Musical Performance Practice on Sensor-based Instruments

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Introduction

Performance has traditionally been a principal outlet for musical expression – it is the moment when music is communicated from musician to listener. This tradition has been challenged and augmented in this century – recorded and broadcast media technologies have brought new modes of listening to music, while conceptual developments have given rise to extremes such as music not to be heard. Computer music makes up part of these developments in new methods of creation and reception of music. It is at its origin a studio based art, one that gave composers possibilities to create a music not possible with traditional performative means. Realizing music in the electronic and computer music studios freed the composer from traditional channels of composition-interpretation-performance, allowing him to focus in a new way on sonic materials.

Advancements in computer processing speeds have brought with it the capabilities to realize this music in real time, in effect giving us the possibility to take it out of the studio and put it on stage. This has introduced the problematic of how to articulate computer generated music in a concert setting. Concurrently, developments in the fields of computer-human interface (CHI) and virtual reality (VR) have introduced tools to investigate new interaction modalities between user and computer (Laurel 1990). The intersection of these fields with computer music has resulted in the field of gestural computer music instrument design. The creation of gestural and sensor based musical instruments makes possible the articulation of computer generated sound live through performer intervention. While this may be a recent area of research, the musical issues of engaging performance are something that have been addressed before the arrival of the computer. So while from a technical standpoint research in this field may represent advances in musical and perceptual bases of gestural human-machine interaction, musically these efforts in computer music have precedence in instrumental music. It can be said that musically this brings us full circle, back to the concert as forum for the communication of music.

If concert performance is the medium of communication then the instrument becomes the conduit between performer and listener. The listener's perception of the music is contingent on the instrument's efficiency at transmitting the performer's musical expression, and the performer's ability to channel his creativity through his instrument. We must integrate what we know about human machine interaction with our musical sensibility. What follows is a personal reflection on a performance practice developed on sensor based instruments, drawn from several years of concert performance with the BioMuse (Tanaka 1993), ensemble work with Sensorband (Bongers 1998) in the creation of the Soundnet, and the application of instrumental thinking to an installation and network based project: *Global String*. Observations have been made from personal reflections during practice and development, discussion with other artists, audience reactions, and interaction with students.

Tools

A musical instrument, as part of an engaging performance, becomes an expressive device in the hands of the performer. This gives an instrument a distinguishing characteristic when compared to a simple tool. The term tool implies that an apparatus takes on a specific task, utilitarian in nature, carried out in an efficient manner. A tool can be improved to be more efficient, can take on new features to help in realizing

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its task, and can even take on other, new tasks not part of the original design specification. In the ideal case, a tool expands the limits of what it can do. It should be easy to use, and be accessible to wide range of naive users. Limitations or defaults are seen as aspects that can be improved upon.

A musical instrument's *raison-d'être*, on the other hand, is not at all utilitarian. It is not meant to carry out a single defined task as a tool is. Instead, a musical instrument often changes context, withstanding changes of musical style played on it while maintaining its identity. A tool gets better as it attains perfection in realizing its tasks. The evolution of an instrument is less driven by practical concerns, and is motivated instead by the quality of sound the instrument produces. In this regard, it is not so necessary for an instrument to be perfect as much as it is important for it to display distinguishing characteristics, or "personality". What might be considered imperfections or limitations from the perspective of tool design often contribute to a "personality" of a musical instrument.

Computers are generalist machines with which tools are programmed. By itself, a computer is a *tabula rasa*, full of potential, but without specific inherent orientation. Software applications endow the computer with specific capabilities. It is with such a machine that we seek to create instruments with which we can establish a profound musical rapport.

The input device is the gateway through which the user accesses the computer software's functionality. As a generalist device, generalized input devices like the keyboard or mouse allow the manipulation of a variety of different software tools. Music software can be written to give musically specific capabilities to the computer. Input devices can be built to exploit the specific capabilities of this software. On this general platform, then, we begin to build a specialized system, each component becoming part of the total instrument description.

Instrument definition

With a traditional acoustic instrument, defining what comprises the instrument is straightforward - it is the object that the performer holds or plays on. It and its acoustical properties are the medium between performer action and sound. Through the instrument, the performer is able to affect all aspects of the music: from the micro-level of timbre to the event level of note articulation, to the macro level that reflects compositional structure. In a wind instrument, the breath of the performer affects both the micro-timbral qualities as well as articulate the note-events from the instrument – articulating the event, defining the harmonic being articulated. The fingerings work in tandem to further define the note-level event. An attachment like a mute can be seen to work on the micro level, affecting the timbre of the instrument at the same time it can be considered to work at a structural level – causing a section of a piece to take on a certain sound (Wessel 1987).

In the case of a computer based instrument, the medium between performer input and sound output is comprised of several distinct stages, spanning input device, software, and hardware. It is a reprogrammable system, differing from the dedicated nature of a traditional instrument. The input device is often a sensor system capturing the physical gesture of the performer. This input is detected and digitized, producing computer data representing the actions of the musician. This data is passed on to the software component of the instrument that maps gestural data to musical and sonic parameters. This software most commonly runs on the host CPU but could reside in firmware on the input device or in the sound synthesis unit. The sensors define the physical modes of interaction between musician and instrument while the software defines the responsiveness and articulative possibilities of the instrument.

Much as an acoustic instrument operates on the multiple micro, event, and macro levels, a computer instrument can be viewed in this way. Choices made by the instrument designer and composer are implemented in software and define the performative qualities of the instrument. Certain gestures can manipulate sound synthesis directly (Wanderley 1998), while others articulate notelike events, while other actions direct the structural progress of the piece. Applying these concepts to computer realization gives rise to new possibilities that blur the boundaries separating event articulation and structural modification. A single articulation can elicit not just a note, but an entire structural block. Variations in the articulation could very well modify the timbre with which that structure is played, or could introduce slight variations on the structure itself or could modify which structure is elicited. The potential combinatorial space of complexity is quite large. It is also possible to focus entirely on one level, in effect ignoring others: with computer generated sound, a musical event in the classical sense does not have to be articulated for the sound to be modified. One could imagine a system that is comprised simply of an ongoing stream of sound that is sculpted by the performer's gestures.

Instrument types

Given this broad, encompassing definition of an instrument, we can define several categories to help delineate the different classes of gesture instruments (Pressing 1990), (Cadoz 1994). Instruments can be physical or non-physical, based on their mode of interaction. They can independently be mechanical or non-mechanical. Turning a potentiometer is a physical mechanical action translated into electrical potential, whereas creating gestures to modulate light being picked up by a photocell, as much as it is a physical gesture, is not physical or mechanical from the point of view of the sensor. A biosensor is not mechanical, but is physical as it detects corporeal activity.

