Multi-modal Interface for Fluid Dynamics Simulations Using 3–D Localized Sound

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Abstract. Multi-modal capabilities can be added to a simulation system in order to enhance data comprehension. We describe a system for adding sonification capabilities to a real-time computational fluid dynamics (CFD) simulator. Our system uses Max/MSP modules to add sonic properties to CFD solutions. The enhancements described in this paper allow users to locate sound sources in a 3–D environment using stereo auditory cues to identify data features.

1 Introduction

High-performance computing allows us to generate complex simulations in real time, producing large, detailed and dense data sets that are rich with information. Although visualization is often an expressive and effective tool for illustrating data sets or for communicating computational results, it can be difficult to communicate multi-dimensional data using visualization alone. When data sets become highly multi-dimensional, the number of visual features required to illustrate data properties can become confusing or unintelligible to the user. This issue is commonly known as the "curse of dimensionality."

We have created a distributed simulation system that is designed to facilitate multi-modal data communication. The system allows large-scale simulations to be rendered in real-time on a high-performance computational platform, then communicated to the user via a multi-modal workstation. The current system uses visualization and sonification to communicate data to the user, and is also equipped with a haptic interface which will be integrated at a later stage. This paper discusses our sonification strategies for enhancing the presentation of dense multi-dimensional computational fluid dynamics (CFD) data.

There are a number of projects involving the sonification of scientific data sets that are similar to our own approach. The research of Klein and Staadt [6] is particularly relevant as they are also concerned with the sonification of vector fields. They examine how best to sonify local areas of interest as the user

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navigates through large data sets, using parameters of frequency and amplitude to manipulate generated white noise.

Obrenovic *et al.* [7] address sound spatialization in their research, undertaking a user study in order to assess whether sonified data (spatialized sound and amplitude modified by position) helps users to locate a specific target in a data set. Their findings indicate that the use of spatialized and positional sound sources help users find targets more quickly and accurately.

Hunt *et al.* [3] [4] offer an alternative method for data sonification. They introduce the concept of a Model-based Sonification system, whereby the sonification properties are generated directly from the acoustical properties of the simulation. We theorize that an acoustically based approach could produce interesting sonification mappings in a CFD scenario and plan to investigate this strategy at a later date.

As described by Kazakevich *et al.* [5], we have previously experimented with sonification in our CFD system, providing users with auditory feedback when searching for the center of a vortex in a visualized CFD dataset. Our strategies are currently being evaluated in a formal user study to determine their effectiveness. The results indicate that there is an increase in the efficiency of locating the center of a vortex using sound and visualization. Visualization allows users to rapidly locate the rough vortex location, while sonification helps the users refine their identification of the vortex center. This paper presents our continuation of this previous work, introducing new sonifications to the simulation.

2 Structure of the Simulation System

The sonification interface developed for this project serves as a front-end to a large-scale, collaborative computational steering system [1]. This system allows users to access supercomputer systems in order to perform complex CFD simulations in real-time and then using a specialized solution server, transmit the results of their computations to remote users via a high-bandwidth connection. The application we are developing is a simulated “Virtual Wind Tunnel” that allows users to visualize the behaviour of a fluid (air, water, etc.) and to observe how it interacts with virtual objects or terrains.

Visualization and Interactivity. The visualization component of our multimodal interface is a simple 3D rendering created using OpenGL Performer. Wind velocity and direction are represented by mapping the velocity vectors to arrow glyphs which are colored according to each vector’s magnitude.

The user can interact with the visualization using two input devices. A mouse is used for navigation, and a haptic tracker is used to interact with the sonification mechanism. The tracker controls the on-screen pointer that represents the user’s virtual position in the simulation. The sonification system considers the user’s virtual position when computing the auditory feedback that is provided in order to illustrate properties in the dataset. Currently no haptic force-feedback is provided (this functionality will be implemented at a later date.)

Sonification Interface. The sonification component of the system was developed using Max/MSP [2]. Max/MSP is a music and sound analysis and generation development environment with a visually programmed interface that makes it suitable for rapid prototyping and evaluation. Max/MSP applications are developed by drawing lines to connect modules (known as 'objects') to describe the way audio data flows between object components. Max/MSP contains a number of sound synthesis objects which one can use inside a sonification system. The sonified data is transmitted to the user via a stereo headset, allowing sound to be spatialized in two dimensions.

3 Sonification Strategies

The client module that is used to communicate data from the solution server and the position of the haptic device to the sonification module contains the following outputs:

1. Up to 20 data points can be simultaneously sonified. For each point, several pieces of information are available for sonic rendering:
   - the magnitude of the velocity vector;
   - the horizontal distance between the data point and the user's pointer in screen space;
   - the distance (in XYZ coordinate space) between the data point and the user's pointer.
2. The dot product produced by determining the difference between the velocity vector representing the user's pointer's movement in space and the velocity vector closest to the pointer

Using these parameters, we have defined several strategies to associate data exploration with auditory feedback.

3.1 Spatialized Rendering of Sound Sources

We used sound spatialization in the auditory interface in order to provide users wearing stereo headphones with additional cues regarding data location. The Max/MSP toolkit provides capabilities for panning amongst multiple speakers, so we were able to easily integrate stereo sound into the rendering environment.

