SensorChimes: Musical Mapping for Sensor Networks

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ABSTRACT

We present a composition framework that facilitates novel musical mappings for large-scale distributed networks of environmental sensors. A library of C-externals called ChainFlow for the graphical programming language Max/MSP that provides an interface to real-time and historical data for large sensor deployments was designed and implemented. This library along with spatialized audio techniques were used to create immersive musical compositions which can be presented on their own or complemented by a graphical 3D virtual world. Musical works driven by a sensor network deployed in a wetland restoration project called Tidmarsh are presented as case studies in augmented presence through musical mapping.

Author Keywords

composition, mapping, sonification, sensor network, augmented reality, telepresence

ACM Classification

H5.5 [Information Interfaces and Presentation] Sound and Music Computing H5.1 [Information Interfaces and Presentation] Multimedia Information Systems

1. INTRODUCTION

The modern world is increasingly documented not only by our writing, recording, and collective memory, but by the many sensors that are embedded in ubiquitous devices. Modern sensor technology allows for efficient collection of these data at a large scale. Our ability as humans to use this wealth of information is constrained by the physical limitations of human sensory perception and the limitations of the interfaces that mediate it. This paper focuses on how these data can be leveraged for new forms of musical composition, envisioning a synthesis of electronic music composition and ubiquitous sensing toward augmented acoustic ecosystems.

We present a composition framework consisting of several tools that integrate with existing systems with the dual goal of facilitating artistically meaningful interactive music and facilitating auditory display driven by environmental sensor networks. A sensor network deployed in a wetland in southern Massachusetts called Tidmarsh is the impetus and focal point of the exploration. This paper contributes both the composition framework and specific patterns of musical mapping demonstrated through case study works by collaborating composers inspired and driven by Tidmarsh.

The main components of the SensorChimes framework are ChainFlow and DoppelMarsh. ChainFlow is an interface for the graphical programming environment Max/MSP[1] which endeavors to make it easy to route any real-time or historical data from a sensor network to any point in a Max patch, allowing for quick realization of mapping ideas with a minimum of work and expertise. DoppelMarsh is a virtual replica of Tidmarsh created with the Unity game engine as part of a related project [13]. In the musical works presented in this paper, the virtual environment is leveraged to render an immersive virtual exploration of the wetland with spatialized musical mappings.

The goal of this framework is to allow composers to create works that express their own musical conception of the space (Tidmarsh) under its real-time conditions, driven by the spatial and temporal variation of the metrics measured by the sensor network. These works do not aim to be utilitarian sonifications; however, convincing correspondence between the composer's conception and the real conditions driving that conception forms another criterion for evaluating the framework. If the composer wants to associate a timbre with aridity, this timbre should be perceptible only to the extent that the real-time conditions are dry. Tidmarsh is an ideal testbed for this framework, but the tools are general and could be used with other sensor networks in the future. SensorChimes is presented in more detail in [12].

2. MOTIVATION AND PRIOR ART

2.1 Presence

When an observer enters a space, some aspects of their environment are obvious, but many phenomena (e.g. barometric pressure, climate change, soil moisture) remain mostly imperceptible because we do not have appropriate biological sensors to detect them, they are too large or small, they change on timescales that are too long or short, or they are beyond our reach. How "present" we are in an environment relates not to how much we know abstractly about the environment but to how much we *feel* about the environment. This project aims to augment our "presence" by providing additional information about the environment through the acoustic medium, expanding what we can readily intuit. The windchime, a prehistoric wind sensor that makes music, inspires this project. The windchime is an augmentation to the acoustic environment that mechanically couples wind speed and direction to sound. This project reimagines, generalizes, and augments this concept in the digital domain with electronic sensors that measure many parameters, electronic music composition, and virtual reality.