A computer instrument may or may not have an associative connection with a traditional instrument. This association with an existing instrument can be direct, metaphorical, or an extension of the instrument. With direct association, the natural sound of the instrument can be used as a control source (Bailey 1993). Or, sensors can be placed on an existing instrument in such a way to pick up traditional performance practice on the instrument – a MIDI guitar can be viewed in this way. Extensions to the instrument can include sensors to pick up new articulations on the instrument particular to the sensors (Katayose 1994). Or the traditional instrument can become the metaphorical model for a new instrument, providing a point of familiarity and departure. The Synthophone (Hurney) is an example that is extremely close in keeping to the original instrument - to the extent that it modifies an actual saxophone - but where the end result is a pure electronic instrument that no longer makes acoustical sound. Suguru Goto's SuperPolm is an example of fantasies on the metaphor of the violin [Editors' note: see the article by Goto in this volume].

In the area of totally new instruments not based on a traditional instrument as referent, new gestural instruments can be created. Despite the independence from existing instruments, they can nonetheless be designed based on the model of a musical instrument as an articulatory musically expressive object in the hands of a musician. Alternatively, new paradigms can be investigated: the definition of a musical instrument can be expanded to embrace environments such as public installations experienced by non-musicians. Even the concert spaces can conceptually be considered instruments: as resonant acoustic bodies that respond to performer's gestures, with loudspeakers as transducer/actuators (Bongers 1998). In the case of network music, the network can be considered an instrument that responds with certain characteristics to user gestures represented as network data (Tanaka 1999).

BioMuse

The BioMuse is a biosignal musical interface developed by Hugh Lusted and Ben Knapp of BioControl Systems (Knapp 1990, Lusted 1996). It was developed at Stanford University's Center for Computer Research in Music and Acoustics (CCRMA), Medical School, and Electrical Engineering Departments. It takes bioelectrical signals in the form of electroencephalogram (EEG), electromyogram (EMG) and electrooculogram (EOG) and translates them into serial digital data and MIDI. Surface gel electrodes on the skin establish electrical contact, conducting neuronal impulses from the muscles and brain. Each of the eight (8) input channels receives a differential signal from an electrode triplet. Upon reception by the BioMuse main unit, the signals are amplified, filtered, digitized, and processed according to a number of user configurable algorithms including envelope following and spectral analysis.

I began work with the BioMuse in 1992 and was commissioned by BioControl to create its concert premier. I continued concertizing with it in Europe from 1992 to 1997. Upon moving to Japan in 1997, I have been in contact with various teams seeking to make miniaturized EMG devices (Nagashima 1998). My work with the BioMuse has been exclusively with the EMG (muscle) channels. Elastic bands are used to place the electrodes in locations to detect arm gestures. The BioMuse runs a program implementing envelope following on the muscle tension signal. This is sent to the host computer as MIDI or 12 bit serial data. This data enters the MAX software environment (Puckette 1990), is further processed, then drives the MSP real time audio engine.

The placement of electrodes on the two arms is asymmetrical - on my left arm, I have electrodes on the inner and outer forearm. On my right art, the electrodes are on a general lower arm location and triceps. While the differential nature of the signal averages muscle contraction impulses across the area covered by the electrode triplet, placement of the triplets allows differentiation of large muscle groups. The triceps band therefore detects outward and upward movement of the upper arm. The general lower arm band detects average muscle tension in the lower arm, while the outer and inner lower arm bands can differentiate two muscle groups. The outer band detects wrist movement that lifts the hand whereas the inner band detects gesture that curls the hand inward (Putnam 1993).

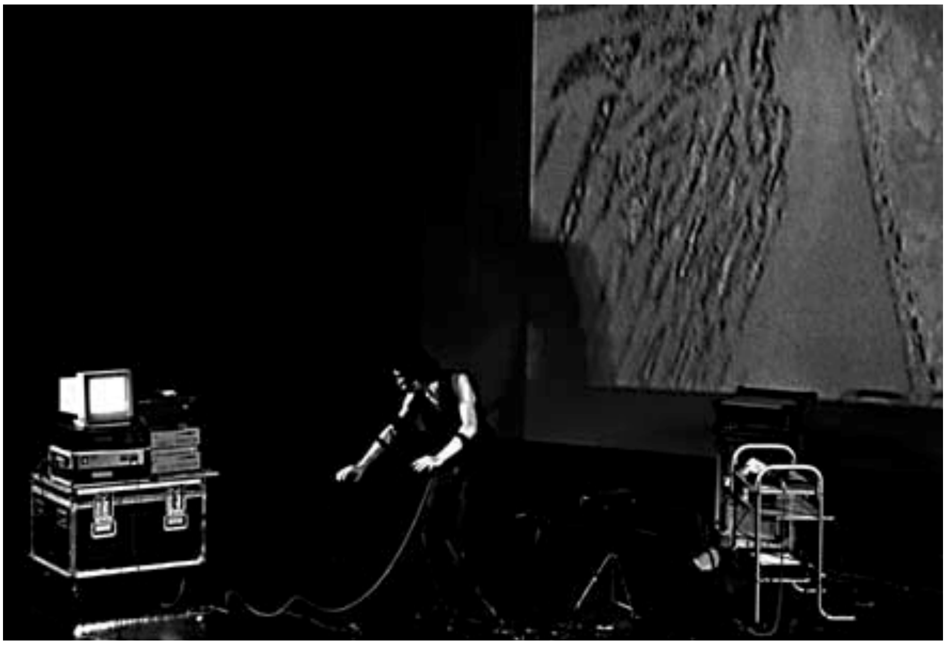

Fig. 1. The author in performance at the festival Manca in 1995. The Biomuse controls the sound and image using MidiKaleido by Eric Wenger.

It is interesting to apply observations of the way the body works in selecting electrode placement. The movement of any member is often created by muscle action on the member above it. Thus hand and wrist motion and rotation implicates the lower arm muscles. Even finger movement can be detected in the tension trajectories of the lower arm muscles. This creates the interesting possibility to detect small level gesture without having to put sensors on every finger, but to observe these gestures through data from a larger member. The data from the lower arm, then, is rich in information. Data processing can begin to extract this information from the signal (Warner 1995).

The signal entering the host computer is a continuous data flow that is the amplitude envelope of the muscle group under each electrode set. This data can be treated in several simple ways to render it musical. We can program level sensitive triggers to transform the continuous input to event-type data, useful for the macro, event, or structural interventions mentioned in the previous section. The trigger is implemented in MAX, armed to detect the input signal crossing a defined threshold. Hysteresis is added such that a separate downward threshold is defined that re-arms the upward trigger, often referred to as a Schmitt trigger (Strange 1983). This has the immediate application of suppressing multiple false triggers. A hysteresis combined with a dynamic upward trigger level could be used in tandem to depict a kind of "effort" of articulation. This kind of use of hysteresis then is a special case of memory of the trigger. A software based trigger can hold data on the number of times and frequency with which it has been articulated, with this data affecting the nature of the trigger itself.

