Granular Wall: Approaches to sonifying fluid motion

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ABSTRACT

This paper describes the materials and techniques for creating a sound installation that relies on fluid motion as a source of musical control. A 4' by 4' acrylic tank is filled with water and several thousand neutrally-buoyant, fluorescent, polyethylene microspheres, which hover in stillness or create formations consistent with a variety of turbulent flows. Fluid motion is driven by four mounted propulsion jets, synchronized to create a variety of flow patterns. The resultant motion is sonified using three essential mapping techniques: feature matching, optical flow estimation, and the direct mapping from motion data to spectral audio data. The primary aim of the artists is to create direct engagement with the visual qualities of kinetic energy of a fluid and the unique musical possibilities generated through this fluid motion.

1. INTRODUCTION

The study and application of fluid mechanics covers a universal and wide-ranging array of phenomena that occur in nature and in day-to-day human activities. Natural fluid behaviors of the smallest scale to extreme magnitudes can include everything from microscopic swimming animals and blood flow to continental drift and meteorological phenomena. [1] As generative processes for sound synthesis and sonification become more accessible and creative, we feel that there exist many possibilities for sonic exploration for a whole range of fluid behaviors. *Granular Wall* is an attempt to engage directly with certain physical aspects of fluid flow–namely, specific types of turbulent fluid flow in water. Our primary point of departure is to discover compositional structures between fluid statics and fluid dynamics.

Recent research in areas related to sound-synthesis based on the physics of liquids in motion primarily has dealt with innovations in auditory display and simulations related to smoothed particle hydrodynamics. [2] While these methods continue to contribute greatly to the fields of computer graphics and animation, *Granular Wall* is an attempt to present a variety of fluid phenomena in an aesthetically-oriented and immersive sonic and sculptural form.

2. COMPOSITIONAL MOTIVATIONS

Besides a general interest in sonifying complex geometries, vortices, and chaotic processes, there were several compositional motivations for designing and building the sound installation. Iannis Xenakis's ideas related to algorithmic music served as an important analytical foundation while designing and composing with such unpredictable parameters as turbulent fluid flow. Perhaps the most interesting observation of his is that certain mechanizable aspects of artistic creation may be simulated by certain physical mechanisms or machines. [3] And certainly from a compositional point of view this process works in reverse. Many of the ideas outlined in Xenakis's *Formalized Music* eloquently describe how composers can turn to complex natural processes for the creation of musical structures. For example, sonic events can be made out of thousands of isolated sounds, and that multitude of sounds, understood as a totality, becomes a new sonic event. This mass event is articulated and forms a "plastic mold" of time, which reflects aleatory and stochastic laws. [4]

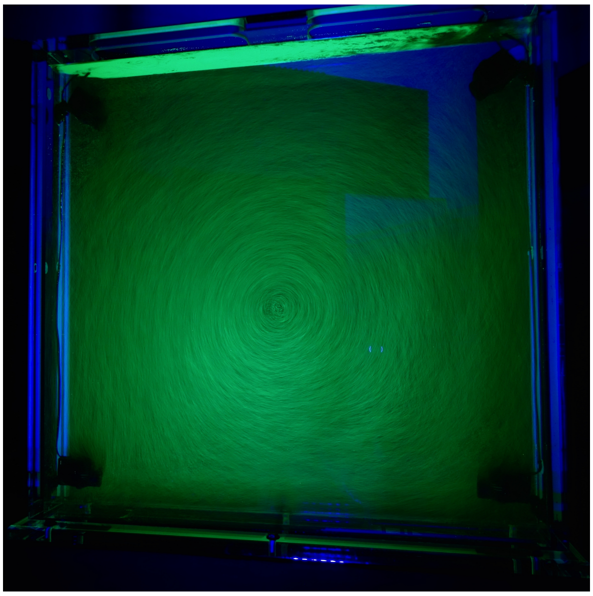

Figure 1. A time-lapse image of *Granular Wall* showing a spiral vortex created by four jets within the tank.

