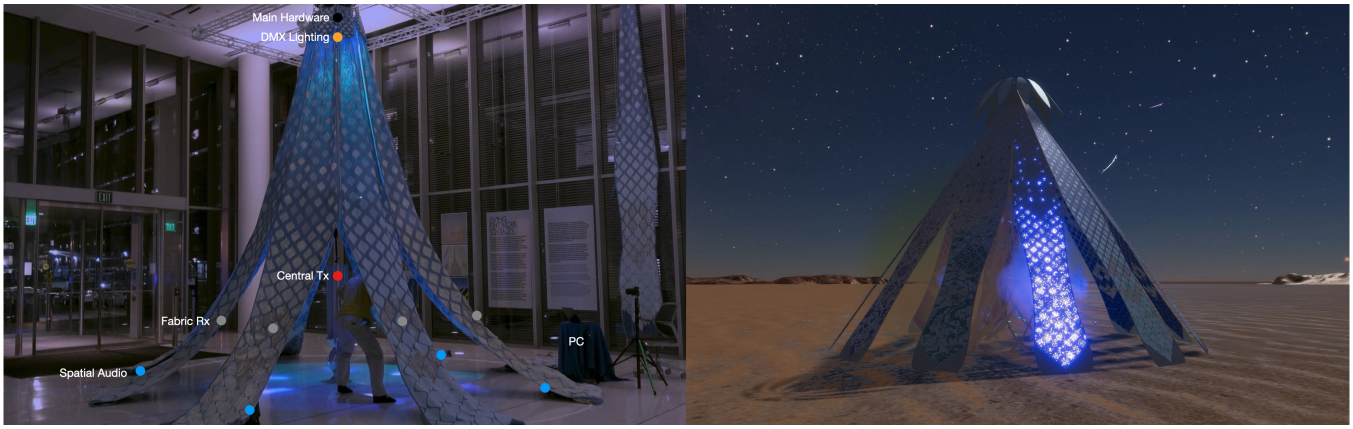

Figure 3: The Living Knitwork Pavilion integrated system (left) with its KnitworkVR, a digital twin companion and a dual-reality platform or virtual environment driven by real-time sensor data (right).

2.1 Textile Design and Fabrication

The Living Knitwork panel features 90 textile reliefs parametrically distributed across its surface (Figure 2). Inspired by Indonesian textile arts and the intricate carvings of Balinese and Javanese temples, the Living Knitwork hand-designed narrative embodies the spiritual and cultural richness of these traditions with our hopeful vision of the future. We set to weave contemporary and traditional motifs in a Knitwork petal narrative ranging from bio-machine symbiosis, solarpunk cities, to deep ocean and space exploration.

We used a flat, two-bed digital knitting machine (Super-NJ 212, Matsuya) to knit silver conductive yarns (3x 210D/Denier, Weiwei Line Industry). Each panel has two embedded antennas, with each being able to serve as transmitter or receiver electrode (Figure 4a).

2.2 Hardware System and E-field Sensing

As illustrated in Figure 4b-c, the transmitter circuit consists of a microcontroller that outputs a square wave with a half duty cycle from its digital pin with pulse-width modulation, driving a resonant LC oscillator. When the square wave's frequency matches the oscillator's resonant frequency, the output connected to the knitted transmitter (Tx) is a high-amplitude alternating wave (180 kHz, 100V). The receiver (Rx) circuit comprises two main stages: the first stage is a transimpedance amplifier that converts current coupled with the transmitter into voltage with a gain, and the second stage is an integrated active narrow band-pass filter, envelope detector, and limiter. The microcontroller (Teensy) scans through each ADC channel and converts the sensor data into MIDI signals for wireless data transfer to KnitworkVR and real-time audio and lighting controls.

By monitoring variations and distribution of the e-field, the system enables the detection of body movements and locations. Furthermore, when the human body intrudes into an existing electric field, it distorts the field, much like how the proximity of a musician's hands disrupts the electromagnetic fields around a theremin's antennas (Figure 4d). Figure 5 shows the sensor data and visualization of the e-field body sensing. In the transmit mode, the human body is becoming an extension of the transmitter electrodes (Figure 5a). Conversely, in the receive mode, the system detects changes in the electric field induced by the human body interacting with the receiver electrodes. In the shunt and loading modes, our activities either disrupt or boost displacement current, thereby impacting sensor values based on our grounding (Figure 5b-c).