The continuous nature of the muscle envelope signal is well suited for timbral control of the sound synthesis. It can also shape or affect the nature of an event trajectory. Simple processing on the continuous input include defining the active range, scaling linearly or non-linearly, and using in conjunction with triggers listening to the same data. Using the continuous data from more than one of the arm bands together can create the possibility of dependencies and variations. The inner and outer lower arm signals can be combined and averaged to give a general lower arm band tension signal, or can be combined in counterphase to provide one signal that represents left-right or inner-outer "steering" action of the wrist. Other possibilities include applying integrators (for accumulation, with the possibility of a "leaky" parameter) and differentiators (used in the calculation of velocity and acceleration).

Based on the concepts outlined in the previous section on instrument definition, we can define the musical instrument built around the BioMuse system. The instrument for me, then, is made up of the specific placement of the electrode armbands, the BioMuse hardware, the firmware program running inside the BioMuse, the MAX software on the host computer post-processing the biosignal data, and the sound synthesis implemented in software in MSP and realized in hardware on the Macintosh. This instrument has remained more or less a constant. With each piece, the middle area between the MAX processing of BioMuse input and the sound output change - the composition then is the choice and combination of different biosignal post-processing techniques as connected to various synthesis articulations, place in context of a musical structure over time. The "shell" of the MAX patch - input from BioMuse, output to synthesis - is part of the instrument, while the inner contents of the MAX patch - the specific mappings of gesture to sound and their development in time - form the score of the composition.

The BioMuse is not a mechanical instrument, however it is quite a physical one as it depends directly on corporeal gesture. Though not based on any existing instrument, it is possible to program the software to emulate instruments. For example, the BioMuse/MAX system can be programmed to create an "air guitar". It is a kind of arbitrary imitation, since the biosignals used to drive the air-guitar patch are in no way scientifically linked to a true guitarists gestures. My work with the BioMuse has not been concerned with instrumental emulation. However, my use of the BioMuse is an abstraction of instrumental gesture in the absence of a physical object to articulate music through corporeal gesture.

Soundnet

Soundnet is a large scale multiuser sensor instrument created by Sensorband (Atau Tanaka, Zbigniew Karkowski, Edwin van der Heide). It is a musical instrument that takes on an architectural dimension and monumental proportions (Sensorband). It is a giant web measuring 11meters x 11 meters, strung with 400m of 16mm thick shipping rope. At the end of the ropes are eleven sensors that detect stretching and movement. The three musicians of Sensorband perform on the instrument by climbing it. It is an instrument commissioned by the festivals Visas and Exit in France, and has been performed at the DEAF festival organized by V2 in Rotterdam.

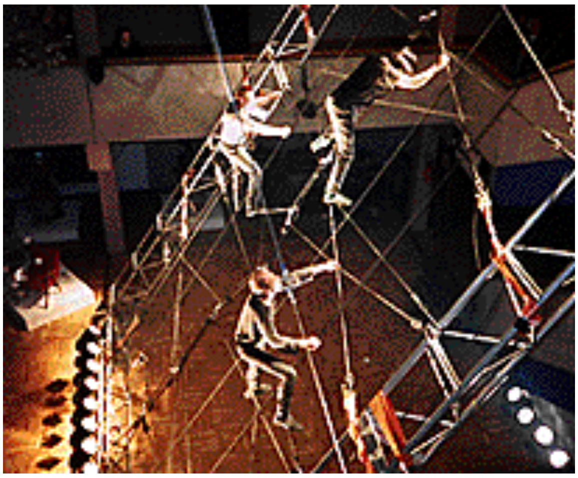

Fig. 2 & 3. Sensorband performing on the Soundnet at festival Exit in 1996.

Soundnet is inspired by The Web, a 1 meter diameter spider's web created by Michel Waisvisz, at STEIM (Krefeld 1990). The idea with Soundnet was to create a life sized version of The Web. The sensors were designed by Bert Bongers and fabricated by Theo Borsboom. Each sensor consists of a cylinder and piston that can sustain 500kg of force. Inside is a large spring connected to a linear potentiometer. As the performers climb the ropes, the sensors stretch and move in response to their movements. This displaces the faders inside, sending a variable resistance control signal to an I-Cube interface which in turn digitizes the data, sending the result as MIDI continuous controllers to the host computer.

Fig. 4. One of the eleven sensors.

Soundnet is a musical instrument in the classical sense in as much as it is a soundmaking object articulated by the performer. The instrument is comprised of the physical structure, the sensors and interface, and the computer and software. It takes this basis as a point of departure to extend certain areas of the notion of an instrument. The most readily apparent quality of the instrument is its scale – it is an order of magnitude larger than the performer. In addition, Soundnet is a multiuser instrument. All the ropes are interconnected, making it impossible to isolate the movement of one sensor. Pulling on one rope changes the state of the whole net, creating a sort of physical network. And one performer's movements take place in relation to the position and actions of the others.

The output from the sensors are continuous signals. As the piston is spring loaded, the sensor movement tends to be in non-regular oscillation about a static tension point. Interesting qualities to extract from the signal thus include velocity and acceleration, and change of direction. These data has been used to control filter parameters as well as granular synthesis.

Soundnet is a musical instrument that is physical and mechanical. Its scale and proportion is such that the physical part overwhelms the technological part. This creates an inversion of the typical concerns surrounding interactive technology, de-emphasizing issues of sensing and processing, and focusing more on the pure organic nature of a human confronted with a dynamic architectural system.

Global string

Global String is a multi-site network music installation, a collaboration between myself and Kasper Toeplitz (Tanaka and Toeplitz). It is a musical instrument where the network is the resonating body of the instrument, by use of a real time sound synthesis server. The concept is to create a musical string (like the string of a violin) that spans the world. Its resonance circles the globe, allowing musical communication and collaboration among the people at each site.

