Parasitic Signals: Multimodal Sonata for Real-time Interactive Simulation of the SARS-CoV-2 Virus

Myungin Lee*
Immersive Media Design,
University of Maryland,
College Park, USA

Sabina Hyoju Ahn†
Media Arts and Technology,
University of California,
Santa Barbara, USA

Yoojin Oh‡
Institute of Biophysics,
Johannes Kepler University,
Linz, Austria

JoAnn Kuchera-Morin§
AlloSphere Research Group,
University of California,
Santa Barbara, USA

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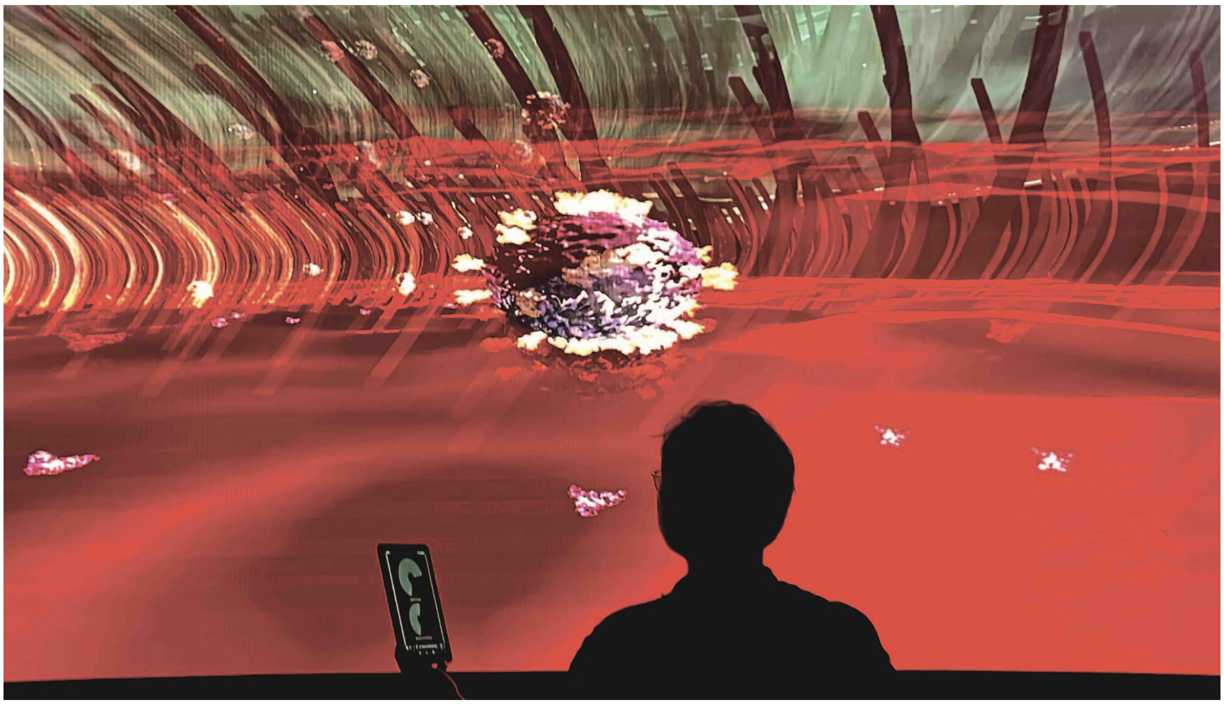

Figure 1: Installation of Coexistence with the SARS-CoV-2 virus

Abstract

This project aims to transform the nano-scale of a striking biological phenomenon, the relationship between the SARS-CoV-2 virus and human molecules, into an interactive audiovisual simulation. In this work, Atomic Force Microscopy (AFM) touching and imaging a single molecule measures the interaction between the spike protein of SARS-CoV-2 and human cellular proteins and measures the dynamic of the spike protein. We create a comprehensive scientific model based on diverse datasets and theories presenting a real-time interactive complex system with efficient rendering and sonification using a single C++ platform. This project invites the audience into an immersive space where they can control the behavior of biomolecules, allowing them to intuitively perceive biological properties. This project is not only a demonstration of scientific data but also attempts to look at the interspecies relationship in parasitism which particularly deals with our current and post-pandemic life with coronavirus and how we might control our coexistence in a virtual space.

Index Terms: Art & Graphic Design—Art-science collaboration—Visualization techniques; Biology—Atomic Force Microscope; Interaction Design—Temporal Data; Storytelling—Real-time audiovisualization

1 Introduction

Over the past three years, the virus has been of great interest across various fields of science, particularly in understanding how the spikes of the virus interact with human cell components and how this knowledge can be used for therapeutic purposes [12, 18, 49]. This project has been developed as an interactive audiovisual simulation in an immersive space through interdisciplinary collaboration among scientists, artists, and engineers, where participants can control the behavior of biomolecules to intuitively recognize their biological characteristics. The project also examines the historical and contemporary impacts of diseases on human populations, as well as the social and political aspects of the pandemic, including COVID-19. Moreover, it explores how virtual reality can be used to better understand and manage our coexistence with pathogens.

1.1 Research Background : Pathogen and Human host Relationship

COVID-19, caused by the SARS-CoV-2 virus, has triggered a pandemic that has disrupted our healthcare, social, and economic environments. Despite significant technological advancements achieved

*e-mail: myunginlee@mat.ucsb.edu
†e-mail: sabina_ahn@ucsb.edu
‡e-mail: yoo_jin.oh@jku.at
§e-mail: jkm@create.ucsb.edu

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in managing this pandemic over the last three years, a tremendous number of people are still infected and suffering from the virus. Globally, as of May 3, 2023, there have been 765,222,932 confirmed cases of COVID-19, including 6,921,614 deaths, reported to the World Health Organization (WHO) [31].

