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The Entanglement: Volumetric Music Performances in a Virtual Metaverse Environment

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The Entanglement: Volumetric Music Performances in a Virtual Metaverse Environment

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Abstract

Telematic music performances are an established performance practice in contemporary music. Performing music pieces with geographically distributed musicians is both a technological challenge and an artistic one. These challenges and the resulting possibilities can lead to innovative aesthetic realizations. This paper presents the implementation and realization of "The Entanglement," a telematic concert performance in a metaverse environment. The system is realized using web-based frameworks to implement a platform-independent online multi-user environment with volumetric, three-dimensional, streaming of audio and video. This allows live performance of this improvisation piece based on an algorithmic quantum computer composition within a freely explorational virtual environment. We describe the development and realization of the piece and metaverse environment, as well as its artistic and conceptual contextualization.

Introduction

In this paper, we present "The Entanglement,"[3] a telematic improvisation piece based on a quantum computer algorithmic composition.[4] Telematic music is a performance practice that has been widely researched and put into practice with numerous concert performances.[5] The crucial similarity here is the geographically distributed musicians who are connected via network technologies. An important aspect thereby is the final form of the presentation. Conventional telematic concert performances exist with different combinations of on-site and streamed elements and their representation using projections and loudspeaker reproduction. But another form of presentation that gained popularity in recent years is completely virtual performances. The decisive factor was not only the lack of

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[3] Damian T. Dziwis, "The Entanglement," 2022, https://www.youtube.com/watch?v=yKGc8dYJSLs.
[4] A recorded performance of "The Entanglement" may be viewed on the article home page under "Additional Files."
[5] Pauline Oliveros, Sarah Weaver, Mark Dresser, Jefferson Pitcher, Jonas Braasch, and Chris Chafe, "Telematic Music: Six Perspectives," *Leonardo Music Journal* 19 (2009): 95–96, https://doi.org/10.1162/lmj.2009.19.95.

alternatives during the global COVID-19 pandemic, but also technological progress, especially around streaming possibilities, which increased interest in this type of telematic performance.

We have seen a rise in the use of videoconferencing platforms, which offer neither specific possibilities nor optimization for music-making, as well as the streaming of live sessions through video streaming platforms, using special transmission systems optimized for online collaborative music-making.[6] Their similarity is thereby the two-dimensional representation using stereo sound and monoscopic pixel-based video streams. An enhancement, especially regarding a more immersive presentation, is offered by social, persistent, networked, virtual, multi-user environments, known as metaverse environments.[7] There have been several approaches to metaverse performances, from using multiplayer games to virtual social-network platforms. Here, too, the form of presentation varies from embedded video streams[8] to motion-tracked avatars[9] or pre-produced volumetric recordings.[10] Depending on the platform used, the 3D world experience is screen-based or in virtual reality (VR). However, this does not necessarily involve a live performance with additional immersive features such as a six-degree-of-freedom (6-DoF) environment with 3D actors and spatial audio or the possibility of geographically distributed music performers.

This paper presents the implementation of such a multi-user metaverse environment for telematic concert performances. It uses low-latency, WebRTC-based peer-to-peer (P2P) live-streaming of audio and video for audiovisual, volumetric and spatial rendering. The system is realized using web-based frameworks to implement a platform-independent online multi-user environment compatible with the WebXR standard. The performers' and audience's audio can be streamed into the environment and rendered binaurally. In addition, the performers' depth image is streamed from 3D cameras and rendered in the environment as a three-dimensional point cloud. The result is a real-time 6-DoF volumetric performance in a virtual 3D world that provides an immersive telematic concert experience. It can be experienced with WebXR-compatible devices, whether screen-based on the computer, mobile, or on VR and AR systems. The implemented system was developed and evaluated with the virtual performance "The Entanglement", with two geographically distributed violin players improvising in a custom-designed 3D world to an algorithmic composition running on a quantum computer. This realization for the artistic-research residency at the Institute for Computer Music and Sound Technology (Zurich University of the Arts), included a virtual 3D environment accessible from everywhere online, and a simultaneous version for a local audience in a performance hall.

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[6] E.g. Henrick von Coler, "Discount," virtual performance, New York City Electroacoustic Music Festival (2021), accessed January 05, 2023, https://drive.google.com/file/d/1uY2xWGtExIcxS4dxuX949OADua2fE5mC/view.

