Schwelle: Sensor Augmented, Adaptive Sound Design for Live Theatrical Performance

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ABSTRACT

This paper describes work on a newly created large-scale interactive theater performance entitled *Schwelle* (Thresholds). The authors discuss an innovative approach towards the conception, development and implementation of dynamic and responsive *audio scenography*: a constantly evolving, multi-layered sound design generated by continuous input from a series of distributed wireless sensors deployed both on the body of a performer and placed within the physical stage environment. The paper is divided into conceptual and technological parts. We first describe the project's dramaturgical and conceptual context in order to situate the artistic framework that has guided the technological system design. Specifically, this framework discusses the team's approach in combining techniques from situated computing, theatrical sound design practice and dynamical systems in order to create a new kind of adaptive audio scenographic environment augmented by wireless, distributed sensing for use in live theatrical performance. The goal of this adaptive sound design is to move beyond both existing playback models used in theatre sound as well as the purely human-centered, controller-instrument approach used in much current interactive performance practice.

Keywords

Interactive performance, dynamical systems, wireless sensing, adaptive audio scenography, audio dramaturgy, situated computing, sound design

1. INTRODUCTION

This paper describes work on an experimental, large-scale media performance project entitled *Schwelle* (German for *Thresholds*). The three-act project has been in development between August 2005-January 2007 in Berlin, Montreal and Amsterdam and has involved a number of cultural and academic institutions. The project had its premiere in February 2007 at the Transmediale Festival For Art and Digital Culture in Berlin followed by performances in Montreal in May. Future performances will follow in Shanghai in 2007 and elsewhere in Europe and North America during 2008.

Figure 1: The dancer, Michael Schumacher, in front of the wall object during the performance of *Schwelle* in Berlin (photo by Thomas Spier).

Schwelle is an evening length theatrical event which explores the varying threshold states of consciousness that confront human beings in everyday life experience, such as the onset of sleep or the moments before physical death. Part II of the project consists of a theatrical performance that takes place between a solo dancer/actor and a "sensate room". The exerted force of the performers movement and changing ambient data such as light and sound are captured by wireless sensors located on both the body of a performer as well as within the theater space. The continuously generated data from both the performer and environment is then used to influence what we term *adaptive audio scenography*, a dynamically evolving sound design that creates the dramatic impression of a living, breathing room for a spectator. While the concept of scenography in theatrical performance contexts traditionally refers to visual-based scenic design (the integration of scenery, costumes and lighting), this paper presents a set of conceptual techniques and a technological system design aimed at creating an auditory environment whose sonic behaviour is determined continuously over different time scales, depending on the current input, past input and the internal state of the system generated by performer and environment in partnership with one another.

Much of the work to date in the genre of interactive performance has been chiefly based around the notion of a gesture-based, human-to instrument control paradigm: the classic NIME model in which a sensor augmented dancer or musical performer uses body-based expression to "compose" or influence an accompanying musical or visual (in the case of lighting or video) score. In contrast, recent work in the areas of "situated computing" and dynamical systems suggests new ways to advance thinking about the conception and design of sensor-augmented, adaptive audio environments in live performance that may utilize and, at the same time, go beyond the instrument/controller paradigm. This paper thus examines the potential of such an adaptive sound design generated not solely from a human performer but rather from a complex intertwining of human and environmental behaviours.

2. CONCEPTUAL FRAMEWORK

2.1 Dramaturgical background and context

Part II, the subject of this paper, is a live performance for one actor/dancer that takes place in a 20 x 40 foot space, with audience seated on both sides of the stage. During the course of the one-hour work, the performer enacts a series of extreme bodily states, ranging from hard to notice micro-movements of the fingers and joints to violent, full body movement in which his head is pulled to the ground and moved about in random directions across the floor. Although the sources used to develop the work are varied, one central one, the *Tibetan Book of the Dead*[35], provides a core dramatic foundation through its description of states of experience undergone by the body after death, specifically, the interactions that take place between the dead person and the environment he/she inhabits: an environment of "live matter" that literally behaves according to its own sentience.