The relationship between humans and pathogens, along with their social and cultural impacts, has been the subject of study for quite some time. Although medical science has made significant progress with antibiotics, vaccines, and improved hygiene, the spread rate and contamination of hazardous epidemics continue to pose major threats to human well-being and mortality [11].

Throughout history, critical diseases have plagued the human population. For example, the Spanish Flu was an immense epidemic causing at least twenty million deaths from 1918 to 1920. Smallpox, measles, and typhus spread from Europe to Central and South America, reducing the native population from twenty million to three million in Mexico from 1518 to 1568. Furthermore, after Columbus returned from the American continent, syphilis was also introduced across European countries [4]. Additionally, flu is a highly contagious disease caused by influenza viruses, and due to rapid changes in their genetic material (known as mutation), it is difficult to find perfect vaccines against these viruses.

In addition to exploring the historical relationship with pathogens, this project delves into the complex and mutualistic relationships between species. According to Dawkins, parasitic relationships can be long-term, as parasites cease to become mutualistic by transmitting their genes to the host's offspring, and ultimately, their own bodies disappear, merging into the host body completely [14]. This idea echoes contemporary philosophy, cultural studies, and art practices that aim to avoid a human-centric viewpoint and extend democratic distribution by embracing human and non-human living beings [24]. Lynn Margulis also highlights symbiogenesis, where human and non-human living beings evolve equally through abiding physical contact and 'becoming by living together,' leading to a paradigm shift from neo-Darwinism [28]. In this sense, parasitism has been studied in this series of works as an interspecies relationship between humans and other species, examining various contexts in social, artistic, and scientific practices.

"Parasitic Signals: Coexistence with the SARS-CoV-2 Virus" not only demonstrates the use of simulation to understand and convey scientific data through visualization and sonification but also examines the interspecies relationship in parasitism as a mutualistic and long-term connection.

1.2 Research Process and Goal

"Parasitic Signals" has evolved since 2019 as an interdisciplinary project based on scientific pathogen research [40]. In 2021, the first iteration of the project sonified scientific data of *Borrelia burgdorferi* and presented it through a quadraphonic sound installation [39]. The current version of the project focuses on analyzing the interactions between the SARS-CoV-2 viral protein and human cell components, employing artistic frameworks to transform datasets into multi-perceptional experiences.

To obtain high-resolution images of the bio-molecular structures and their dynamics, we utilized cutting-edge microscopic technology. Atomic Force Microscopy (AFM) was used to observe the mechanical interaction between the spike protein and the angiotensin-converting enzyme 2 (ACE2) human protein, which is known to be expressed on the host cell's surface.

Since human senses are limited to specific ranges (the human audible range being 20 Hz to 20 kHz and the visible light region ranging in wavelength from 400 to 750 nm), nano-scale data must undergo transformation through sonification, audification, and visualization to make it perceptible. Particularly in the context of a complex biological narrative such as the virus infection mechanism, we have established coherent connections between the science, narrative, graphics, audio, and interface in the simulation. Therefore, the research question aims to provide new perspectives on scientific discoveries in complex biosystems by creating interactive audiovisual simulations that accurately depict the physical characteristics of the interactions between the coronavirus and human protein molecules. This approach not only aims to impart educational knowledge but also to encourage conversations from diverse viewpoints encompassing art, science, and technology.

2 Related Work

The philosophical foundation of this work is rooted in posthumanism, the Anthropocene, and media theories on ecological crises, which are relevant to contemporary media artworks. One figure in media theories, Roy Ascott, coined the term 'moist media' to describe art practices in the 21st century that are influenced by the intersection of wet biological processes and dry computational systems [5]. Indeed, in recent times, the discoveries and techniques from scientific research in bioscience have become the intellectual catalyst for artists and scientists collaborating within the context of artistic research practices.

A few examples of art-science collaboration involve the utilization of advanced technology in bioscience, such as AFM, a high-resolution microscopy technique that can probe cellular structures. AFM allows for the characterization of microbial surfaces at the nanoscale without disrupting their physiological environment. Scientist James Gimzewski demonstrated that a single yeast cell exhibits periodic nanoscale motion, which is influenced by environmental conditions such as temperature [32]. In collaboration with media artist Victoria Vesna, Gimzewski developed a meditative audiovisual installation titled "Blue Morph," which sonifies the electric signals derived from the morphology of pupa cells [44].

In the "Midas" by artist Paul Thomas, AFM was employed to create artwork that explores a nanotechnological observation of touch and draws analogies between the hand and gold, following the

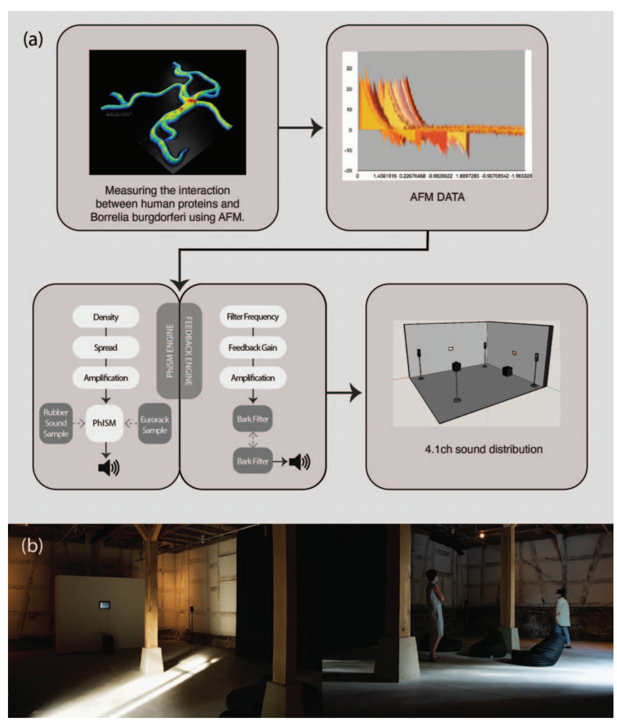

Figure 2: (a) Sonification design process of Parasitic Signals (2021). (b) 4.1 ch sound distribution in the exhibition space (2021)

concept of the King Midas fable [41].