[7] Stylianos Mystakidis, "Metaverse," *Encyclopedia* 2, no. 1 (2022): 486–97, https://doi.org/10.3390/encyclopedia2010031.

[8] E.g. Toplap Berlin, "Toplap Berlin Mozilla Hubs," Mozilla Hubs concert space, accessed December 02, 2022, https://hubs.mozilla.com/oUQRigk/toplap-berlin/.

[9] E.g. VRROOM, "Jean Michel Jarre - ZERO GRAVITY - IN VR - Welcome to the Other Side," recording of virtual live concert in VRChat, May 9, 2021, https://vimeo.com/547145530.

[10] E.g. VRROOM, "Oxymore 2 - Overview," virtual album release live event, accessed December 02, 2022, https://vimeo.com/767098450/6fcf797c5a.

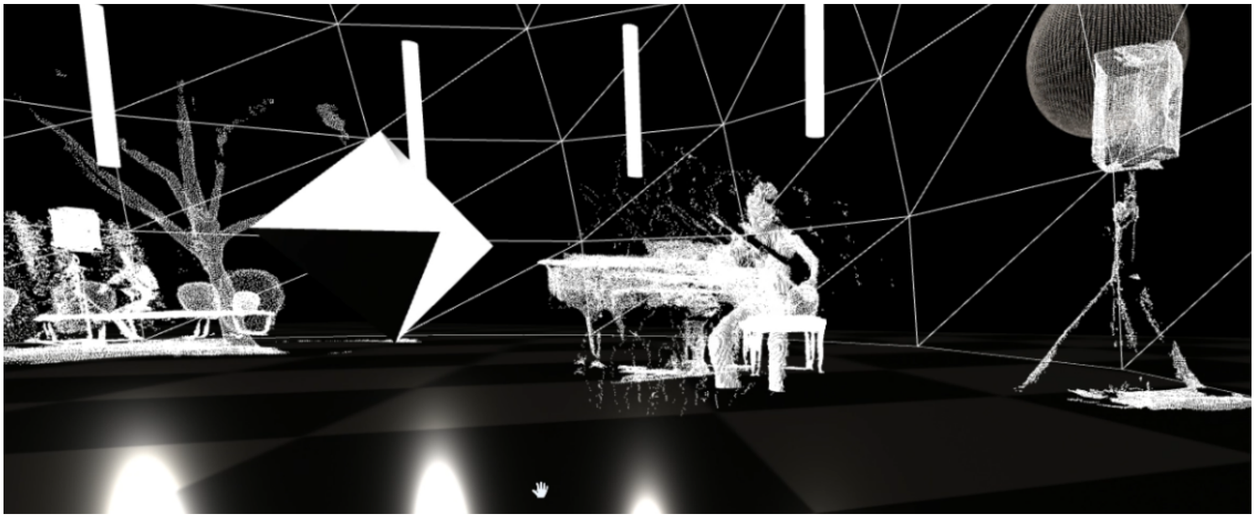

Figure 1: A screen-capture from the metaverse environment of "The Entanglement." The image shows a violinist rendered as 3D point clouds, together in the virtual environment with mixed virtual objects.

In the following, we describe the technological development and realization of the metaverse environment and quantum computer composition with all included technologies. Furthermore, we show the artistic and conceptual ideas and their contextualization resulting in this piece.

Motivation

The improvisation in "The Entanglement" is derived from an algorithmic composition running on an actual quantum computer. The algorithm is an implementation of the so-called Bell test,[11] an experiment to prove particle entanglement beyond the limits of the concept of local realism. This entanglement, one of the most important principles of quantum mechanics, has been observed in several experiments, leaving only a few theoretical loopholes that would invalidate the results. One of them is the "freedom of choice/free will" loophole,[12] which refers to the concept of superdeterminism and assumes that all our thoughts and actions, including the execution and parameterization of the Bell test, are already determined in the origin of the universe. So, this could mean it only appears to us as if we could observe quantum entanglement.

This idea alone is quite perplexing, but it raises an important question in the context of improvisation: if there is no free will, there is no improvisation. If there is free will, there could be no local realism, and improvisation would exist only in a quantum mechanical reality. Derived from this concept of quantum entanglement, the idea was to realize this as a telematic performance in which the

[11] Alain Aspect, Philippe Grangier, and Gérard Roger, "Experimental Tests of Realistic Local Theories via Bell's Theorem," *Physical Review Letters* 47, no. 7 (1981): 460–63, https://doi.org/10.1103/PhysRevLett.47.460.

