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Interactive exploration of a hierarchical spider web structure with sound

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Abstract: 3D spider webs exhibit highly intricate fiber architectures and owe their outstanding performance to a hierarchical organization that spans orders of magnitude in length scale from the molecular silk protein, to micrometer-sized fibers, and up to cm-scale web. Similarly, but in a completely different physical manifestation, music has a hierarchical structure composed of elementary sine wave building blocks that can be combined with other waveforms to create complex timbres, which are then arranged within larger-scale musical compositions. Although apparently different, spider webs and music have many similarities, as we point out in this work. Here, we propose an intuitive and interactive way to explore and visualize a 3D *Cyrtophora citricola* spider web geometry that has been digitally modeled with micron-scale details from full-scale laboratory experiments. We use model-based sonification to translate the web architecture into sound, allowing for aural perception and interpretation of its essential topological features. We implement this sonification using Unity3D and Max/MSP to create an interactive spider web environment in which a user travels through a virtual spider web. Each silk fiber in their field of view is sonified using different sine waves. Together, the sonified fibers create new and more complex timbres that reflects the architecture of 3D spider webs. These concepts are implemented into a spider web-based instrument for live performances, art installations and data exploration. It provides an unprecedented and creative way to immerse the composer, audience and user in an immersive multimedia experience generated by the complexity of a 3D spider web.

Keywords: Interactive sonification, 3D spider webs, fibers networks, data exploration, immersive multimedia experience.

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1. Introduction

Sonification, a method of auditory display, is a method to aurally conceptualize data with non-speech audio, allowing the users to explore information acoustically [1–5]. Sonification is used in numerous applications such as fire alarms, cardiac monitoring, and data exploration, as well as creative art installations [2]. Sonification is an excellent tool for data exploration [2] as the human ear is well-suited to the perception of temporal changes and pattern identification, allowing for the identification of interesting data patterns in large and complex datasets [6–8]. Combined with a visual representation, data sonification provides a more holistic experience of the data and can deepen our understanding of it, especially when the data is difficult to interpret with sight only [1, 2].

Depending on the application and the interactivity of the system, a specific sonification technique may be used. Parameter-mapping sonification is the most commonly used method, and consists of translating data into sonic events and assigning variables to a variety of acoustic characteristics, such as pitch, amplitude, time, and envelope [1, 2]. A more recent method is model-based sonification: the data is transformed into a dynamic model, which generates sound through user excitation [2]. Interacting with this dynamic model is similar to tuning and playing a musical instrument [9], since in both cases the user is able to adjust and excite the model. Aside from observation, humans primarily learn through interaction with the physical world [3], which explains how interactive sonification can be effective. Sonification for scientific applications such as data mining or exploration requires accuracy, while sonification for musical applications needs to be aesthetically pleasing [10]. Nevertheless, accuracy and aesthetics often work together in sonification, both for art and science. Aesthetics helps the user stay focused on the sonification piece [10]. Accuracy conserves data precision and prevents introduction of human artifacts [10]. Using interactive sonification, the user can decide which aspect of the sonification to prioritize, and tune the parameters to find a suitable balance between accuracy and aesthetics for a particular application [10].

The hierarchical architectures of spider webs and music have many similarities. Spider webs' hierarchical structure ranges from silk protein, to micrometer-sized fibers, to cm-scale spider webs [11–14]. Similarly, music is organized at its lowest scale in sine wave building blocks, which can be assembled to design richer timbres. At its highest scale, musical compositions are created from a combination of timbres [1, 15, 16]. Spiders use vibrations to communicate and sense prey, predators, and the environment [17, 18]. A spider web can also be compared to a musical instrument as the spider tunes and plays its web for communicating, foraging, and protecting itself [19, 20]. The correspondence between spider webs and musical instruments (and the spider as 'musician') was previously explored artistically by Saraceno et al. [21] through the scientific framework of biotremology (vibrational communication). Contrarily to well-known 2D orb web geometries, arranged in radial and spiral threads, three-dimensional (3D) webs have a complex and intricate architecture that is difficult to quantify and visualize due to the micron-scale size of the fibers [22]. Su et al. [22] developed an automatic method to capture such 3D silk networks in an automated way, which consists in taking high-resolution images of slices of the web illuminated by a moving sheet laser and then constructing a 3D model from image processing algorithms. The first manual method was developed by [23–25].

Using this 3D model, it is possible to visualize the structure; however, adding sonification would bring another perspective for comprehending the model and natural spider webs, and identifying key web features. This model was sonified as reported in [1], using parameter-mapping and combined with animations through which the listener can determine the fiber lengths, connectivity, and web porosity, depending on the virtual location of the listener in the spider web. This earlier non-interactive sonification approach requires the listeners to know and understand the sonification rules in order to analyze the piece and derive insights from the web [1]. As humans already intuitively interact with real-world objects, their environment, and other humans [2], adding an interactive aspect to spider web sonification can improve user experience and allow them to navigate through and manipulate the complex 3D fiber network data more efficiently [7, 9]. An interactive 3D web holistic exploration audiovisual tool can help researchers, musicians, artists, and any listeners to locate essential features and patterns of the web. Understanding 3D spider topology can lead to a better comprehension of its role, with silk, in carrying out the functions of the webs.

3D spider webs are difficult to visualize and comprehend because of their micrometer size fibers and their complex macroscale fiber network architecture. Presently, analyzing the structure of a 3D spider web is limited to the manual manipulation of a 3D spider web model, by rotating the model or zooming in and out, and a computational data analysis to find the spider web features. Therefore, adding sonification would complement the visualization and enhance pattern identification in complex datasets [26]. The objective of this study is to visualize and interact with the complex architecture of the 3D spider web data through sight and sound in an intuitive and holistic way. We aim to create a platform for visualizing 3D spider web architectures and for creative purposes. Our hypothesis is that the combination of interactive sonification and visualization can provide a more immersive and holistic experience and understanding of 3D spider web geometry data. This research has led to the development of an interactive and immersive platform for visualizing 3D spider web data through sight and sound.

Using model-based sonification and the analogy between spider webs and music, we introduce a novel interactive tool for exploring complex fiber networks that can also be used as a virtual musical instrument for live performances and creative art installations. The user is immersed in a virtual 3D spider web environment, travels through the web, and hears the fibers that are in their field of view. This data exploration and manipulation tool can be used for numerous and versatile 3D network applications beyond spider web topologies, such as social, transportation, or neural networks [7], just to mention a few. It is also a creative platform with built-in parametrizing freedom for artists to create, tune, and perform unique musical pieces from spider web data.

Our paper is organized as follows. First, the interactive sonification model of the 3D spider web and its implementation are presented. Second, we describe how this model can be used as a musical instrument for art performances, which we have produced and named the “Spider’s Canvas/Arachnodrone” project (arachnodrone.com). Third, we discuss how we can use this model for exploring spider web architecture and finding key topological features. Finally, in the fourth part, we explore future applications of this data exploration musical instrument for data mining, arts, and 3D network holistic experiences.

2. Materials and methods

2.1 Spider web sonification model

Model-based sonification

Contrarily to parameter-mapping sonification, where data is mapped to sound with acoustic characteristics, model-based sonification (MBS) is a sonification technique that translates data into a dynamic model which produces sound with user excitation [2, 3]. It is by definition an interactive sonification. The model generates sound with user interaction in real time [2, 3], just as a musical instrument would respond to user action [9], and here, the data or the model is the instrument. Sounds rendered by the sonification model should be independent of the data [2], and the model is reusable for other data types. An MBS model is configured following the six stages of model setup, dynamics, excitation, initialization, parameters, and listener characteristics [2, 3]. The sonification model is summarized in **Fig. 1**.