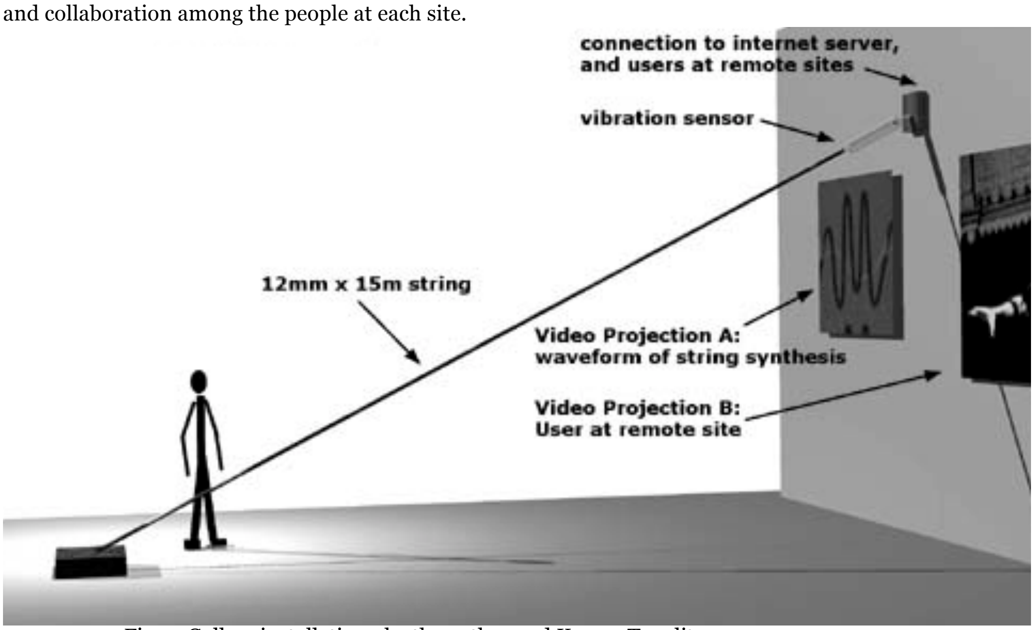

Fig. 5. Gallery installationn by the author and Kasper Toeplitz.

The installation consists of a real physical string connected to a virtual string on the network. The real string (12 mm diameter, 15 m length) stretches from the floor diagonally up to the ceiling of the installation space. On the floor is one end point - the earth. Up above is the connection to the network, connecting it to another end point at a remote location. Sensors translate the vibrations into data to be transmitted to the other end via network protocol. The server is the "bridge" of the instrument - the reflecting point. It runs software that is a physical model of a string. Data is streamed back to each site as sound and as data – causing the string to become audible, and to be actuated to vibrate, on the other end. A real time video conferencing connection, gives a visual connection between the users. Through this connection, visitors at each of the remote sites can play together. Visual and aural cues allow the development of ensemble practice over distance. Their tandem interventions on the single conceptual string create interference patterns and harmonies.

Global String extends the concept of instrument definition in several ways. It is one string that is comprised of distinct components – physical endpoints and virtual midpoints. The installation space, as well as the auxiliary communications channel (video) become part of the instrument. Most importantly, the medium of transmission, the network, becomes part of the instrument. In implementation and practice, *Global String* is a scalable multi-mode installation. The number of sites can range from two and up – creating the possibility of multiple end points not easily realized in the physical world. The installation can be used in concert mode for soloists at each site to perform together or as an installation for gallery visitors to share a musical experience.

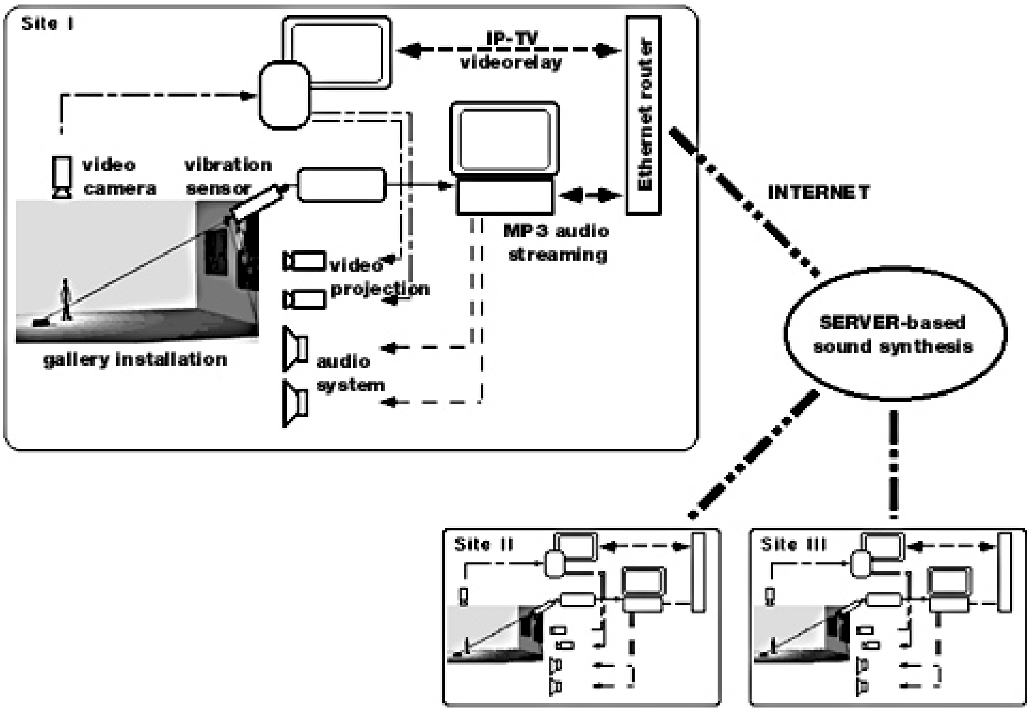

Fig. 6. Global String system diagram.

Limits

Musical instrument characteristics are defined as much by their limitations as they are by their capabilities. These limits, such as note range and articulative speed, must be considered and respected to compose playable, idiomatic music for that instrument. The topic of idiomatic writing will be discussed below. The limits are seen not as hindrances to the composer, but as constraints that can be challenged and extended.

A computer is often thought of as a tool with no limits. When designing a sensorbased instrument, the standard response to queries about an instrument's capabilities is that anything is possible. In reality, computers and interfaces to computers are in fact quite limited machines. Typical constraints include processor speed and degrees of freedom of an input device. As these are regarded as technical limitations, composers do not have the reflex to use the limitations as creative material, and instead wish for an amelioration in an ensuing version of the hard or software (Zicarelli 1992). Though development includes the pursuit of fewer such limitations, it can also be said that the lack of limitations creates an absence of boundaries against which a composer can play.

Discussions of computer based instruments often tend to focus on the power or capability of the instrument. With sensor instruments the question typically raised is how many synthesis parameters it allows the musician to control. The temptation is to follow this with the possibility that sensor technology opens up possibilities to control not just synthesis and musical parameters but other media, including lighting and image. The danger is in ending up not with a *gesamtkunstwerk*, but with a kind of theme park "one-man band" (Puckette 1993). While this may show off the power of computers to simultaneously control multiple parameters across multiple media, it does little to convey the expression of the performer. Instead, viewing the situations from the standpoint of creative applications of limitations may yield more musical results.