A more recent example, related to the SARS-CoV-2 virus, is the physical manifestation of COVID-19 data presented by Ompteda in 2021, connecting people to the incomprehensible magnitude of loss experienced during the pandemic [43].

In 2021, the Parasitic Signals project presented its first iteration, exploring artistic research on the relationship between pathogens and humans through an auditory experience [2]. AFM data were sonically transformed based on the interaction forces between a single protein from the Borrelia burgdorferi bacteria, the major human parasite causing Lyme disease, and human extracellular layers. Specifically, the interactions with vector-borne pathogens such as ticks, mosquitoes, bats, pigs, and others were analyzed to observe the mutualistic relationship and mechanical interaction between the human host and pathogens. The experiment focused on the direct physical contact between the parasite (Borrelia burgdorferi and Escherichia coli) and human tissue fragments (human extracellular matrix) using Bio-AFM [40].

During the first iteration of the research, the sound programming software Supercollider was employed to implement the sonification strategy. Figure 2(a) illustrates the sonification design. Sound designer Kyriakos Charalampides and artist Sabina Hyoju Ahn collaborated to create two sound engines: one based on Physically Informed Sonic Modeling (PhISM) [13], and another using a feedback-based approach. The data values were mapped onto parameters such as density, speed, and sound levels to generate a rich sound texture. The resulting sound was distributed through a 4.1 channel sound system [2]. In 2021, "Parasitic Signals" was exhibited at various public spaces. Figure 2(b) showcases the premiere of the Parasitic Signals exhibition in Germany [39].

3 Parasitic Signals : Coexistence with the SARS-CoV-2 virus

"Coexistence with the SARS-CoV-2 virus" has been developed from the previous pathogen research between Borrelia bacteria and human extracellular interaction. From the previous work, this project has evolved by focusing on our current pandemic situation with pathogens, – SARS-CoV-2, known as coronaviruses. Chapter 3.1 describes the fundamental biological discoveries resulting from this collaboration. From there, we established the narrative of the simulation, elaborating on the interaction between the coronavirus and the human body. The following chapters delve into specific domains of the project, including simulation (Chapter 3.2), graphics (Chapter 3.3), audio (Chapter 3.4), interface (Chapter 3.5), and artistic representation (Chapter 3.6). These chapters provide a comprehensive examination of the project from theoretical, technical, and artistic perspectives.

3.1 Scientific Backgrounds

Over the past three years of the pandemic, the SARS-CoV-2 virus has been of significant interest in all scientific disciplines, especially research into how the coronavirus spikes can bind to a human cell component and how these findings can be utilized for therapeutic purposes [12, 18]. In 2020, biophysicists in the department of Applied Experimental Biophysics at Johannes Kepler University showed the first short movie of the spike protein in action using a high-speed AFM. Although the spike protein of SARS-CoV-2 is surprisingly weak, the movements and dynamics of the spike protein were recorded under physiological conditions. Moreover, the interaction forces between the virus's spike protein and the ACE2 receptors expressed on the cell membrane were also successfully measured using a derivative technique of AFM. Successful binding to ACE2 requires at least one of the three receptor-binding domains (RBDs) on a Spike trimer. The dynamic movement of the spike protein underlies the process of virus attachment to human cells during the early stages of viral infection. This scientific discovery, which depicts the movement of the spike protein of SARS-CoV-2 in real-time, has been presented at several public events and published in well-known international conferences and journals [12, 49].

3.2 Simulation of SARS-CoV-2 and Human Cell

This project embraces the discoveries by bringing them into one programmable simulation. To achieve a comprehensive representation of a complex biosystem, we established a narrative based on the mechanism of SARS-CoV-2 propagation from the conducting zone of the airway to cellular membranes with ACE2 receptors. This narrative is developed into an interactive audiovisual. To achieve a coherent multimodal experience, the software is implemented on a single C++ platform using open-source libraries including *AlloLib, OpenGL, RtAudio, and OSC* [1, 36, 38, 46] with custom codes except for the external interface hub implemented with interface.js [35]. This approach allows for manual access to model establishment, data processing, sonification, and rendering, in contrast to commercial software platforms like game engines. As a result, it enables interactive control of numerous agents in the system, allowing for the composition of virtual, organic 3D audiovisual environments in real time. Figure 3 provides a schematic illustration of the simulation's components, while Figure 4 depicts the infection mechanism as a narrative. Figure 5 shows the procedure of achieving the dynamic rendering of the coronavirus spike from AFM video to graphics. Figure 6 illustrates the overall structure of the interactive multimodal design, and the following sections elaborate the methodology of simulation in detail directing the corresponding figures.

3.2.1 Narrative: Infection mechanism

We present the narrative based on the infection mechanism of coronavirus within the lung along the airway. The narrative is divided into four stages (Figure 4): *Appearance, Diffusion, Penetration, and Binding for Entry*. These stages align with the steps of musical plot structure, such as the *Exposition, Development, Recapitulation, Climax*. This connection between the scientific mechanism and artistic representation strengthens the coherence of the overall presentation.

