REAL-TIME SONIFICATION OF PHYSIOLOGICAL DATA IN AN ARTISTIC PERFORMANCE CONTEXT

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ABSTRACT

This paper presents an approach for real-time sonification of physiological measurements and its extension to artistic creation. Three sensors where used to measure heart pulse, breathing, and thoracic volume expansion. A different sound process based on sound synthesis and digital audio effects was used for each sensor. We designed the system in order to produce three different streams clearly separables and to allow listeners to perceive as clearly as possible the physiological phenomena. The data were measured in the context of an artistic performance. Because the first purpose of this sonification is to participate to an artistic project we tried to produce an interesting sound results from an aesthetic point of view, but at the same time we tried to keep an auditory display highly correlated to the data flows.

1. INTRODUCTION

This study was made in the context of a workshop organized by Christian Jacquemin at LIMSI. This workshop is part of the VIDA project [1]. The aim of this workshop was to bring artists, scientists and engineers to work together on a project related to capture and use of physiological signals. Among the research topics covered by this project, one of them is to map data from sensors into video and sound. A first approach concerning sound, is to generate a *auditory display*, a *sonification* of the data. This *sonification* can be extend to a musical process or to be include in a musical composition. Moreover, the resulting sound generation should be designed in such a way that it can be included in a global artistic performance. This study proposes a new environment for the capture of physiological signals adapted to the performing arts. It allows for real-time sound generation and proposes a clear perceptual correspondence between body signals and sound synthesis parameters in the case of breathe amplitude and heart beat capture. The result of this work is a new approach to sound synthesis based on multi-channel bio-signals through the dynamic parameterization of sound synthesis models based on substractive synthesis and resonance modeling. It can be extended to or combined with additional sensor outputs, and offers an innovative approach to live sound synthesis intermediate between data sonification, live art performance, and medical monitoring.

Sonification is the use of audio to convey information or perceptualize data. Several approaches have been already explored to use sonification as an alternative or complement to vizualisation techniques [2]. Generally, methods to create sound from data are used: **or** following a musical aesthetic [3] **or** to display data in a way to convey information in a more systematic way. We believe that the field ‘in between’ the pure sonification and the data generated music can in fact enrich both fields and assists in the exploration of sound and music perception. In the music field, a particular case is when the performer use the sensing system to explicitly control the artistic result. Atau Tanaka was a pioneer in this case. In the early 1990s, Benjamin Knapp designed a human-computer interface called the BioMuse, allowing a human subject to control certain computer functions via bioelectric signals [4]. The Biomuse system was widely experienced by composer Atau Tanaka [5] who composed and performed live music using this system, primarily as an EMG controller, throughout the 1990s.

Sonification can be used for biomedical data (EEG, EMG, ECG), for the display of physical phenomena (for example: particle trajectories [6]), for meteorological data or many other data. Few contexts such as where a person is in movement have already been explored. This kind of context can correspond as example to sport training or artistic performance. In such cases, the sensors and strategies for data collection must be adapted, and real-time interactive approach is desirable. Few sensors and systems are actually really suitable for a context of physical performance. EEG for example are difficult to use outside of laboratory context.

In the literature, sonification is classified using five main categories: *Audification* (the data is directly translated to the audible domain), *Earcons* (structured sound pattern are used to represent a specific item) *Auditory Icons* (a classification process selects one of a set of sound pieces), *Parameter Mapping Sonification* (the data drives the parameters of a synthesizer), and *Model-Based Sonification* [6] (using dynamic processes that are parameterized by the data). Two of the cited categories are used in our study, the *Audification* and the *Parameter mapping Sonification*. For the signal that is close to an electrocardiogram, we used a special audification including resonance modeling. For the two others sensors we used parameter mapping between the data and substrative synthesis models. The mapping strategies are one-to-many; each data flow is mapped to several parameters of the same synthesiser. In order to produce sounds, which are more dynamic and pleasant, we added digital audio effects at the output of the synthesizers. We preferred in this study to drive parameters as energy and resonance frequencies instead of pitch (although a low change in pitch is used in one of them). This choice is justified by three considerations: firstly to avoid ambiguities related to pitch dimensions [7] and possible correlation between pitch and energy [8], [9], secondly to reserve pitch for a tuning to a global musical context or automatic data driven composition, thirdly to provide smooth but efficient sonification that will not be irritating or disturbing during a long time use.