It bears repeating here that the project's technological system design described in detail in section 3 *specifically* arises out of the artistic intent to construct an emotionally compelling dramatic event in which a viewer can experience multiple forms of human, machine and environmental "expression" which interact with and influence each other. The dramaturgical and design "brief" for *Schwelle* thus poses the challenge of constructing a technical system that enables the generation of an auditory and visual environment that behaves in a rich, articulate and surprising manner while simultaneously, gives a substantial sense of presence or "agency" to the spectator. It is important to briefly articulate a conceptual framework that distinguishes the work pursued from current paradigms in the area of what is commonly referred to as interactive performance. We thus identify three specific areas that have influenced the development of the project: (1) interactive performance paradigms (2) theatrical sound design, (3) responsive audio environments arising from situated computing paradigms that explore more complex interaction between human and environmental-generated data.

2.2 Interactive Performance

Interactive performance commonly refers to a set of practices that offer sensor equipped live performers (usually dancers or musicians) real time control over media elements and events using their physical movements and gestures[28]. Not surprisingly, in part due to the close coupling of individual artists/researchers working between the fields of computer music and dance, this paradigm has been carried over into dance performance following the conceptual construct of the performer as controller or instrument whose gestures or movements are mapped to sets of parameters that can be controlled in real time. This model and the technologies that support it usually results in some kind of musical or sonic score that falls between scripted composition and "on the fly" improvisation generated by the performer and sensing infrastructure. The mechanics of this model are well established and documented in both the technical literature[37, 7, 14, 33] and in performance practice[2, 7]. Less attention, however, has been paid to the problem of audience experience of such interactive performance. While it is generally acknowledged that the interest in using worn sensor-based controllers for dancers lies in the potential for improvisation between a human and a real time control system, there has been little inquiry into why such interaction in necessary other than technical novelty. How do we experience an interactive system, especially as a passive, seated spectator? How does real time interaction between a performer, sensors and audio/visual display distinguish itself from pure playback or a pre-existing score?

2.3 Sound Design for Theater and Audio Dramaturgy

Another area that *Schwelle* situates itself is the practice of sound design for live theater. Sound's use in the majority of theatrical performances, however, is usually confused with sound reinforcement, subsumed under the rubric of music (background) or following commercial film, restricted to the role of sound effects accompanying stage action within traditional dramatic narratives, helping to establish a sense of place, location, time or mood. The theatrical projects of a handful of iconoclastic theater directors like Robert Wilson, Richard Foreman and Peter Sellars (United States), Robert Lepage in Canada, Romeo Castellucci in Italy, William Forsythe working with Joel Ryan and Andreas Breitscheid in Germany[4] and the work of avant-garde collectives like the New York based Wooster Group[8] and Kyoto based Dumb Type[1], however, have attempted to put sound on an equal footing with other theatrical elements, including human performers. Interestingly enough, although compelling, these examples do not incorporate the real time techniques found in interactive dance or music performance described above, instead relying on playback or, in the case of the Wooster Group, live musicians/designers "playing" samples simultaneously with the stage action.

Live theater's deployment of sound in a scenographic context presents a powerful yet, little researched model for the creation of responsive audio environments since theater not only fuses spatial/architectural and dramatic functions into a total media event but, as seen in the examples, can approach sound in a non-representational way, chiefly exploiting its physical, material and spatial dimensions for dramatic means without relying on its use as music or sonic illustration. Already, the early 20th century French theatre director/theorist Antonin Artaud's[13] notion of using sound as a physical *force* to generate potential "spaces for expression" in the spectator predates Cage as well as Iannis Xenakis' performative and immersive light and sound environments like the Philips Pavilion[34] or the interactive *Polytopes*[19]. Explored as a shapeable, malleable and ultimately, dynamic material through both its physical characteristics (timbre, frequency, duration) as well as its spatio-temporal behavior, sound becomes a dramatic character or force in and of itself.

2.4 Situated Computing and Responsive Audio Environments

A third area of influence that utilizes real time sensing for control of media but does not conscribe to a musical controller paradigm is what is commonly referred to as "situated" or ambient computing. Described as "the set of technologies and usage experiences that make up the burgeoning area of contextually informed system design"[17], situated computing foregrounds not only a "user" but also the context or "situatedness" of that user's actions within the physical environment.

One of the defining characteristics of situated computing is its reliance on the specific environment that action takes place within versus the "anytime, anyplace" vision of mobile computing[15]. In this way, situated computing aligns itself much closer to Mark Weiser's original vision of ubiquitous computing in the early 1990s where computation would be situated in the inhabited, material world[36]. The notion of situation thus presents a framework for shifting towards what has been labeled "inhabitant-environment interaction" versus the traditional HCI model of human to machine communication[25]. What situated computing suggests is the need to take into account the "background context" of the physical environment itself as a source of "ambient" information through the monitoring, capture and analysis of light, temperature, humidity, acoustic and chemical changes in order to gather contextual clues about the events that take place within it.