Model setup

The setup stage consists in connecting data to the dynamic model [2]. The spider web sonification model is based on fiber topology data of a real 3D spider web contained in a 35.6 x 35.6 x 24.4 cm frame, that Su et al. [22] scanned and modeled. The natural spider web is a tent-web built by a *Cyrtophora citricola* species of spider. The spider web is a network composed of nodes (connections) and links (fibers). The network data is composed of a list of nodes with their xyz coordinates in space and a list of links with their two extremity nodes. The data has been normalized so that the longest edge of the frame is 1, to facilitate calculations. Here, the data space is the same as the model space, except for their dimensions; the model is also a spider web network. The user in the model space is modeled as a capsule (virtual body) and a camera (virtual eyes).

Model dynamics

The model dynamics configuration stage determines how the data under analysis will produce sound [2]. The user of the spider web exploration tool controls what they look at in the modeled web. For example, they can decide whether to look at a cluster of fibers or not. The fibers in their field and within an adjustable hearing radius produce sound, or else they stay silent. Those rules are illustrated in **Fig. 2**. The user can also choose to pluck a fiber that will produce sound and excite the neighboring fibers, which may produce sound as well. The sound propagation time depends on the length of the neighboring fibers. The user can also produce plucking when their virtual body in model space touches a fiber.

Model excitation

The model excitation setup defines the interplay between the user and the model [2]. The user plays by choosing their field of view, the hearing radius, and which fibers to pluck, and tunes the model by changing the parameters. They use a mouse or MIDI (Musical Instrument Digital Interface) continuous controllers to change the direction of their field of view and the hearing distance. For example, if the field of view is an area of the model space with no fibers the model stays silent, but if they change their field of view toward fibers, they will be sonified and produce sound if they are within the hearing radius set by the user. The user also can move their field of view using a virtual reality (VR) headset (HTC Vive), intensifying the immersive experience. When the user has the VR headset on, they can change their field of view by moving their head, and consequently navigate in the spider web. They operate both VR controllers to change the sonification parameters. They choose the parameter they desire to change on the left controller by pushing the trackpad or the trigger, then assign the parameter value by rotating the trackpad on the right controller. For the VR version of the sonification model, the parameters are limited to: hearing radius, frequency range, frequency rounding, frequency filter, and the speed of the user. The user can also choose to pluck a fiber by using the MIDI keyboard to send a command. They can tune many more parameters that can change the sound synthesized by controlling frequency assignment, frequency modification, frequency range, frequency filter, fiber colors, and others. For example, they can click on the Max 8 interface or on the MIDI keyboard the button assigned to the parameter they wish to change; they use the interface's sliders or the keyboard's knobs to change the parameter values. In this sonification model, the user manually sends commands through MIDI controls, computer, VR headset and controllers, keyboard, and mouse: they have a direct interaction with the model.

Model initialization

Initialization is the status of the model immediately after setup [2]. After setup, the user is placed at the origin of the model space and the hearing radius is set to 0. Whether there are fibers or not in the field of view of the user, they will not be sonified, as they are considered to be not within the hearing radius.

Model parameters

This stage explains the rules that transform data into sound [2]. The principal parameters that the user can adjust are summarized in **Table 1**. Each sonified fiber is a sound source and produces a simple sine wave, the frequency of which is determined by the length of that fiber. By default, the frequency of the fiber is inversely proportional to the fiber length, which is the case for string vibration. Indeed, the resonance frequencies of a string under tension and fixed at its extremities for a given mode n are:

$$f_n = \frac{1}{L}\left(\frac{n}{2}\sqrt{\frac{T}{\mu}}\right) \quad (1)$$

with μ the mass density, T the tension, and L the length of the string [27, 28]. For simplicity, we choose the fundamental harmonic (n=1). We choose this fiber length-frequency relationship as the model's default setting because we are already intuitively accustomed to this rule. For example, if we look at the strings of a harp, we expect the shorter string to have a higher pitch than the longer fiber string. The user can also choose to assign frequencies linearly to the fiber lengths or even personalize their own fiber length-frequency relationship (**Fig. 2**). The fiber frequencies can also undergo frequency modification such as frequency rounding, low resonance frequency filtering, frequency shifting by addition, and frequency modification through adding a percentage. The frequency ranges to the limits of human hearing frequencies, from 20Hz to 20,000Hz. To get a richer and more complex timbre, those extremes are adjustable.

The amplitude of the sound produced by the fibers is related to their distance from the user. The fiber distance is defined as the distance between the center of the fiber and the user's virtual body in the model space (**Fig. 2**). Similar to the fiber-frequency relationship, by default, the amplitude is inversely proportional to the distance, which is the case for sound waves. The user has the option to change this relation to linear or to free-hand draw a relation. The user has infinite ways to optimize and tune the relationships between fiber length-frequency or fiber distance-amplitude.

The plucked fibers follow the same fiber length-frequency and distance-amplitude relationships as the fibers in the user's field of view. To distinguish them from the sound produced by the static fibers, the user can change the plucked fibers' amplitude envelope (attack, decay, sustain, release) and the amplitude dissipation factor. The envelope will define how fast the sound will reach its highest amplitude, how long it will decay and sustain, and how slowly the amplitude will drop to zero. The amplitude dissipation factor measures the loss of amplitude as the plucking propagates to neighboring fibers.

Model listener characteristics

The listener characteristics describe the relation between the user/listener and the sound sources (fibers), and how fiber locations, orientations, and distances influence the user's perception of sound [2]. In our model, the user is in a virtual world where they are surrounded by a fiber network – here, the 3D spider web. In this world, the user's body is modeled as a 2 m capsule and their eyes are a virtual camera placed at 1.58 m from the bottom of the capsule (feet). The user has the option for the capsule to have a rigid body, in which case it allows collisions to trigger fiber plucks. They either have free movement inside of the space (including flying), or they are placed in a predefined adjustable path. On the path, the user controls their speed and path direction. It allows them to focus only on looking (moving their field of view) and finding interesting parts of the data, while still allowing movement to explore the whole network. Because the user only hears what is in front of them, and needs to move their head to explore the data, our spatial model does not require a multi-channel audio system; however, with more speakers, the user receives additional information on fiber location and distribution. The user can adjust the number of output channels (default 1). For a multi-channel setup, the rectangular field of view is divided into a grid whose row and column numbers are defined by the user. A grid cell represents one channel output. Only cells containing fibers output sound. When a fiber crosses multiple grid cells, its amplitude is distributed across the associated channels following this law:

$$A_{Channel} = \left(\frac{1}{N}\right)^{0.75} A \qquad (2)$$

with $A_{Channel}$ being the amplitude of the fiber that is produced by the channel assigned to the cell containing the fiber, N is the number of cells the fiber is seen in, and A being the amplitude of the fiber related only to the distance to the user.

2.2 Implementation and code development

The sonification model is implemented in Unity3D (unity3d.com) and Max 8 (cycling74.com) (**Fig. 3**). We use the game engine Unity3D to navigate inside a virtual spider web environment, to compute the basic sonification parameters based on the virtual model, and to create visuals to aid the interpretation of the sonification. We use Max 8, a programming software for music and multimedia applications, for sound synthesis and the creation of a user interface. Max 8 and Unity3D communicate through OSC (Open Sound Control) messages using UDP (User Datagram Protocol) packets. Instead of using only Unity3D to create the sonification model, we use two communicating software packages because Max 8 provides richer support for sound synthesis and for creating user interfaces independent of the visualization of the web.

