

SENSORY THREADS: SONIFYING IMPERCEPTIBLE PHENOMENA IN THE WILD

Robin Fencott

Interaction, Media, and Communication Group
Queen Mary University of London
robinfencott@dcs.qmul.ac.uk

Nick Bryan-Kinns

Centre for Digital Music
Queen Mary University of London
nickbk@dcs.qmul.ac.uk

ABSTRACT

Sensory Threads is a pervasive multi-person interactive experience in which sensors monitor phenomena that are imperceptible or periphery to our everyday senses. These phenomena include light temperature, heart-rate and spatial-density. Participants each wear a sensor as they move around an urban environment, and the sensor data is mapped in real-time to an interactive soundscape which is transmitted wirelessly back to the participants.

This paper discusses the design requirements for the Sensory Threads soundscape. These requirements include intuitive mappings between sensor data and audible representation and the ability for participants to identify individual sensor representations within the overall soundscape mix. Our solutions to these requirements draw upon work from divergent research fields such as musical interface design, data sonification, auditory scene analysis, and the theory of electroacoustic music. We discuss mapping strategies between sensor data and audible representation, our decisions about sound design and issues surrounding the concurrent presentation of multiple data sets. We also explore the synergy and tension between functional and aesthetic design, considering in particular how affective design can provide solutions to functional requirements.

1 INTRODUCTION

Our everyday surroundings contain countless phenomena to which we are oblivious. Our eyes and ears can only detect within a limited range, while within our own bodies there are countless rhythms and processes which we cannot feel or sense.

Sensory Threads is an interdisciplinary research project that combines the expertise of several institutions, and builds upon technologies developed for *Snout* [1] and *Feral Robots* [8]. The aim of the project is to create a collective and shared sensing experience which highlights imperceptible



Figure 1. Participant wearing a mobile sensor.

phenomena in our everyday surroundings. In the Sensory Threads experience, participants wear mobile sensing technology (see figure 1, with discussion in section 4) and go on an expedition through the urban environment. During their expedition, a generative soundscape translates the real-time sensor data into an audible representation, allowing the participants to explore and experience the hidden quantities and patterns of imperceptible phenomena that surround them.

A key requirement for the soundscape is the audible presentation of sensor data in a form which is intuitively perceivable, thus allowing a participant to isolate the contributions made by their own sensor or those of others in the group. The soundscape also needs to be pleasant to listen to, so as to retain participant attention during the expedition. Solutions to these design challenges have been informed by research from a range of fields, including data sonification, electro-acoustic music and Auditory Scene Analysis.

The rest of the paper is structured as follows. Section 2 surveys related work and introduces research which informed our approach to sound design, section 3 summarises the requirements for the soundscape, stressing design problems posed by these requirements. Section 4 documents the implementation process, giving examples of how the

ory from the above-mentioned fields was applied to satisfy the design requirements. Section 5 outlines future work, and the paper is concluded in 6.

2 RELATED WORK AND SOUND DESIGN INFLUENCES

2.1 Related Work

Pervasive games are a form of interactive experience which attempt to blur the boundaries between the physical world and digital representations [16]. A good example is *Can You See Me Now* [2], a game which involves real-world ‘runners’ in an urban environment chasing online players who are navigating a virtual model of the same physical location. While using similar technologies (e.g., Global Positioning System) to these pervasive games, the Sensory Threads experience is not game-like or task-based in design; emphasis is instead placed on the reflective experience of listening to changes in the soundscape while exploring the urban environment. Sensory Threads therefore shares more commonality with mobile experiences such as *Sonic City* [10] and *‘Ere be Dragons* [7]. *Sonic City* is a mobile automatic music creation system that uses mobile sensors to control the manipulation of environmental sounds surrounding the participant as they move through the city. *‘Ere be Dragons* is a pervasive experience which uses the participant’s heart rate to control the real-time generation of a virtual environment.

Sensory Threads is also similar to Christina Kubisch’s ‘Electrical Walks’ [6], in which participants walk around a city while wearing headphones that are designed to amplify the electro-magnetic interference caused by wireless networks, electrical lighting and suchlike. However unlike Kubisch’s walks, which give direct access to the phenomena under observation, the sonification process in Sensory Threads places a layer of abstraction between the raw sensor data and the audible representation.

Although [10] [7] and [6] generate real-time audio in response to live sensor data, they are solitary experiences, and are therefore distinct from Sensory Threads, which is a collective sound experience. An example of a collaboratively generated, sensor controlled soundscape is presented in [13], however the emphasis is on encouraging spontaneous performance activities, rather than reflection on the sensor data itself.