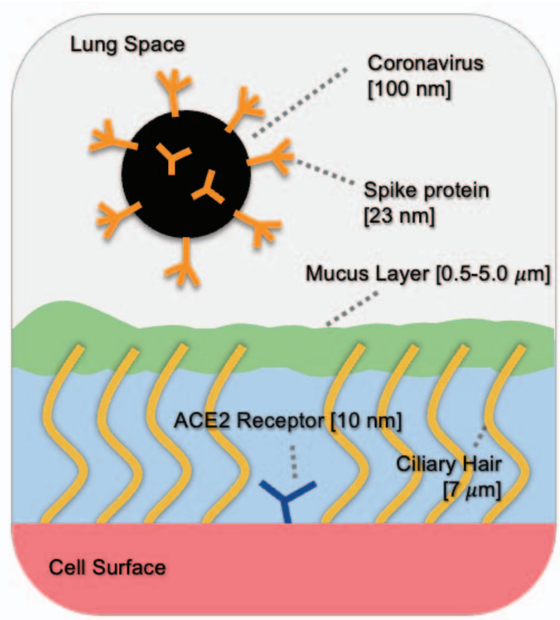

Figure 3: Schematic image of components in the simulation with the actual sizes.

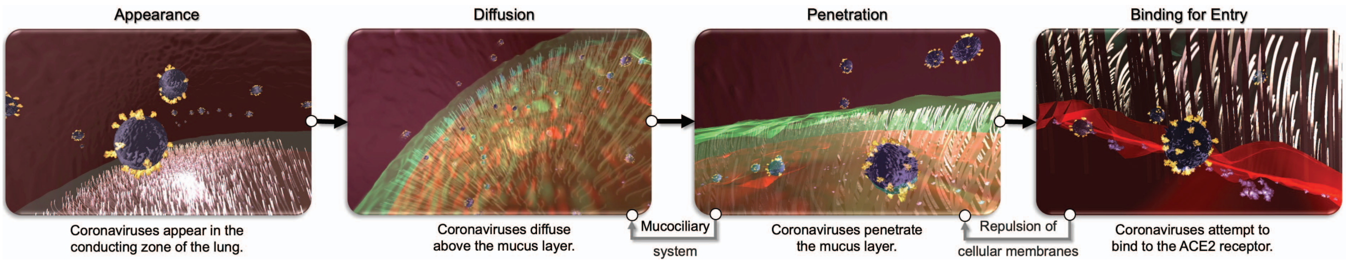

Figure 4: Four stages of SARS-CoV-2 infection toward the lung along the airway: Appearance, Diffusion, Penetration, and Binding for Entry

Appearance (Exposition): The narrative begins with the appearance of the coronavirus as it follows the route of infection towards the lung along the airway.

Diffusion (Development): A recent study by Johnson et al. [20] shows the behavior of viruses at the early moments of infection using 3D tracking and imaging microscopy. Inspired by these observations, a diffusion model is programmed to simulate the movement of multiple agents with Brownian-like motions. Additionally, a steering algorithm is implemented to demonstrate the natural behavior of coronaviruses fluctuating the lung space and seeking cell-surface receptors. An exemplary trace of multiple coronaviruses, generated by this algorithm, is depicted in Figure 6(c). This algorithm is controlled by three parameters: *urging, grouping, and hunting*. The parameter *urging* determines how fast the viruses are accelerated in an arbitrary direction, *grouping* determines the tendency of the viruses to swarm, and the *hunting* parameter drags the viruses towards the ACE2 receptors. We empirically determined the presets of these parameters, which change over the stages composing the flow of the entire narrative.

Penetration (Recapitulation): The mucus layer and ciliary hairs function as the primary innate defense mechanisms of the airway [9]. The slimy texture of the mucus layer significantly slows down the propagation of the virus and repels it away from the ACE2 receptors. At this stage, some of the coronaviruses are expelled from the mucus layer, recapitulating the penetration stage.

Binding for Entry (Climax): After the coronavirus penetrates the mucociliary defense mechanism, it attempts to bind with ACE2 receptors on the cell. When the virus is close enough to an ACE2 receptor, the spikes stretch and morph to bind to the receptor. These dynamics are simulated based on binding force data [49]. Chapter 3.2.2 describes the methodology. The virus has approximately a 30 % chance of binding to the receptor and entering human cells when the innate repulsion between the virus and the cellular membranes can be overcome with sufficient energy [19, 37]. Once 90 % of coronaviruses bind to the receptors, the narrative ends and loops back to the beginning.

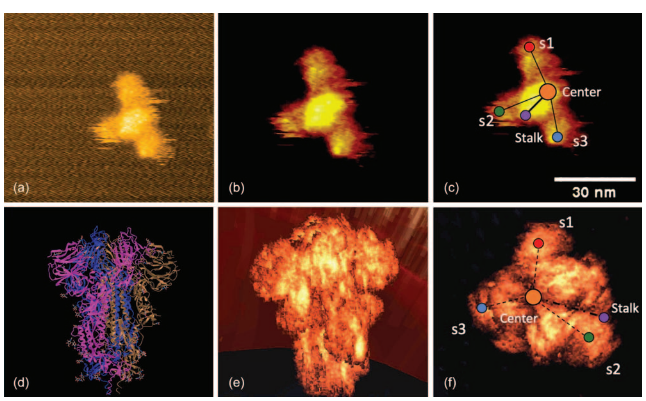

Figure 5: (a) Spike trimer of the SARS-CoV-2 virus observed with a high-speed atomic force microscope (AFM). (b) denoised frame using a deep neural network. (c) labeled frame. (d) 3D model of the SARS-CoV-2 virus spike trimmer. (e) rendering of the spike in the project. (f) rendered spike with the labels.

This entire procedure can be accelerated, decelerated, stressed, released, or initiated by the interactive components composing a musical structure. The details of the interaction design will be described in Chapter 3.5.

3.2.2 Probe: Atomic Force Microscopy (AFM)

From AFM footage data, we obtained the position of the stalk and each of the RBDs over time. The spike center, three RBDs, and stalk were manually labeled initially, as shown in Figure 5(c). Using the known length of the stalk and RBD as the ground truth, we calculated the 3D position of three RBDs by considering the length of the RBDs from the spike center and the rotational angle, using trigonometric functions [12, 49]. The 3D structure of the SARS-CoV-2 spike protein trimer, Figure 5(d), [47] was utilized and a branch was separated from the trimer. By rotating and scaling the individual branches with the data, dynamic 3D spikes were reconstructed digitally, Figure 5(e-f), based on the real protein model, incorporating observed dynamics from temporal AFM data.