Unity3D

Unity3D renders the 3D spider web network from a list of point coordinates and a list of pairs of points that need to be linked. For each point and link on the lists, the program generates a 0.1 m diameter sphere and cylinder, respectively. We use Unity3D to create a first-person point of view interface where all the graphics are rendered from the user's point of view. The user navigates through the web by moving the mouse or their head with a VR headset, the positions of which are tracked and translated in camera direction. The virtual camera renders the user's field of view. For each fiber, rendered by a cylinder, in the field of view of the user, if the distance between the center of the fiber and the user is shorter than the chosen hearing radius, then we compute the frequency and amplitude of the sonified fiber according to the fiber length-frequency and fiber distance-amplitude relations chosen. A list of frequency-amplitude pairs, corresponding to the sonified fibers, per audio channel is sent to Max 8, where the sound synthesis happens. To aid user interpretation, the visuals respond to the sonification by changing the colors and textures of the spheres and cylinders that are in the field of view and within the hearing radius, corresponding to sonified fibers. The user can visually distinguish the fibers that produce sound from the fibers that are silent.

Several user-controllable parameters allow for manipulating the frequency and amplitude associated with a fiber, shown in **Fig. 4**. Several, such as the number of columns and rows (described in section 2.1) and data thinning options, are typically set before interaction begins. Others can be changed dynamically to affect the output of the system.

Other parameters allow for controlling the frequencies assigned to the fibers. The minimum and maximum frequency (i.e. the frequency assigned to the longest and shortest fiber, respectively) can be set with a variety of frequency distributions available, ranging from linear to user-defined transfer functions. In addition, an arbitrary rounding frequency can be chosen. This defines the 'fundamental frequency' of the web, and the frequency for each fiber is quantized to the closest integer multiple of this fundamental.

Max 8 implementation

Lists of frequency-amplitude pairs are sent to Max when an animation frame is rendered in Unity3D, with one list being sent for each audio channel. These lists are used as parameters for multiple instances of an additive synthesis algorithm. The output of each instance is the sum of a bank of sine wave oscillators, one oscillator for each frequency-amplitude pair.

Each new set of values is assigned to an additive synthesis instance with an attack-decay amplitude envelope. The use of multiple synthesis instances, each with their own envelope, prevents audible discontinuities when new sets of frequency-amplitude pairs are received, and the overlap of instances smooths the transition between new parameter values.

The output of the synthesis instances is then further processed as described in Section 2.3, and each channel is sent to a dedicated output of a multi-channel audio interface.

We also used Max 8 to create a simple user interface to send commands and parameters to Unity3D. This interface provides access to all of the Unity parameters shown in **Fig. 4**. The user interface also allows for the use of standard MIDI controllers for control of parameters for both Unity and Max.

2.3 Application: Spider's Canvas/Arachnodrone

The spider web interactive sonification model was used as a creative platform for live performance and art installations, where the composer and audience are immersed into a multimedia experience inside of a complex 3D spider web. Inspired and commissioned by Studio Tomás Saraceno (STS), in the context of Saraceno's carte blanche exhibition, *ON AIR*, at the Palais de Tokyo, Paris (2018), Spider's Canvas/Arachnodrone is the name of a multimedia live performance in which the sonification of the fibers of the spider web is used as a virtual spider web musical instrument. The premiere of Spider's Canvas/Arachnodrone was performed by Isabelle Su and Ian Hattwick on the spider web instrument, Evan Ziporyn on the EWI (Electronic Wind Instrument), and Christine Southworth on the guitar and EBow (Electronic Bow) (**Fig. 5(a,b,c)**). The composers, performers and audience travel together sonically through the intricate architecture of the *Cyrtophora citricola* 3D spider web. Following its premiere at the Palais de Tokyo in November 2018 for Saraceno's public program, 'ON AIR live with …', the Spider's Canvas/Arachnodrone was performed on three subsequent occasions at the MIT Theater and on several popup performances (**Fig. 5(d,e)**) at MIT.nano in February 2019. The videos **Online Resource 1** and **Online Resource 2** are excerpts of the performances at Palais de Tokyo (Paris) and the MIT Theatre, respectively. The Spider's Canvas/Arachnodrone also was also exhibited as an immersive environment at MIT.nano, where the virtual spider web sonification model musical instrument runs automatically (**Fig. 5(f)**).

Sound Sculpting/design

The MBS methodology described in Section 2.1 was designed in order for the data regarding the spider web structure to be perceptible. In order to prepare the instrument for a concert performance, we implemented additional synthesis functionality in Max and designed a user interface that controls both Unity and Max.

The primary concern in designing these additional functionalities was to support the creation of a wide range of sonic textures. Several kinds of parameters were defined when creating the Unity model, as described in Section 2.2 above. For example, one parameter was the selection of audible fibers, determined by the player's location, orientation, hearing radius, and also the frequency distribution of the fibers.

Several additional processing steps were applied to the lists of frequency-amplitude pairs once they were received in Max, as detailed in **Fig. 4**. First, frequency-dependent amplitude scaling was applied to individual frequency components to compensate for perceptual differences [29]. An empirically derived scaling function was applied via a lookup table, rather than using an existing standard such as A-weighting. However, this resulted in a gradual amplitude attenuation as the frequency increased. Second, the lowest five frequencies from the list were sent to a sub-harmonic generator. This generator produced an additional set of frequencies, consisting of varying subdivisions of incoming frequencies (e.g. 4/5, 3/4, 1/2, 1/4, etc.), which were sent to a separate additive synthesizer. It is worth noting that the amplitude of this subharmonic generator tracked the RMS amplitude of the web's primary additive synthesizer, with additional user-control of the final level of the subharmonics. Finally, a random detuning of individual frequencies was applied to the frequency-amplitude lists.

Each final list of frequency-amplitude pairs was sent to an additive synthesizer. The audio output of each synthesizer was sent through additional audio processing stages: a 4-pole resonant lowpass filter, a delay module, an amplitude modulator with a frequency range of 0-100 Hz, and a reverb generator. The overall structure of the processing contained within Max 8 is presented in **Fig. 6**.

Performance with the Web

The sonification model is a virtual musical instrument where the musician plays the spider web data. Together, the performers improvised on the spider web instrument, the EWI, the guitar, and EBow, creating a new holistic experience for both performers and audience. In the case of the semi-permanent art installation, the spider web instrument played autonomously, continuously, and randomly, generating at each moment a unique audience experience. In this situation, the virtual avatar was still following a predefined path but the sonification parameters changed over time.

For the performance of Spider's Canvas/Arachnodrone, control of the Spider Web instrument was shared between Isabelle Su and Ian Hattwick. Su determined the orientation of the avatar within Unity as it followed a predefined path, and also determined visual characteristics of the web as rendered by Unity, including color, transparency, and other visual effects. Hattwick controlled parameters relating to the audio output of the web. Within the set of Unity parameters available, hearing radius, frequency range, and frequency rounding were found to be the most aesthetically useful for the performances and the art installation.

The division of labor in performance was driven by the lack of cognitive bandwidth as well as the importance of the multimodal visual-auditory rendering of the spider web. Having one player focused on both the orientation of the player and the overall visual output contributed to a more reliably interesting visual presentation to the audience. The division of labor was only used for live performances for creative purposes.

Given a specific field of view as determined by visual considerations, the hearing radius became a critical control for creating a perceptual link between the fibers and their sonic output. In general, we found that smaller hearing radii, with fewer active fibers, made the appearance or disappearance of individual fibers more noticeable. In addition, this enabled a perceptual distinction between the frequencies of fibers with varying lengths.

As the hearing radius increased, the contribution of individual fibers became more difficult to discern to the casual listener. At this point, sculpting of the overall sonic output of the web became more important. Several performance parameters were used to influence the audible frequency content of the web, specifically the minimum frequency used by Unity to determine the frequency spread of the fibers, as well as the frequency of the lowpass filter.

