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Oxygen Flute: A Computer Music Instrument that Grows

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Abstract

The quality of the air we breathe depends on a balance of plant and animal life. Oxygen Flute is an interactive computer music environment that makes the exchange of gases audible. Gallery visitors enter a chamber with bamboo and four continuously performing (digitally modeled) flutes. Patterns in levels of carbon dioxide measured inside the chamber create the music. The computer flutes are played both in real time and from the accumulated history of fluctuations recorded in the space. The flute models are simulations of 9,000 year-old bone flutes from China.

1. Introduction

Artist Greg Niemeyer was commissioned in 2000 to create an interactive installation for the San Jose Museum of Art, located in the heart of Silicon Valley. Greg knew he wanted to make a tangible, sonic exhibit and enlisted me as musician. The result is a 1,500 kg sculpture (Figure 1) exhibited from October 2001, and then from September 2002 at the Kroeber Museum of the University of California, Berkeley.

The project became the second collaboration in a series whose theme is revealing hidden dynamic aspects of our world. These pieces involve sensor technology that extends our sensory organs (Chafe & Niemeyer, 2001). Oxygen Flute reveals plant and animal respiration through gas concentration readings. Our sense of our own respiration is normally functional ("I'm gasping") or observational (scientific). Oxygen Flute is intended to open a different mode of perception, one which fosters intuitive and emotional awareness. The musical and sculptural design focuses attention on a dynamic exchange that is so simple, yet so vital and largely taken for granted. Visitors to the flute gain a qualitative feeling for the interdependence of respiration between plants and animals, and the carbon/oxygen transport that takes place.

2. Listening to breath

The first thing to note is that patterns in the dynamics of respiration are exhibited on various time scales. Oxygen Flute operates a continuous sensor that logs carbon dioxide concentrations at two samples per second. On the fastest time scale, visitors' breathing inside the chamber triggers reactions and interaction. And on the farthest scale, the sensor accurately records the gradual increase of atmospheric CO_2 due to carbon emissions. Patterns in-between these extremes include the flow of visitors and the much slower flux from plant photosynthesis superimposed on the daily cycle of gallery visiting hours. The overall range of temporal patterns is shown in Table 1.

Figure 2 shows the daily cycles recorded over one week of the exhibition. The hours of museum operation are distinguishable as a 24-hour rhythm, and closed days are relatively quiet. Underneath this "animal" activity, the 24-hour pattern of photosynthesis is visible.

2.1 A paradoxical zoom

As observers of this time-series data containing multi-layered patterns, we are confronted with the "zoom question" whenever we step out of real time – that is, what is the ratio of compression or expansion to employ? Paradoxically, as shown in Figure 3, slowed-down fast patterns appear quite similar to speeded-up slow

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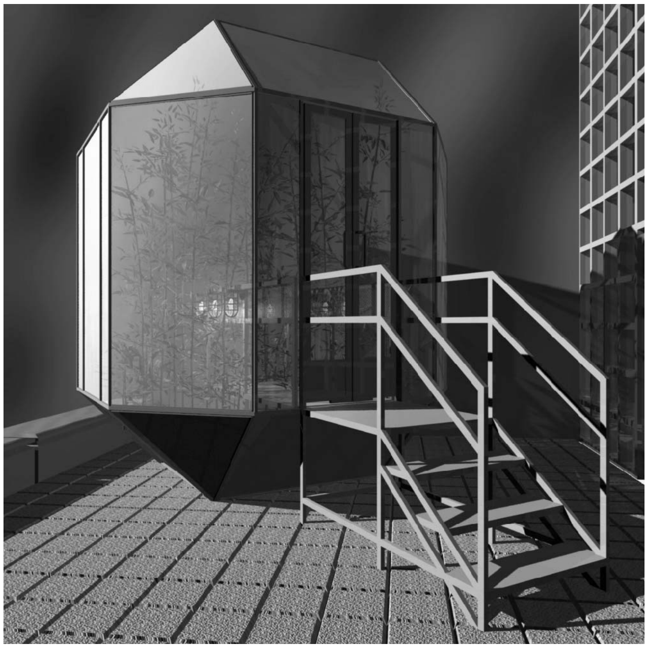

Fig. 1. The Oxygen Flute is a bamboo growth chamber in an art gallery setting.