While we do not view Sensory Threads as an instrument or musical interface, it is important to mention collaborative interactive music systems. Blane and Fells [3] present a comparison of many such projects, however in the majority of cases, these projects are based around a fixed location such as a computer system or physical interface(s). A notable exception to this is [17], who present a large scale mobile collaborative music system using GPS and wireless technologies. Despite differences in the style and presenta-

tion of these multi-party experiences, we can view them, and Sensory Threads, within the framework of creative mutual engagement [5].

2.2 Sound Design Influences

This section introduces fields of research which informed the development of the sound design for the Sensory Threads soundscape. Concrete examples of their application are given in subsequent sections.

2.2.1 Sonification

Sonification is the process of representing data in an audible format, using speech or non-speech sounds. Within the field of sonification, we are particularly interested in approaches to presenting several pieces of information concurrently. McGookin [12] notes that the larger the quantity of information presented simultaneously, the more problematic it is for a user to interpret it correctly. [12] suggests several design guidelines for addressing this problem, such as using a range pitch registers and timbres for different information sets, and de-correlating the temporal onset of concurrent events.

While the field of data sonification provides guidelines for the audible representation of data, there have been few attempts to address the aesthetic quality of the sonification. One exception is Vickers [15], who notes that the approaches to organising sound used by electro-acoustic music composers could be employed to enhance the aesthetic appeal of sonified data.

2.2.2 Auditory Scene Analysis

Auditory Scene Analysis (ASA) investigates the means by which humans interpret auditory signals. A key theory in ASA is that of segregation; the process which allows us to pick individual components, (e.g., voices or music) from the noisy mix of sounds in our environment; a phenomenon commonly known as the ‘cocktail party effect’. ASA attempts to uncover the strategies we apply when segregating signals into discrete channels (referred to as streams), and the factors which affect our ability to perform this segregation. ASA also investigates the perceptual fusion of auditory components; where sounds from different sources are perceived as part of a single auditory stream [4].

ASA is useful in our context because it provides suggestions for how to design a soundscape in which the constituent parts are individually identifiable.

2.2.3 Spectromorphology

Spectromorphology, proposed by electroacoustic music composer Dennis Smalley, is a theoretical framework for understanding the activity of listening, and the process of recog-

nising sounds or sound-types [14]. Spectromorphology refers to the spectral qualities of a sound (the *spectro*) and the ways these qualities change over time (the *morphology*). In his theory, Smalley argues that listeners have a ‘natural’ ability to associate sounds with possible causes, a process he calls ‘source-bonding’. One implication of the theory of spectromorphology is that composers can try to suggest the cause or nature of imaginary or synthetic sounds, by designing sounds which may appeal to a listener’s innate tendency to perform source-bonding.

In the Sensory Threads soundscape we try to leverage the idea of source-bonding, by giving each audio stream distinct spectromorphological characteristics, each intended to mirror the properties of the phenomena they represent. This also helps us to separate the different sensor representations within the overall mix of the soundscape, as each representation is distinct.

2.2.4 Summary

Sonification and spectromorphology are both concerned with the use of sound as a medium for description or representation. Sonification seeks to present some external source of information in an audible format, using speech or synthesised sound. Spectromorphology on the other hand is a theoretical framework for classifying and explaining sound types, and can be used as a tool for describing specific features *within* a sound event. Underlying both sonification and spectromorphology we find the field of Auditory Scene Analysis, which investigates the human perception of sound.

3 SOUNDSCAPE DESIGN REQUIREMENTS

This section gives more detail about the specific design requirements and features we identified for the Sensory Threads soundscape. Most of the aesthetic and experience related requirements were drawn from consultations with Proboscis, the arts organisation co-ordinating the Sensory Threads project. Other requirements were drawn from our previous experience in creating interactive sound experiences (e.g., [9] [13]) and our reflections on related research. Solutions to our design requirements are presented in the subsequent section, where we also consider the issue of balancing aesthetic concerns and functionality.

3.1 Perceivable mapping between sensor data and sound

The soundscape must provide feedback to the participants about the state of the environment and their own physiological systems. Therefore one of the most important requirements is that incoming sensor data is mapped to an audible representation in a direct and perceivable fashion, thus allowing participants to listen to the contribution their own sensor is making to the soundscape as a whole.

To facilitate this, we decided that each sensor data stream should be matched to a specific voice or instrument within the soundscape. To avoid confusion while listening, we require these voices to be sonically distinct, so that each voice is perceived within its own auditory stream, and voices do not interfere with, or mask one another. We also argue that the sound design for the sensor representation should reflect the phenomena being monitored, so participants can intuitively interpret the meaning of the soundscape.