These two different approaches to shaping the frequency spectrum led to radically different effects. Increasing the minimum frequency used in Unity did not affect the number of sounding fibers, but instead rescaled their frequencies. The lowpass filter, on the other hand, attenuated the amplitudes of fibers whose frequency was above the center frequency of the filter (as well as amplifying frequencies at the cutoff frequency, dependent upon the filter's resonance). A combination of both the minimum frequency parameter and the lowpass filter allowed for the creation of a band-limited spectrum whose density was determined by the minimum frequency and whose width was determined by the lowpass filter.

A variety of modulation options also allowed for temporal coloration of the sound. A single performance control was created to scale the amplitude envelope of the additive synthesis instances. The rate at which new additive synthesis instances was triggered was not controllable as this was fixed by the frame rate of Unity. In normal operation, the length in seconds of the amplitude envelope is chosen to create smooth overlaps between these instances, removing any temporal perception of the frame rate. However, with shorter envelopes the triggering of a new instance can become perceptible, ranging from a subtle pulsation to a more granular sound as envelopes grow shorter than the frame rate.

Additional temporal coloration can be applied by using modulation of amplitude and of delay time. Performance controls for these parameters were created which entirely removed modulation at their minimum setting, and exceeded the ability to perceive individual sonic events (e.g., the modulation rate moves into the audible frequency range) at their maximum setting. The control of the amplitude envelopes, rate of amplitude modulation, and rate of delay time modulation allowed for the creation of a variety of interlocking rhythmic cycles.

The rounding parameter in Unity was chosen to create of harmonic sounds. Rounding, specified in Hertz, quantized fiber frequencies to the nearest integer multiples of the rounding value, effectively setting the fundamental frequency of a harmonic series. At higher values it also reduced the total number of possible frequencies (which was limited both by Unity's maximum frequency parameter and the bounds of human perception). At lower rounding frequencies, fibers needed to be quite similar in length before they quantized to the same frequency. However, as the rounding frequency increased each harmonic was generated by an increasing range of fibers. The consequent reduction of the total number of frequency components caused an audible sparseness in the frequency domain. Generally, we found a rounding frequency of between 32 and 90 Hz to provide a consistent sense of a harmonic fundamental while preserving a rich spectrum of upper harmonics. The inclusion of a subharmonic generator whose amplitude can be controlled independently of the main additive synthesizer allowed for further reinforcement of the fundamental. Below 32 Hz a clear sense of the fundamental was lost, and as the rounding decreased to 0 the harmonic complexity of the web increases, until it approached the unquantized state.

Rounding frequencies above 32 Hz increased the consonance of the sound. Given the digital nature of the additive synthesizer, it could lead to textures that were unnaturally pure. To allow for the reintroduction of small tuning discrepancies, a detune parameter was implemented, which randomly detuned each fiber, with the maximum amount of detuning being exponentially scaled from +/-100% to +/-150%.

Performing with the Spider's Canvas/Arachnodrone is reminiscent of electronic music performance practices which focus on interactive systems [30]. At moderate hearing radii, it could be difficult to predict the sonic texture which came from the web, and even at smaller hearing radii the ability to predict or control which frequencies would arise from the web was limited. Instead, the web became a source of sonic complexity constantly shifting character, which forced the performer to listen carefully and react accordingly in order to shape the sound to fit the emerging musical form of the performance.

Given this complex interaction between performer and web, there were several performance strategies which provided fairly consistent control. The shaping of the frequency spectrum, as described above, is one example, and the use of rounding to create sequential series of fundamentals is another. However, even with these strategies it was necessary to listen carefully as the frequency spectrum of the web shifts from moment to moment.

Installation

Following the concert series at MIT, Spider's Canvas/Arachnodrone was installed as a multimedia installation at MIT.nano, on MIT's campus. We built a 10'x10'x10' aluminum frame with 3 of the 4 vertical sides of the cube being covered with grey shark tooth scrim, and 3 projectors projecting through each side. The installation was first used for the performances and reused for the art installation. For this installation, a fixed trajectory and player orientation was set to repeat within Unity, and a procedural function was created to morph between snapshots of audio parameters within Max 8. While the exact trajectory within the audio parameter space was non-deterministic, the overall character of the visual and audio parameters was set to repeat every 15 minutes. We created a video montage of photographs of local Lexington (Massachusetts) spider webs mixed with scans and model images of the spider web used for the sonification. Inspired by STS' multi-species hybrid spider webs [31], we projected on the 3 screens the video montage overlapped with the spider web instrument user's viewpoint. Just as the spider plays inside the web, the performers played inside the cube, creating the illusion that they are inside a large-scale and dynamic spider web (**Fig. 5**).

2.4 Empirical Evaluation

We used an online survey to measure and analyze the immersiveness and holistic constructs of our 3D spider web interactive sonification model. We aimed to evaluate how interactive sonification can enhance intuitive understanding of spider web architecture data. We developed an online survey using Google forms that included demographic questions and exercises to complete. We invited participants through social media, emails, and our networks. We expected the survey to last about 20 min.

The demographic information collected includes: age, gender, highest degree received, level of expertise with spider webs, sonification, virtual reality, musical instrument, and musical composition experiences. We also asked the participants whether they played the actual sonification game, whether they were in the audience of the Spider's Canvas/Arachnodrone performances, and whether they saw the art installation.

Following the demographic questions, they were asked to complete a series of exercises in which they watched video recordings with sound of the spider web sonification platform and then answered questions. The videos for the six exercises are described in **Table 2**, with their order in the survey. Following each video, a series of questions using a five-point Likert-type scale (1: Strongly Disagree, 2: Somewhat Disagree, 3: Neither Disagree nor Agree, 4: Somewhat Agree, 5: Strongly Agree) and comment questions were presented to the participants. The questions focused on their understanding of the rules and qualities of the sonification model. The questions are summarized in **Table 3**. The questions assigned to the exercises 5 and 6 were adapted from [32]. The results were analyzed using MATLAB [33]

3. Results and discussion

The spider web sonification model could be used not only as an artistic creative platform but also as a scientific research tool for visualizing, exploring, and understanding large and complex network datasets. Here, we use the model for identifying and locating key topological features of a *Cyrtophora citricola* 3D spider web, such as its fiber length distribution and web density. This particular spider web is composed of a dense mesh-like region sandwiched between more porous tangle regions. We choose to investigate a 76 mm cube sample of the web, belonging to the tangle region. The spider web network is scaled up so that its size is 30 m, making the 2 m tall user fully immersed in the structure. For the data exploration analysis, we restrict the interactivity to these parameters: field of view, movement, and hearing radius.

The user has complete control of their viewpoint (**Online Resource 3**) and hearing radius (**Online Resource 4**): they decide which fiber regions to look at and therefore hear. Novice users can start learning how to use the sonification tool by assigning a short hearing radius (for example, 2 m), allowing them to hear one to a few fibers at a time when fibers are in their field of view. Using the default inversely proportional fiber length-frequency relationship, if the user hears a high pitched or a low pitched sine wave, it would mean that the sonified fiber in front them is very short or very long, respectively. The user can adjust and personalize the fiber length-frequency parameters to their needs. For example, if they cannot hear very high frequencies, they can decrease it to a hearing level. The video **Online Resource 5** is an example on how to use the spider web instrument model with VR headset and controllers.

As the user gets familiar with the tool, they can increase the hearing radius to include more sonified fibers. They hear a complex sound produced by a superposition of simple sine waves of different frequencies and amplitudes, corresponding to different fiber lengths and distances, respectively. The user is facing a high-density region of the web where they can distinguish numerous different sine waves and a more porous web region where they only hear a few different sine waves. Similarly, if they hear many high frequencies, they are in front of a region of short fibers, or long fibers if they hear low frequencies. The user can differentiate high or low fiber density regions and determine the distribution of fiber lengths.

One effective method to use the model for data exploration is to start with a larger hearing radius to locate fiber regions of interest, then slowly zoom in by decreasing the hearing radius so only a few fibers are heard, and observe the details of the structure. By adjusting the hearing radius, we can also clearly conceptualize, both through sight and hearing, the hierarchical structure of the spider web.