Another point of historical influence is James Tenney's influential *META+Hodos*, a work that puts its primary focus on how music is codified within multidimensional space. Tenney's application of Max Wertheimer's *Laws of*

Organization in Perceptual Form to music theory and analysis was a brilliantly provocative alternative to traditional score-based analytical methods. In particular, numerous musical analogies to "points and lines in the visual field," as well as the concept of using factors of proximity, similarity, and intensity for organizing musical elements allows for a seamless conceptualization between the visual and acoustic dimensions. [5] Indeed, the mechanical differences between the auditory and visual apparatus–and thusly, our comprehension of visual and acoustic material–are so fundamentally contrasting that an analytical application of evolutionary gestalt psychology is probably necessary for any "fluid" discussion of visual sonification.

In *Granular Wall*, the motion tracking of moving particle clouds, spiraling formations and traveling internal waves allows for the creation of parameters that can effectively be mapped to sonic fields: pitch, register, overall density and intensity, spatial location, morphology, timbre and the general progress of the form. For example, a spiral vortex can correspond to a range of musical ideas by sonifying its shape (Figure 1). Because of the immediate and arresting visual qualities that fluid motion provides, perhaps it is fitting that Xenakis directly speaks to fluid motion serving a musical purpose: "the archetypal example is fluid turbulence, which develops, for example, when water flows rapidly around an obstruction…[resulting in] a set of mathematical mechanisms common to many systems that give rise to complicated behavior." [6].

Furthermore, many fluid physicists are motivated not only by their important scientific goals of their work, but also by a visceral fascination with their work. [7] Van Dyke's seminal *An Album of Fluid Motion* and the annual Gallery of Fluid Motion presents fascinating and dazzling visualizations of innovative flow techniques related to both liquids and gases. [8] The striking variety and complex beauty of the visual phenomena, coupled with the sonic component offers a multi-faceted reading of the limits and capabilities of our various perceptual apparati, as well as how they can be represented in an artistic context. We also quickly realized during the development phase of the sound installation that we could re-create many sophisticated fluid flows using relatively simple visualization techniques.

3. DESIGN AND MATERIALS

In order to visualize fluid motion patterns at a scale appropriate for observers within a gallery space, we designed a custom standing tank of clear polished 3.175 cm acrylic (1.2 meter length x 20cm width x 1.2 meter height). The top is partially closed with a flanged bottom for bolting to a metal stand. The 208 liter tank then holds some tens of thousands of bright fluorescent green (505nm peak) and neutrally buoyant polyethylene microspheres (500μm) designed with density ~1g/cc for suspension in fresh water. Precision density calibration ensures that during extended periods of inactivity in the propulsion jets, the spheres saturate the tank with even dispersion, rather than gradually sinking or floating to the top. Because the spheres are manufactured to be hydrophobic, we coated them with a soap surfactant prior to suspending them in the tank. A Chauvet ultraviolet lighting system is placed in front (diagonally) of the tank so that the microspheres are maximally illuminated.

Four propulsion jets are attached with neodymium magnet suction mounts to the four corners of the tank. The location and directionality of the jets is carefully calibrated to ensure vertical orientation of fluid motion, allowing for the possibility of vertically and horizontally symmetrical flow shapes (ascending convection pattern, descending convection pattern, "four-leaf clover," right/left-facing double spirals, turbulent collisions, etc.).