2. DESCRIPTION OF THE PHYSIOLOGICAL SIGNALS

During the recordings several sensors were used to measure different physiological signals. The sensors were designed and provided by Julien Marro-Dauzat from the BIOGENE compagny [10]. Three of these sensors were used simultaneously in the sonification work that will be described in this paper. A first sensor measures the heart pulse. This sensor is identical to the ones used for cardio-sensing in commercial products for sports training. It sends a signal close to a pulse as shown in figure 4. The second sensor measures the breathing temperature and is positioned at the output of the nostril. The corresponding signal is a smooth but considerably dynamic curve correlated with breath amplitude. The third sensor measures the expansion of the thoracic volume. The signal from this sensor is also smooth but has a lower dynamics than the breath temperature sensor. The two last sensors produce signals that are correlated but have also their own dynamics and specificities.

3. DESCRIPTION OF DATA ACQUISITION SYSTEM

The signals from the sensors were sent with a wireless system to a PC and the acquisition was done using a graphical programming environment well-known for its performance in signal processing and automatic laboratories (LabView). The sampling rate used was 190 Hz and the quantification 10 bits per sensor. The wireless system is based on a Zigbee protocol [1]. Although this protocol is slower than Bluetooth or WiFi, it appears to be more adapted to a performance context for a relatively low number of sensors. Regarding to other systems available it is also definitely a low cost system.The data were vizualized using this software and projected on a screen during the recordings (see figure 1).

The data are sent to different platforms using OSC (Open Sound Control [2]). One of these platforms, a Macintosh running Max/MSP [3] was used to record the data. This was done using a patch for multi-track recording, which allows the replay of the data in the same environment. Another similar computer, running a similar patch, was used to receive the data, and design interactively a patch for sonification of the data. In this way, the designer was able to see the performer action, to vizualize the data and to build the system interactively and simultaneously. The replay of the data was first used to design the sonification, then adjustments and improvements were done during the course of the performance.

4. DESCRIPTION OF SOUND PROCESSING

The sonification of the three physiological signals is made using sound synthesis techniques and digital audio effects. These three interactive sound designs were done in this way in order to produce three different audio tracks clearly identifiable and to reflect closely each sensor signals. In particular, in absence of a clear differentiation, breathing and thoracic volume could be misidentified as they have more or less similar behaviors. When using sound synthesis, mapping strategies between data and synthesis models is an important consideration, some methods used in the the following descriptions are related to methods described in [11] and [12] [13]. The framework architecture is shown in figure 3. In this figure, the third synthesiser used for sonification of the thoracic volume is detailed.

Figure 1: Performers in action. On the background, the signals were displayed in real-time for the audience and the performers

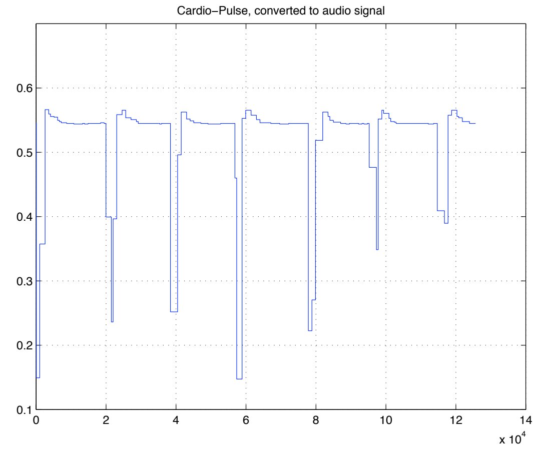

Figure 2: Cardio-pulse, converted to audio signal (the amplitude is modulated)

4.1. Heart pulse: an extented audification

For heart pulse, we used the sensor signal converted to an audio signal, then we processed it using 3 resonant band-pass filters. To convert the sensor signal to audio signal a ‘sample and hold’ tech-