Although there has been work in the use of ambient data for the control of media and specifically, audio environments, the majority of this research has been focused either on workday environments[22], as sound installations that function as art objects without a total theatrical context or, more frequently, sound design within the mobile or architectural urban environment[23, 16, 24, 6]. In comparison, to date there has been little in the exploration of conceptual and technological issues for larger scale responsive audio environments for live performance or entertainment contexts that explicitly attempt to fuse dramatic, compositional/sound design and technical design factors simultaneously.

3. TECHNICAL FRAMEWORK AND SYSTEM DESIGN

Given *Schwelle*'s artistic necessity of constructing a theatrical event where a believable living and "breathing" environment exerts its own expression, we have attempted to create a system where data gathered from both the room and the body drives the time-based behavior of sound, light and movement output during the performance event. The following sections give a detailed description of the system's hardware and software components.

3.1 Hardware - Sensors and Actuators

In terms of sensor choice, the devices used in *Schwelle* were not determined a priori but instead, through an extensive series of trial and error rehearsal sessions in which the team explored different modalities of input, ranging from movement, touch, chest contraction and expansion and sound. Based on these initial sessions, we then chose the following devices:

1. On the dancer/performer, we employed two ADXL320[10] (with a range of $5g$) accelerometers mounted on the wrists, and one ADXL322 (range: $2g$) mounted on the chest. As the chest makes less extreme movements, we chose an accelerometer with a smaller range but greater accuracy within that range. The use of accelerometers also has a specific dramaturgical function. As related by Sawada, Onoe and Hashimoto, accelerometers are ideal since the "most important emotional information in human gestures seems to appear in the forces applied to the body"[31].

2. Within the stage environment itself (henceforth known as the "room"), light is the most noticeable parameter that can be measured and yield interesting features. Based on the exact position of direct lighting sources within the room (fluorescent tubes lined on the floor and a light table), a strip of eight photoelectric sensors, spaced ca. 20 cm. apart from each other, are used to gather data from continuous lighting changes in the environment. The mean value of lighting changes is used as input to the room system.

In addition to the body and room sensing, a number of other objects with either sensing and/or actuating properties are placed in the stage environment. Positioned on the light table is a small box equipped with a commercially available Nintendo Wii-controller[5]. The controller measures the movement of the object by the performer over 3 axes of rotation. Furthermore, the stage environment contains several objects embedded or outfitted with small servo motors that, when actuated, can move. Examples of these include a bundle of servo-controlled electro-luminescent wires that are mounted inside an object hanging from the ceiling as well as small cell-phone vibration motors that are embedded in specially made paper sheets that are strewn on the floor at one end of the room and which occasionally move.

Apart from the Wii-controller, all sensing and actuating is done with a custom designed sensorboard[1] (see figure 2), based on the PIC18F4550[11]. As a starting point for the design of this board, we used the Create USB Interface[29]. We have added wireless transmission capabilities to these, based on the Microchip RF-modules[9]. The goal of the design was to create a low cost wireless solution, as most commercially available devices currently on the market are too expensive to scale to multiple devices within one space, are not capable of actuating devices, are not small and robust enough to be worn or used under professional performance conditions, or are not open[2] enough to be adapted for specific artistic purposes.

Wireless transmission/communication was chosen for two specific reasons: first, the dancer must be able to move freely and second, the setup time in theatres is extremely short (2-3 days), making the use of wired systems and complex

[1] which we have called the NASCIO: Networked Actuator and Sensor Creative Input/Output

[2] in the sense of open source; both in terms of hardware and software

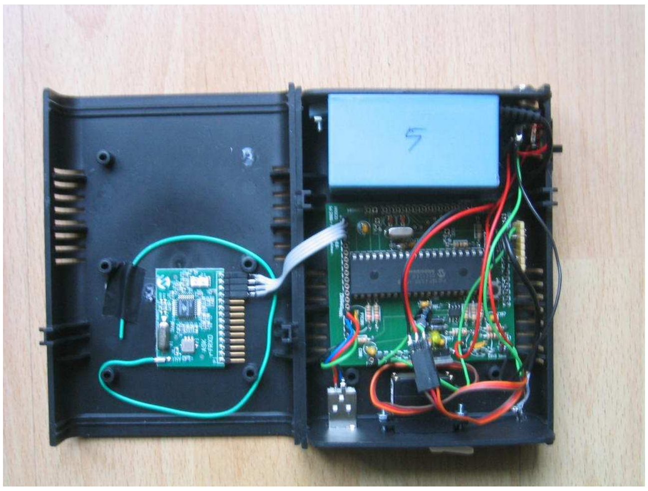

Figure 2: The NASCIO: the sensor/actuator board used for Schwelle II. The box shown is an actuator for moving and lighting electro-lumeniscent wire.