Table 1. The time scales of Oxygen Flute's gas measurements (CO_2)

Duration	People pattern	Bamboo pattern
decades	carbon emission	forest growth
weeks	museum vacations	plant growth
days	museum weekends	weather patterns
hours	museum hours	photosynthesis
minutes	visitor presence	–
seconds	inhale and exhale	–
milliseconds	breath shape	–

patterns. Here, the top trace shows the reading logged from one day in the exhibit. Spikes represent visitor interaction. Smaller deflections show visitors coming and going.

The middle trace shows a zoom-in on 10 milliseconds of data, equivalent to decreasing the playback tempo by a factor of 100. Compare the appearance of events in this graph to those in the bottom trace, which is an accelerated (downsampled) view of the top trace's eight hours worth of data. The blurring of finer detail by zooming out leads to confusingly similar event patterns.

An observer cannot tell from these graphs or from their corresponding flute sounds what the time window or zoom factor actually is. That, however, is problematic

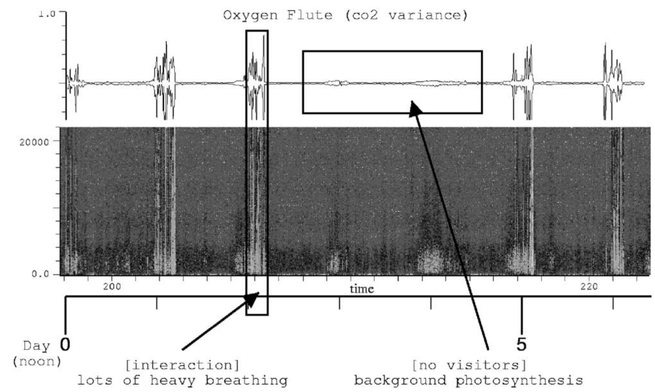

Fig. 2. CO_2 data logged inside Oxygen Flute over one week. The lower graph is a spectral analysis that highlights the high-frequency content of visitor interaction.

since the point of the piece is to project an appreciation of the "total" dynamic. The problem can be solved by making zoom itself perceptible.

Oxygen Flute employs a "performer algorithm" that has two modes: real-time and playback. In its relaxed state, the music follows a languorously slow-motion (very zoomed-in) time course through logged data. At the moment a visitor's breath is detected, it switches into real-time mode, obviously awakened and excited. The awakened mode is something of a tease, which invites the visitor to breath harder and faster. At some point, it detects a lack of visitor interaction and decays from very excited back to the slower, ambient tempo of events.

Level-of-zoom is communicated as a "voice" to be perceived through the music, thereby disambiguating it from the patterns themselves. The solution was found by giving zoom itself a pattern that registers perceptually. This pattern came from simple mechanics, a system that is common to everyone's experience. We created a zoom "pendulum" (in software) that begins to swing when a visitor blows on it. At rest, the level of zoom returns to the ambient level (the slow tempo, as in Figure 3's middle graph). As it begins to swing, there is a clear sense of tempo change, moving forward or backward through the data. Tempo and direction are in direct relation to angular displacement of the pendulum. The greatest excursion zooms out the tempi to the point where it creates the same musical effect as fully zoomed-in tempi (as shown in the graphs in Figure 3). However, to get there, the visitor must continue to blow on the pendulum in phase with its resonance, building its oscillation. The pendulum's period is two seconds – about right to induce hyperventilation. Design-wise, this was entirely intended and has been kept secret, or at least unmentioned in the exhibit's onsite documentation; "maximum swing" is meant to be a discovery that rewards the best (and most dizzy) participants.