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[1] http://www.zigbee.org

[2] http://opensoundcontrol.org

[3] http://www.cycling74.com

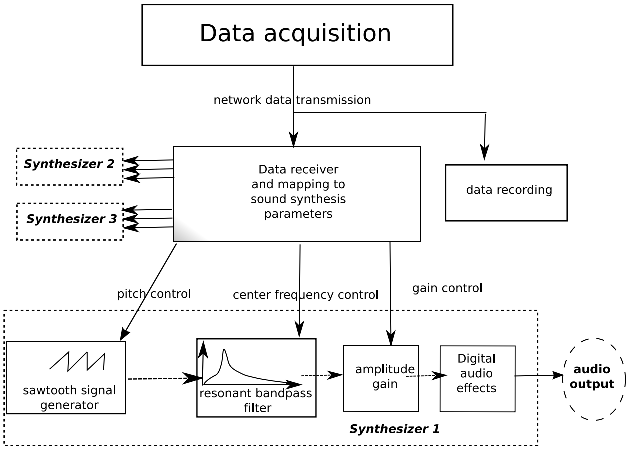

Figure 3: Framework architecture of the sonification. Only one of the sound synthesizers is detailed here.

nique is used, the resulting signal can be seen in figure 2. The center frequencies of these filters were tuned respectively to 55 Hz, 110 Hz and 220 Hz. An octave interval separates their center frequencies. The purpose of using three filters instead of just a single one is to increase the perceptual impact of the synthesized sound. The resulting sound using an unique filter was judged be be too poor and unpleasant. In this way, we get closed to a harmonic resonance model. Extending the three resonant filters to a filter bank with a large number of filters has been experimented. In particular, using resonance models of real acoustic instruments (stored and imported using SDIF format thanks to CNMAT Max/MSP externals [4]) gives interesting results.

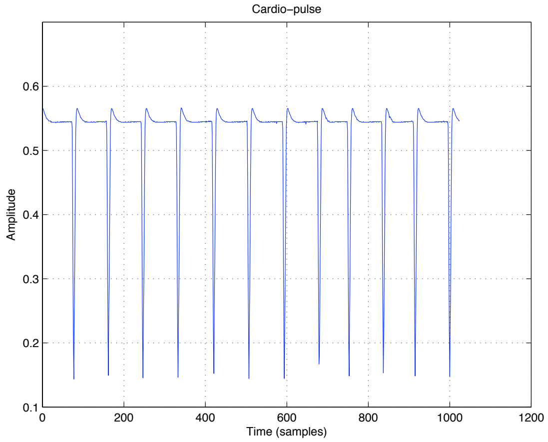

Figure 4: Cardio signal from sensor

4.2. Breathing: a parameter mapping using unvoiced substractive synthesis

For breathing we used the sensor signal to modulate a filtered noise. As the signal is not smooth, if we do not want to smooth and filter it, we can not map it to any kind of parameter. We used a white noise and a band-pass filter with a moderate coefficient of resonance. The signal from the breath temperature sensor was connected to both the amplitude of the output signal and the center frequency of the filter. The filter is driven with a constant quality factor ($Q = \delta f/f$) and the center frequency is mapped from the sensor signal to vary between 30 Hz and 150 Hz. We apply a flange effect at the output of the filter in order to give a coloration to the resulting sound. A description of the flange effect and other effects can be found in [14]. The resulting synthesized sound has in fact a lot in common with a real breathing sound. One could ask 'why not using a microphone to capture a real breathing sound?' That's an option. But then we can hardly parametrize the resulting sound and adapt it to the global final rendering of all the sensors. Also the audio signal can be less 'readable' than the synthesized one. Finally, the microphone may be sensible to movement or capture of other sounds. As the sensor measures a difference in temperature to reflect breathing we don't have any source or parasite sounds to take in account.