The derivative technique of AFM can also describe molecular scale dynamics. This technique enables the observation of mechanical interaction forces between the spike protein of the virus and ACE2 receptors expressed on the cell membrane, where the initial interchange between the human protein ACE2 receptor and the coronavirus takes place. Figure 6(f) displays four exemplary cases of ACE2 interaction out of the 846 sets of experiments. In the graph, the y-axis represents the interaction force data, while the x-axis indicates the observation time over 10 seconds. From the data, we can observe the impulsive spark, labeled as purple boxes in Figure 6(f), which indicates the number of RBDs bonded with the receptor. Similarly, the experiment yielded 846 sets of data offering diverse cases of human protein-coronavirus interaction. In this simulation, resembling how the AFM probe observes ACE2 receptors through collision, the coronavirus collides with the cell surface and ACE2 receptors based on randomly selected incidences from the 846 cases. This simulation provides a profound and dynamic depiction of the scenery above the cell surface during the *Binding for Entry* stage.

3.2.3 Defense mechanism: Mucociliary system

Based on previous biological research and their conceptual image of the mucociliary system [16, 26, 29, 33, 45], we implemented a viscous mucus layer and a myriad of cilia that fluctuate. Figures 6(d) and 6(e) illustrate the moment when the coronavirus penetrates the mucus layer. When the coronavirus comes into contact with

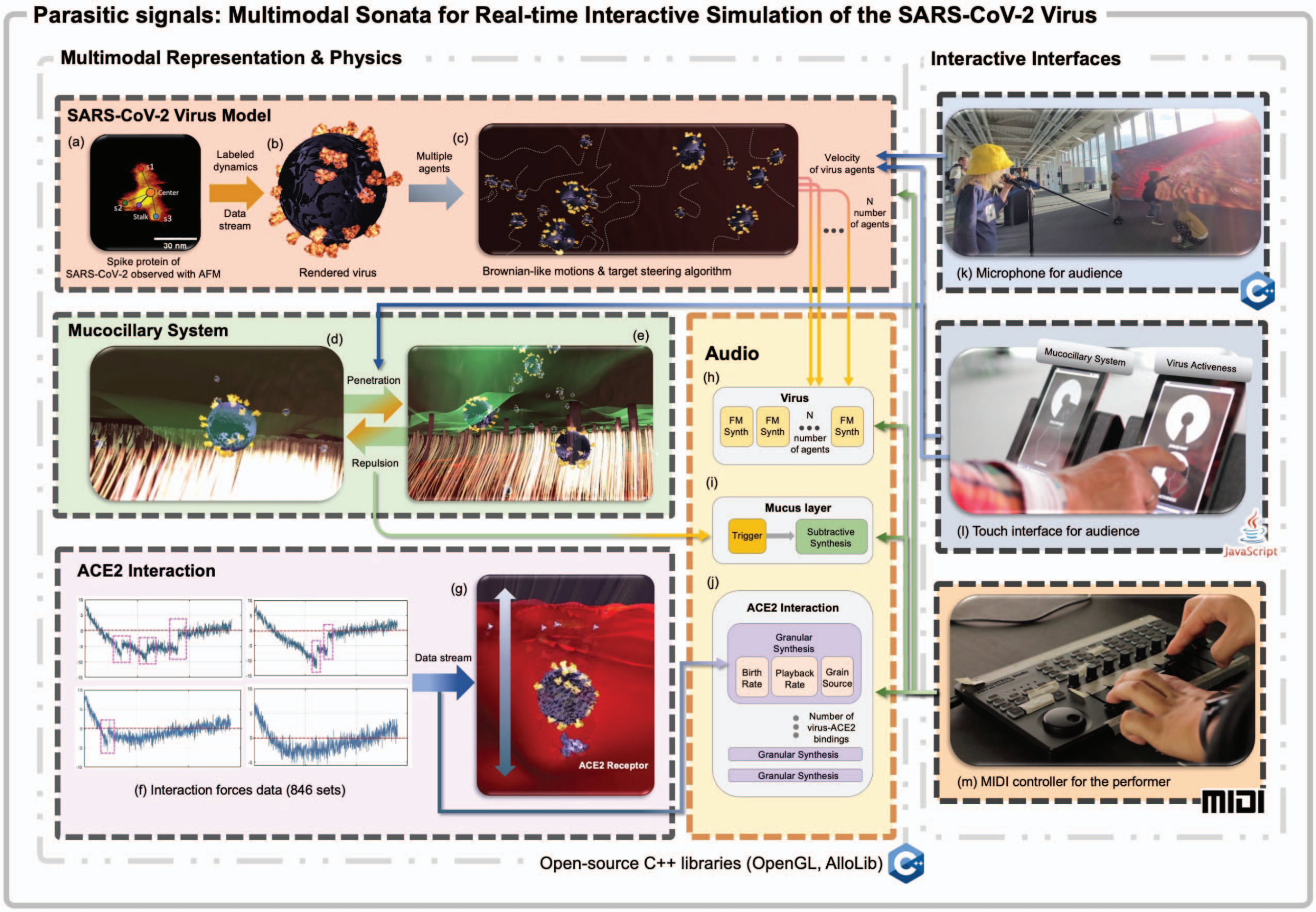

Figure 6: Overall structure of multimodal design. (a) spike protein of SARS-CoV-2 observed with AFM. (b) Rendered SARS-CoV-2. (c) an exemplary movement of coronaviruses. (d-e) the moment coronavirus penetrates the mucus layer. (f) interaction forces data observed with AFM. (g) coronavirus trying to bind with ACE2 receptor. (h) sound of coronavirus: frequency modulation. (i) sound of mucus layer: subtractive synthesis (j) sound of ACE2 receptor and coronavirus interaction: granular synthesis. (k) microphone for audience interaction. (l) touch interface for audience interaction, mucociliary system and virus activeness. (m) MIDI controller for the performer.