[1]Max/MSP: https://cycling74.com/products/max/

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In "Composing perceptual geographies", Maryanne Amacher references the emerging "technologies of presence" that allowed for immersive experiences that function at a very basic perceptual level. In previous decades, technologies like amplifiers, loudspeakers, spatialized audio, DSP, etc. provided the means to author immersive sonic experiences leveraging presence like Amacher's pioneering "Music For Sound Joined Rooms [1]." "Public Supply" and "Drive in Music," two installations by another composer Max Neuhaus, augmented specific locations with sound to accentuate their perceptual characteristics, using the sound, and space itself, as an expanded instrument [9]. Recent developments, particularly sound spatialization techniques and the advent of ubiquitous sensing devices and cheap, low-power wireless networks, provide an opportunity to go a step further: to augment our perception through immersive sound and image in a dynamic way that responds to the environment itself. In "3-D Sound for Virtual Reality and Multimedia," Begault points out that spatialized 3D audio can contribute greatly to immersivity, and as a display, provide fast and fluid attention shifting in comparison to visual displays providing "situational awareness [2]." Lombard and Ditton define presence as "the perceptual illusion of non-mediation [10]." With 3D audio, new axies of presence measured by sensor networks can be presented with this illusion.

2.2 Acoustic Ecology

In a discussion of music sourced from a wetland, it would be remiss to ignore Acoustic Ecology. The term comes from composer R. Murray Schafer and has a philosophical connection to the work of John Cage. It is a philosophy that "suggests that we try to hear the acoustic environment as a musical composition and further, that we own responsibility for its composition [19]." In recent history, expanded technology and recording techniques such as bioacoustics have created new niches for musicians and artists studying the natural world, and the term "Acoustic Ecology" has broadened its meaning beyond the academic school of thought that coined it. Works like David Dunn's "The Sound of Light in Trees" and John Bullit's "Earthsound"[2] record the imperceptible and make it audible "achieving a deeper understanding of how sound and our sensory modality of hearing are unique organizing forces within human society, and our physical/ecological environment." David Dunn contrasts this new concern to the more traditional role of the composer in western art music, to "express" the self through compositional acumen [5]. In contemporary practice, both concerns are frequently present, and some have pointed out the connection between sonification and romanticism [18].

Related to Acoustic Ecology is the art of emulating natural soundscapes with synthetic and manipulated sounds. Works like Wendy Carlos' "Sonic Seasonings" and Apostolos Loufopoulos's "Bee" are inspired by and evoke phenomena of the natural world in profound ways [3, 11]. Other artists, like Jana Winderen, have made music concrete with vivid field recordings of the natural world [14]. While these works do not use real-time sensing or sonification, they set a high bar for composition that seeks to evoke and transform nature. It is hoped that this project will facilitate sensor-aware compositions that achieve the same resonance.

Where this project transcends Acoustic Ecology is its embrace of non-audible "sensory modalities" that can only be understood by the human through mediation. Previous works that use non-audible data in the context of ecological consideration are numerous. Matthew Burtner's "Iceprints"[3] uses the sound of melting glaciers and a century of data marking the extent of Arctic ice in a composition for piano and electronics. Marty Quinn's "Climate Symphony" make prosaic use of sonifications of climate related data on huge timescales including chemical analysis of ice cores, ice sheet movement and change, and solar intensity [15]. These works make use of static data sets rather than real-time sensing.

[2]Earthsound: http://www.jtbullitt.com/earthsound/

[3]Iceprints: http://matthewburtner.com/iceprints/

2.3 Telepresence

In Maryanne Amacher's first works, an installation series called "CITY-LINKS" begun in 1967, she pioneered the use of telepresence in art. In these works, sound from disparate locations were transmitted to an exhibition space in real-time to be experienced synchronously, inviting perception beyond the walls of the exhibition, and inspiring simultaneous presence in those spaces [8].

Echoing Amacher's work, this project records the soundscape of Tidmarsh in real-time with numerous microphones. These audio streams can be used and blended into a musical composition with sonification elements driven by the environmental sensors which add extra dimensions of telepresence. These audio streams were presented as part of a project called ListenTree which used transducers attached to the roots of trees to create an audio-haptic display that blends into the natural environment [4].

2.4 DoppelLab

DoppelLab is a 3D cross-reality representation of the MIT Media Lab populated with visual representations of sensor devices located throughout the lab and spatialized audio streams from microphones distributed throughout the lab [7]. DoppelLab began the process of imagining spatialized sonification of non-audible data in a cross-reality virtual environment, but stopped short of building a platform for composers to work with to realize music. This project is a logical next step, building a versatile system for exploring both musical composition with a new sensor deployment.