The jets are driven by an Arduino-controlled electrical relay switch, which follows a pre-composed 20-minute cycle of synchronized on/off steps. Every combination of jets is represented in the relay sequence, and the ordering of the sequence is designed to highlight and contrast the various possible motion types. For example, a full-tank clockwise spiral vortex is achieved by initiating the top left and bottom right jets, and this is followed by a spiral vortex in the opposite direction (bottom left and top right jets, counterclockwise flow direction), resulting in a period of chaotic disruption before a relatively laminar flow pattern is reestablished. In another scenario all four jets are initiated for a relatively brief period of time–long enough to disrupt all of the fluid in the tank but not long enough to create a stable clover-shaped flow pattern–followed by an extended period of inactivity in which the complex interactions of the initial burst are slowly played out. By and large, the compositional work of the sound installation is located in this sequence of relay switches. The timings, durations, spatial locations, and juxtapositions of the jet motions are analogous to compositional ideas of contrast, sectional divisions, and large-scale form.

Two cameras for motion tracking are located on the opposite side of the tank from the viewers. Two laptop computers (processing the flow visualizations in real-time), audio interfaces and a mixer are all hidden underneath the tank. The resultant sound synthesis is sent to left and right channel monitors placed approximately 1 meter from each side of the tank.

4. SONIFICATION AND MOTION TRACKING

Several prevalent computer vision techniques are used to translate the various flow visualizations to sound. It was our desire to find mapping strategies that both give a direct correspondence to the directionality and velocity of flow patterns as well as a less direct sonification of the unpredictable patterns created through turbulent flow. The motion tracking is implemented using various analysis processes within the Max/MSP/Jitter programming environment. [9] Computer vision and motion tracking methods are implemented using the cv.jit library. [10] In *Granular Wall*, we were primarily interested in mapping the movement of the microspheres in a fluid medium in more than one way at once. This sonification technique is consistent with Yeo and Berger's application of image sonification methods to music, where both scanning and probing the image or video input are both used. [11] More specifically, we settled on methods that both sonified the video images in a fixed, non-modifiable order and more arbitrarily at different regions of the video image (regions of the tank).

4.1. Feature Matching and Optical Flow

Within computer vision literature, the term feature matching can refer to the analysis of visual structures defined by interest points, curve vertices, image edges, lines and curves, or clearly outlined shapes. [12] By tracking the motion of the particles either as a singular cloud shape or in several localized cloud shapes we are able to analyze the morphing images by matching different features in one frame to the most similar features in the second. [13]. One such motion flow analysis method used is the mapping of this cloud motion of microspheres within a matrix of 36 (6 x 6) subsections of the tank (Figure 2). As propulsion jets are turned on and off, flow patterns can be tracked by narrowing in on these specific subsections of the tank. We found that the Horn Schunk optical flow algorithm was the most efficient way of estimating the directionality and velocity of particles within the individual chambers. The resultant synthesis presents granular sounds moving up and down in frequency and spatialized either to the left or right channel.

One aspect of motion tracking that is distinctive to fluid motion–and in particular to the motion of neutrally-buoyant particles within a fluid medium–is the difficulty of defining region boundaries within a highly dispersed field. Neutrally-buoyant particles reflect the highly entropic nature of internal fluid dynamics, as opposed to particles of a different density than the fluid medium, which will form into more clearly differentiated shapes and patterns. While the gravity-defying qualities of the 1g/cc particles lend a striking elegance and beauty to the installation–in addition to more accurately reflecting the internal motion in the tank–it presents a challenge in terms of motion analysis. In order to successfully translate the fluid motion into digital information, the captured video image was first reduced using an adaptive threshold limiter to filter out less bright particles (the adaptive capability of the limiter was also essential due to the difficulty in achieving a perfectly even diffusion of ultraviolet light throughout the tank). After filtering out darker pixels, remaining pixels were "dilated" (new pixels were added surrounding the filtered pixels in order to make them appear larger). Finally, a visual delay effect (or "slide") was added to more prominently express the motion of the pixels over time. To do this, illuminated pixels decrease gradually in luminosity in subsequent matrix frames. The resulting image more closely resembles a group of isolated entities with clearly visible vector paths as opposed to the unprocessed image, which is closer in appearance to undifferentiated static. A careful balance needed to be negotiated during the visual processing phase so as not to reduce the image to the point that the complexity of the fluid motion was no longer communicated.