With the BioMuse, limitations can arise from the human body's own capabilities. This supports the argument to include the body as part of the instrument definition. A very basic limitation of the body is fatigue. The performer has a certain capacity for continued muscle exertion over time. Another limitation, quite characteristic of biosignals is the difficulty of maintaining an absolutely stable tension level. The EMG signal is a truly living signal, and will invariably waver. This creates an output that is quite distinct from other types of continuous input devices.

Limitations of the Soundnet are related to its physical scale and interconnected nature. Moving the sensors takes enormous effort on the part of the performer. At the same time, there is considerable inadvertent movement of the sensors in response to displacement of the performers. Isolating individual sensor movement is nearly impossible. These effects combine to give the instrument its qualities of structural resonance and creates a dynamic where pure control in the strict sense is put in question (Broeckmann 1997).

With *Global String*, data transmission latency can be considered defining qualities of the instrument. The transmission delay is significant, and is non-constant. Typically in network music applications, these effects are defaults to be eliminated or improved upon. In the case of *Global String*, the instrument has been conceived to include these network characteristics as part of the instrument definition. As a vibrational feedback is created, the transmission delay creates a resonance. The variable transmission delay creates a breathing resonance that prevents self oscillation. If delay were not present, the feedback would degenerate instantaneously.

Idiomatic composition

By virtue of the relationship established between performer and instrument, we create a gestural language for the instrument. This is the basis of development of a performance practice. Issues of idiomatic writing invariably enter discussions of composing for specific instruments. Idiomatic writing is the art of writing music that is suited, adapted, and optimized for an instrument. In this way, a standard vocabulary of performance practice for a particular instrument is established, giving the instrument a musical identity. The ultimate result is the creation of a body of work, a repertoire for that instrument. We can retrace the development of repertory for instruments such as the violin and piano in this way – each evolving as instrument based on a predecessor (the *de gamba* family in the case of the violin, the harpsichord and clavichord with the piano), culminating in virtuoso showpieces of the romantic era, furthered in experiments of extended technique in the 20th century.

The tenets of idiomatic writing take into consideration features of the instrument such as basic articulation, and note-range. Articulation technique and resulting timbre are considered together to consider what kinds of phrases and passages are most appropriate for the instrument. In this way the sonic timbral qualities are tied to the event structure in defining a characteristic for the instrument. A wind instrument may be capable of smooth legato, but the fact that its articulation is based on the human breath, for example, puts a practical limit on the length of a phrase. This is the standard material of books on orchestration.

An instrument may be able to play in a wide pitch range, but more easily in its principle register than in an extended register. This has consequences on the resulting performance that must be anticipated by the composer. Mastering thus the variations in facility and effort help the composer create a dramatic trajectory for a composition that is in fact based on the nature of the instrument itself. In this way, he is composing with an eye towards the energy of performance. Knowing the idioms of performance practice on an instrument help the composer imagine and thus compose in absence of the instrument and in anticipation of a performance.

These basic idioms for each instrument can be challenged through extended technique. This practice explores alternate articulations and methods for extending the pitch and timbral range of an instrument. As much as they may challenge what is considered idiomatic for that instrument, extended technique in fact builds on, adds to, and can even negate the existing vocabulary of that instrument. All such considerations are taken in respect of an instrument's capabilities and limitations. Recognizing the limits of an instrument (be they physical, acoustic, or practical), delineate a reference point that help to distinguish standard practice vs. extended technique.

How can this notion of idiomatic writing be applied to new instruments? The lack of history that new instruments enjoy means that what is idiomatic has not yet been defined. There is *a priori* no codified performance practice for a new instrument – this must be created for each new sensor instrument. The performance vocabulary can be particular to a piece, it can also be specific to a composer's own oeuvre. This gives enormous freedom for a composer to create a personal voice for an instrument. Sometimes a new performance vocabulary is created for each new piece. From the listener's point of view, however, there is no point of reference as key to comprehension. This places the burden of introduction, elucidation, and development of a performance practice on the composer.

I have had the unique opportunity with the BioMuse to be at once composer for the instrument and performer on it, an instrument that otherwise is not widely used in this context. This allowed for me development of an extremely personal vocabulary on the instrument. Whether this establishes a more general performance practice for the BioMuse is unsure. With *Global String*, its multiple uses gives us immediate indications on the potential or a performative idiom on the instrument. It is a collaborative project, so as the two artists perform on it, not only will our personal tendencies emerge, but a common tendency that is identified with the instrument. As different visitors play on the installation version, the instrument's orientation and potential will become clear. First reactions of users are often quite useful in identifying these potentials of an instrument.

Improvisation

In improvisation, many of the concepts of instrumental vocabulary and idiom apply, they are broached on the spot in performance placing focus on spontaneity and response of the instrument. Despite the limitations and well defined range of articulations associated with a traditional instrument, a traditional instrument has a remarkable capacity of responding to spontaneous gesture on the part of the performer with a large variation in timbre. A violinist for example can very quickly move from *arco* to *pizzicato* to *sul ponticello* to *col legno*. Relative to the timbral range of a violin, the computer can be said to have fewer limits, but here we encounter the problem of the ease and organic sense of moving from one timbral variation to another and the relationship and coherence that tie them together.

Synthesizers and computer generated sounds are typically preprogrammed, the different timbres being accessed by selecting and switching among presets. Input from a sensor, on the other hand, is often a continuous signal. The question becomes then how to find a way to move from one timbre to another that is consistent with gestural input. Solutions to this lie both in the sound synthesis programming on the computer side and some thought given to articulative range and variation on the sensor interface. Given a certain sensor system, the software determines the suitability for improvisational performance. Software can be created for compositional performance, improvisation, or somewhere in between.

Fig. 7. Video available in the original CD-Rom version. Sensorband performance at SonicAkts festival in Amsterdam, 1994.

These issues lead to a performance of greater fluidity on an instrument, enlarging the possibility of spontaneity for the performer. Spontaneity can be thought of as the ease with which a performer arrives at different states he desires (Vertegaal 1996). However, this paradigm of intention and control can be challenged, putting in question the simple definition of spontaneity as the will and whim of the musician. The instrument itself could have a spontaneous or chaotic nature, becoming a living entity with which the performer enters in relation with. The performer discovers new spaces of coaxing or cajoling an instrument, taming an instrument, and shaping the nature of the instrument to articulate and engaging musical trajectory.