While providing identifiable sensor readings is integral to the functionality of the soundscape, we also argue that it is important for promoting group interaction and mutual engagement. We believe participants should be able to identify changes caused by their sensor, and also become aware of the way their fellow explorers are shaping the auditory experience.

In summary, the mapping and sound design for the soundscape should serve the dual purpose of representing the data in an easily readable format and promoting a sense of self identify and group awareness within the participants.

3.2 Longitudinal Requirements

As the Sensory Threads experience lasts for up to an hour, we recognise the need to incorporate temporal development into the soundscape, to retain interest, counter fatigue and avoid desensitisation to changes in the sensor data. We therefore considered additional, indirect sensor mappings to control longer term development of the soundscape, and also ‘composed’ changes within the soundscape, such as musical progressions or sounds which gradually evolve.

4 IMPLEMENTATION

4.1 Development Process

We developed the soundscape iteratively, starting with a primitive prototype, and making modifications based on informal testing and feedback from meetings at Proboscis.

4.2 Sensing Platform

Our collaborators at Birkbeck College have developed a portable wireless sensing platform using embedded Linux Gumstix computers. The current version of Sensory Threads uses three of these devices, each of which transmits sensor readings via Bluetooth to a small laptop computer, where the soundscape is generated. Each participant carries a single sensor. The sensors used are a light sensor, a noise sensor and a ‘spatial density’ sensor, which uses four ultrasound range finders placed on the front, back and sides of a participant to give an estimation of how cramped or constricted the participant is within their current environment. A heart-rate monitor, GPS receiver, 3G internet uplink and web-camera are also connected to the laptop.



Figure 2. Spatial Density sensors and shoulder bag

A Java program (written by the first author) interfaces with the sensor hardware using Bluetooth and serial port connections, and passes relevant sensor data to the soundscape using Open Sound Control [18]. This Java program also uploads the GPS and sensor data to the web-server for use in a gallery-based listening environment. The program attempts to re-establish Bluetooth or internet connections if they are lost, and all sensor data is logged locally.

A second Java application takes still images using the attached web-camera. Images are taken at points of significant change in the sensor data streams.

Audio is generated in the soundscape program (see below) and transmitted to the four participants using Bluetooth headphones with external Bluetooth audio transmitters. These transmitters are used instead of the laptop's on-board Bluetooth interface, making the system more robust, as headphones can disconnect and reconnect without causing interference to the laptop or soundscape program.

The whole system runs on battery power and is worn in fabric satchels created by a member of Proboscis (see Figure 2).

4.3 Soundscape Program

The soundscape program is written in SuperCollider [11]. All sounds are synthesised in real-time, rather than being based on sampled audio. The main advantage of this approach is that the synthesis parameters can be modulated directly by the incoming sensor data, making the soundscape flexible and sonically varied. Another advantage of this approach is that the synthesis models can be quickly created, modified and tested during development.

4.4 Data Representation Streams

We developed four sound synthesis models, which we refer to as the 'representation streams'. These representa-

tion streams are collections of synthesis graphs coupled with control and mapping algorithms. Each representation stream was designed for a specific sensor.

4.4.1 Heart-Rate Stream

This heart-rate sensor is represented as a high-pitch pulse-train, whose rate is determined by the heart-rate of the participant wearing the heart-rate monitor. Reverberation is applied to the pulse, to make it sound less harsh. Over time, the pitch of the individual pulses begins to modulate, gradually transforming the simplistic tones into a melody.

4.4.2 Spatial Density Stream

The spatial density sensor is represented as a persistent drone, to which frequency and amplitude modulation are applied. As the participant wearing the sensor becomes more tightly constricted in their current environment, the rate of modulation is increased, causing the timbre of the drone to become intense and foreboding. In a low-density environment the drone becomes lighter and less prominent.

4.4.3 Noise Level Stream

The noise level sensor is represented as filtered white noise, where the sensor reading is mapped to the cut-off frequency of a low-pass filter. Some reverberation is applied to make the noise sound less harsh.

4.4.4 Light Stream

The light sensor modulates the filter frequency of a rich synthesised tone. Over time, additional musical notes are introduced to this tone, creating a rich harmonic backdrop to the soundscape. Delay and reverberation effects emphasise the modulations caused by variations in the sensor data.

4.5 Sound Design

We designed the soundscape to stand out against the acoustic environment, using entirely non-speech sounds, and employing synthetic timbres rather than emulations of acoustic instruments. The musical genre of the soundscape could be described as ambient or minimal electronica.