[12] Jan Ake Larsson, "Loopholes in Bell Inequality Tests of Local Realism," *Journal of Physics A: Mathematical and Theoretical* 47, no. 42 (2014): https://doi.org/10.1088/1751-8113/47/42/424003.

two performers are spatially separated, like the particles in the Bell test. They should then encounter each other in an artificial environment, a space that is beyond the possibilities of classical physics, but still immersive and experiential.

Therefore, we developed the performance as a live concert in a metaverse environment. The objective was to create volumetric live streaming of 3D audio and video, with the video rendered as point clouds resonating with the conceptual idea of particles (Figure 1). The virtual environment was intended to provide an interactive, immersive concert experience, with opportunities for social interaction. The focus was not only on transferring the conventional concert experience into virtual reality, but on creating new possibilities that can only be realized in virtuality. This is particularly expressed in the design of the virtual world and the presentation of the musicians' audio and video. The freedoms in the virtual space invite the recipients to move freely in the environment and thus create their individual audio mix and experience the performance from different perspectives, with different impressions.

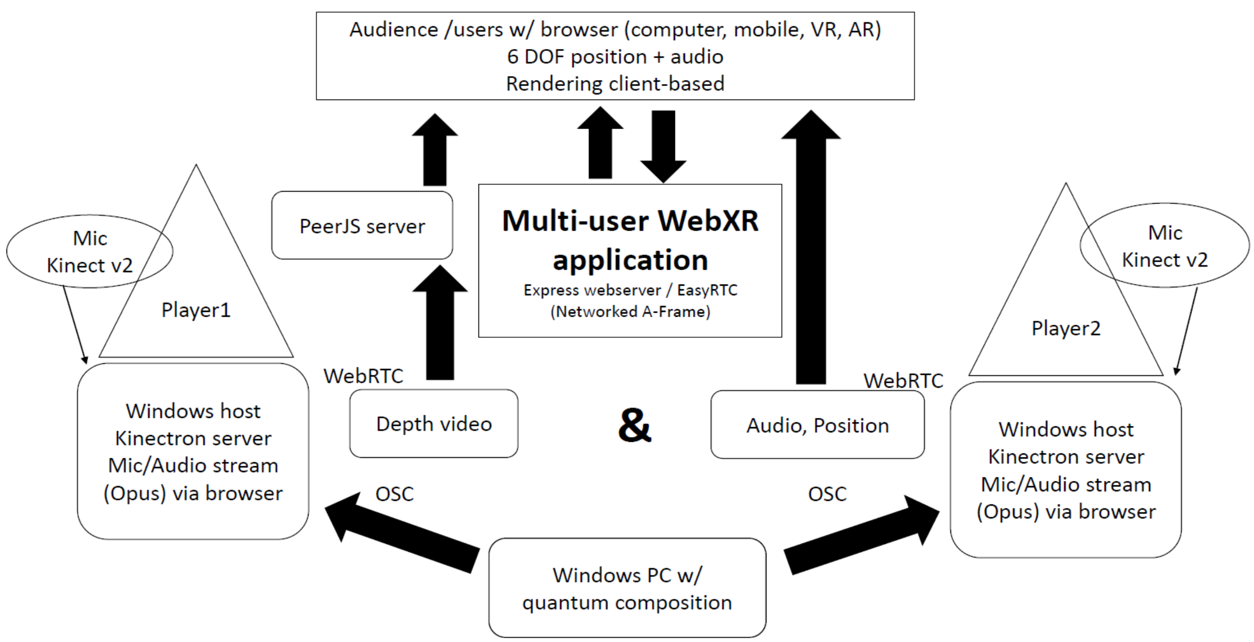

Figure 2: A diagram of the involved technologies in "The Entanglement." Showing the different hardware devices, programming frameworks, servers, programming interfaces, and communication protocols between the different actors (musicians and audience).

Implementation

As shown in Figure 2, "The Entanglement" has been realized using a variety of technologies. These include various hardware devices such as computer systems, 3D cameras, microphones and other audio devices. Several programming frameworks were used to realize the web-based metaverse environment and the algorithmic quantum computer composition. For broadcasting, communication protocols were implemented to exchange video and audio streams, the position of users in the environment and the results of the quantum algorithm. In the following, we describe the development and the use of the implemented technologies in more detail.