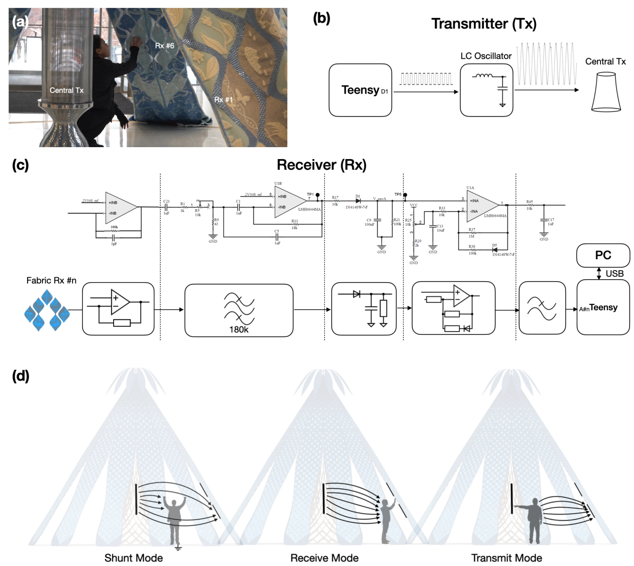

Figure 4: a) Central transmitter and fabric receiver electrodes location. b-c) Transmitter and receiver hardware system (with 8 receiver systems involved in this installation). d) The Tx and Rx antennas can detect audience inside the Pavilion as they walk (shunt), touch the transmitter, or touch the fabric electrodes.

We found that a 2 to 3 meter distance between Tx and Rx can sensitively detect various activities and act in both shunt and transmit modes. Beyond 3 meters, sensing shifts predominantly into transmit mode, as the coupling weakens with increased distance. However, we can improve sensitivity by tuning the gain in the