Our sound design decisions for the representation streams were not arbitrary. Rather, we tried to apply ideas from Smalley's theory of spectromorphology to make each representation stream an intuitive reflection of the phenomena under observation. For instance as the wearer of the spatial density sensor becomes more tightly constricted, the increasing modulation is intended to suggest the sensation of claustrophobia. Another example is the light sensor representation stream, which becomes sonically brighter and more energetic as the ambient light level increases.

We also use the idea of source-bonding, as with the variably spaced pulses of the heart rate representation, which imply a source that is emitting discrete events at a constantly changing speed. Here, we suggest that the pulsation becomes a metaphor for heart rate, as the pulses are not directly aligned with the heart beats of the sensor wearer.

4.6 Concurrent Data Representation

Using a distinct sonic identity for each sensor representation also means that streams can be distinguished from one-another within the overall mix. To ensure that each representation stream is sufficiently distinct, we followed principles outlined by [12] for the concurrent presentation of auditory information. These guidelines include the use of different timbres and pitch registers for each data element. We therefore used a variety of sound types, including high pitched tones, filtered bands of noise, and harmonic textures.

We also applied lessons learnt from the principles of auditory scene analysis (ASA), such as trying to ensure that each sensory representation gets assigned to its own perceptual stream. One approach to this was using a mixture of continuous and discrete sounds, which can be viewed in gestalt terms as *figures* and *grounds*. Where possible we also de-correlated the onset of sound events, and used spatialisation to segregate elements, by placing them at different positions within the stereo field.

To further avoid conflict between the representation streams, we chose not to map sensor data directly to pitch, but instead opted to map the incoming data to temporal and spectral parameters. This approach allows us to place each sensor representation within a specific pitch region, with the assurance that the live sensor data will not cause sensor representations to gravitate towards a common frequency range and become difficult to distinguish between.

4.7 Functionality and Aesthetics

During the development of the soundscape, we became engaged in the tensions and synergy between functional and aesthetic design concerns. Functional problems included providing accurate representation of the data, and allowing for the concurrent presentation of the four data sets. The main aesthetic concerns we faced were developing representation streams which were pleasant to listen to, ensuring that the soundscape is clear and coherent despite multiple layers of audio, and incorporating temporal development.

In some cases the functional and aesthetic requirements were easily satisfied. For instance by assigning each representation stream unique characteristics, we found that the requirement for identifiable concurrent data presentation was met, however in the process we also arrived at a set of interesting and complimentary sonic voices, which work to create a coherent and musical soundscape.

The requirement for pleasant sounding sonification was met by using harmonic and musical sounds where possible, and through applying reverberation to create a more 'polished' presentation. In creating a soundscape that is pleasant to listen to, we also go some way to satisfying the functional requirement of supporting and encouraging engagement over a prolonged duration.

However, functional and aesthetic concerns were not always neatly resolved. As an example, we are conscious that temporal developments of the soundscape (as outlined above) might be confusing or misleading to the participants, who could potentially accredit time-based changes to the incoming sensor data. This is still an unresolved issue.

5 FUTURE WORK

5.1 Soundscape Development

A primary concern is to enhance the temporal evolution of the soundscape over the course of a Sensory Threads expedition. We see this work as important because if the soundscape remains relatively static participants may become bored or fatigued by the sounds. This may involve developing a context sensitive model of the experience, which is maintained as an expedition takes place. This approach is a departure from the current state-machine approach to temporal development, where new behaviour is introduced as certain time thresholds are crossed.

Although the system can recover from communication loss, we plan to introduce audible feedback to indicate when participants stray too far from one-another. As well as being functionally useful, these signals could also become an aspect of the group experience.

5.2 Formal Evaluation

We intend to carry out an evaluation of Sensory Threads, investigating not only the degree to which participants are able to interpret the sensor data, but also social factors such as the characteristics of the group interaction that takes place during the Sensory Threads experience.

We would also like to assess the degree to which our implementation matches our design requirements, and we will use the evaluation to improve the soundscape design, in accordance with the principles of user-centric design.

Sensory Threads will be shown at various events during the summer of 2009, and we aim to use these events as a platform for performing our evaluations.

6 CONCLUSION

Sensory Threads is a pervasive multi-party experience in which four participants listen to an interactive soundscape as they move around an urban environment. Each participant

wears a mobile sensor, which controls a particular element within the soundscape. The soundscape has been designed according to a specific set of requirements, and our solutions to these requirements have been made through the application of ideas and techniques from a variety of research fields and artistic disciplines.

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