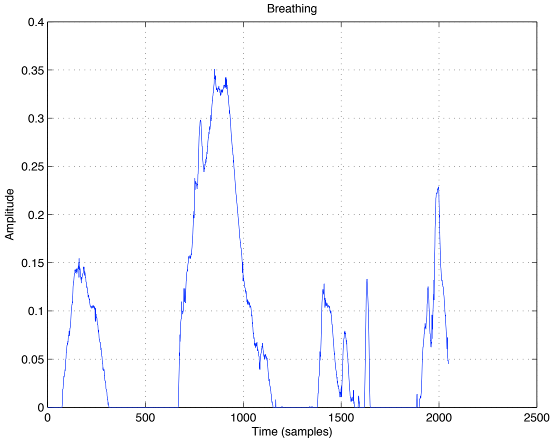

Figure 5: Breathing signal from sensor

4.3. Thoracic volume: voiced substractive synthesis

The sensor signal corresponding to thoracic volume can be seen in figure 6. For this signal a similar source-filter synthesis was used, but in this case we used a voiced source as signal input to feed the filter. This voiced signal is a sawtooth band-limited signal tuned to a low audible frequency (55 Hz). The sensor signal was mapped into three parameters: the fundamental frequency of the voiced source signal itself (producing a small change between zero and one semitone), the amplitude of the output signal, and the center frequency of the signal. As in the previous case, the filter is driven with a constant quality factor ($Q = \delta f/f$) but in this case the center frequency is mapped from the sensor signal to vary between 60 Hz and 400 Hz. In order to have a smooth signal to modulate the

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[4] http://cnmat.berkeley.edu/downloads

amplitude, a linear interpolation was used to convert sensor signal to audio signal. The following equations describe the one-to-many mapping used for this sensor signal.

$$f_c(n) = f_1[x(n)] \tag{1}$$

$$A(n) = f_2[x(n)] \tag{2}$$

$$P(n) = f_3[x(n)] \tag{3}$$

Equation 1 to 3 express the synthesis parameters in function of the sensor signal $x(n)$, where $f_c(n)$ is the center frequency of the filter, $A(n)$ is the amplitude and $P(n)$ is the pitch, f_1, f_2 and f_3 are three different and appropriate mapping functions.

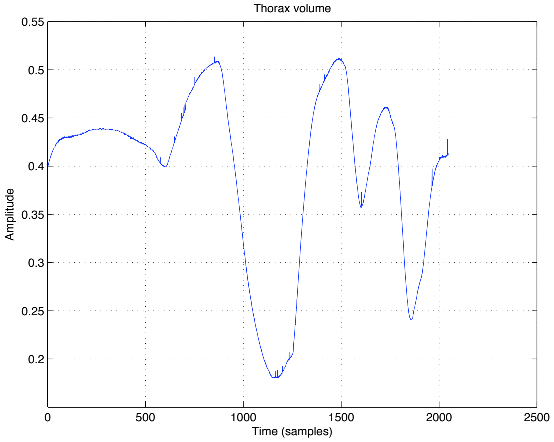

Figure 6: Thoracic signal from sensor

5. AT THE CROSSROAD OF SONIFICATION AND GENERATION OF MUSICAL PROCESSES

The first purpose of the sound generation system described in this study is to produce ‘a sonification’, ‘an auditory display’ of what we receive from the sensors. It is also what one can call ‘biomusic’ in the sense that it is displayed in an artistic context. Other extensions to the sound generation processing that will be mentioned later may improve its musical characteristics and decrease the sonification aspects. But at this stage, according to the definition used by Hermann [6], the process can be called sonification:

> *(A) the sound reflects properties / relations in the input data. (B) the transformation is completely systematic. This means that there is a precise definition of how interactions and data cause the sound to change. (C) the sonification is reproduceable: given the same data and identical interactions/triggers the resulting sound has to be structurally identical. (D) the system can intentionally be used with different data, and also be used in repetition with the same data.*

What will it be if we add other elements based on music aesthetic to the current system? Typically, a way investigated in our study to create music based on this ‘sonification’ is to create new events using delay lines and transformations. For example, a pulse is repeated at different times but with a different pitch, and the sequence of pulses corresponds then to a short melody. One important element that is part of the answer is the perceptive discrimination between the original sonification and the added elements. If the listener can still discern between *cause* in the *effect* and the *ornaments*, then he will still be able to *monitor* the data. If definitions A) and D) can still exist in such a system, B) and D) are seriously compromised. At this point we probably crossed the border between sonification and data generated interactive sound art. But still, a clear relation between data and sound results exists, not only at an emotional or interpreted level but at level of the data flow itself. Another aspect related to use of musical structure is the interaction between perception of tune and rhythm that must be taken in account [15].