Metaverse Environment

For "The Entanglement," the JavaScript framework A-Frame[13] was used to create a web-based multiuser metaverse environment. By abstracting the Three.js JavaScript library into an HTML-like syntax, A-Frame enables easy programming of WebGL applications. The embedding of the WebXR application programming interface (API) makes it compatible with virtual and augmented reality (VR/AR) devices. Through a web browser, the resulting web applications can be used with common VR/AR systems as well as conventional PC and mobile devices. In this way, the largest possible number of users is reached without requiring the use of special hardware or the installation of software. With A-Frame, various so-called "components" can be used to create interactive virtual worlds with virtual objects and 3D models, lighting, material, and multimedia assets such as images, videos, and sounds. For expanding the functionality of the framework, custom A-Frame components can be programmed in JavaScript.

Another framework used in combination is Networked-Aframe.[14] It is intended for developing shared multi-user environments. The Mozilla Hubs metaverse platform is also based on these frameworks, so emerging metaverse environments can provide similar functionality. To synchronize user interaction within the environment, Networked-Aframe provides multiple adapters for exchanging data via WebRTC or WebSockets. The adapters transfer data from user to user in a peer-to-peer (P2P) network. By integrating the WebRTC standard, the low-latency transmission of audio and video streams is possible. Networked-Aframe was implemented in our metaverse environment using the default EasyRTC adapters based on the open-easyrtc library. In this way, audio streaming of the musicians and the audience was realized. Furthermore, the parameters of all A-Frame components can be synchronized, including those that have been custom-developed. Besides data exchange, Networked-Aframe also provides templates for the implementation of avatars and the synchronization of interactions to ensure the interactivity and persistence of the virtual world. By using A-Frame in combination with Networked-Aframe, the whole virtual environment was created. A surreal and minimal virtual space serves as a stage for the performance. Here, there is a blending of virtual artificial elements and 3D-scanned objects from our physical world, which are represented as point clouds in reference to the quantum particle theme. The avatars are also represented as point clouds, mimicking gender-neutral head shapes (Figure 3). Users can interact with each other and with the performers

[13] *A-Frame*, v. 1.3.0, accessed December 03, 2022, https://aframe.io/.

[14] *Networked-Aframe*, official Github repository, accessed December 03, 2022, https://github.com/networked-aframe/.

through audio communication and movement. They can move freely through the world in 6-DoF and have a different audio mix depending on the chosen position. This allows for an alternating experience through all the different interactions.