the surface of the mucus layer, a slight wave occurs, causing fluctuations in the layer. To simulate this phenomenon, we utilized a discretized 2D wave equation, denoted as Equation 1, in which u, r, t, and v represent the wave equation, position, time, and velocity, respectively.

$$\begin{aligned} &u(r,\ t+1) \qquad (1)\\ &= 2u(r,t) - u(r,\ t-1) + v^2[u(r+1,\ t) - 2u(r,t) + u(r-1,\ t)] \end{aligned}$$

This simulation effectively portrays the gluey texture of the mucus layer, enhancing the responsiveness of the scenery to virus invasion [1]. As cilia are hair-like projections, we implemented a simple 1D wave on the ciliary hairs, with their frequency adjusting based on the activity of the defense system. The functions and effects of the interactive parameters are detailed in Chapter 3.5.

3.2.4 Human protein : Angiotensin Converting Enzyme 2 (ACE2)

ACE2 is a viral receptor that the spike protein of the coronavirus can recognize. The virus enters human cells when the viral spike protein successfully binds to ACE2 akin to a lock-and-key interaction. In our study, we utilized the 3D structure of ACE2 [42] and isolated a branch from the dimer. The dynamics of ACE2 dimers are simulated with arbitrary tilt motions that range from 0 to 50°, inspired by research on the flexibility of ACE2 in the context of SARS-CoV-2 infection [6]. While this dynamic is not based on AFM imaging of ACE2 dimers, we elaborate on the interaction between ACE2 dimers and spikes of the coronavirus through AFM sonification. Chapter 3.4 provides detailed information on how we developed this simulation in the sonic domain using multimodal representation.

3.3 Graphics

The graphics of this project encompass both the preprocessing and real-time rendering domains. In the preprocessing phase, the AFM video of the spike is analyzed to label the dynamics and retrieve imagery of the spike more accurately. Figure 5(a) displays a screenshot of the raw real-time AFM video, and Figure 5(b) shows the corresponding frame that has been denoised using a deep neural network [48]. This process has enabled a more accurate graphical estimation of the coronavirus on the nano-scale.

For efficient real-time rendering, a custom instanced rendering method was implemented using OpenGL Shading Language (GLSL) to depict dense scientific models with intricate details in the scenery. Instanced rendering is a computer graphics technique that optimizes the drawing of numerous objects by reusing a single instance, such as a triangle [1, 38]. For example, the 3D model of a spike, Figure

5(e), is generated using the structure of the SARS-CoV-2 spike protein trimer, Figure 5(d) [47], by filling out 125,632 vertexes with transparent instances. This approach completes the skeleton of the 3D model, presenting imagery that closely resembles the original AFM image. To achieve efficient real-time rendering of multiple coronaviruses, each with 35-40 spikes, the number of vertices can be adjusted through sampling of the 3D model.

We determined the color of the objects by referring to iconic images from scientific research (Spike of the coronavirus: gold [49], ACE2 dimer: blue [6], mucus layer: green and blue [29], ciliary hair: orange [9]).

In addition, real-time frame feedback is used to depict the nano-scale scenery in the conducting zone of the airway. This involves copying the frame buffer into a texture and adding it to the next frame. This real-time postprocessing technique is also employed to ensure a smooth transition of the scenery along with the narrative.

3.4 Audio

Audio in this project is a crucial modality that coherently represents the events in the scenery. The agents in the simulation, including coronaviruses, the mucus layer, and ACE2 receptors, act as individual sources for different digital synthesizers. The yellow box in Figure 6 illustrates how each element generates audio. Considering the involvement of dozens to hundreds of agents in this real-time simulation, numerous sonic events occur simultaneously in the scenery, which requires a comprehensive strategy during the design process. To establish a coherent multimodal structure, we aligned the narrative and infection mechanism with a sonic structure based on music composition theories. Figure 7 illustrates the mono-channel auditory structure of an exemplary narrative using a spectrogram, accompanied by labels that explain the corresponding stages. Throughout the sequence, the musical structure generated by sonic elements goes back and forth but eventually flows to the end according to the probability model of the events described in the narrative chapter.

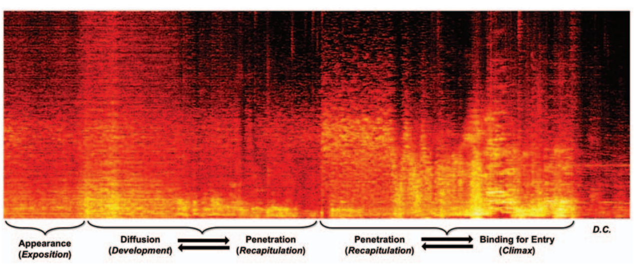

Figure 7: Linear-scale spectrogram of an exemplary narrative over 4 minutes

Each coronavirus emits string-like sounds at its corresponding 3D position, synthesized using frequency modulation (Figure 6(h)). Their speed and sparseness determine their pitch and modulation parameters. The audio evokes a sonata-like structure. In the initial stage of the narrative, the *Exposition*, dozens of coronaviruses slowly appear, creating an ambient soundscape. In the *Development*, the coronaviruses start to diffuse and generate a chaotic 3D orchestral-like structure. As the diffusion progresses, the coronaviruses penetrate the mucus layer, resulting in visible fluctuations on the mucous surface and emitting low-pitch wave-like or whale-like sounds created using subtractive synthesis (Figure 6(i)). These wave-like sounds help alleviate the tension generated by the chaotic virus sounds. These two contrasting sonic elements contribute to the buildup and release of tension, shaping and recapitulating the overall structure.