The sonification model and rules are set up so that if the user closes their virtual eyes (no fiber rendering), they should hear exactly what is in front of them. However, visualization is useful for aiding the comprehension of the sonification and helping the user grasp web features more in detail, especially for beginners. By assigning different colors and textures to the sonified and silent fibers, users can visualize which fibers they are hearing. After using sonification to quickly hear and locate web density and fiber distribution, users can use sight to recognize the heard fibers and carry out a deeper analysis. As the sonification does not provide fiber orientation or connectivity information, visualizing through sight provides more insight into web architecture. With only visuals, we would need to rotate and zoom in and out of the web to capture the web characteristics. Paired with interactive sonification, users have a more complete holistic experience of the data. They can use sonification to have a quick overview of all the data (large hearing radius) while preserving its complexity.

Similar to our sonification model, Papachristodoulou et al. [7, 26] have coupled interactive sonification and visualization for exploring complex network data, for a neuroscience case study. They have shown that sonification deepens the participants' understanding of the human connectome network data space. The connectome is the brain's neural connections map [34]. In their first study, they have assigned sound parameters, such as pitch and volume, to the features of the connectome [7]. In their second study, they have assigned sound samples for a specific brain region, modulated by the users' movements [26]. In both interactive sonification studies, they have shown that the dynamic sonification coupled with visualization helps with the identification and understanding of the connectome features. While our spider web datasets could be used as input in their interactive sonification model, the main difference is that we designed our sonification to enhance the identification of fiber length distribution and fiber density concentration within the complex spider web. One unique advantage of our interactive sonification model is that the sonification parameters are fully tunable by the users to fit their preferences during the interaction.

To measure the immersiveness and holistic constructs of the sonification model, we conducted an online survey. A total of 34 participants aged between 19 and 75 (M_{Age}=43.9; SD_{Age} = 16.25, 20 female, 13 male, and one non-binary) completed the online survey study. Most participants have a Master's (35.3%) or a Doctorate (41.2%) degree. Most participants shared that they know nothing or only know a little about spider webs (88.2%), sonification (82.4%), and VR (94.1%). Half of the participants do not compose or perform music and about a third of them do not play an instrument. Among the 34 participants, three compose, perform, and play a musical instrument professionally. Out of the 34, only one, six, and four participants have used the VR spider web sonification game, seen the Spider's Canvas/Arachnodrone performance, or visited the installation, respectively.

Our exploratory study led to descriptive statistics of the different survey exercises; they can be found in **Tables 4, 5, and 6**. Participants were asked to rate the qualities on a Likert-type scale. The qualities used to describe the sonification model included: immersive, holistic, intuitive, clear, match between sound and image, easily controllable, innovative, enjoyable, and inspiring. Overall, 65% of the participants somewhat agree or strongly agree with the qualities of the sonification model. In addition, 73% of the participants also intuitively understood the sonification rules, by simply watching the survey videos, as the rules were not described in the survey beforehand. They understood that fiber length is correlated to frequency. However, the online survey format of our study may have contributed to questions that led the participants to answer in confirming directions. In the future, we could carry out an in-person study followed by interviews would overcome these limitations.

Table 4 shows the descriptive statistics of the results from Exercises 1, 2, 3, and 4, which tested the participant's understanding of the sonification rules. The participants understood that the sound they heard was correlated to the fibers that were in the field of view of the player playing the sonification interface. All the survey exercises (except for the performance) consisted of video recordings with sound of the interface that a user would play as a first-person player. **Table 5** shows the descriptive statistics of Exercise 5, which asked them to rate the VR sonification interface. Participants have on average a stronger agreement with the VR audiovisual experience being immersive and innovative. **Table 6** shows the descriptive statistics of Exercise 6, which asked the participants to rate the qualities of the Spider's Canvas/Arachnodrone performance. Participants have on average a stronger agreement with the performance being innovative, enjoyable, and inspiring, which are aesthetic qualities [32]. Participants seem to enjoy the aesthetic qualities of the artistic performance.

Furthermore, we conducted two Spearman's correlation tests between the participants' musical instrument background and their understanding of the sonification qualities. We have found a statistically significant negative correlation between the participant's musical background with the immersive construct ($\rho=-0.53$, $p < .01$) of the VR sonification interface and the holistic construct ($\rho=-0.50$, $p < .01$) of the Spider's Canvas/Arachnodrone performance. Notably, the participants with a lower musical instrument background showed a better agreement with the immersive quality of the VR interface and the holistic quality of the performance. This is an interesting finding that we could explore further by increasing the participant sample size or interviewing the participants in the future.

In conclusion, the online survey has shown that participants understand intuitively the sonification rules of the sonification model, and they have found the VR experience immersive and innovative. They also shared a stronger agreement with enjoyable, inspiring, and innovative qualities of the performance. While this exploratory study was only focused on non-interactive video recordings of the sonification interface and performance, these results support that this multimodal work received higher than neutral ratings. However, we still need to measure the interactive quality of the sonification model, which can only be done with an in-person study, where participants would interact and manipulate the data themselves. For example, future research would include a larger participant sample size and would ask participants to interact with and personalize the sonification model to determine and locate fiber density and fiber length distribution.

3.1 Future applications

The intuitive and interactive aspects of this spider web sonification instrument are two of its most compelling features. Users can tune and personalize parameters of the model such as hearing radius, viewpoint, and movement, for a specific purpose, dataset, or personal comfort. Not only can we use the spider web data visualization tool for creative and scientific purposes, we can also apply it to any type of network datasets, including 2D spider orb webs, transportation, social, and many more types of networks. For a social network, where the length of a link between two nodes describes the relationship strength between two individuals, hearing a region of high frequencies (short link) would describe a group of close acquaintances, while low frequencies (long link) would represent a weak connection between individuals. The model's intuitive and tunable parameters allow anybody to use the tool, ranging from novice to expert users. Novices can limit their movements and the number of heard fibers and experts can simultaneously play with all the parameters to construct complex sounds.

This intuitive and interactive data exploration musical tool shows promising future applications in the field of arts, data mining, and holistic experience of 3D network data. For example, we can use it as a dancing platform, where the performers' movement would be tracked and translated into user movements inside of the virtual environment. The dance would not follow the music – but dancing would generate it [9, 35]. We can also use this network visualization method for aiding visually impaired persons to explore data without using their sight [36]. They can travel inside of a virtual 3D space and aurally conceptualize the lengths and locations of the network links directly in front of them. Adding 3D sound, with HRTF (Head-Related Transfer Function), would allow users to locate spatial data more precisely [37].

While this data visualization tool is an innovative and effective method to obtain insights into complex static structures, it does not provide any mechanical information about the spider web. Because rendering and physics features on Unity3D and data processing on Max 8 of large datasets are computationally expensive, we limited our study to static and smaller spider web architectures. In the future, we plan to add real-time mechanics to the method, allowing users to pluck fibers and hear the actual sound propagation in the web or to stretch a fiber and hear its sonified frequency changing with fiber length and its effect on the neighboring fibers. The user will have a more holistic and immersive experience, through touch, sight, and hearing. New mechanical and pattern insights could be derived from using this tool.

4. Conclusion

This paper reports a novel interactive method to visualize, through sight and sound, a 3D spider web architecture that can be used as a data exploration tool or a creative platform. We use model-based sonification to transform data into a model that produces sound with real-time user interaction. In other words, we created a spider web virtual musical instrument, where the data is the musical instrument. We use the game engine Unity3D and the multimedia program Max 8 to create a virtual spider web environment where the user is immersed in the network.