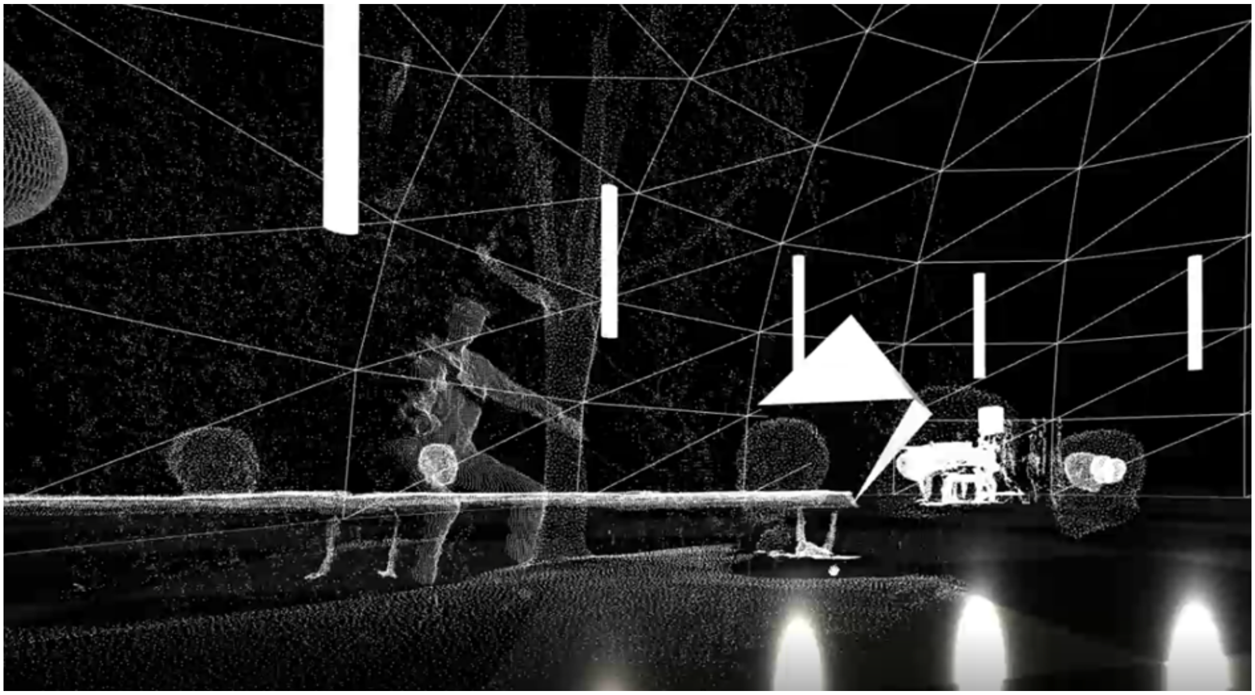

Figure 3: A screen capture from "The Entanglement" live performance. It shows a detailed view of one of the violin performers as a point cloud, placed in a 3D-scanned scene with a tree and bench. The player is surrounded by users from the audience, visible as plain point cloud head avatars.

Spatial Audio Rendering

To enable live-streamed audio in the metaverse environment, the Networked-Aframe framework is used to implement audio streaming over WebRTC. The microphone can be accessed locally via the web browser's microphone capture feature, and audio connections can then be made over a P2P network from RTCPeerConnections using Networked-Aframe's EasyRTC implementation. For encoding and decoding audio streams, WebRTC uses the Opus codec by default. It enables low-latency audio by using the Real-Time Transport (RTP) protocol, which is similar to the User Datagram Protocol (UDP) with a small header on top. This results in the latency essentially being the underlying network latency plus the encoding, decoding, and audio I/O latency. To spatially auralize the audio streams based on their position in space and relative to the listener, they are rendered using binaural reproduction. In this method, intended for playback over headphones, sound sources are convolved using head-related transfer functions (HRTF), resulting in audio signals suitable for the left and right ear.[15] This is implemented by attaching the WebRTC audio streams to an A-Frame positional sound component that corresponds to the PositionalAudio object of Three.js. The PositionalAudio object uses the PannerNode

[15] Henrik Møller, "Fundamentals of Binaural Technology," *Applied Acoustics* 36, no. 3/4 (1992): 171-218.

method with the HRTF panning model from the Web Audio API. The audio streams from the user's microphones are then positioned at the user's position in the virtual space - so as the users move, the audio moves with them.

In the metaverse environment, not only is the audio from the violinists streamed but also the audience can stream their audio for social interaction. In this way, users can chat with each other and interact with the performers by applauding them or performing similar interactions. This is an important feature for the immersion of a concert experience, for the audience as well as the performers.

Volumetric Video Rendering

The volumetric video was rendered as a point cloud using a depth image stream from the Kinect v2 3D camera. Since only one camera was used per player, the camera is not able to capture an entire volumetric body from all sides, but only the front with the corresponding depth planes. This is often referred to as 2.5D. The Kinectron framework[16] was used to broadcast the depth image from the Kinect cameras. It consists of a server application to capture the Kinect depth image and stream it over WebRTC, and a JavaScript API to receive the streams on the client side. As mentioned above, a Peer2Peer network is used for broadcasting. For the depth image, the PeerJS framework is used with an additional server. The Kinectron server application can broadcast data from the different Kinect modes—in this case, the RBGD-image stream was used, a 2D pixel image with the distance information encoded in the alpha channel. To render a 3D point cloud from the 2D RGBD stream, an A-Frame Kinectron component was developed using the OpenGL Shader Language and JavaScript. Building on the Three.js-based Three-Kinectron plugin by Or Fleischer,[17] an A-Frame component was developed to enable the rendering of Kinectron depth streams in virtual environments created with A-Frame. In this way, Kinect-based live streams can be used in metaverse environments. The developed A-Frame component is now part of the Kinectron framework and can be found in the official repository.[18] Since the point clouds from the live streams are only 2.5D, static scanned objects are added to the scene to enrich the 3D impression of the players and the environment, and to support the idea of spatially distributed players (Figure 3).