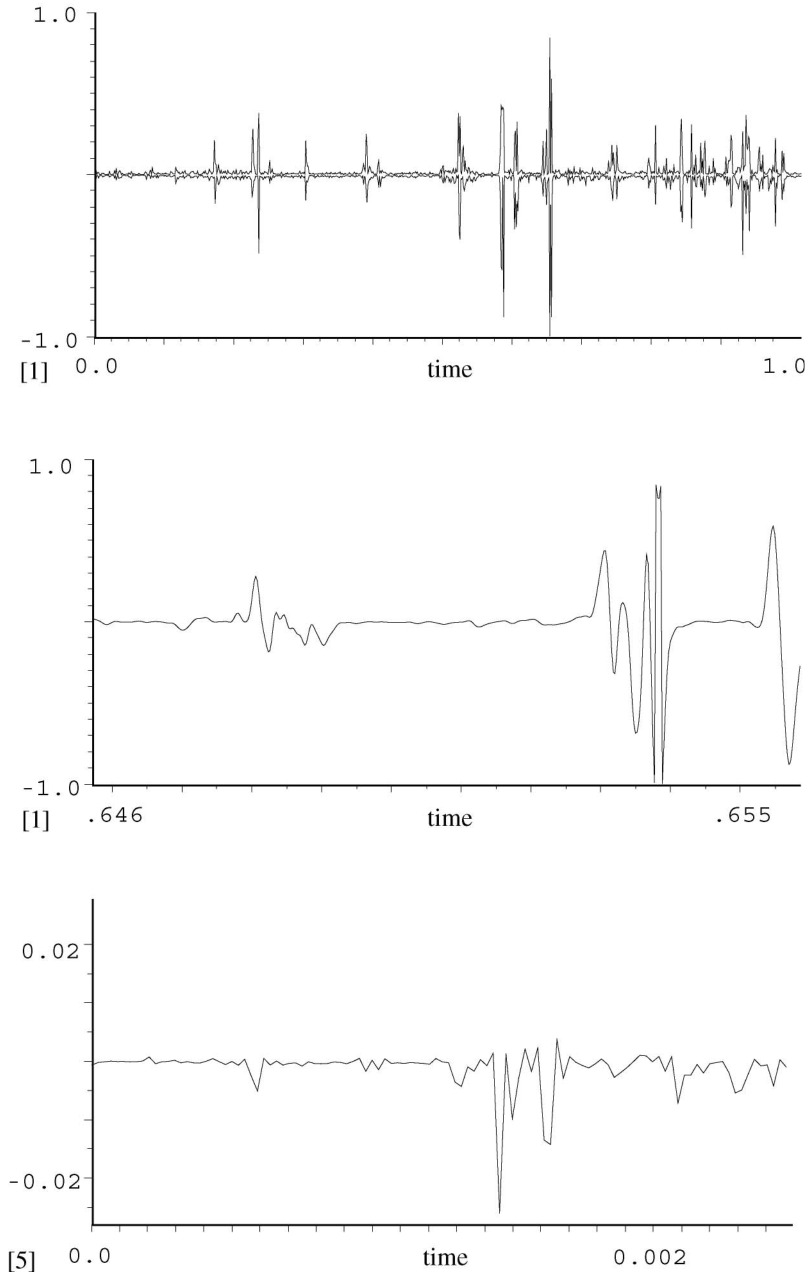

Fig. 3. CO_2 data logged inside Oxygen Flute shown at different zoom (tempo) rates: (top) a full day of museum visitors, 10am – 6pm; (middle) 100 × zoom-in on large spike; (bottom) 400 × zoom-out by downsampling.

2.2 Hyperventilation game and DSP

The Oxygen Flute system (Figure 4) comprises a computer, CO_2 sensor and four loudspeakers in a three-sided pyramid arrangement. Visitors enter onto a walkway (Figure 5) and are surrounded by the bamboo and music. The sensor is unobtrusively located at the end of the walkway.

Flute sound is projected within an artificial reverberant space that can grow or shrink in size using digital signal processing effects. For the listener, this changing synthetic ''room'' is superimposed on the actual room.