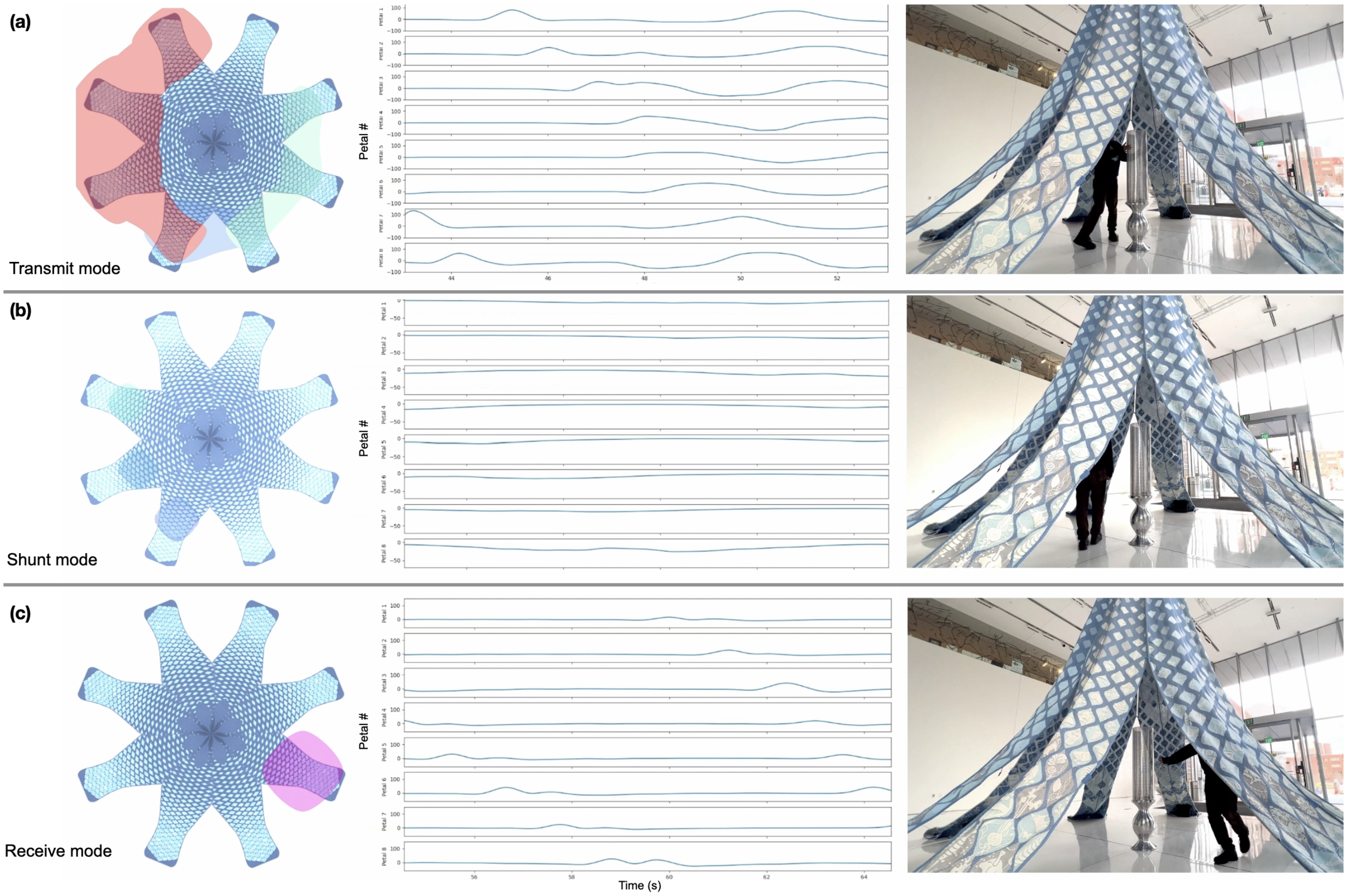

Figure 5: Sensor data and visualization as an occupant: a) touching the transmitter, amplifying its signal to neighboring electrodes and shunting/reducing the opposite, b) walking around, and c) waving and extending their hands without touching inside the Living Knitwork Pavilion.

circuits or amplifying the transmitter signals. These sensing mechanism allows proxemic applications ranging from detecting body position, collaborative interaction or activity, to even finer arm and hand movements. In our knowledge, The Pavilion is the largest architectural e-textile installation with similar principles like the Theremin or Terpsitone, extending the typical scale of such instrument's sensitivity from our fingers to our collective bodies [Latham 2021].

3 Integrated Audiovisual System

3.1 Audio Synthesis and Mapping

As shown in Figure 3 and 6, we have designed an immersive audio experience using a 4-channel distributed speaker system, and make use of state-of-the-art generative AI music models to allow users to engage in a full AI-generated 360-degree auditory environment both in the physical and virtual Pavilion (Figure 7 and 8). By using Max/MSP to interpret the live output of the sensors and through custom-designed interaction modalities and localization techniques, we enable users to explore the different sonic narratives of the installation. The overall system enables real-time audio synthesis and creates a immersive spatial auditory environment. The patch consists of several key modules:

3.1.1 AI-generated Music. We used the Transformer-based generative music system MusicGen [Copet et al. 2023] to generate eight musical loops–one for each panel–that were inspired by the themes and patterns of the Living Knitwork Pavilion, explained in in Section 2.1. The text conditioning modality of the model, together with additional curation, allowed us to generate eight 1-minute-long loops, all in the same key and tempo, creating a harmonious and coherent mix during the experience. Prompts for MusicGen inputs were tailored to the specific themes of each panel, using keywords such as "blackhole," "galaxy," "the stars," and "space-time" for the Space-theme panel, "heart pumping," "brain signals," and "dendrites" for Neuro-theme, and "mythical creatures" and "spirits" for the Mystical-theme. The additional curation process involved fine-tuning the generated music to ensure it not only matched the visual aesthetics but also evoked the desired atmosphere.

3.1.2 Spatialization and Interactivity. We integrated various modalities of interaction and spatialization methodologies inside a Max/MSP