[16] Shawn van Every and Lisa Jamhoury, "Kinectron," official Github repository, accessed December 03, 2022, https://kinectron.github.io/.
[17] Or Fleischer, "Three-Kinectron," official Github repository, accessed December 03, 2022, https://github.com/kinectron/Three-Kinectron.
[18] Damian Dziwis, "Aframe-Kinectron," official Github repository, accessed December 03, 2022, https://github.com/kinectron/AFrame-Kinectron.

Algorithmic quantum composition

With the availability of quantum computers, the field of quantum computer music emerged,[19] offering composers new possibilities for composing in the context of quantum mechanical principles.[20] It allows the composition of algorithmic and aleatoric music using the concepts of superposition and entanglement.[21] "The Entanglement" is one such quantum music piece exploring those concepts and their impact on humanity in the domain of quantum computing. It is an improvisational performance as a sonification of the quantum algorithmic implementation of a Bell test, an experiment used to test the entanglement of particles. The concept goes back to Bell's work and it is today known as Bell's theorem or Bell's inequality.[22] The algorithm, a Bell test with entangled qubits, generates musical events for the performers. It was programmed using the QISKIT Python library.[23] The library allows for the local development of quantum circuit algorithms that can be executed remotely on an actual quantum computer— in this case, a 5-qubit CPU from the IBM Quantum project.[24] Starting with a basic 2-qubit entanglement example,[25] the algorithm was extended to four entangled qubits, with input gates that can be initialized (Figure 4).

The algorithm results in a sequence of four classical bits (i.e. sixteen possible states) being mapped to musical notes and gestures: notes from C to B (octave arbitrary), and four playing gestures (scratching on strings, tapping on strings, tapping on the body, making noise).

These are the only instructions for the violinists, and their improvisations are fed back into the algorithm as parameter settings for the Bell test. The attributes "fast," "slow," "loud," and "quiet", are randomized in position for each performance, and the playing style of the performers is then mapped to the qubit input sequence using these attributes. This creates a feedback loop that controls each iteration of the algorithm results.

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[19] Eduardo Reck Miranda, ed., *Quantum Computer Music: Foundations, Methods, and Advanced Concepts* (Basel: Springer, 2022): https://doi.org/10.1007/978-3-031-13909-3.

[20] Werner Heisenberg, "Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen," *Z. Physik* 33 (1925): 879–893, https://doi.org/10.1007/BF01328377.

[21] Alexis Kirke and Eduardo R. Miranda, "Experiments in Sound and Music Quantum Computing," in *Guide to Unconventional Computing for Music*, ed. Eduardo Reck Miranda (Basel: Springer, 2017): 121–57, https://doi.org/https://doi.org/10.1007/ 978-3-319-49881-2.

[22] John Stewart Bell, "On the Einstein Podolsky Rosen Paradox," *Physics Physique Fizika* 1, no. 3 (1964): 195-200, https://doi.org/10.1103/PhysicsPhysiqueFizika.1.195.

[23] *Qiskit*, v. 0.35.0, accessed January 05, 2023, https://qiskit.org/.

[24] IBM Quantum, accessed January 05, 2023, https://quantum-computing.ibm.com/.

[25] IBM Quantum, "Bell Test Example," example from the documentation, accessed January 05, 2023, https://quantum-computing.ibm.com/composer/docs/iqx/example-circuits/bell.

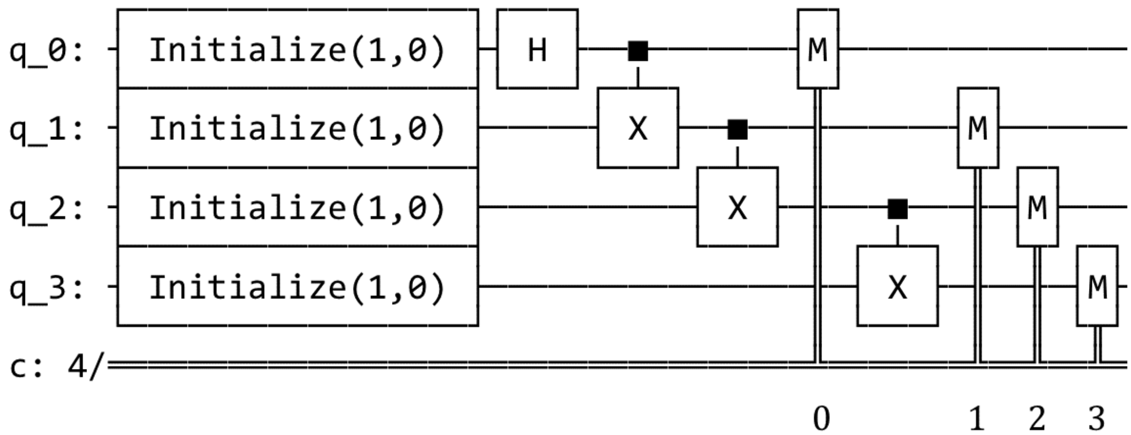

Figure 4: Schematic diagram of the quantum algorithm used in "The Entanglement." It shows the coded quantum circuit that is executed on the IBM quantum computer.