3. BACKGROUND

Tidmarsh is a 577 acre wetland restoration project in southern Massachusetts which is host to a large environmental sensor network, a part of the Living Observatory Initiative [13]. It was a cranberry bog until 2010 when the restoration of its wild ecology began. The Living Observatory Initiative documents ecological processes in the wetland as it undergoes a ten year restoration process. The scale of the Tidmarsh sensor deployment is large, with many sensors distributed across a large area. It represents a testing ground for ideas that require this kind of rich data that will be available everywhere in the near future, and is the focal point of a variety of ongoing investigations ranging from data visualization and augmented reality, to innovative ways of studying environmental processes and change. Recording everything that is happening in a place like Tidmarsh is still the realm of science fiction, but the dense sensor network at Tidmarsh is step forward. While the wild ecology is restored, sensors monitor the transformation.

The sensor network at Tidmarsh consists of dozens of battery powered nodes designed by Responsive Environments RA Brian Mayton that form a low-power mesh network built on the IEEE 802.15.4 specification [13]. Each device measures environmental parameters including temperature, humidity, illumination, and pressure, and is designed to be extensible so that other sensors of interest (such as soil moisture, wind, gas levels, etc.) can be easily added. The data are relayed to a base station via a wireless mesh network where they are uploaded to a remote server. From this server, historical data can be browsed, and the live data can be streamed as they are collected.

4. CHAINFLOW

ChainFlow is a low-level interface for working with data from a sensor network in the graphical programming language Max/MSP. This section gives an overview of the structure of ChainFlow and then focuses on three mapping challenges that ChainFlow solves: normalization, mapping multiple time scales, and spatial mapping.

ChainFlow is library of objects implemented with the Max SDK, which provides a way for developers to integrate their own objects into Max written in C. It is built on top of ChainAPI, an HTTP and Websocket API developed by Russell et. al to provide a common interface for accessing data and metadata from sensor networks in the absence of broadly adopted standards [17]. The examples in this paper reference Tidmarsh exclusively. However, ChainAPI is easy to set up with any networked time-series data source, making these tools useful in general.

ChainAPI and ChainFlow are organized around three abstractions: "site," "device," and "sensor." Tidmarsh is a "site," the battery powered boxes that transmit data are "devices," and the collocated sensors in each box are "sensors." A "metric" is something measured by the network—temperature, humidity, etc. In ChainFlow, a `[chain.site]` master object loads a summary of a site from ChainAPI and begins a websocket connection with the ChainAPI server. Other objects in the library are worker objects that attach to the master object to receive updates and access the site summary. These include, among others, `[chain.device]`, which provides an interface to data for a chosen device, and `[chain.metric]` that provides a general interface to a chosen metric across many devices that measure it. A full description of the ChainFlow objects and their use is beyond the scope of this paper. For a more detailed explanation of the implementation and use of ChainFlow see [12].

4.1 Normalization

A primary goal of this project is to facilitate composition which manifests the variation of the environment over time and through space. For a composer, normalizing and linearizing a data set to a range which is useful for modulating a parameterized musical abstraction is a key step in mapping. When the data set is a real-time stream, this normalization is an extra challenge as its behavior must be predicted.

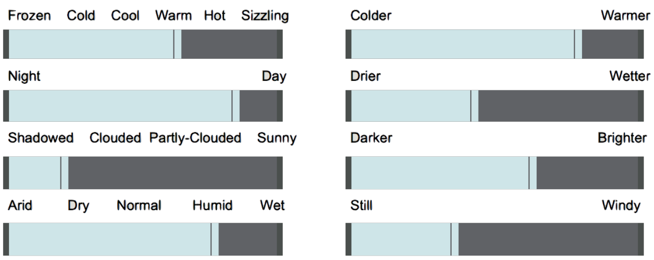

Figure 1: Semantic normalization of environmental parameters

An experimental normalization interface, shown in Figure 1, was created by adding a "semantic" mapping layer. This is a site-specific abstraction implemented with ChainFlow. Rather than presenting the composer with the raw or analytic environmental parameters (temperature in degrees, illuminance in lux, temperature deviation, etc.), the composer is presented with "semantic" parameters, each on a 1 to 128 scale. While this abstraction is specific to the sensor network at Tidmarsh, it could be easily adapted to another context.