When the coronavirus interacts with the ACE2 receptor, the AFM data is utilized to parameterize the birth rate, pitch, and duration of the granular synthesis (Figure 6(j)). This approach, known as granular synthesis, enables the creation of complex tones by combining and mixing simple micro-sonic elements [34]. By applying the AFM data to multiple parameters of the granular synthesis, we can effectively capture and emphasize the variations in the AFM data (Figure 6(f)). This approach effectively represents the intense interaction between the coronavirus and the ACE2 receptor while also incorporating symbolic messages through its granular sources, such as coughing, crying, whispering, and laughing sounds. These complex tones intensify the tension leading to the *Climax* as multiple coronaviruses bind to ACE2 receptors. Eventually, the narrative returns to the beginning with a *Da Capo*, repeating the sequence. In the same way, we have designed the real-time sonic landscape not only to sonify the data and theory, but also to compose a musical plot structure that aligns with the events in the simulation. As a result, the sonic landscape is filled with unique and dynamic patterns that are interconnected with the simulation, visualization, and narrative.

3.5 Interface

We have designed the interface to invite the audience to participate in the audiovisual narrative. The interface incorporates two methods, a voice-based interface and a touch-based interface, allowing users to intuitively explore the dynamic biophysics of the coronavirus and human cells. Figures 6(k) and (l) show the installation spaces and provide a demonstration of the interaction.

Both the audience and performers have access to multiple tablet interfaces, featuring bars, buttons, and knobs, which allow them to dynamically control various parameters of the simulation. Participants have the opportunity to collaboratively shape the audiovisual narrative by engaging with the defense mechanism (the activeness of the mucus layer & mucociliary clearance) and affecting the activeness of the virus (diffusion of viruses & seeking ACE2). The server connecting the tablets is implemented using interface.js [35]. This interactive setup empowers participants to actively participate and contribute to the unfolding of the narrative.

In addition to the tablets, a microphone is utilized to capture the voices and ambient noise within the installation space, symbolizing human activity and the characteristics of coronavirus transmission from an infected person's respiratory tract. As the input volume increases, the mucociliary system dynamically responds by exhibiting fluctuations in color and height. Simultaneously, the movements of the virus become more vigorous, as it accelerates and undergoes morphological changes in its spike structure. These changes increase the chances of the virus penetrating the mucociliary system and finding the ACE2 receptor.

The performative installation also offers precise control over the parameters of the simulation through a MIDI controller (Figure 6(m)). With its multitude of buttons and knobs, the controller provides various options for audiovisual manipulation, such as adjusting time, speed, camera angles, and corresponding audio effects. This functionality expands the possibilities for audiovisual composition, allowing the performer to plan and/or improvise within the dynamic narrative, much like playing a musical instrument.

3.6 Artistic representation

3.6.1 Performance

While we have categorized the overall narrative into a musical plot structure, the active participation of the audience and the control of the performer significantly influence the composition. As if a waterfall, maintaining its continuous flow yet never pouring down the same water, the system has the ability to compose numerous multimodal sonatas for each occurrence involving different audiences and performers. Within the given mechanism, the structure morphs and blends through the ensemble of participants and performers, sometimes faster, sometimes slower. This aspect also provides creative opportunities for individuals or groups to improvise and develop their virtuosity, enabling them to deliver unique live performances

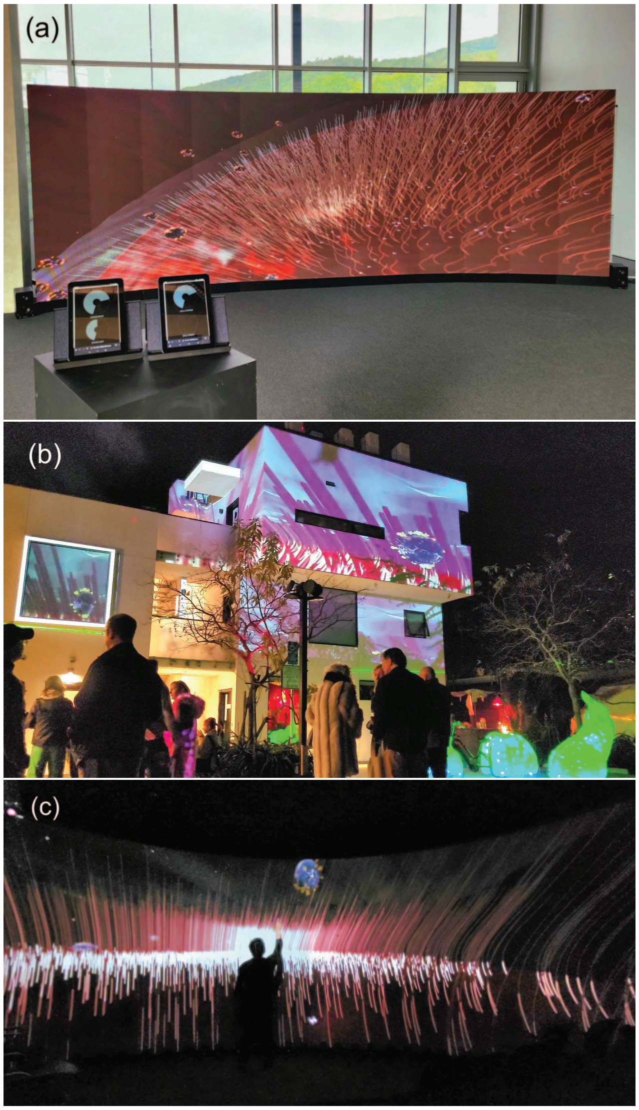

Figure 8: The installations are made in various environments and diverse audiences are invited for the interaction. (a) Ars Electronica Festival 2022. (b) Santa Barbara Center for Art, Science and Technology (SBCAST) 2023. (c) AlloPortal (3D) in the California NanoSystems Institute 2022-2023.

with a specific artistic vision. The online audiovisual demonstration and performance are available in [3, 25].