Hyperventilation creates a dizziness spell that goes away after relaxing one's breathing rate. During the spell, disorienting acoustical effects are noted by some. I have always experienced a kind of change to the spatial quality of sounds. The walls seem to move inward. This is not dangerous, and maybe it is only me, but it is something the performer algorithm capitalizes on. During a sustained period of pendulum swinging, the algorithm instigates a shift of spatialization to reinforce this effect. Figure 6 shows the (inverse) coupling of heavy breathing that accumulates CO_2 to a narrowing of the artificial reverberant space.

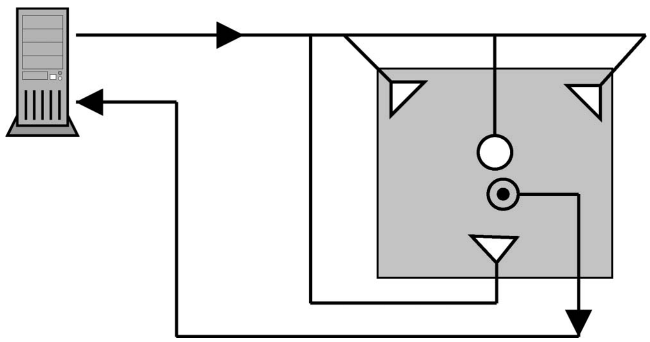

Fig. 4. Oxygen Flute components showing CO_2 sensor and four loudspeakers in pyramid arrangement.

Fig. 5. Walkway for visitors inside Oxygen Flute.

The change is reinforced with a concomitant change to synchrony of a continuous background percussion sound.

2.3 Small snapping shrimp (inside flutes)

A popcorn-like sound plays continuously in the background. These are the ‘‘snaps’’ from thousands of small (l cm) shrimp recorded by hydrophone at Monterey Bay on 11 September 2001. Their inclusion serves three functions: first, to create a musical connection to the visual surround of constantly trembling bamboo leaves; second, to provide a separate percussion line (part of a musical dimension of synchrony versus asynchrony); and third, to add key-click sounds to the flutes that would still project the flute pitch even when there is no breath excitation (sounding like tuned drums).

The walls of the Oxygen Flute chamber are stretched sheets of silicone rubber. At the outdoor sites where it has been installed, the air is never still, so the walls continuously stir the air inside. Thus the slight trembling of the leaves. This jittery visual background is complemented by aromas (bamboo, earth and silicone) and a sonic background of the continuously snapping shrimp.

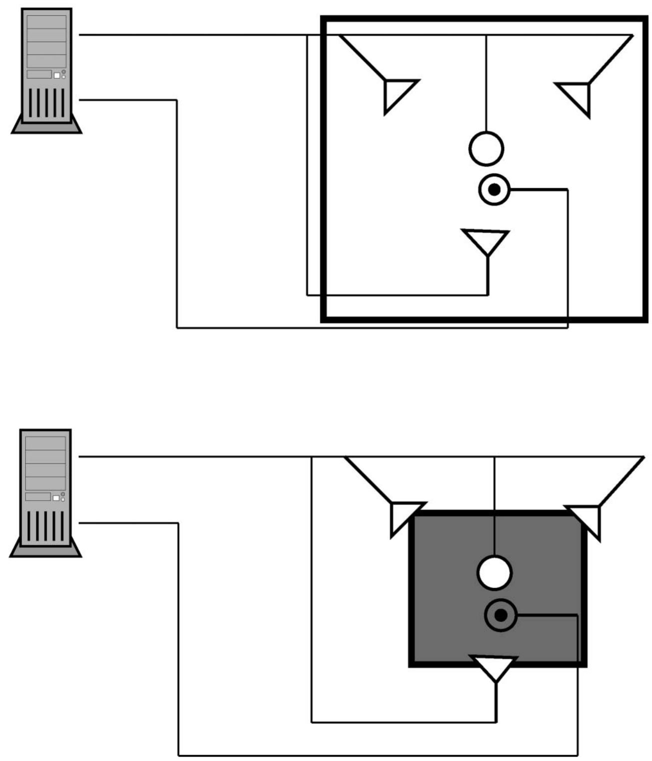

Fig. 6. Sensor readings invoke changes to artificial reverberation, strong readings causing the perceived ‘‘walls’’ to shrink.