In addition to the left/right and up/down directional analysis, the relative speed of fluid motion was able to be described by measuring varying levels of overall (averaged) luminosity within each of the 36 subsections. When the fluid motion is slow, the fluorescent microspheres are more stationary and thus reflect more continuous light into the camera, and vice versa, fast-moving spheres do not reflect as much light. Thus, the overall luminosity is inversely proportional to the velocity of the fluid motion. A range of luminosity readings is typically created for each performance of the installation (depending on the ambient light in the space as well as the number of spheres and placement of the lights) and this is scaled to a range of rhythmic values for the sound synthesis. Note durations are also mapped to fluid speed, thus there is a continuous transformation between rapid, short blips and slow, gradually decaying tones.

The synthesis consists entirely of sine tones with a bell-like amplitude envelope (20 ms attack, variable-duration exponential decay). Musical parameters of pitch, panning, glissando direction, note density, and note duration are determined both by the location of the subsection of the tank and by the motion of the microspheres. The six vertical rows of the tank are divided into six octaves with low frequencies mapped to the bottom of the tank and high frequencies mapped to the top of the tank. Within each of the one-octave ranges, a pitch set built on a justly tuned scale is randomly applied to the granular synthesis tones. The frequencies for the lowest octave are: 110 Hz, 123.75 Hz, 137.5 Hz, 151.25 Hz, 165 Hz, 178.75 Hz,

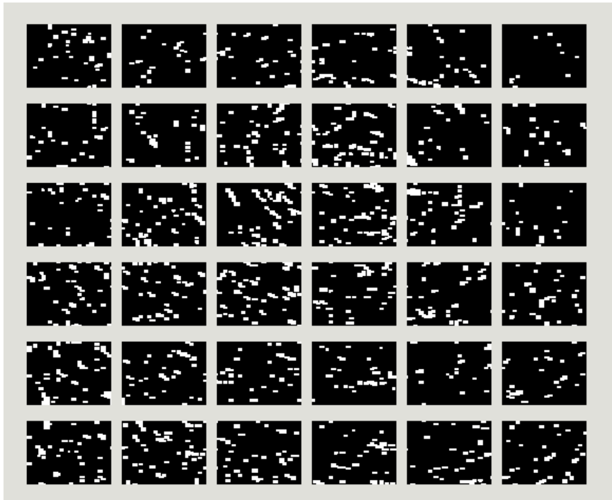

Figure 2. The separation of the tank into 36 chambers for optical flow analysis and feature matching.

192.5 Hz, 206.25 Hz. These frequencies are doubled to provide ascending octaves in each of the horizontal rows of the tank. However, due to the glissandi applied to each tone, the aggregate harmonic quality of the pitch set is only faintly discernible.

The six vertical columns are mapped to the global panning ranges for the tones as follows (from left to right): Column 1 - 100% pan left, Column 2 - 80% pan right, Column 3 - 60% pan left, Column 4 - 60% pan right, Column 5 - 80% pan right, Column 6 - 100% pan right. The glissando for each note direction is determined by the up/down direction of the microspheres provided by the motion tracking analysis. The overall speed of directional movement of the microspheres is mapped to a percent deviation from the starting frequency with faster movement up or down resulting in a greater percent deviation from the starting pitch. The range of frequency deviation in the glissandi is 0% to 20% of the starting pitch. Musical parameters of note density and note duration are inversely proportional and are mapped to the sum of the pixel values of a particular subsection (range of 10,000 to 800,000). Each subsection is monophonic (allowing for 36-voice polyphony overall), with a note duration range of 50 ms to 3000 ms. Depending on the overall lighting in the gallery space, the visual threshold in the image processing must be adjusted to ensure an even displacement of note durations.