For a metric like temperature, most people have an intuitive sense of what the raw data means. However, for measurements like illuminance and humidity, these semantic parameters can be reasoned about more intuitively than the raw data. For this iteration, the semantic parameters and the equations of raw parameters that define them were authored. Future work could experiment with generating these semantic parameters through principle component analysis or by using the historical data record.

The second normalization problem is how to systematically relate the measurement at specific a device to the site as a whole—how to characterize the spatial variation of the metric. This problem is solved by providing easy access to the "deviation" of a specific device from the real-time site average, normalized by the standard of deviation. These deviation measurements are incorporated into the "semantic" mapping layer.

4.2 Mapping on Multiple Timescales

The sensors at Tidmarsh document changes that occur on many timescales: daily cycles, weather patterns, seasonal change, climate change, etc. Real-time data can drive music determined by the status of the environment. However, to render music that manifests the temporal variation of the environment on timescales too long for a listener to observe in real-time, data gleaned from the historical record must be woven into the composition. ChainFlow offers several features for working with these different time scales.

4.2.1 Sequences of Historical Data

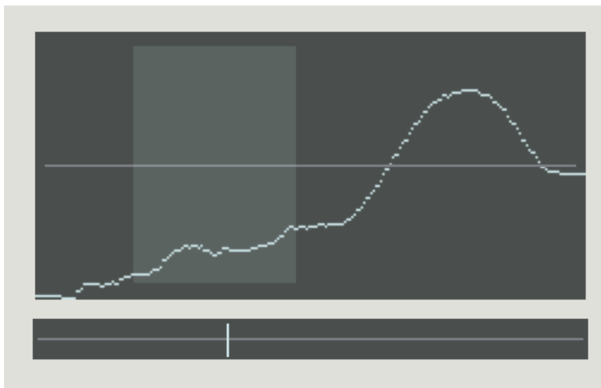

Figure 2: The `[chain.itertable]` abstraction stores, displays, and iterates through an historical data sequence. Shown here: normalized temperature over twenty-four hours

An interface to request historical data sequences is implemented by the `[chain.device]` object. In experimenting with using real-time and historical data simultaneously, we developed an abstraction to format requests for historical data with messages like: `last 4hour`, `next 3hour 2sec`, and `from now -1day to now`. This makes it easy to, as a simple example, request the last hour of temperature data to use as a melodic contour for a synth which is then run through a DSP effect modulated by the real-time temperature or normalized deviation of the temperature from the site mean, simultaneously presenting the real-time and the recent past.

If a large historical time span is requested, this can be an enormous number of data points, so the behavior can be modified to return only one point per chosen interval. Data in ChainAPI are not necessarily sampled periodically, and each have a potentially arbitrary (though monotonically increasing) timestamp. The [chain.data] abstraction also provides an interface for resampling a data sequence on a specified fixed interval via linear interpolation, and the [chain.itertable] pictured in Figure 2 provides a means of visualizing and iterating through this resampled sequence. [chain.data] can also normalize a data sequence to fall within 0 and 1 to simplify mapping where the gesture of the contour but not the absolute value is salient.

4.2.2 *Real-time and Pseudo-real-time*

Each [chain.site] instance has a clock which can either run in "real-time" following the system clock, or in "pseudo-real-time" specified by a chosen rate in historical seconds per second and a starting point in the past. This design means that choosing to run a composition in real-time or as if from a point in the past is a simple option at the highest level, requiring no re-patching. To use multiple clocks simultaneously, multiple instances of [chain.site] can be instantiated.

4.3 Mapping with Spatial Variation

The spatial variation of a sensor network can be rendered in sound by immersive virtual exploration of the space with spatialized musical mappings. A musical composition that follows this pattern is thus parameterized by the exploring observer's position. ChainFlow provides several features for handling this parameterization by presenting data relevant in the neighborhood of the observer.