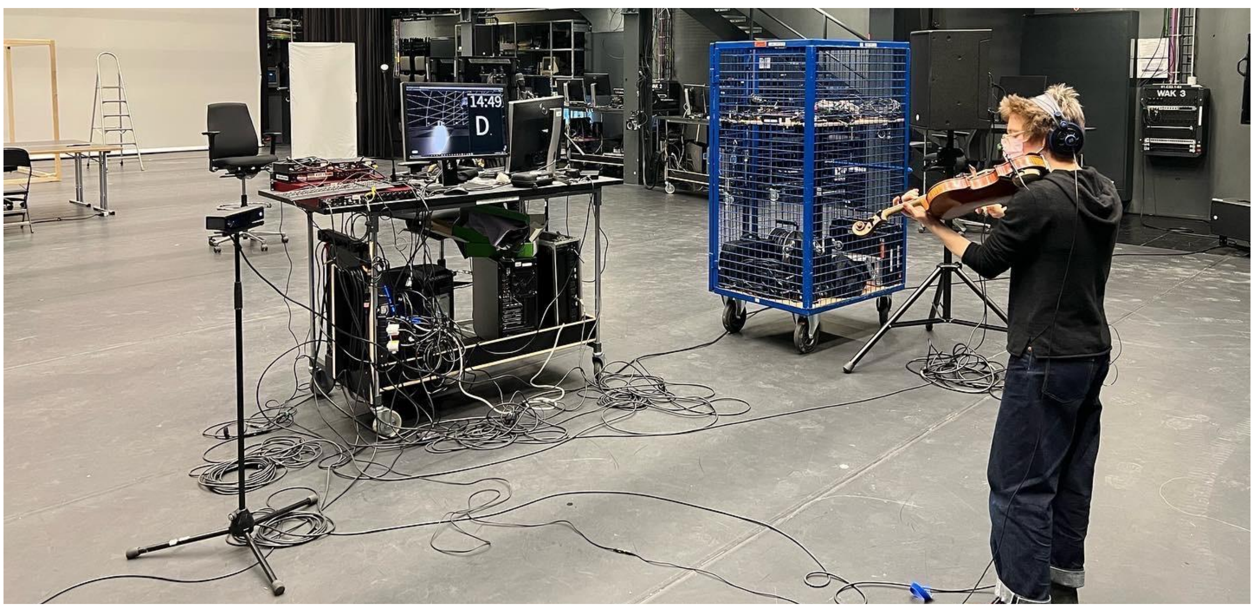

Figure 5: Set-up for a violin player. Each streaming site consisted of a Windows PC hosting a Kinectron streaming server with a Microsoft Kinect v2 camera, an audio interface and a DPA microphone attached to the violin. A screen is showing the metaverse environment and the Processing application with the results/playing instructions from the quantum computer algorithm.