I have brought the BioMuse into numerous different musical situations – composed solo performances, structured Sensorband trio concerts, improvised music festivals with other electronic as well as acoustic instrumentalists. Across these different contexts, the personality of the instrument begins to emerge. The different situations create different demands on the instrument. These can be met by changing the software and synthesis running behind the interface. In a compositional setting, the MAX patch is at once the score of the piece as it is part of the instrument definition. In an improvisational context, the patches are programmed in such a way to give the widest possible range of expression in each sound without changing settings.

As a concert instrument, *Global String* is an instrument that can be played to realize a composition between remote performers. As an installation, this same instrument must take on the capability to respond to an improvisatory situation. The types of visitors at the installation, as well as the ways in which they will play the instrument are unknowns. The instrument is designed to be played with a certain articulatory technique, but the installation should not force the visitor to follow these techniques. We can only evoke a musical image - we cannot presuppose the response of the visitors. The software taking physical input at the string and articulating sound synthesis, then, must be general enough to respond musically to a wide range of possible input.

Relationship

In traditional instrument performance the relationship between the musician and their instrument is highly developed. This includes the years of time necessary to learn the instrument, establish a proficiency on it, then finally master the instrument. This results in a dynamic relationship that goes beyond the athletics of technique, and highlights the musical qualities of a personal interaction created between the musician and his instrument. In this regard the relationship of a musician and his instrument are deeper than what we expect in typical human machine interaction. A relationship with an instrument is based on the time we spend living with it. In the accelerated pace of hi-technology development, we rarely have time to spend with any one given hardware or software configuration before it is replaced by a new version. This is quite contrary to the time needed to develop a deep relationship with an instrument.

If an instrument is to become a communicative vehicle for the musician, he must attain a certain fluency. In musical instrument performance, we often talk of the state where the musician "speaks" through their instrument. Ultimately, this produces virtuosi who combine unparalleled technical proficiency and expressive charisma on their instrument. Creating a performer/instrument dynamic this intimate is a worthy goal in computer instrument design. It means creating a situation where the performer can attain a level of intuition with regard to his instrument where he is not preoccupied with every detail of its manipulation. How to achieve this intuitive musical fluency with a technology based instrument becomes an artistic challenge.

More important than the purely athletic qualities of technique, clarity and subtlety of musical delivery is an important test of the relationship between a musician and his instrument. Compared with a sensor instrument, subtlety is probably greater in a traditional instrument due to its history and expressive range developed within instrumental limitations. Acoustical consistency and preexisting perceived image of the instrument lend to clarity in performance. These qualities of an instrument not only help the audience comprehend a performance, but help the performer to feel at ease with his instrument. The clarity of interaction then goes beyond the simple question of parameter and event mapping of "what controls what" to a more high-level analysis of how different gestural inputs are used to derive the different types of articulative signals (Mulder 1996), and how different variations on these types of input affect and express the sonic and structural space of the music.

This issue of performer-instrument relationship is a central issue in each of the projects introduced here. With the BioMuse, this relationship is deepest – I have been performing on the instrument since 1992. While the host computer and MAX software has been updated several times in this period, my basic approach to the instrument has remained constant. The electrode placement was established over the course of three years and has since stayed the same. The basic gestural vocabulary has developed in an evolutive way over the course of different pieces and projects.

Soundnet, on the other hand, poses problems in this regard. As the instrument requires significant space and means to set up, we have had little time to live and work with the instrument. The instrument was developed in the abstract, then prototyped and presented in small scale. The sensor mapping and synthesis programs were written apart from the instrument. The only opportunity to have the complete instrument installed has been at the concert sites. This experience has been akin to composing for orchestra – one typically does not have the means to have the full orchestra onhand for experiments during the composition process. The composer relies on his knowledge of the components of the ensemble to create for the whole. The performance brings the ultimate test, a realization of the abstract act.

In concert, the Soundnet exhibited a behavior and response more or less was consistent with what we had imagined in the abstract during its development. As performers, however, we felt like beginners, trying to make articulations on an enormously powerful instrument with little practice time. These elements, plus the larger than life size of the instrument introduce an enormous challenge to the notion of instrumental virtuosity. With Soundnet, the concept of control is put completely in question - the instrument is too large and complex for humans to thoroughly master. The conflict of control vs. discontrol becomes a central conceptual focus of Soundnet.

Global String is, as it has been mentioned, a multi-mode instrument. It can be used in concert or as an installation. In concert, it will be performed upon by musicians who know the instrument. As an installation, it will be played by gallery visitors who are encountering the instrument for the first time. These visitors may or may not be musicians, and may or may not be sensitive to interactive or network technologies. In its design, then, *Global String* must accommodate these different situations. In the hands of a trained performer, it must be an expressive and sensitive instrument. When played by an uninitiated visitor, it must be clear, and responsive. The instrument does not so much adapt to these different situations inasmuch as it needs to continue to be musical across this range of use.

Feedback

The intuitive sense the performer has with his instrument gives him the "verve" that communicates to the audience. It is a confidence in his instrument that helps the musician to create a flowing musical dynamic that is conveyed to the audience. Of the factors that contribute to helping the musician achieve this, feedback is an essential component. Feedback can take on several forms, but in essense is information that gives the musician an indication or confirmation of what he has just articulated. It can be physical, tactile, or sonic and musical. The successful integration of more than one of these modes (*e.g.* tactile, sonic) contributes to creating a clear understandable coherence. While feedback is first apparent to the musician, giving him a point of reference for what he is doing, the action/reaction feedback dynamic should also be apparent to the audience. This gives the listeners the key to following the expressive space that the performer is creating.

Tactile feedback in acoustical instruments is an inherent characteristic. Traditional instruments are mechanical, and display mechano-acoustical coupling. This coupling can fold back to provide an acoustically based form of tactile feedback to the performer. This is seen in the harmonics beating in the lips of a brass player (Chafe 1993). With computer instruments on the other hand, mechanical action is acquired, digitized, and mediated through logic and data processing to produce synthesized sound. Tactile feedback in the traditional sense then must also be synthesized (Gillespie 1992). As much as it may help recreate a sought after dynamic, it is in its very nature artificial. For it to be effective, coherence in the generated feedback with respect to the generated sound are paramount considerations.

Other forms of physical feedback can be achieved through sonic means. A 'cello body is resonant, and vibrates in close contact with the performer's body, providing a valuable secondary feedback channel. Computer instruments in general do not possess such acoustical properties. That is, they lack resonant bodies. The acoustical space of sound diffusion, then becomes the closest thing to an "instrument body". Coupling then takes place through the speakers of the sound system through the concert space to the body. Modern sound systems are powerful enough and of sufficient quality, they can produce air pressure modes that can set the concert space in resonance and the perceiver's body into vibration. This is perhaps one of the purest sense of tactile feedback we have in technology based systems.