A shrimp recording is looped over its length, but seems infinite because the snapping is uncorrelated. The recording plays into each of the four flutes, exciting the tube resonators. Before entering the flutes, however, the recording is split by delay lines of different lengths. If the illusory walls are in the ‘‘relaxed, ambient, wide’’ setting (Figure 6, top), then the delays are set to rhythmically significant lengths (i.e., a single snap entering the system will sound in a correlated four-part rhythm). When ‘‘dizziness mode’’ is triggered, the delays instead shorten to sub-rhythm lengths (<50 milliseconds), adding distinct early reflections to the reverberation. The walls close in making for an illusory suffocatingly small room around the listener’s head (Figure 6, bottom). Since the delays are nearly the same, the correlated rhythm disappears.

2.4 Music from old bones: Recreating ensembles of ancient Chinese flutes through digital simulation

Archaeological finds from the Jiahu site, Henan Province, of Central China have included 25 Neolithic bone flutes similar to the present-day bamboo *xiao*. These five- to eight-hole vertical flutes were fashioned from *ulnae* (wing bones) of the red-crowned crane. A team at CCRMA has attempted to bring these 9,000 year-old instruments to life using physical modeling synthesis.

We have been engaged in extrapolating synthesized ensemble performances through simulations that have been calibrated by ear to two flutes found in playable condition. The team's "fantasy" performances do not claim authenticity of style or practice. Rather, we are interested in an evaluation of whether advanced computer music techniques might serve musical archeology by providing replicas for experimentation. Oxygen Flute is a completely different application for these models, attempting improvisational-sounding performance instead of scored or traditional melodies.

Our interest in simulating the Jiahu flutes was sparked by a published description of the instruments and the accompanying web posting of a 45-second recording made at the Music Institute of the Art Research Institute of China (Zhang et al., 1999), one of several analog recordings made between 1987 and 1992. Conservation now dictates that the flutes no longer be played.

The site has been dated to 7000 to 5700 BC. With 25 flutes already discovered and only 5 per cent of the area excavated, it is likely that others will be found. The toneholes were apparently drilled using quartz tools, as inferred from the discovery of a quartz mine near the Jiahu area. The careful placement (and adjustment) of toneholes provide evidence of an advanced multi-note musical practice. None of the flutes have register holes. Their construction (Figure 7) resembles bamboo and various other wooden flutes found worldwide, including simple tourist flutes commonly sold as souvenirs. However, unlike many types of vertical flutes, the blowing edge was not modified by sharpening, nor was it notched.

2.5 Simulation technique

An earlier report (De la Cuadra et al., 2001) describes details of our physical model synthesis. The synthesis technique has been implemented in several computer environments, both as a real-time instrument and as a faster-than-real-time soundfile score renderer. Briefly, we have built on the now classical one-dimensional waveguide model that simulates flute physics from first principles (McIntyre et al., 1983; Smith, 1992; Hanninen & Valimaki, 1996). Toneholes have been added (Scavone, 1997) providing appropriate pitch control (replacing earlier slide-flute-style implementations in the literature). The synthesis system creates individual instrument simulations automatically from physical measurements of each of the Jiahu flutes. Since our present design implements a one-dimensional waveguide, only length, tonehole placement and tonehole diameter are relevant.

Two categories of parameters belong to the present model: those manipulated in performance and those that are qualities of each individual instrument (Figure 8). Breath noise is implemented using the vortex noise technique described in Chafe (1995).

For the Oxygen Flute ensemble, experimentation with different instrument combinations led to a quartet based on two flutes recovered from the same period at Jiahu. A copy