The [chain.zone] object is designed to statically manage the list of devices that are within a circular "zone," specified by center point and radius. If the zone moves such that a device crosses the boundary into the zone, that device is added to the list and the object outputs added [device_name]. If the device leaves the boundary, the device is removed from the list and the object outputs removed [device_name]. Hysteresis prevents oscillation between adding and removing a device when it is very close to the boundary. In particular, this object is used in the implementation of the virtual environment described in Section 5.

The [chain.metric] object provides a more general interface for a specified metric which provides access to its value and measures on its spatial variation across all devices that measure it. For example, this object can be used to determine the mean temperature in a radius of ten meters around a selected point or to perform a bilinear interpolation to estimate the temperature between sensor devices at the observers exact location.

5. VIRTUAL ENVIRONMENT

SensorChimes integrates several existing tools and systems and a novel mapping interface to experiment with musical mapping for the network of environmental sensor nodes deployed at Tidmarsh. Some of these components are specific to this site such as the deployment of sensor nodes themselves, while other components could be reused for other sites or applications. The "product" of this integration is an application that runs on a client machine that renders both a graphical and sonic display.

At a high level, SensorChimes follows a client-server architecture. Figure 3 gives an overview of the entire system. The "server" is Tidmarsh, the sensors deployed there, and the ChainAPI server, which provides access to sensor measurements. The "clients" are DoppelMarsh and Max/MSP through ChainFlow.

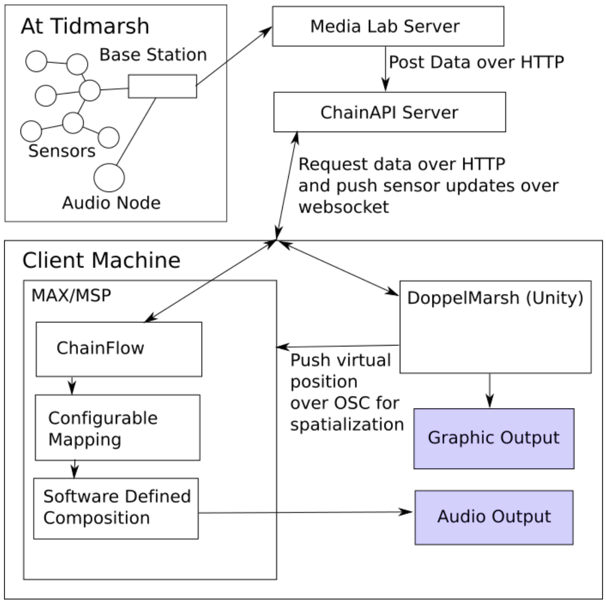

Figure 3: Within Tidmarsh, sensor nodes communicate low-level messages to a base station connected to the internet which relays to a server at the lab. These messages are parsed and posted to the ChainAPI server over HTTP.

5.1 DoppelMarsh

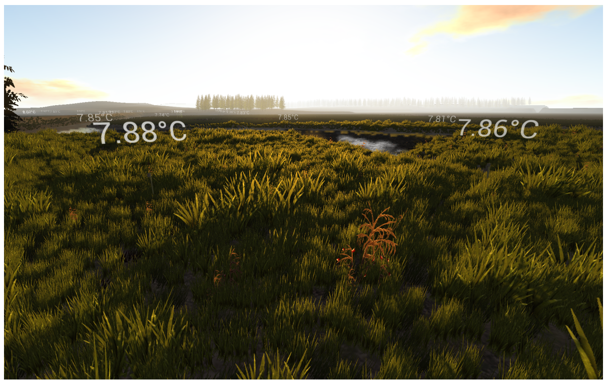

Figure 4: Virtual Tidmarsh

DoppelMarsh is a "cross-reality sensor data browser constructed using the Unity[4] game engine to experiment with presence and multimodal sensory experiences" created by Responsive Environments RAs Gershon Dublon and Brian Mayton [13]. It presents a virtual rendering of the marsh with real-time sensor readings visualized as floating numbers above the sensor nodes pictured in Figure 4. In the future, graphical elements that more subtly blend in to the scene will visualize sensor readings. The user controls the position of the camera using controls common to first-person video games. This virtual position and direction are sent to Max/MSP over OSC[5] so that audio generation that is contingent on the player position is synchronized with the graphical display. Previous versions of DoppelMarsh have integrated both the live audio streams and a hard-coded sonification of the temperature and humidity composed by Dublon and Russell.