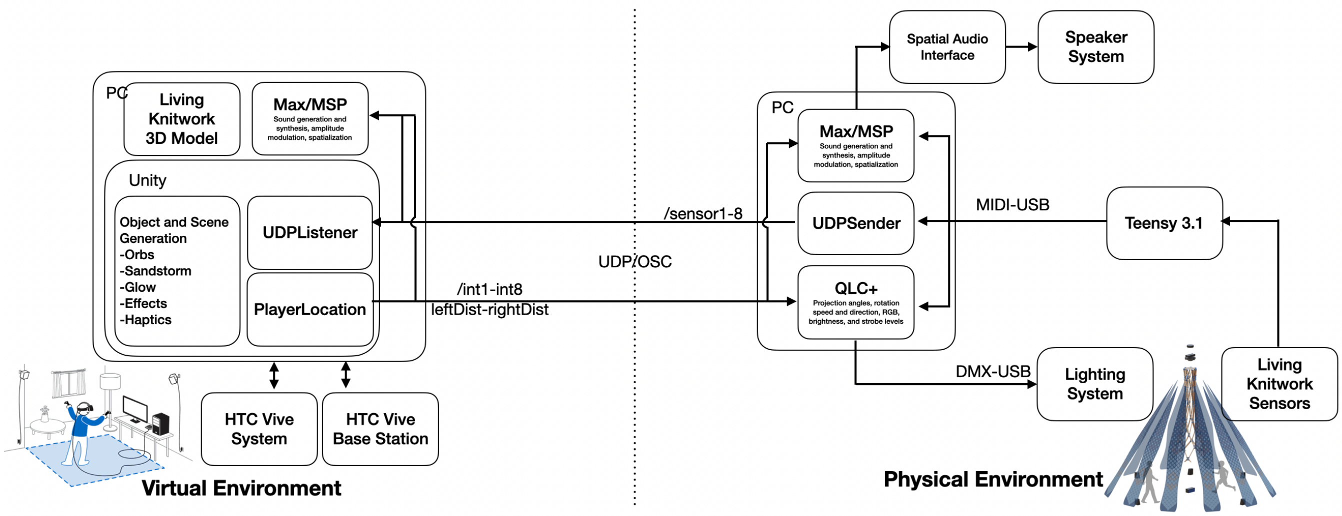

Figure 6: Dual-reality system framework. Diagram of the integrated system and data transfer protocol within individual and between KnitworkVR and the Living Knitwork Pavilion for co and telepresence.

patch to create a fully immersive experience with or without KnitworkVR. Notably, we enabled users in the physical and virtual Pavilion to both directly interact with each individual panel and explore the soundscapes created by the unison of multiple. Through the collection of 8/16 distinct sensor values, we can precisely locate the users within the structure and modulate the sound characteristic and volume of each loop accordingly to let them perceive the musical narrative associated with each panel. Additionally, using an ambisonic spatialization module, we distribute each musical component according to the physical location of each panel, creating a rich immersive experience in which the user can orchestrate the distribution of each musical element (Figure 7d-e). By sensing the user's touch on individual panels, we can select specific musical loops and let them surround the entire sonic space to let users explore specific details at their own pace (Figure 7a).

3.2 Lighting System and Mapping

The PC connected to the Teensy interfaces with a rotating head light module (Figure 11a, YRZJ DMX Stage Light, Yuer Inc.) through a MIDI-DMX universal data transfer protocol mediated by QLC+ software. The rotating head light module consists of six individually motorized 30W RGB beam lights and a single motor controlling six 10W RGB beam lights. The module has 42 DMX channels that can control various parameters (Figure 6) such as the movement of each of the six motorized lights, RGB levels, brightness levels, strobe levels, and rotation speed and direction.

3.2.1 Mapping and Interactivity. MIDI sensor data corresponding to movements on each petal can be individually or spatially mapped to control the nearest motorized beam lights in real-time (Figure 7b-c). This allows occupants to control the movement and intensity of the lights as they walk (green), dance (blue), and interact (movement of the light) within the space and each fabric panel of the Living Knitwork Pavilion (Figure 7d). The aggregate sensor data corresponding to crowd and activity levels can also be represented by adjusting the total brightness and rotation speed, creating a collective immersive experience.

The QLC+ also accepts OSC data representative of the user location (int1/8) and hand extension (left/rightDist) in the VR environment. By connecting these values to the individual color of the RGB beam lights (physical/virtual location), as well as its strobe level (hand extension) we can demonstrate visual experience of dual reality co-presence by merging the blue (physical) with red light (virtual), as shown in the Figure 7e.

4 VR System and Experience

4.1 Sensor and Location Data Processing

Sensor data in KnitworkVR is received via OSC/UDP to the Unity environment connected to HTC Vive and SteamVR system with base trackers (Figure 6). Within Unity, a Listener GameObject receives this data, facilitating real-time updates and interactions within the virtual environment (Figure 8). The PlayerLocation script calculates the spatial position and orientation of a player's head in radial distance and angular orientation, as well as hand extension in the VR environment, transmitting this data via UDP. This fast, connectionless data transmission method ensures real-time updates crucial for immersive VR experiences.

4.2 Interaction, Animation, and Soundscape

The Unity environment reacts to sensor data from the physical Pavilion through various visual and interactive elements. Additionally, we have incorporated haptic feedback action through our SteamVR plugin as the user hand reaches physical objects (i.e. fabric and structure) in the virtual environment (Figure 8b).