Figure 3: The bodypack, the dancer is wearing. The box is attached to a belt on the waist with the clip. The cables are fixed to his body at certain crucial points (on the chest, on the shoulders and near the elbow) to ensure that the cables stay close to the body, yet have enough slack to move with the body.

cabling difficult within the demands of a professional production calendar. In other words, the less cables that need to be laid out, the better. The current solution with the Microchip wireless boards functions adequate enough for our application as we do not use the data directly, however, the data transmission rate rate of ca. 20 Hz[3] is rather slow. We plan to further develop the boards to use the Nordic 2401A chip[12] for the transmission in order to both increase the data rate as well as to have onboard error detection during transmission.

The dancer's sensorpack needed to be robust, small and lightweight. Here, choices in cabling and power were made based on the following criteria: (1) robust connectors for the sensorpack, so the connectors could not easily be pulled out but at the same time, lightweight enough so as not to impair the performer's movements, and (2) the device had to utilize low power consumption as it needed to be battery powered. We found that with the NASCIO, we can run for several hours on one rechargable 9V-battery (250 mAh, NiMH), which is usually sufficient. We specifically chose Hirose video connectors due to their interlocking abilities and light weight. The cables have a diameter of 3mm. and contain 7 signal cables (of which only 4 are used) and are very flexible. They are connected to the box with the Hirose connector. The sensors are attached with 4 pin connectors as found in PC technology (usually used for connecting fans). Here we needed to ensure that the soldered connection between the wires was strain relieved. A picture of the bodypack is shown in figure 3. In order to be able to wash the dancer's shirt, the sensors are attached to the body using velcro. At the wrists we additionally put an elastic band around them to keep them in place.

Future development of the NASCIO board will include moving to a SMD-design, to reduce the size of the board even further.

[3]this is the actual rate how often a new packet of data is received. A packet contains 2 bytes for the ID of the transmitting device, and ca. 12 data bytes, plus a preamble, header, flags and guard time

3.2 Data flow and processing

The data from the sensors is statistically analyzed so the system reacts to changes in the environment, rather than absolute values. The statistical data is then scaled dynamically, before being fed into a system inspired from J.F. Herbart's theory on the strength of ideas, on which will be elaborated below. The dynamic scaling ensures that when there is little change in the sensor data, the system is more sensitive to it. The output of the Herbart systems is mapped to the density, as well as to the amplitude of various sounds that comprise a "room" compositional structure of 16 different layers. An overview of the data flow is given in figure 4. The mapping, which is indicated between the dynamic scaling and the Herbart Groups, is a matrix which determines the degree to which each sensor influences which sound.

The diagram also shows that there is a second data flow path, which constitutes a more classical, NIME instrumental approach of using the sensor data. The mapping between a movement created within the room by the performer or objects in the room and a resulting lighting or sonic event is direct, and recognizable as an action-reaction interaction. This interaction has been carefully tuned to certain dramatic sequences within the piece, and is easily switched on and off, depending on which scene is taking place. In some scenes the strength of the interaction is changed dynamically by the artist controlling the dynamic system at suitable points in the dance, thus creating a duet with the dancer.

These two different paths of data processing represent two very different approaches on two different time scales: the first path is concerned with using measured data on a long term, whereas the second path deals with short term use of the data, i.e. a clear action-reaction scheme.