[4]Unity: https://unity3d.com/5
[5]Open Sound Control: http://opensoundcontrol.org/

5.2 Immersive Sound in Max/MSP

A system was created to render an immersive sonic environment with each sensor device at Tidmarsh generating an audio voice. A different musical audio signal is generated for each sensor device based on the environmental conditions local to that device. These signals are delivered to the listener simultaneously, each spatialized to sound as if emanating from the device. The listener moves around the virtual space and explores the different signals and the underlying environment.

In Max, the environment patch is broken down into three parts: device voice, spatializer, and polyphony handler. The device voice *is* the composition in some sense. Each device will contribute a voice to a chorus of nearby devices, the device voice patch determines this voice. A `[chain.device]` object is used to access real-time data for the specified device. A few strategies for the musical mapping that makes these devices sound are explored in the case studies that follow. The spatializer processes the device voice for spatialization using the HOA library for Max/MSP from CICM[6] to encode the signal of a device voice patch on the spherical harmonics based on the displacement of the device from the listener. The polyphony handler uses a combination of the `[chain.zone]` object and Max/MSP's built in `[poly~]` object to instantiate a number of unassigned spatializers and assign and reassign them to nearby devices as the listener's position moves around.

5.3 Deployment

Initial demonstrations were deployed as an installation with a dedicated computer, display, and sound system that remote visitors were invited to use. With a keystroke, the user could switch between different real-time musical conceptions of the marsh. However, to reach a broad audience, a web deployment was devised.

For the first installation, the computer ran both the Max/MSP and DoppelMarsh clients simultaneously. The user sat in front of the display wearing headphones and used the keyboard to navigate through the virtual world. As the user moved around the virtual space, the Max/MSP client used binaural spatialization to make a convincing immersive sonic environment consistent with the graphical experience.

A proposed installation that has not yet been put into practice would make use of a fairly large space and a large number of omnidirectional speakers. These speakers would be arranged in the space following the arrangement of sensor devices at Tidmarsh. The DoppelMarsh client would not be used, and spatial exploration would instead occur in the real space filled with speakers. A computer running the Max/MSP client would route a signal to each speaker for each mapped node at Tidmarsh.

This project is deployed on the web as a downloadable application. The two clients (DoppelMarsh and Max/MSP) are bundled together as a client application with a wrapping application written in Objective-C for Mac OS X.

In the future it may be possible to deploy SensorChimes onsite at Tidmarsh for visitors to enjoy. This project would build on a vision for auditory augmented reality presented by Russell et. al. at the 7th Augmented Human International Conference [16].

6. COMPOSITION CASE STUDIES

Three compositions have been created with this framework. Each uses a different mapping strategy and is the composer's unique conception of Tidmarsh. This section describes each work and then draws some conclusions. The case studies and related material can be accessed at `http://resenv.media.mit.edu/sensorchimes/`.

[6]HOA: http://www.mshparisnord.fr/hoalibrary/en/

6.1 "The Bog Blues" – Parametric Mixing

This piece is constructed from looping improvised acoustic passages performed on cello, guitar, bass, and drum. The layers of sound emulate the many layers of narrative that unfold in a complex ecosystem like Tidmarsh. Many distinct tracks for each instrument were recorded with consistent meter and harmonic rhythm but composed to produce a range of moods and perceived energy levels when layered on top of each other.

Each device in the virtual environment adds a voice, which mixes these tracks with weights parameterized by the sensor readings of that device. Each track is assigned a max-one axis-aligned multivariate Gaussian distribution in a five-dimensional parameter space consisting of temperature, illuminance, deviation temperature, deviation illuminance, and deviation humidity. The mix of tracks for a given point in this five-dimensional space is the linear combination of the tracks, each weighted by the evaluation of its respective Gaussian distribution at the relevant point. An interface called *Dynamix* was designed to help visualize this five-dimensional space and the distributions to help author this mapping.