Fibers, if in the field of view of the user and within a chosen hearing radius, are sonified with sine waves, the frequencies and amplitudes of which are determined by fiber lengths and fiber-to-user distances, respectively. Overlapping multiple simple sine waves create a complex timbre, which reflects the hierarchical structure of the spider web, ranging from simple silk threads to an intricate 3D fiber network.

This tool can be used as a musical instrument but also a method to recognize spider web topological features. The method's intuitive and interactive aspects make it multipurpose and accessible for everyone. It provides a new way to understand data and find interesting patterns that would be difficult to comprehend with sight only.

Electronic Supplementary Material

- **Video 1**: ESM _1.mp4: Spider's Canvas/Arachnodrone show excerpt at Palais de Tokyo, Paris, on November 2018. Video by MIT CAST. More videos can be found on www.arachnodrone.com.
- **Video 2**: ESM _2.mp4: Spider's Canvas/Arachnodrone show excerpt at MIT theatre, on February 2019. Video by Robby MacBain (MIT CAST).
- **Video 3**: ESM _3.mp4: The user controls their field of view and fixes the hearing radius. The fibers on the screen are different every time the user changes viewpoint, and consequently the sonified fibers.
- **Video 4**: ESM _4.mp4: The user changes their hearing radius and fix their field of view. Only the fibers within the hearing radius are sonified.
- **Video 5**: ESM _5.mp4: VR version of the spider web sonification model. The video starts with a tutorial with the sonification and interaction rules. The second part of the video is a demonstration on how to use the sonification model. The user can change multiple sonification parameters such as the hearing distance, their field of view, maximum/minimum frequency, frequency rounding, filters…

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Figures and Tables

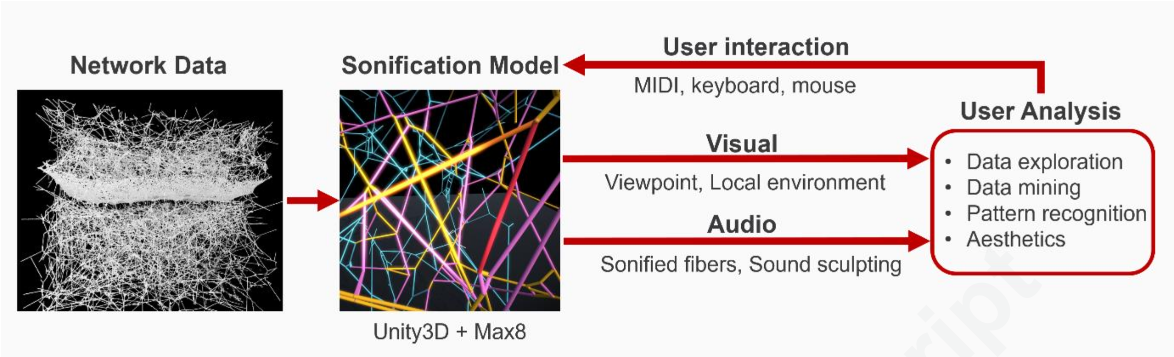

Fig. 1 Schematic of the interactive sonification process of the 3D spider web. We load the network data, here, the 3D spider web structure, to the sonification model, built on Unity3D and Max 8. The user interacts with the model by sending commands through MIDI messages, keyboard and computer mouse. The sonification model produces audiovisuals that the user can use for data exploration, pattern recognition and arts

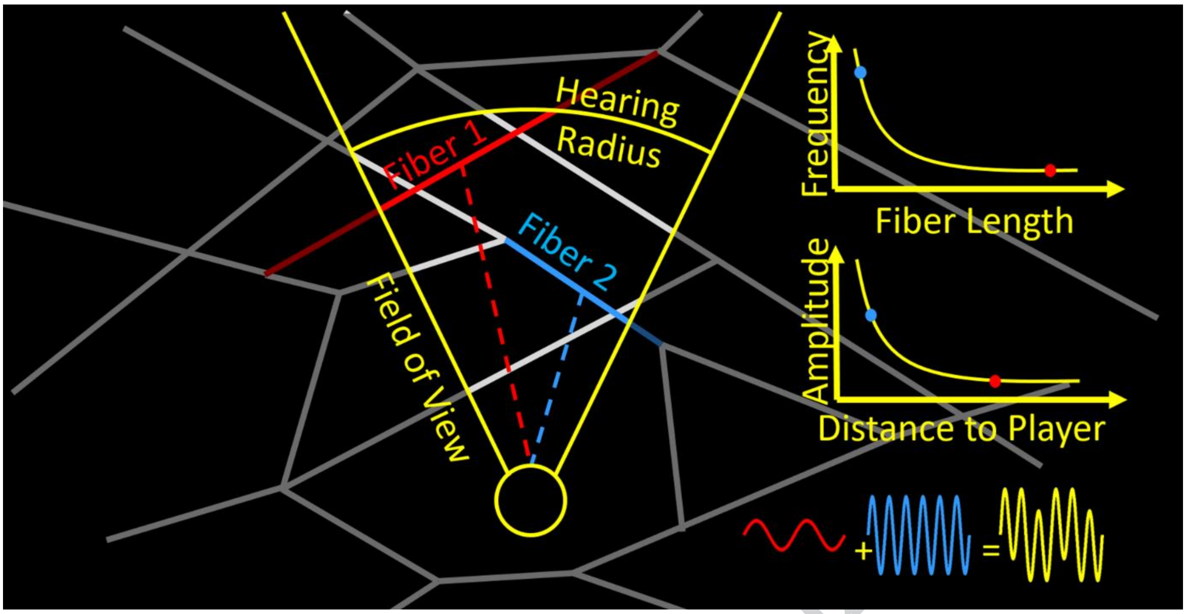

Fig. 2 Schematic of the sonification rules. The frequencies and amplitudes are inversely proportional (default) to the fiber lengths and distances to the player, respectively. The fibers inside of the user's field of view and within a chosen hearing radius are sonified with sine waves. In white the fibers that are sonified, and grey the silent ones. The superposition of simple sine waves creates a new waveform and consequently a more complicated timbre.

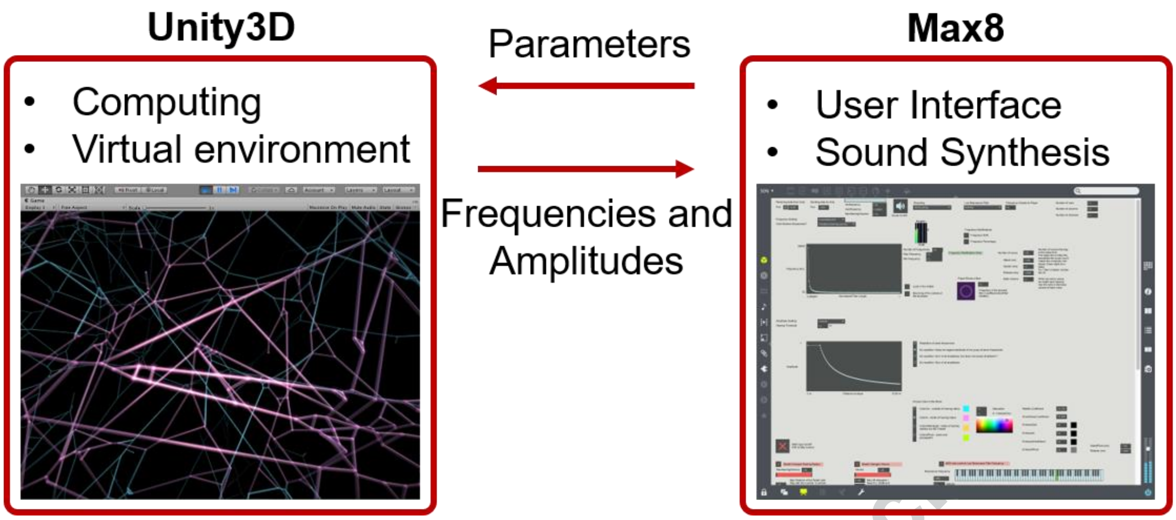

Fig. 3: Simplified schematic of the sonification model's implementation using Unity3D and Max 8