3.2.1 Statistical analysis

For each stream of sensor data (3 times light sensor data

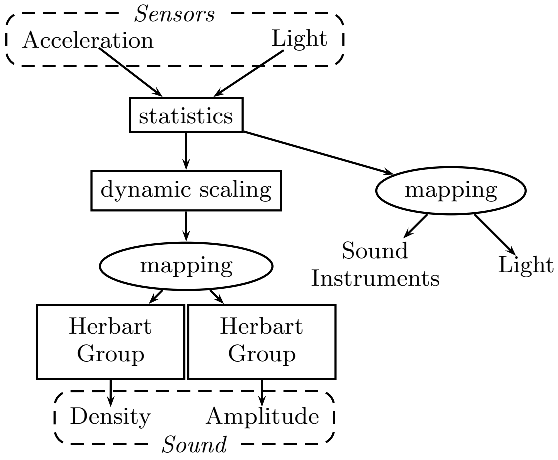

Figure 4: Data flow diagram

and 6 axes of acceleration) the sample variance[4] $s_{N,\Delta t}$ over a time window with length N is calculated, where the data is sampled at time intervals Δt:

$$s^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2 \tag{1}$$

Δt has an influence on the detail of the motion that can be detected. N influences the smoothness of the resulting time signal. The sample variance itself is a measure of the amount (or the energy) of movement that is going on. The change of the sample variance over time thus tells us something about the type of movement; whether it is sudden or slow and sustained.

The resulting data is used as a time signal again and its sample variance is calculated and used as a parameter at some points in the system.

3.2.2 Dynamic scaling

To scale the data dynamically, an analysis was done of the amount of fluctuation in the data, which we define as:

$$\phi = \frac{s_{M,\Delta t}}{s_{N,\Delta t}} \tag{2}$$

where ϕ is the fluctuation, $s_{M,\Delta t}$ the sample variance over the last M samples, and $s_{N,\Delta t}$ over the last N samples. If M is smaller than N, ϕ is a measure of the change in activity. For one data stream, the data is rescaled when the fluctuation is less than a certain threshold (e.g. 0.9) or above a certain threshold (e.g. 1.1). The scale of the data is then changed to: scale $= f/s_{N,\Delta t}$, where f is an arbitrary factor to set the amount of dynamic scaling. For a set of streams, the smallest scale-factor (as calculated for an individual stream) of all the streams is used as the actual scaling factor.

3.2.3 Herbartian system

The 19th century German philosopher and early mathematical psychologist Johann Friedrich Herbart[20, 21] described a mathematical model to explain the strength of ideas, due to sensory impressions, as a function of time. The model describes an increase of the strength of an idea due to the time behaviour of an impression. When an impression is fresh, a faster increase in the idea's strength results while a slower increase occurs when an impression has lingered over time. Mathematically this is described as follows:

$$S_z = \sigma(1 - e^{-it_i}) \tag{3}$$

where S_z is the Strength of the idea due to an impression that is present, i is the strength of the impression, σ is the sensitivity to the impression of the idea and t_i the time the impression has been present from a certain threshold on. There has to be a threshold set above which an impulse is on, and a threshold for it to turn off. Simultaneously, an idea decreases in strength when there is no impression, which is represented as:

$$S_{c,N} = (S_z + S_{c,N-1})e^{-d\Delta t} \tag{4}$$

where $S_{c,N}$ the strength of an idea at time point N, evaluated at each time step Δt. d is a decay factor.

These ideas are grouped. The sum of S_C of all ideas in a group produce a *Hemmungssumme* H. H is then divided over the ideas in a reverse way, that is: the weakest idea gets the strongest part of the Hemmungssumme, the strongest idea the smallest. If the current strength of an idea is below zero, it is completely pushed back to a *subconscious* level. However, if at a later time, the other ideas are weaker, the idea can come back to a *conscious* level, without the need for a new impression to excite the idea.

The interesting aspect of this model lies in its *behaviour*. Though it is possible that there is a direct reaction based on a new impulse into the system, its reaction depends on the current state of the system. If, for example, there is still a lot of energy from previous impulses, a new impulse will not impact the system as much as when there is little energy left in the system.

This system constitutes a dynamic model, i.e. it is a mathematical model of a dynamic process, based on a set of differential equations[5] that describe the dynamic behaviour of the system[18, ch. 2]. It is important to make this distinction, as the label "dynamic system" is often misused in other work (e.g. [27] where systems based on cellular automata and fractals are labeled as dynamic systems). Our system has two important characteristics: first, the system is continuous, i.e. there are no discrete states between what is chosen, such as in agent based systems or (discrete) state based systems. Secondly, the system needs no training phase, as is needed for example, in systems based on neural networks, or hidden Markov models[6]. There has been some interesting work on the development of continuous state systems[32] for specific control of real time media elements, but these systems are also based on a specified training phase.