In cases where synthesized tactile feedback or sonic pressure feedback are not possible, we resort to the essential case of musical feedback. The physical gesture of the performer must be apparent in some resulting musical gesture. This is important both to the musician to have a sense of what he is doing, and for the audience to have an understanding of what is taking place. This replaces the direct physical effect of acoustic coupling with a kind of intellectual language parsing. Independent of the channel of feedback, representation creates the essential response from the instrument that helps the performer create his relationship with the instrument as described above. These considerations become important in sensor instrument design: Creating a successful performance dynamic rests not on a unidirectional control paradigm, but on an organic set of interactions between performer and instrument.

The physical nature of the three instruments discussed here gives each of them a dimension feedback. Although none of them have implemented explicit user feedback mechanisms, a tactile sense is apparent. With both the BioMuse and Soundnet, it is the performer's own body which confront the instrument, each in its distinct way. With the BioMuse, there is a near contradiction, since there is no object of action that provides feedback. Instead it is pure exertion fatigue in absence of an object. With Soundnet, the object of action is completely overwhelming in scale relative to the performer.

With *Global String*, the hybrid physical/virtual nature of the instrument leads to a mixed feedback strategy. The remote distance between performers creates a separation. Actuating the string at an end point with the action of the performer on the opposite end gives a sense of telepresence. This supplements the videoconferencing connection that provides the visual link. In view of the transmission delay for action and sound from one side to reach the other, the performer must feel his own actions manifested immediately – helping him distinguish his contribution to the total sound. These actions are both sonified by local synthesis and visualized onscreen as vibrational data is displayed.

Effort

While the performer has feedback cues from this instrument, and the perception of cause/effect from creative intention to musical result, the audience arrives at an understanding of the music through an abstract reconstruction of this chain. One key to the audience is the manifestation of feedback as exertion of effort on the part of the performer.

A problem arises when considering effort and execution on the computer. The nature of typical computer input devices is that they take little physical force to manipulate. This results in interfaces that do not differentiate power of articulation. Musical instruments are quite different - most instruments have a characteristic and particular response to applied force in articulation. The response differs among different instruments, and varies within an instrument according to range or dynamic.

Regulating exerted effort can be used in an articulatory fashion to shape expressivity in a phrase. It can also be employed compositionally to shape the evolution of a piece. The realization of an energy trajectory can be the basis for choices of instrumental register and timbre through a piece. The misuse of energy exertion in gratuitous display or for theatrical effect, however, have the potential of rendering the music equally ineffective (Ryan 1992). In fact, rules of inversion can apply. A virtuoso is often appreciated not for his display of playing technically difficult passages, but more because he is able to play such difficult passages with ease. A theatrical performer who plays an easy passage with an air of difficulty is bound to be less appreciated.

Sensor instruments often lack the sophisticated inherent feedback characteristic that causes them to require real physical effort in execution. With the absence of varying effort to achieve different articulations on an instrument, compositional development begins to lose its dramatic sense. Artificially adding physical obstacles to require effort would only create the undesired gratuitous effect described above. It becomes thus a challenge for the instrument builder to conceive of coherent model for requirement or representation of physical effort on a technology based instrument.

The BioMuse and Soundnet share a characteristic in that they are both extremely physical instruments. The effort of the performer is apparent in performance, and is conveyed intuitively to the audience. Physical limits of the performer's strength create interesting boundaries as the performer strains to reach a certain level or point. These asymptotic trajectories are heard in the music, and have been successful in building a dynamic tension in performance.

Nonessential gesture

Similar to the issue of the fine distinction between genuine physical exertion and gratuitous display, the topic of essential vs. nonessential gesture on an instrument treads the thin line between musical artistry and vain theatre. In any instrument, there are gestures essential to sonic production on the instrument as well as those that are independent of the acoustic of the instrument (Delalande 1988). To understand the notion of non-essential gesture, consider the piano as example. As a percussive instrument, the essential gesture tied to the physics of the instrument is the striking of a key. According to the mechanics of the piano action, any gesture following the strike theoretically has no acoustical effect on the sound produced by the instrument. However, musically we cannot invalidate the practice seen among numerous pianists to dig into the keys after the strike. Visually more evident is the raising of the hand and wrist following the attack, arching to the next note. Here we meet the fine line between theatre and musicality. Some pianists admittedly over-theatricize this aspect of their performance, but this superficial nature is quickly uncovered. In a musically satisfying case, however, this moderated gesture makes a positive contribution to the musicality of the performance. The claim is that gesture non-essential to the physics of the piano itself is not all theatre, but musically vital element that directs musical flow, phrasing and articulation.

The first step in investigating nonessential gesture is to define the gesture that is tied to the instrument's mode of action - the essential gesture. From there, we can define the ancillary gestures not essential to the direct functioning of the sensor, but that are important to the musician's articulation on that instrument.

This issue applies most directly to the BioMuse. Although it is an instrument that sense corporeal gesture, it does not sense gross movement *per se*. The actions detected are muscle tension, and not limb displacement. This means that the instrument could be played while standing or sitting absolutely still, simply by flexing the muscles where the electrodes are placed. However in practice, this is not so musical – much in the way a violinist who saws mechanically at his instrument is not as musical as one who sways gracefully into certain phrases, or a pianist who flowingly lifts his hand in anticipation of the next passage.

These effects are not purely visual, but affect the musical phrasing and articulation. In the same way, although each muscle tension trajectory could probably be realized standing exactly still, I have found that certain trajectories are more naturally realized with the aid of certain arm movement and gesture.

Memory

Instruments can be designed and created with a specific performance in mind (Aperghis). Instruments have also been designed for and custom built for particular musicians. In both cases, the instrument can retain it's singular nature to the situation or performer, or can expand its acceptance and use beyond the scope of the original situation. In the latter case, it is the range of articulative expression possible with an instrument and its adaptability to new musical situations that gains a wider acceptance for a new instrument.

For the listener, comprehension of instrumental performance practice is based on association and familiarity. The ease with which the listener parses different musical parts in a group performance is based on their prior knowledge of the instruments making up the ensemble. New ensemble combinations or musically new compositions can be understood based on the listener's existing knowledge of the sound of each instrument. This association and memory also provide keys to comprehension as the listener listens to a recording in the absence of visual cues.