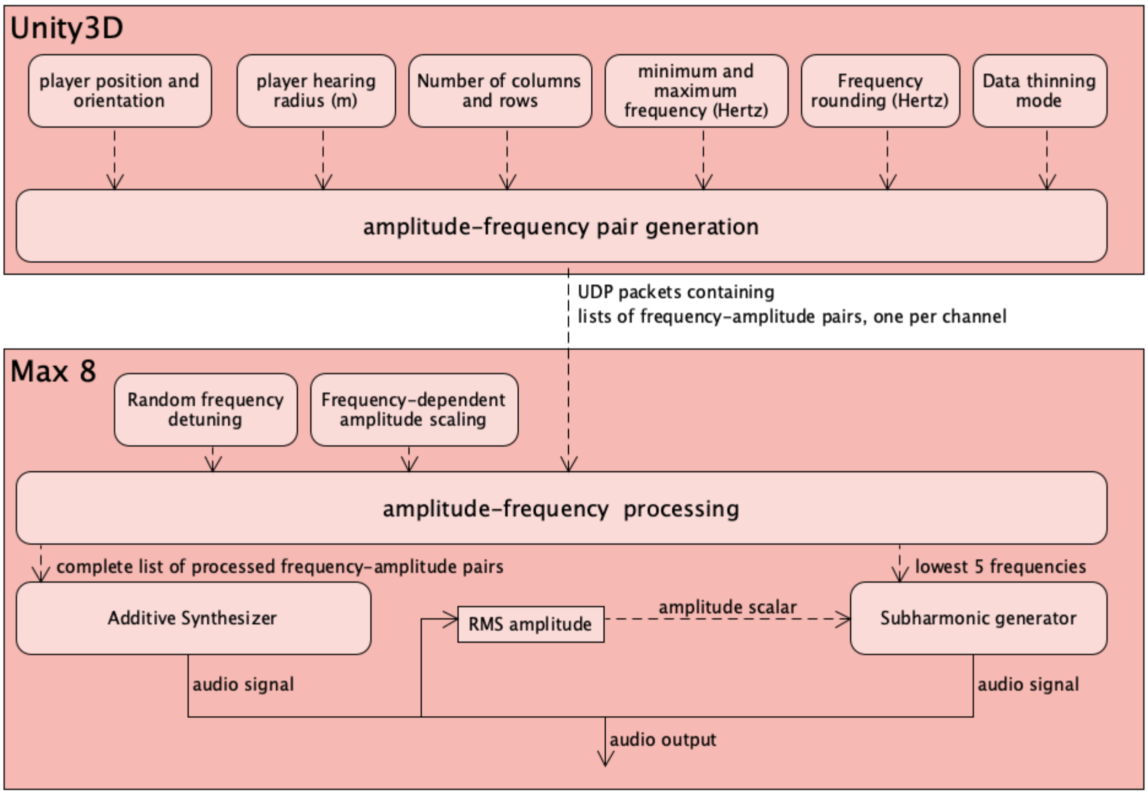

Fig. 4: Detailed schematic and workflow of the sonification model's implementation using Unity3D and Max 8.

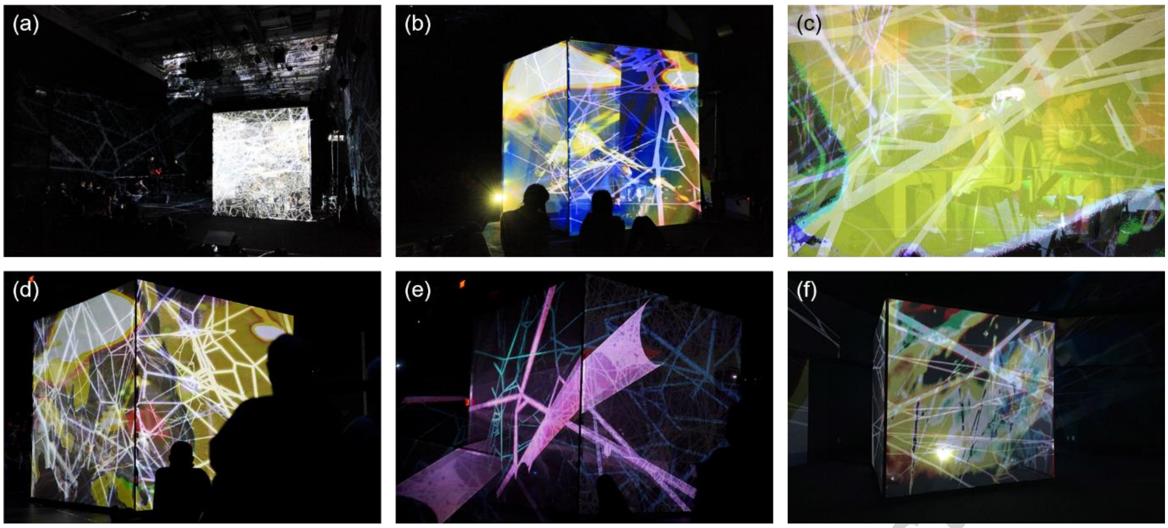

Fig. 5 Spider's Canvas/Arachnodrone performed by Isabelle Su and Ian Hattwick on the spider web instrument, Evan Ziporyn on the EWI (Electronic Wind Instrument), and Christine Southworth on the guitar and EBow (Electronic Bow). **(a, b, c)** Premiere of the Spider's Canvas/Arachnodrone performance at the Palais de Tokyo, Paris (2018). The performance was commissioned by Studio Tomás Saraceno (STS), in the context of Saraceno's carte blanche exhibition, *ON AIR*. **(d, e)** Spider's Canvas/Arachnodrone performances at MIT Theatre (February 2019). **(f)** Spider's Canvas/Arachnodrone installation at MIT.nano (February-June 2019). The installation runs automatically and autonomously. **(a, b, c)** Photo credit: Aurelie Cenno/Palais de Tokyo. **(d, e)** Photo credit: Leon Yim/MIT. **(f)** Photo credit: Isabelle Su/MIT