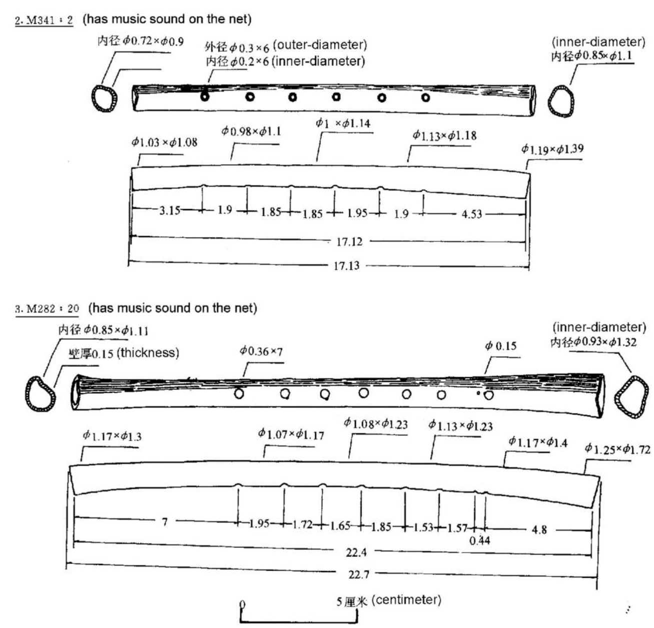

Fig. 7. The two Jiahu flutes for which there are example sound recordings.

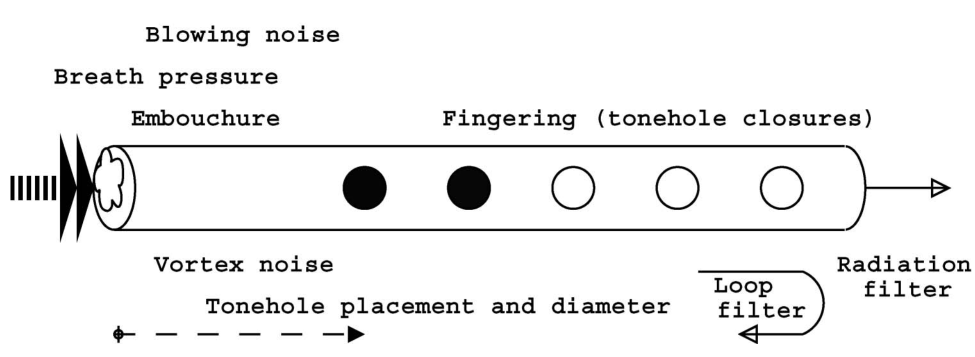

Fig. 8. Simulation parameters: Breath, blowing noise and fingering are controlled in real time. Tonehole geometry, filters, and vortex noise parameters are set during instrument creation.

of this pair was then digitally modified to create a second pair with longer alto flute lengths as shown in Figure 9. For installation at the exhibit's second venue, these lower flutes were revoiced by extending them into the bass register.

2.6 Mapping CO_2 readings to flute performance

At any given instant, the flutes are receiving a combination of real-time CO_2 data and recorded data that has accumulated since the beginning of the exhibit ("historical" data). This one-dimensional time-series data arrives at the performer algorithm and is split into several streams (Figure 10). As described above, the presence of a visitor determines the mix of real-time and historical data, and a "zoom pendulum" controls the tempo (and direction) of historical data playback (Figure 11).

A mix of real-time data and (historical) logged time series data is used to determine instantaneous values for the performance parameters in Figure 8, plus one other: the amount of shrimp snapping sound admitted into the flute. The following translations are provided by the performer algorithm:

- Translation to breath pressure.
- Translation to vortex operating point (affects spectral content of breath noise).
- A translation to tonehole closings and portamento. The scale ranges from fully-open to fully-closed and the toneholes can be closed abruptly or gently according to portamento value.
- Embouchure (blowing angle) changes with tonehole fingering and also follows a translation to amount of desired overblowing (for harmonics).
- Translation to shrimp input gain.

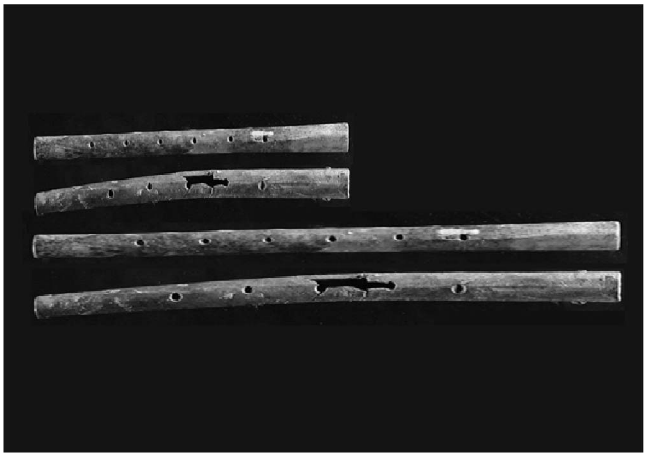

Fig. 9. Two of the flutes shown in Fig. 7 are digitally altered.