3.6.2 Space Design

"Coexistence with the SARS-CoV-2 virus" has been shown in various forms at the immersive installation spaces. The customized open-source C++ components, including *AlloLib* [1] allow diverse graphic and audio configurations that vary with the installation space and environment. For instance, the project can be performed in compact head-mounted displays and the *AlloSphere*, a three-story facility presenting 360 degree 3D visuals and audio powered by 26 stereo projectors and 54.1 speakers [10].

In the international media arts exhibition, Ars Electronica Festival 2022 [30], we presented our installation using a 6-meter-wide and 2-meter-high curved LED wall, accompanied by a 4.1 channel sound system (Figure 8(a)). This immersive audiovisual experience offered interactive elements, including tactile sensations through a 16-inch sub-woofer, allowing visitors to engage with complex biophysical data through multiple senses.

Furthermore, this project was showcased as a building projection on the intricate surfaces of the Santa Barbara Center for Art, Science, and Technology (SBCAST) in 2023, aiming to engage a broader audience in the city and provide them with an immersive experience (Figure 8(b)).

Currently, the project is archived and accessible through the *AlloPortal* in the California NanoSystems Institute at the University of California Santa Barbara, offering 3D visuals and spatial audio with the support of two stereo projectors and a curved screen, along with 32 speakers (Figure 8(c)) [22]. This platform welcomes diverse audiences on a regular basis.

4 Discussion

In the exhibitions, spectators were invited to a designated space to experience an interactive immersive audiovisual simulation. The spectators were astonished, as they had not encountered the pandemic in such a comprehensive visual, sonic, and tactile environment before. It was fortunate that the festival took place at the end of the quarantine period when arts events were starting to resume.

Encountering COVID-19 as an endemic, the audience was curious about our experiences over the past three years and how the virus interacts with our bodies. By delving into the concept of parasitism in humans, the project challenges traditional host-parasite dynamics, offering new perspectives on the virus-host relationship as a mutualistic and long-term association. This exploration reflects the complex interdependencies between humans and the environment.

Throughout the event and the project's evolution, we received various types of feedback from diverse audiences, including artists, scientists, engineers, physicians, and the general public. Artists expressed curiosity about the philosophical background and the aesthetic audiovisual representation, while engineers inquired about software technology and interaction design. Scientists and physicians recognized the project's value in presenting concepts through interactive audiovisual means that would not have been otherwise observable. Their expertise deepened their engagement, providing valuable insights and perspectives. The collaboration between art, science, and engineering brought multifaceted discussions to the immersive audiovisual simulation, enriching the project.

During the development phase, we received valuable feedback on the scale of particles, dynamics, and mechanisms of the coronavirus, as well as the components within the human body. This feedback improved the scientific realism of the project, while considering broader socio-political implications within the framework of cultural and critical theories. By incorporating suggestions and insights, we enhanced the accuracy and authenticity of the simulation, ensuring a faithful representation of the scientific concepts involved. This aspect facilitated precise conversations among scientists and highlighted different perspectives on the imaging and understanding of the coronavirus and its mechanisms. Through visual and audio expressions, the project sparked extensive discussions, encouraging a deeper exploration of the subject matter from cultural and critical perspectives.

The visual-sonic artistic representation of science served as a catalyst for dialogue among a diverse audience, fostering a greater understanding and appreciation of the scientific concepts presented. By envisioning strategies for coexistence with the virus in a virtual space, the project opens up possibilities for challenging dominant narratives and exploring alternative ways of navigating the complex social, political, and cultural dimensions of the pandemic. Still, this research primarily focuses on the transformation of data stemming from the human-pathogen relationship, rather than the socio-political impacts that have arisen since the pandemic became a part of our daily lives. We acknowledge that the research has also prompted critical questions regarding power structures, ideologies, and the unequal impacts of the pandemic on various communities. These concerns encompass issues such as hate crimes, with a particular focus on those targeting Asians [17,23], as well as domestic violence [21] and disparities in hardware availability within remote education systems [7, 8, 15, 27]. These intricate matters, closely tied to cultural and social backgrounds, can be integrated into our future endeavors to coexist with the SARS-CoV-2 virus.

For the forthcoming advancement of this research, we intend to address the societal aspects of our communities, expanding the research data's scope to examine how pathogens can influence our society from the nano to macro level.

5 Conclusion

This paper delves into the artistic interpretation of the intricate interactions between the SARS-CoV-2 virus and various components of human cells. Drawing inspiration from sociocultural perspectives on the relationship between humans and pathogens, we embarked on developing an immersive audiovisual narrative that simulates the mechanisms of SARS-CoV-2 propagation, articulating the complex process from the conducting zone of the airway to the cellular membranes containing ACE2 receptors.

Different stages of the mechanism can be intervened with, allowing for back-and-forth interactions or the acceleration and deceleration of the narrative through the use of interactive components. This interactive element actively engages the audience and enables the performer to create more intricate audiovisual structures with compositional motives. The realistic scenery not only imparts pedagogical knowledge but also sparks discussions from various perspectives, encompassing art, science, and technology.

Over the past three years during the pandemic, the SARS-CoV-2 virus has had a profound impact on both society and individuals. This project delves into the use of simulation to comprehend and communicate scientific data through visualization, while also exploring the interspecies relationship of parasitism as a long-term and mutualistic association.

Through the collaboration between scientists and artists, this ongoing project represents an exploration of parasitism research, with a specific emphasis on our current and future coexistence with the coronavirus and its broader connections to social, political, and cultural aspects. As the global population continues to navigate the effects of the pandemic, this project convincingly presents the potential of virtual reality in envisioning effective strategies to manage our relationship with the virus.

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