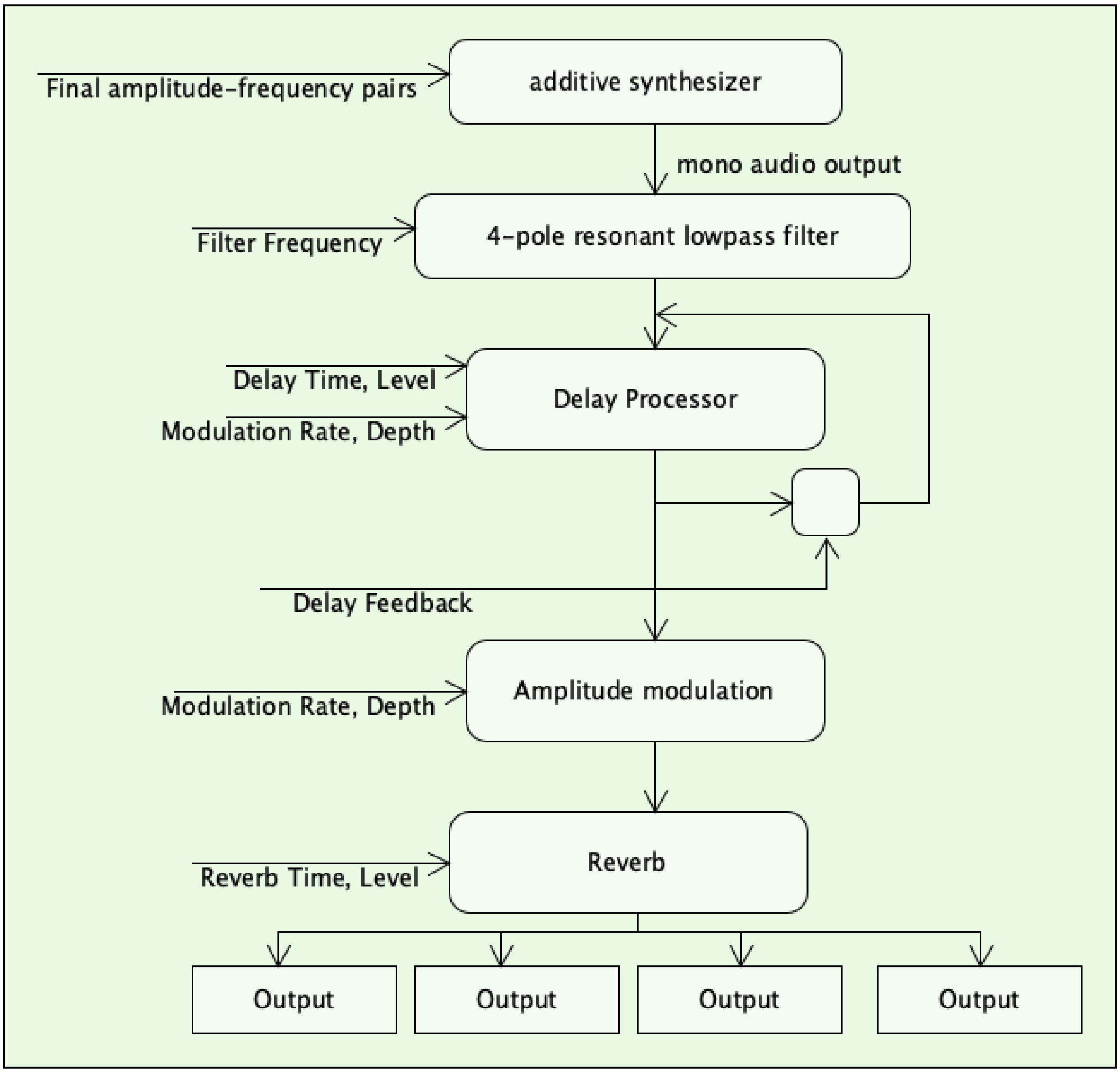

Fig. 6: Detailed schematic of the overall structure of the processing contained within Max 8.

Parameters	Description	Usage
Frequency	Relationship between fiber length and frequency	Data exploration
Amplitude	Relationship between fiber distance-to-user and amplitude	
Movement and speed	Navigate in space and control movement speed	
Field of view	Control of the camera movement in the virtual environment	
Frequency shifting by addition	Shift all the frequencies by adding a value or a percentage	Personalization and Artistic Creation
Frequency rounding	Round all the frequencies to the nearest multiple of a chosen integer	
Low resonance filter	Filter all the frequencies that are not a multiple or factor of a chosen value	
Fiber colors and textures	Colors/rendering texture of the sonified and silent fibers	
Spatialization	Choose a spatialization grid	
Fiber Plucking	Choose a frequency and pluck the fiber that is sonified to this frequency	

Table 1: Principal parameters for data exploration, personalization and artistic creation

Exercise	Input	Hearing radius	Field of view
1	Simple vertical fibers	Fixed	Variable
2	Simple vertical fibers	Variable	Fixed
3	Complex 3D spider web	Variable	Fixed
4	Complex 3D spider web	Fixed	Variable
5	Complex 3D spider web (VR demo)	Variable	Variable
6	Complex 3D spider web (Performance)	Variable	Variable

Table 2: Description and order of survey exercises showing video recordings with sound in the survey.

Questions		Exercise
What I hear is correlated to what I see (fibers) (1-5)		1, 2, 3, 4
Shorter fibers are assigned higher sounds (1-5)		1, 2, 3, 4
Longer fibers are assigned lower sounds (1-5)		1, 2, 3, 4
Pink fibers are assigned a sound (1-5)		2, 3, 4
Blue fibers do not produce sound (1-5)		2, 3, 4
I understand how the interface was used in the video (1-5)		5
The audiovisual experience is (1-5):	Immersive	5
	Holistic	5, 6
	Intuitive	5, 6
	Clear	5, 6
	Sound/Image Match	5, 6
	Easily controllable	5
	Innovative	5, 6
	Enjoyable	5, 6
	Inspiring	5, 6
What suggestions do you have for improving the experience?		5, 6
Please share any other comments you have on the Spider's Canvas/Arachonodrone performance or installation:		6

Table 3: List of survey questions with their exercises.

Question	N	Min	Max	Mean	SD
Pink fibers are assigned a sound	102	1	5	4.39	0.91
Blue fibers do not produce sound	102	1	5	3.91	1.16
What I hear is correlated to what I see (fibers)	136	1	5	4.21	0.96
Shorter fibers are assigned higher sounds	135	1	5	3.98	1.07
Longer fibers are assigned lower sounds	135	1	5	3.92	1.14

Table 4: Descriptive statistics of the combined survey responses for Exercises 1, 2, 3, and 4.

Question		N	Min	Max	Mean	SD
I understand how the interface was used in the video		34	1	5	3.38	1.33
The audiovisual experience is:	Immersive	34	2	5	4.15	0.99
	Holistic	33	1	5	3.48	1.06
	Intuitive	33	2	5	3.52	1.12
	Clear	34	1	5	3.35	1.25
	Sound/Image Match	34	2	5	3.71	1.14
	Easily controllable	34	1	5	3.59	1.21
	Innovative	34	1	5	4.12	1.01
	Enjoyable	34	1	5	3.38	1.18
	Inspiring	34	1	5	3.53	1.13

Table 5: Descriptive statistics of the survey responses for Exercise 5.

Question		N	Min	Max	Mean	SD
The audiovisual experience is:	Holistic	33	1	5	3.73	1.07
	Intuitive	34	1	5	3.65	1.12
	Clear	34	1	5	3.62	1.13
	Sound/Image Match	33	2	5	3.82	1.04
	Innovative	34	1	5	4.24	0.96
	Enjoyable	34	1	5	4.00	1.10
	Inspiring	33	1	5	4.03	1.07

Table 6: Descriptive statistics of the combined survey responses for Exercise 6.

Declarations:

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Conflicts of interest/Competing interests: We declare we have no conflicts of interest and competing interest.

Availability of data and material: The spider web images and model are available from the corresponding author on reasonable request.

Code availability: The sonification model (Unity3D game and Max/MSP patch) are available from the corresponding author on reasonable request.

Authors' contributions: I.S., I.H., C.S., E.Z., T.S., and M.J.B. designed the research and overall project. I.S created the spider web model, the Unity3D game, virtual reality, and Max/MSP patch for the real-time interactive sonification model. I.S., I.H, C.S., E.Z and M.J.B designed the sonification model. I.H. created the Max/MSP patch for real-time sound sculpting of the sonification of the spider web. C.S. and E.Z. designed the Spider's Canvas/Arachnodrone physical installation and performance. C.S. collected photographs of spiders and webs and created a photo montage video superposed onto the spider web model projections. C.S. designed the visuals for the performance. I.S., I.H., C.S., E.Z. performed together the Spider's Canvas/Arachnodrone. During the performances: I.S controlled player's point of view in the virtual spider web and fiber esthetics, I.H. sound-sculpted in real-time web sonification, C.S. performed on the Ebow and E.Z. performed the EWI. T.S. commissioned the premiere of the Spider's Canvas/Arachnodrone. A.B. and R.M. edided the paper. I.S, I.H, C.S., E.Z. and M.J.B. wrote the paper.