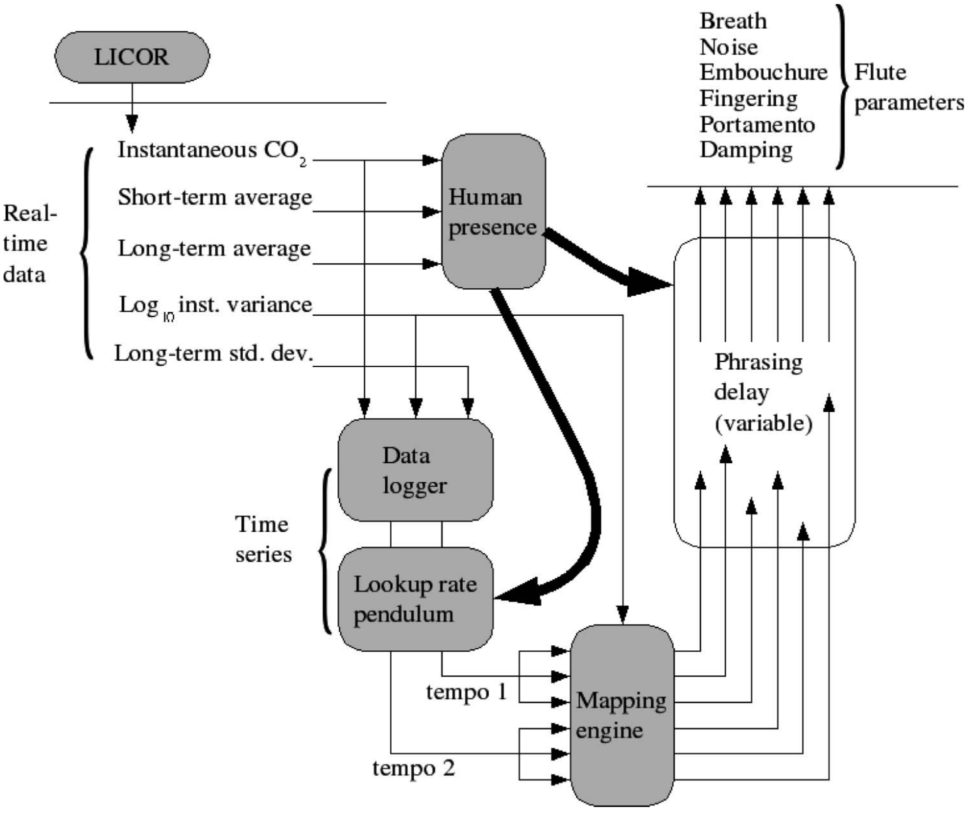

Fig. 10. Flute parameters are manipulated by incoming CO_2 readings (from LICOR device). Software modules analyze the readings and translate visitor behavior into virtual pendulum motion and musical phrasing.