6. FUTURE WORKS

In a future work we wish to study how the performer and the audience perceive this sonification as a auditory feedback. During the previous experiment, the performer never heard the sonification during her/his performance and data recording. It will be interesting to see whether, when and how his behavior is modified by the presence of an audio feedback. Also, more subjectively, we want to see if this feedback is perceived as pleasant or disturbing by the performer and, of course also, by the audience. We intend to use other modalities such as video and proprioceptive feedback that will be controlled by the data. Indeed, all the interrogations previously mentioned will be transposed to a multimodal system, and interaction between modalities will have to be considered. Also we already experimented the use of other sensors, such as Electrooculography (EOG) and we would like to extend the system to process other physiological signals. The main constraint will be to still being able to use them in a dancer/actor performance in motion. The techniques for such an environment are very different from biomedical applications; they require robust real-time captures and processes. New types of sensors will certainly have to be designed to fulfill such requirements. The opacity of more elaborated signals such as EEG is apparently an obstacle for live performance and a minimal transparency between the performers actions and sound synthesis. However, a robust sensing and adequate data interpretation and mapping would provide us with a interesting set of additional features.

7. DISCUSSION

It could be difficult to understand what can be this ‘in between’ between sonification and data-driven music. This is problematic because ultimately every sonification strives for a good sound design (with more or less success). But a what is a “good sound design” is also difficult to define. “Good” can mean “meaningful” but also “pleasant” or can refer to aesthetic considerations. Also artistic applications of Biomusic can depend on transparency (if the source of the data is to be recognized as the underlying source) but it is not always the case. Biomusic can use the source in order to create a music correlated to it but extrapolated to generative music. For example, one can use an emotional state derived from the data and associates it to a musical pattern. In this case, although a correlation can still exist between the source and the music, transparency may be lost for the artistic purpose. In other cases, the biosignals may be use at a higher level, through interpretation of their characteristic, in an explicit way (for example: using rhythm detection, range of signal, short-term or long-term statistics) or in a more implicite way (for example: using automatic classification of emotion or stress state). Yet both areas, science and the arts, have different goals. Although this work follows the design pattern established by Fitch and Kramer in their sonification of the body electric [16], it is not only a repetition of it. Different elements have been introduce here. First, in this implementation, we use several one-tomany mapping to improve the sound expressiveness, for example breath is controlling at the same time energy, filter cutoff frequency and fundamental frequency for the thoracic sensor signal. Also a pertinent use of audio effects is include in this work. Secondly, a method for generating tunable musical sequences, generated from heart pulsation is presented too. Thirdly, the final audio signal for the heart beat is a transformation of the sensor signal and not a mapping to an external synthesizer through MIDI protocol with all the inconvenient associated (in [16] a Yamaha DX100 was used). Also, the use of multiple flexible resonance models is used here, and will be used in a more advanced way in future works.

8. CONCLUSION

We presented a process related to interactive sonification of biological data in a context of artistic performance. Using a set of three sensors we create an auditory display that allows to monitor the three signals. This sonification based partly on *audification* and partly on *parameter mapping* is useable as: a basis for a sound part of an artistic project or as a basis for bio-generated algorithmic music. Although it is not the purpose of this study, the strategies used here can be applied to other domains such as sports training or medical monitoring for example. We used processes based on resonances and substractive synthesis and audio effects, which are apparently efficient and sufficient for our application. These methods have the advantage to provide a very clear relationship between sound spectrum and driving parameters. Not using pitch intervals, as described in the paper, has several advantages for our application and also avoid other iinconveniences regarding ambiguities related to sound perception. As the number of sensors used simultaneously was quite limited in this study, extension to a higher number of sensors must be studied. This could be done in several ways: augmenting number of synthesis models that are used at the same time, using more complex models and adequate mapping strategies or interpreting data to reduce the number of driving data (i.e., preliminary many-to-one mapping).

This work would not have been possible without the participation of the two performers (Benedicte Adessi and Fabienne Gotusso), and also Julien Marrot-Dauzat (Biogene: http://biogene.fr) and Ivan Chabanaud (Chabalab: http://www.chabalab.net) who contributed to this study concerning sensors and data acquisition.

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