3.2.4 Sound synthesis

The room sound design concept for Part II of *Schwelle* is built from 16 layers of sound with the following qualitative

[4]There is a formal difference between the standard deviation and the sample variance, the latter being an estimate of the former[30].

[5]the equations shown in this subsection are derived from these differential equations

[6]in fact a Markov model is a 'state-space' representation of an autoregressive moving average (ARMA) time series model[30, 10.4.4].

characteristics (in parentheses the parameters which can be modulated of these sounds):

- Continuous background noise (frequency, amplitude, modulation speed ('activity'))
- Clouded events (density, frequency range, amplitude range, duration, amplitude)
- Regular, discrete events (frequency, tempo, amplitude, duration)

We use two Herbart Idea groups, one which influences the frequency or density of events and the other, the amplitude of the sound. Other parameters are determined randomly at each spawning of an event. The two groups have a different setting for the decayspeed, while they get the exact same input. This parameter results in each group having a different time evolution.

3.2.5 Implementation

All of these systems have been implemented in the SuperCollider (SC3)[26] environment. While USB-HID data input is available within the programming language, data output via USB-HID has been custom implemented in SC3 during the development/rehearsal phases of the project. The input from the Wii-controller, and DMX output to the light system (except for the electro-luminescent wires, which are controlled by the NASCIO), are exclusively controlled by Max/MSP[3] as there is currently no Wii[7] or DMX object implementation within SC3. Thus, SC3 serves multiple functions: (1) sound synthesis (scsynth), (2) the adaptive dynamic system (sclang) and (3), as an environment for scripted show control (sclang).

3.2.6 Tuning of the system

Having created such a complex multi-layered system for processing data (fig. 4), the issue and importance of tuning cannot be underestimated. As each layer has several parameters which can be tuned, choosing these parameters becomes all the more difficult[8].

The first step we have taken is to listen to each layer of the sound separately in order to determine what the limits of the amplitude and the frequency occurrence should be. The rows of the mapping matrix all add up to 1 (i.e. they are normalised), which means that all layers are influenced by a similar amount of sensor input. Furthermore, each type of sensor input has a separate scaling factor to determine the amount of influence it has on the system. As the light tends to change more slowly than the acceleration of the body, the acceleration of the body is given a lower scaling factor. The sensitivity of the Herbart groups is also varied during the piece. When the sensitivity is changed, the decayspeed is also changed after a certain time, which is dependent on the current decayspeed. Thus, the sensitivity of the system can be used as a dramaturgical parameter to yield different levels of room behaviour.

[7]at the time of creation of the piece, there was only an experimental server side implementation by Pete Moss for SC3

[8]this is the general challenge of the NIME paradigm: having severed the mechanical user action from the acoustical effect, we have an infinite number of possibilities to map user action to sound and it is the artist's task to determine which mappings are interesting, useful and compelling to a performer and a spectator

4. EVALUATION AND RECEPTION

Based on the Berlin performances and the audience reactions which were gathered through questionnaires, we have been able to evaluate the effectiveness of the system. On the hardware side, the devices did indeed have the robustness[9] that we hoped for. All devices worked throughout the dress rehearsals and performances. Additionally, the dynamic system worked in principle. It was possible to distinguish between low and high activity within the system, though the general athmosphere of the room sound was perceived by the public as too static. For the Montreal performance, we are planning to implement an additional state-based system layer in order to enable the public to more clearly distinguish between the different atmospheres exhibited by the room. This further layer influenced by the output from the Herbart groups will influence how the system moves through the state space, which will determine the mapping and patterning of sounds.

5. FUTURE WORK AND CONCLUSION

We have described work done on *Schwelle*, a large performance project in which we attempt to couple conceptual, dramaturgical and technological design factors to create a new type of adaptive sound design infrastructure to be used in live performance or location based entertainment applications. While the work described emerges based on the clear artistic end goal to create an aesthetically compelling event in which the behavior of the sonic environment is influenced by body and environment-based real time sensor data thus giving a life like presence to a performer inhabited environment, the project has also suggested several interesting avenues for future work. Our system setup is still centralised with regard to computation. We now plan to experiment with the creation of a larger distributed wireless sensor network, where each node within the network behaves more autonomously yet, with input from its nearby neighbours. This kind of network topology opens up a new field of interactive possibilities through distributed sensor augmentation in physical spaces as we search for new ways to advance live performance practice towards its increasingly situated and responsive future.

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[9]robustness tests included throwing the sensorpack around a room, during which it kept sending data

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