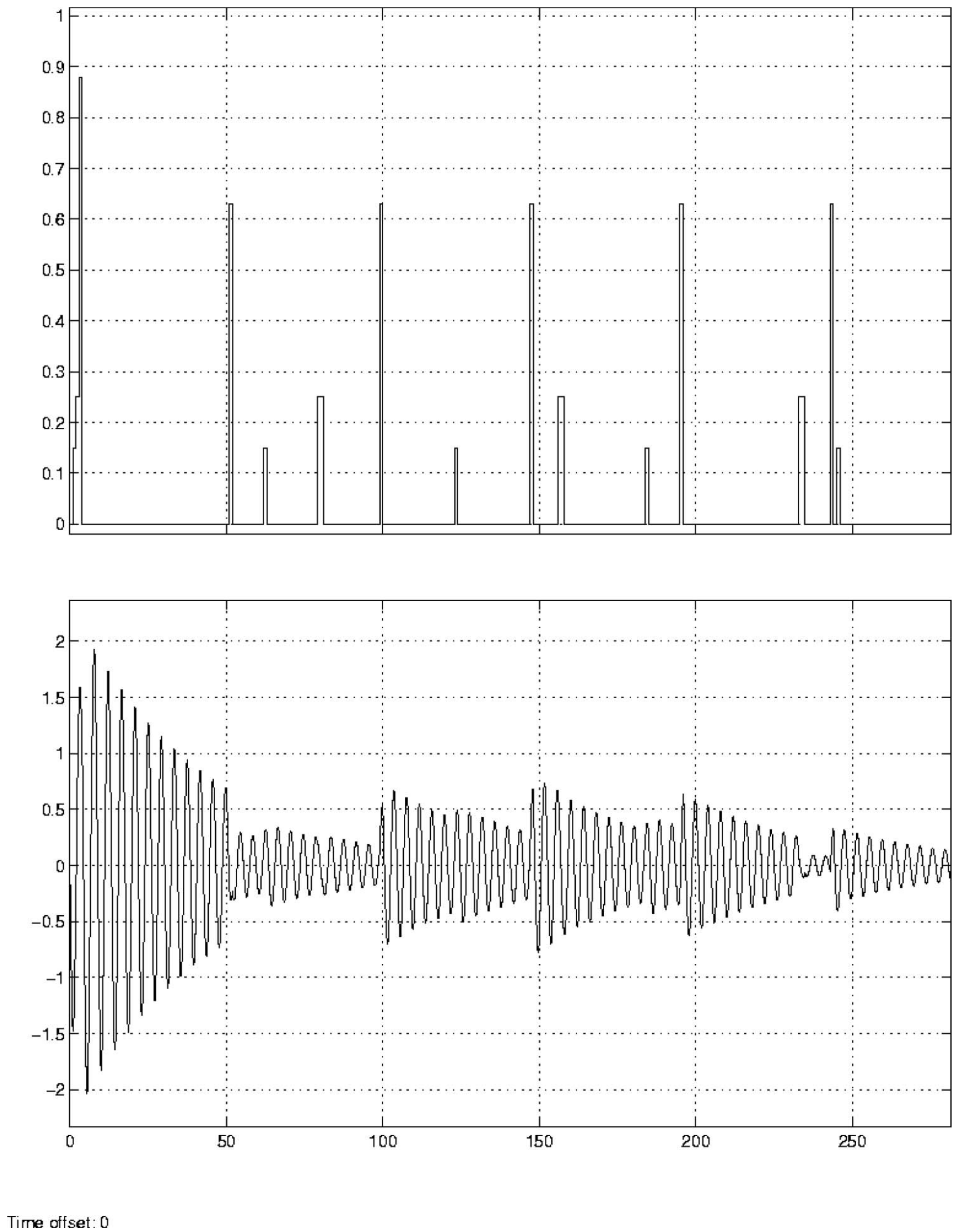

Fig. 11. Software pendulum swinging motion (lower trace) is excited by excitations derived from CO_2 flux.

Each flute in the quartet maintains an independent index into the historical data. These pointers move into and out of synchrony with each other depending upon visitor interaction. Sometimes the ensemble plays in coordinated phrases, otherwise the pointers travel at different tempi and at different locations through the historical data.

2.7 Software architecture

The application is written in C++ using the Synthesis ToolKit (STK, 2003) and the Qt library (Qt, 2003). The preferred operating system has been Linux running on an Intel PIII 866 MHz processor with four-channel soundcard (44.1 kHz sampling rate).

The application is divided into eight threads: one each for the flutes plus one each for the application event loop, sound output, CO_2 sensor and pendulum model. The pendulum was designed in the Matlab Simulink package and exported to C using Realtime Workshop package (Matlab, 2003).

Acknowledgments

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