6.2 Evan Ziporyn – Effects Chain Mapping

Evan Ziporyn, an accomplished composer and clarinetist, generated looping tracks of clarinet textures inspired by the birds and frogs of the marsh. The idea behind the piece is to layer and process these textures through various effects to create a large parameterized space of sounds. An "instrument" abstraction that produces this texture exposes a set of adjustable parameters to which are mapped the semantic parameters as described in Section 4.1. Following Ziporyn's interest in improvisation, we intend to add an interface along the lines of Harmonix's "The AXE," which allows the user to improvise an arpeggiated melody on top of the texture in a harmonic and timbre space adjusted by real-time sensing.[7]

6.3 Ricky Graham – Multiple Timescales

Ricky Graham, a guitarist and computer musician, was interested in working with data from Tidmarsh's history and developed an interface that allows a listener/improviser to select data ranges to iterate through driving his own granular synthesis patch. This interaction encourages exploration of how data sets can drive timbral and temporal changes in electronic music. Using this interface, a piece was created based on the contour which barometric pressure, humidity, and illuminance take over the course of a day on the full-moon. This piece was presented at the Fall 2015 Media Lab Member's Event and appeared as a research presentation at SEAMUS 2016 [6]. The second version of this piece is presented within the virtual environment. Each device drives it's own granular synthesis patch with real-time data, as well as ranges of recent historical data on multiple timescales.

6.4 Discussion

The experience of exploring the first two case studies demonstrate the potential for parametric music as a rough auditory display. Both pieces admit perceptual correspondence between the real conditions and the sound, and exceptional environmental conditions are interpreted as exceptional versions of the sound. In both pieces, the mapping exhibits smooth transitions between regions of the parameter space

[7]The AXE: http://www.harmonixmusic.com/past-games/

so similar conditions always produce similar music, and these changes are reflected immediately so the mapping is responsive. For *The Bog Blues*, the *Dynamix* interface makes it easy to see that the specified mapping will be active and interesting across the regime of the parameter space in which the environment is likely to fall. In demonstrating the piece in the 3D virtual environment, after a few minutes, one user noted that they found themselves navigating through the world looking for a particularly humid region by ear despite the visual representation of the humidity data.

The second piece produces an ambiance fitting to the marsh both during the day when it sounds bright and fast and at night when it sounds slow and dark. Variation in the semantic parameters is obvious to the listener, and after a little exploration, the sound is enough to estimate the conditions with ease. The mapping was carefully authored with much experimentation, a process made easy by the SensorChimes framework.

The third piece takes an entirely different approach, focusing on using snippets of historical data to drive long musical structures rather than instantaneous parameter modulation. This piece was less successful as an auditory display, but was received well by listeners as an effective aesthetic reflection of the overlapping and shifting contours of environmental conditions.

7. CONCLUSIONS

In the contemporary world, the rate at which we collect and generate data and information vastly outpaces our ability to process and interpret it. Spaces are increasingly instrumented with sensors, but the insights that we might gain from these data remain mostly untapped. The technologies that mediate our access to digital information give us only small glimpses into this world of dense data. We need powerful new paradigms to render these data interpretable. On the path to these new paradigms, these data present themselves as a canvas for the contemporary artist. We cannot yet walk through a marsh and internalize everything we can measure with sensors about the world around us as easily as we can feel the warm rays of sun on our skin and the moist soil beneath our feet. However, music that speaks to these experiences, which reacts to these data, is a step toward a world where data is interpreted incidentally.

The potential for music creation along the lines of the pieces presented here is large and mostly unexplored. It is hoped that ChainFlow will be adopted by or inspire more composers interested in the vision of this project who will take it in their own unique directions.

One direction this work could take in the near future is to break out of the confines of the virtual world and make a showing onsite at Tidmarsh: a real auditory augmentation. Spatialization that uses head tracking has the potential to make this a reality.

ChainFlow is a good first draft of a versatile interface for sensor networks in Max/MSP; however, some things could be improved. Most significantly, ChainFlow is only useful within Max/MSP. A similar tool could be built for Pure Data which would open up a new realm of portability because of the open-source nature of PureData and the libpd C library, which makes it possible to build Pure Data patches into other native code projects.[8] Additionally, the limits of ChainFlow have not been tested and significant optimization may be required to handle substantially larger deployments.

8. ACKNOWLEDGMENTS

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