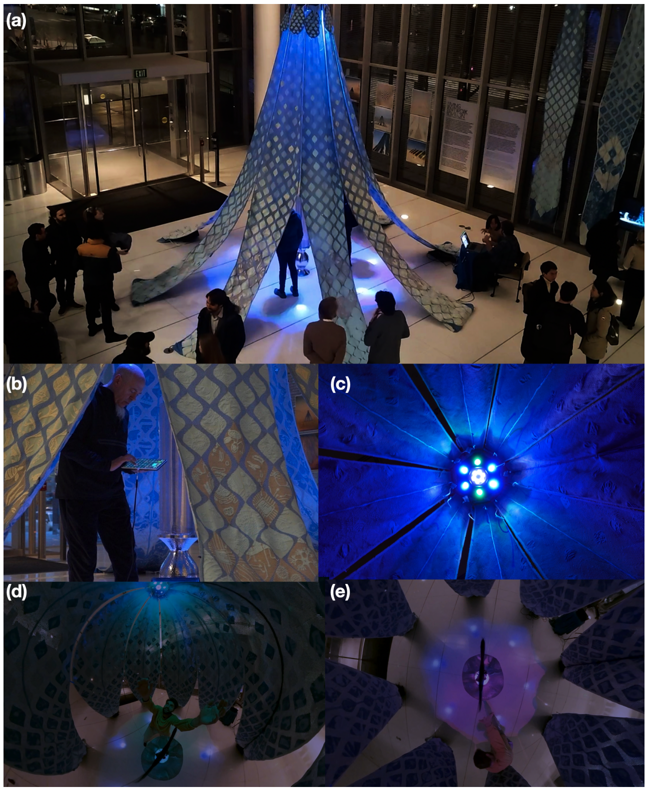

Figure 7: a) Public exhibition of the Living Knitwork showing people interacting with the immersive space. b) Keyboardist Jordan Rudess playing GeoShred inside the Living Knitwork Pavilion combining direct mapping from finger-strokes with the soundscape generated by his movement and location within the space. c-d) Dancer Treyden Chiavaralotti interacting with DMX lighting and spatial audio system. e) The copresence of users in both KnitworkVR and physical Pavilion trigerring color projections from the RGB LED.

Our object and scene generation involves creating various animations with properties inputted from the sensor data. Orbs/Fireballs, handled by the Fireball script, vary in intensity and behavior depending on interaction levels, using a 5x5 matrix to adjust properties like size and lifespan (Figure 8c). The GlowObserver script controls the virtual fabric's glowing patterns, adjusting the intensity based on the player's proximity and touch interactions, using the MeshRenderer's MaterialPropertyBlock to modify the EmissiveColor property (Figure 8d). Fireflies, managed by the Fireflies script, represent the crowd density in the Pavilion, emitting particles based on the number of panels interacted with (Figure 8c-d). Sandstorms, controlled by the Sand script, emit particles when users interact with corresponding panels or when the VR player approaches, enhancing immersion by dynamically adjusting the ParticleSystem's emission rate (Figure 8e).

At the same time, Max/MSP system is run in the machine where both the OSC data from the player location in VR and the distributed sensors from the physical Pavilion create a sonic landscape driven by both performers. The VR component directly maps into the mellow version of the aforementioned eight AI-generated musical loops.

5 Reflection and Conclusion

Living Knitwork Pavilion offered a unique opportunity to explore the interplay between interactive textiles, dual-reality immersive technologies, and social engagement in both physical-digital architectural space. Due to the Pavilion's high sensitivity in detecting subtle gestures, the users experience surprising and delightful interactions. For example, actions such as hand claps, body touches, or hugging create significant signal changes that are reflected in the audiovisual feedback, enhancing the collective experience and intimacy inside the Pavilion.

Throughout its installation, the Pavilion hosted a variety of events, including an opening, public demonstrations (Figure 7a), collaborative human-architecture live performance with experimental keyboardist Jordan Rudess (Figure 7b), and interactive dance with contemporary dancer Treyden Chiavaralotti (Figure 7d-e). These activities highlighted the pavilion's versatility and ability to facilitate various intimate performances and immersive experiences.

Future work will focus on expanding both the physical and digital dimensions of the installation, allowing for more in-depth exploration of occupant experiences and interactions with the Pavilion. Enhancements in lighting design, dynamic animations, and spatial audio mapping will create more immersive environments, while multi-user functionality in KnitworkVR will enable co/telepresence and collaborative interactions. These developments aim to push the boundaries of sensorial architecture, blending art and technology to craft spaces that respond intelligently to human presence and movement.