4.2. Mapping to Spectral Audio

Another method we found successful for sonifying the fluid motion types in the tank was to translate the tank directly as a visual spectrogram, where the lowest sound frequencies of one aspect of the audio output were rendered by the particle motion in the lower regions of the tank. This video analysis simply calculates the absolute frame difference between subsequent video frames. [14] The particle movement is mapped more easily using the same thresholding technique described earlier. Using this method, we are able to generate additive synthesis while considering the entire area of the microsphere movement. The inverse spectrogram approach of taking the square tank and transferring the video tracked images on the Y-axis (frequency) and X-axis (time) is also adapted partially from the sonification methods in motiongrams–where video analysis tracks a moving display as a series of motion images. [15] This is similar to the now common technique of 'drawing' a spectrogram onto a two-dimensional plane. In our Jitter implementation, the matrix data is mapped to audio via jit.peek~, and then sent to an interpolated oscillator bank (640 oscillators) to generate the drone layer. The resultant timbres are then applied to the audio mix to create a timbrally-rich musical background, which can represent the tank at its most static (stillness) and at its most dynamic (turbulent flow). Figure 3 presents a screenshot from our motion tracking sequence of the inverse spectrogram method.

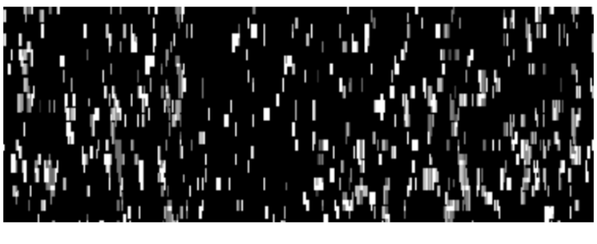

Figure 3. A video screenshot of our implementation of the inverse spectrogram technique: particle movement is translated to frequencies and amplitudes on the 2D spectrographic plane.

As we can see from the previous description of the sonification mappings, a significant reduction in information occurs during the translation from the visual to sonic realms. This is due both to the computational limitations of the real-time synthesis as well as the different perceptual capacities of the eyes and ears. With these mappings and parameter ranges, the general motions of the microspheres can be clearly discerned aurally, which is the primary goal of this aspect of the sonification process.

5. FUTURE WORK

Sonifying fluid motion has many rich possibilities both within electroacoustic composition and, more importantly, in intermedia art forms. Because there are many creative ways that artists can make fluid dynamics visible, it follows that sound artists and composers will be able to find ways to make flow visualization audible. Taking our initial motivations further, we are interested in turning the process back on itself–where sound can be used to alter the fluid flow of a liquid or gas. The use of ultrasound, surface acoustic waves, and even acoustic microfluidics offer some possible points of departure.

As composers we are interested in finding other ways of generating timbre and spatialization that corresponds to the movement of the fluid. Because of the challenging nature of mapping motion to music, and that many times we are led to make arbitrary decisions about timbre, it is important to consider a wide range of synthesis techniques that represent our chosen materials–in this case, water and fluorescent particles. Future sound processing strategies could include using audio sampled from our visual and/or physical source, and then assigning vector positions to sound file positions. [16]

6. CONCLUSIONS

Sonification of fluid dynamics presents technological challenges in the analysis and distillation of highly entropic and dispersed environments. Image reduction and compartmentalized directional flow analysis must be balanced with a computationally-intensive representation of the complex interplay of internal motions of the fluid. Sonification of such an environment is achievable through flow analysis and simulated granular resynthesis, as well as more directly via direct visual mapping to spectral audio.

A conceptual challenge–one that likely applies to most attempts at sonification of visual phenomena–is that complexity of fluid dynamics is more fully comprehensible to the eye than to the ear. Sound artists must necessarily make creative and sometimes arbitrary decisions regarding the materials and morphology of the music in order to create connections between the audio and visual realms. The most direct translation of data may not necessarily provide the clearest expression of the visual elements.

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