The question arises then of how to establish a base of association and knowledge when the instrument is completely new to the listener. What are the keys to understanding unfamiliar instruments? The most straightforward answer is history, consistency, and repetition. Repeated performances or different pieces making consistent use of an instrument establish in the listener a cognitive memory that can be applied to appreciating a new piece or the use on the same instrument or to distinguish that instrument from others. Solutions can be compositional – an instrument can be presented in an informative way in the piece itself, though composers should not be reduced to creating educational demo pieces.

The field of computer music is already one where the propos is that we are creating a new universe of sound for each piece. The audience has little associative sonic memory between pieces at their disposition as an aid to understanding the music. One thing that sensor instruments potentially afford is an associative element to unfamiliar computer generated sounds, a kind of visual key. To fully serve this potential, the composer's responsibility becomes to develop a performance vocabulary on the new instrument. The success of such a performative language particular to an instrument is contingent on the coherence and clarity with which performance gesture is tied to the musical result that is heard (Choi 1998). Part of Sensorband's approach as a sensor instrument ensemble has been to work with this compositionally - at moments creating clarity where the three instruments are differentiated, and at moments confusing this differentiation - to construct a musical dramaturgy.

Communication

Several communication channels exist in a performance environment: musician-musician, musician-audience, and musician-instrument. These can be regarded as ways in which music is interactive. The give and play that creates ensemble unity is interaction and communication among the musicians sharing the stage. The musical art and energy as perceived by the audience is the musician-audience channel. The feeling of responsiveness of an instrument is the musician's reaction to his interaction with his instrument. These modes of interaction culled from traditional musical practice give us material to supplement considerations of human-machine interaction theory.

Issues of gestural-aural coherence (Goldstein 1998) and clarity may be more effective at exposing the capabilities and weaknesses of an instrument than an analysis from an interface design standpoint. Computer human interaction considerations aside, the performance becomes the ultimate test of success of a musical instrument. The focus then should perhaps not be on how much a computer allows us to do, but on how we can begin to approach the kind of fluid communicative way we have with acoustic instruments. This is not to say that we should necessarily create computer emulations of existing instruments. Rather, my goal has been to seek an organic interaction with the machine, to establish a conversational exchange with the instrument. Seen in this light, emphasis is placed not on power and control, but on clarity and fluidity. This places an emphasis of the musician/instrument dynamic on expression, articulation, and spontaneity. These are qualities we seek to achieve with any musical instrument – be it technological or not. We can draw from traditional instrument performance practice to offer valuable guidance in developing a musical language with technology based musical instruments.

Evaluation of an instrument is often made from the action standpoint, that is, judging the articulatory fit and satisfaction for the performer. The evaluation can however also take place from the reception standpoint, viewing the situation from the regard of the perception of the listener (Iazzetta 2000, in this volume). The success of an instrument in both regards indicates a high potential for the creation of a musically communicative experience. A traditional instrument benefits from its consistent nature of sound production for subtlety, and benefits from established image for clarity. The subtlety and clarity perceived is dependent on how gesture types are associated with resulting musical output. Different types of articulation can be associated with timbral, event, and structural modes of expression. These types of articulation can be derived from the nature of the sensor itself or be defined in software.

The issues discussed in the previous sections - idiomatic composition, feedback, memory, all contribute to establishing a communication channel between performer and listener. In this new field, these become important considerations in instrument design, composition, and performance. Although the BioMuse is capable of sensing brainwaves and detecting eye movement, I have chosen only to use muscle signals. Generating music from the brain is a fascinating topic (Rosenboom 1990), but one that in its very nature better adapted for personal experience than for performance. Transition between brain states provide no visual cue for the audience to connect with. Although eye movement has a great potential for gesture-music mapping, the ocular channel is also difficult to exploit in performance. While eye movement is quite evident, it is a rather fine gesture that may be difficult to perceive at a distance. More importantly, there are many involuntary movements of the eyes that risk to cause artifacts.

Conclusion

Gestural, or *sensor-based instruments* is an inclusive term that encompasses a wide range of related musical instruments. Here in this text, we have created a broad definition of a musical instrument as a basis for more specific investigation. Traditional acoustical instruments are used as a model, not in any specific sense, but as a guide to understanding the composer performers' relationship with an instrument. The definition of musical instrument as proposed here applies to all musical instruments, whether acoustic or computer-based. This is used as a point of departure to introduce three sensor-instrument projects I have worked with over the past several years.

Instruments are regarded as systems that respond musically to performer action. They take some form of physical intervention by the musician as the articulative component to producing music. Specific details include the locus of the performer's action, the manner in which it is transduced, and the destination where this is musically manifested. This process of transformation becomes the defining characteristic of an instrument.

Beyond the purely technical description of an instrument, important human factors arise. In this way, instruments are distinguished from tools. These may be subjective from the standpoint of the performer or audience, and deal with not just performer-instrument interaction but the role of the instrument in performer-audience communication. Seen in this light, the successful design of a sensor-based musical instrument is the result of a fusion of computer-human interface design and acoustic instrument lutherie.

If the limitations of an acoustical instrument contribute to characteristics giving it a personality or identity, the open-ended nature of computer based instruments at first preclude this kind of identity. The separation of gestural input from sound production means that here is no hardwired gestural vocabulary connecting action to sound. This connection is created in software — bringing programming into the realm of creative musical instrument building.

The relationship that the performer creates with his instrument becomes the source of musical communication. The relationship is nurtured by responsive qualities of the instrument such as feedback. Fluency, coherence and clarity are seen as essential criteria. The classical model of a performer's relationship with an acoustic instrument is seen as a valuable model, however this is not intended to establish a traditionalist or reactionary stance. The simple emulation or imitation of existing instruments is not what is advocated, but rather the application of these rich traditions to new technology.

The use of new instruments open possibilities of performance integrating other media. The concept of presentation can be expanded beyond the classical concert to embrace new spaces and modes of interaction. Applying the instrumental concept to these situations, they can be treated in a musical way. It is argued, however, that the focus should remain on the efficiency of gestural communication and expression over techno-wizardry.

We are faced with a dilemma – computer sound synthesis gives us an enormous range of parametrized control. Sensor devices give us a freedom from mechanical and acoustical constraints. Despite this, an acoustic instrument is capable of responding to a player's expressive subtlety in a way we can only hope to approach with new instruments. And as much as the computer allows an unlimited sonic palette, an acoustical instrument is extremely rich in the range of related and articulated timbres it can produce.

With each new instrument, a balance must be found between the expansive possibilities and the unfamiliarity of newness. While the lack of preconceived association give the composer enormous freedom, it also places the burden of educating and informing the audience on the composer. A performative vocabulary and memory must be developed for each new instrument, sometimes even within the course of one piece. By doing so, the composer helps the performer to establish the clarity and coherence of gesture, and provides the audience with keys to musical comprehension.

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