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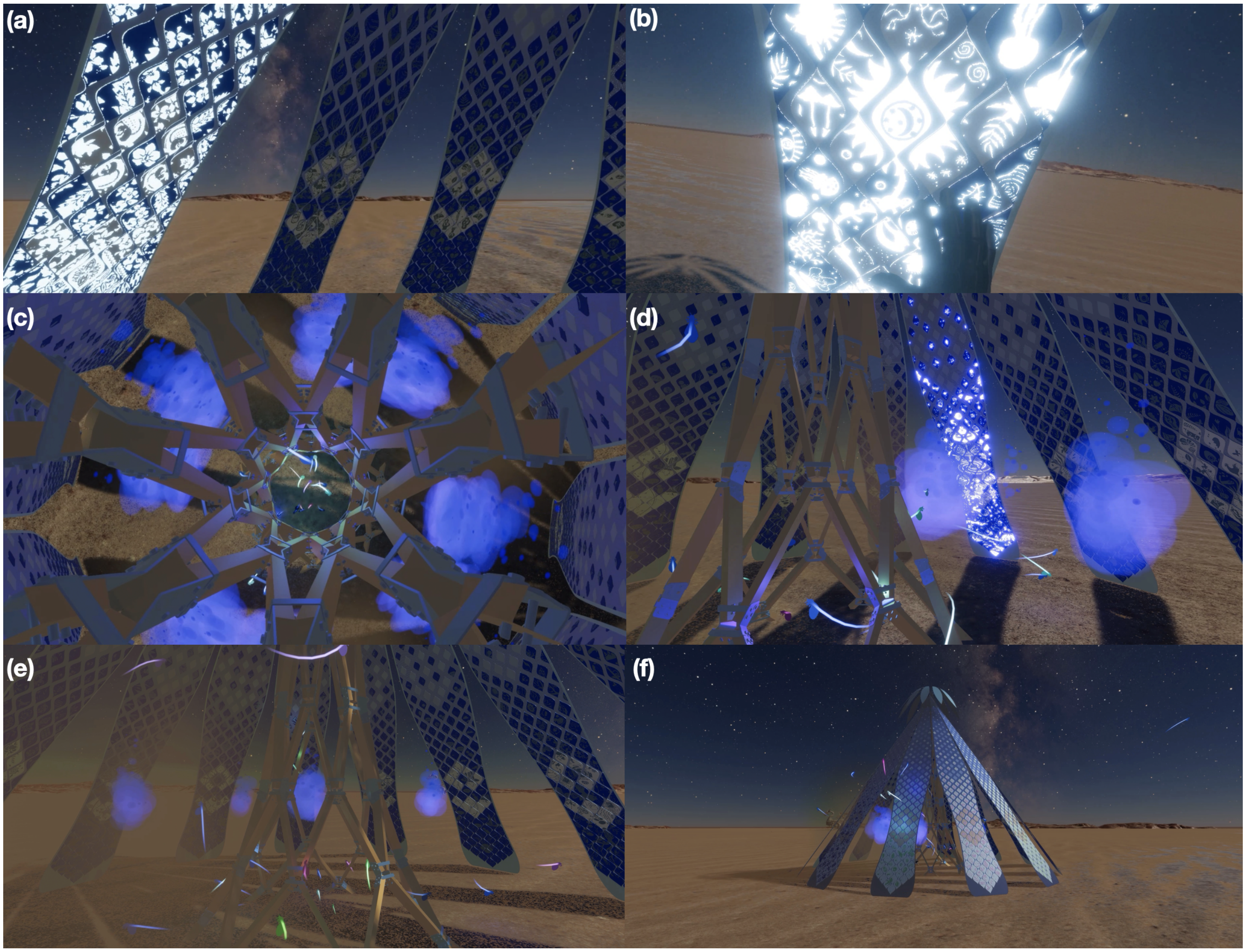

Figure 8: Virtual reality interaction and experience within the KnitworkVR: a) white-glow on the fabric patterns as a user walking toward it, b) haptic sensation as the hand-tracker collides with the digital fabric, c-e) orbs/fireballs representing presence of users in the physical Pavilion, with behavior and intensity of fireflies and sandstorm driven by the aggregate sensor data or collective movements, and bright blue-glow on the fabric patterns as users in the physical Pavilion touch the corresponding fabric. f) View of the Living Knitwork Pavilion from the outside.

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