Targeting Regions of Interest. We devised a sonification strategy to allow users to target the spatial location of regions of interest in a simulation. For the purposes of investigation, we determined regions of interest to be regions of high vorticity. We chose to sonify the 20 points of highest vorticity in a simulation and created a sonification scheme that allowed the user to 'hear' the data points from any position inside the simulation. Distance to/from the regions of interest is communicated to the user in several ways:

- The closer to a point the user's pointer is, the louder that point sounds
- The user's pointer position relative to the each sonified point determines how the sound is balanced between the stereo headphones
- The intensity of the sonified point is relayed to the user via frequency modulation of the sound

Each sonified point is associated with a "pink noise" sound, generated using the MSP `pink~` object [2].

Distance Sonified Through Amplitude. The amplitude of the signal associated with each point is manipulated based on its distance from the user's pointer. To do this, the sonification module is supplied with an input which describes the distance between the user's pointer and the point being sonified. The cube root of this distance is determined, so that amplitude increases non-linearly as the user approaches the data point. This increases the user's ability to perceive the increase in amplitude and is based on psycho-physical considerations, as is discussed by Kazakevich *et al* [5].

Velocity Sonified Through Frequency. To manipulate the frequency component of the sounds associated with each data point, we adjust a `lowres~` low-pass filter which affects the presence of high frequency components on the audio stream and manipulates the perceived "pitch" of the sound. In this way, one can map point velocity to the maximum frequency found in the auditory output stream, causing the points with the highest velocities to be sonified by the highest pitched pink noise stream.

Stereo Sonification. The sonification module is given a parameter reflecting the left-right position of the data point relative to the user's pointer in screen-space. This parameter is then mapped to the input of the Max/MSP `pan~` object, so that Max/MSP outputs the sound through the stereo headphones proportionally to the distance the data point appears to the left or right of the user's pointer. Data points that are far to the left are sonified primarily through the leftmost headphone speaker, but as the user changes position, the left-right balance becomes more equal, or shifts to the rightmost speaker if the user's pointer crosses to the opposite side of the data point.

Stereo sonification gives the user an additional cue as to whether or not he or she is moving closer or farther to the sound source, and in which direction he or she should move the pointer in order to reduce the distance to the region of interest.

The spatialization provided interesting auditory feedback regarding the position of the data points in space, despite the fact that it was rudimentary (a surround-sound 3-dimensional system would be more effective.) The drawback to this sonification scheme is that the global maximum is not clearly evident, since the sonified data points are all associated with similar sounds, making it difficult to distinguish fine features in the data. For this reason, we experimented with an alternative sound generation strategy in the next sonification.

3.2 Frequency Targeting for Sound Sources

This scheme was proposed as a way to rapidly identify the global maximum in a data set by using frequency modulation and stereo spatialization to guide the user towards the data element with the highest velocity value.

To create this sonification, only one data point (the maximum) was sonified, and the user's distance to the target point affected the frequency output by Max/MSP. Stereo sound was also used to guide the user in the direction of the target point.

In order to generate the sound mapping between distance and frequency, sine waves were generated using the Max/MSP `cycle~` object. The sine waves were generated at several frequencies to provide the user with a complex tone rather than a single pure sine wave. As the user's pointer approached the target data element, the frequency of the sine waves increased causing the user to perceive an increase in pitch. Conversely, if the user moved the pointer further away from the target, the pitch of the sound decreased.

This sonification scheme appeared to assist a user in locating the target point in the data set. The stereo spatialization helped identify the point's location at large distances, and changes in the sonified frequency helped the user to fine-tune their search.

3.3 Consonance and Dissonance When Traversing Flow

This sonification scheme was devised as a way to indicate to the user whether he or she was moving with or against the airflow in the simulation as described by the direction of the velocity vectors in the fluid field.

To determine this, the user's movement vector was determined by monitoring the distance between his or her current position and his or her position in the previous timestep. This movement vector could then be compared to the nearest velocity vector in the simulation. The dot product between the two vectors indicates the difference between them, and it can be used to determine whether the user is moving with or against the velocity vectors in the simulation. When the dot product between the two vectors is negative, the user is moving against the airflow; when it is positive, he or she is moving with the airflow.

To sonify this information, a series of sine tones were created. The tones were separated by a consonant interval when the dot product is positive and the user is moving with the airflow, and a dissonant interval when the dot product is negative and the user is moving against the airflow.

This is done by layering several sine waves created using the Max/MSP `cycle~` object. The sine waves corresponding to the consonant and dissonant components of the sonification are triggered on and off based on the value of the dot product, causing the user to perceive a consonant sound when travelling with the direction of flow, and a dissonant sound when travelling against the direction of flow.

After some exploration of this sonification strategy, our team theorized that the use of consonance and dissonance in relation to flow direction could aid in the comprehension of a simulation which used streamlines to describe continuous airflow. We plan to explore this use of sonification in future project development.

4 Future Work

While the sonification strategies presented in this paper appear to be useful, user studies are required to validate their effectiveness in improving users' comprehension and exploration of multi-dimensional data sets.

Currently, a user study is underway evaluating our previously developed sonification strategies described by Kazakevich *et al.*[5]. Extending the user study to evaluate our new sonification methods is required in order to assess their merit and refine their parameters to achieve the optimal configuration for each strategy.

In the future, we would like to expand our multi-modal platform to include not only sonification strategies, but also haptic strategies that would allow the user to obtain force-feedback information about their interactions with the data set, and provide them with a more concrete spatial understanding of the rendered solution. It is our hope that incorporating multi-modal interaction will allow us to give users a better understanding of the complex simulation data that our solution server is capable of computing and distributing to collaborative research groups.

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