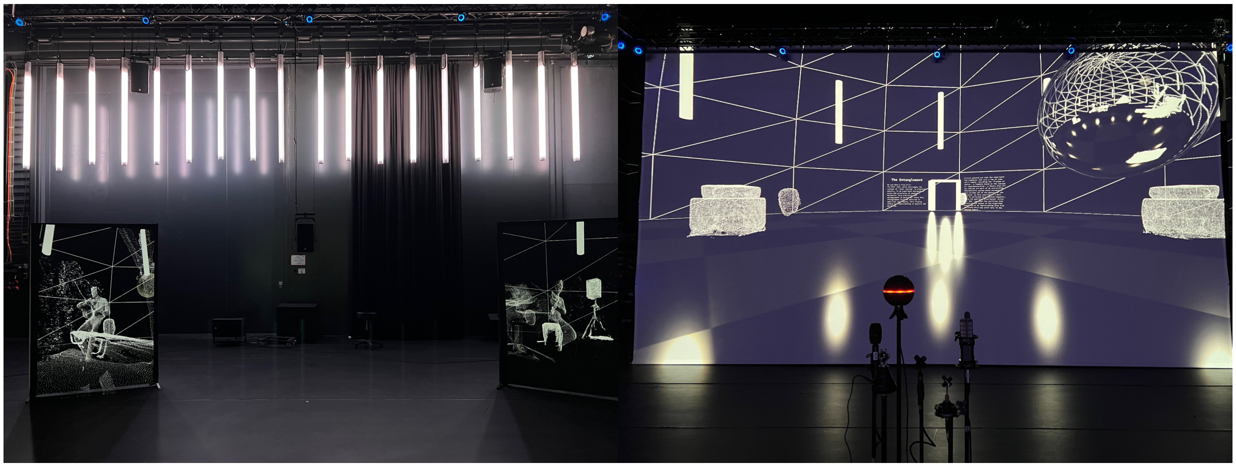

Figure 6: Images of the on-site augmented reality concert installation of "The Entanglement". Two semi-transparent projection surfaces were used to display the violin players (left), and a big projection in the back (right) displayed the metaverse environment with the audience.

Telematic Metaverse Performance

The premiere of "The Entanglement" took place in April 2022 in the Immersive Art Space (IA Space) of the Zurich University of the Arts. Besides the development of the metaverse environment and the algorithmic quantum computer composition, the performance of "The Entanglement" required further technical effort. As usual for a telematic performance, the two violinists were in two different locations for the performance. The focus here was on the realization of the artistic concept of the Bell test— the players were in different spaces of the university, resembling the entangled particles separated from each other in the Bell test. As shown in Figure 5, the technical set-up of each player consisted of a Windows PC, with an audio interface for the violins' DPA microphone, and a Microsoft Kinect v2 camera for volumetric video. The depth image from the Kinect cameras is streamed from the Windows PCs using the Kinectron server application. Throughout the performance, the players, along with the audience, are in the metaverse environment via a web browser. In this way, they stream the audio of their violin and receive the sound from the virtual environment binaurally through headphones. The players can follow the activities in the metaverse on a screen. In addition, a Processing[26] application is running that receives and outputs improvisation instructions of the quantum algorithm from an external computer via the Open Sound Control (OSC) protocol.

Alongside the online VR metaverse performance, a local augmented reality concert installation was realized in the IA Space (Figure 6). For this, two camera perspectives from the metaverse environment showing the two players were projected onto semi-transparent projection screens. The projections were set up in the hall in analogy to the virtual positions. Behind each projection a loudspeaker is placed, which reproduces the sound of the respective player. On the rear projection screen of the hall, the audience area of the virtual environment is streamed - in this way, the IA Space is extended by the

[26] *Processing*, v. 4.0b4, accessed April 20, 2023, https://processing.org/.

virtual environment, and the audience on site can follow the activities in the metaverse.

Conclusion & Future Work

In the context of "The Entanglement," we created a system for telematic music performances in metaverse environments. In these immersive, virtual multi-user environments, artists and audiences can engage with each other in multimodal forms. This way, virtual live concerts can be experienced similarly to physical ones. Furthermore, virtualization enables the realization of compositional concepts and their audiovisual presentation in a way that would be difficult or impossible to realize in physical reality. As demonstrated with "The Entanglement" as an improvised sonification of a quantum algorithmic Bell test as particle-appearing performers in a surreal virtual world.

We have shown the development of a metaverse environment for telematic music performances and the artistic possibilities it offers. As part of ongoing development, the technical and artistic possibilities are continuously expanded. Further immersive components like a spatial room simulation have already been developed.[27] In addition, systems for further performance practices such as live coding or the development of virtual music instruments for networked music performances in the metaverse are being developed.[28] Novel art experiences can be created in this way and the immersion and possibilities of virtual music performances can be enhanced.

Acknowledgments

"The Entanglement" was realized for the telematic artistic-research residency at the Institute for Computer Music and Sound Technology of the Zurich University of the Arts.

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[27] AudioGroup Cologne, "Aframe-Resonance-Audio-Component", Github repository, accessed January 05, 2023, https://github.com/AudioGroupCologne/aframe-resonance-audio-component.

[28] Damian Dziwis, Henrik von Coler, and Christoph Pörschmann. "Orchestra: a Toolbox for Live Music Performances in a Web-Based Metaverse." *Journal of the Audio Engineering Society* (forthcoming).

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