Electronic Musical Instruments: Experiences of a New Luthier

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ABSTRACT

The author reflects on his experiences as a designer of new electronic musical instruments, which have led to further insights and applications in other domains such as video performance, architectural design and knowledge applied in the general field of human-computer interaction.

Musical instruments are extreme examples of precise, expressive and versatile interfaces. With the transition to the use of electronics as a sound source, a new type of nonmechanical instrument was needed. The limitations of mechanical systems (e.g. the length, thickness and tension of a string is directly related to its pitch and timbre) have also gone, which means that there is almost total freedom in the design of the instrument. In fact, there is so much freedom that new guidelines and approaches to design for this complexity have not yet been established. With the introduction of the MIDI communication protocol in the mid-1980s, the control surface or *interface* became increasingly detached from the *sound source*—splitting the "instrument" in two as it were. In the last 20 years, many developers have worked on creating new instruments—new interfaces as well as new forms of sound synthesis. These instruments show that it is becoming possible to create new instrument forms, unrestrained by mechanical limitations, fitting to the player at the close, *intimate* level.

Technological Stages

Technology has developed from the first human artifacts to our current stage of interactive tools and media. Each new technology has been used for musical purposes—new technologies have often led to new instruments, which in turn have led to new insights and potential uses in technologies. Musical instrument development reflects the stages of technological development [1].

The first human artifacts were *objects,* such as hand axes, knives and other tools, first made of wood and stone, later made of bronze, and yet later of iron. Many examples of current object tools still exist, and our interaction with them is usually straightforward and effective.

Later mechanical contraptions were invented to distribute and manipulate power in different ways, first through *passive mechanical* systems, which were driven by natural power sources (e.g. muscles of humans, horses and oxen, or water power) and later as *active mechanical* systems, which were driven by added power sources (e.g. steam engines, internal combustion engines or other motors).

Although electricity has been known of since early history, one of the first practical applications of an *electrical* system was in use of the telegraph as a communication medium in the first half of the 19th century. *Electronic* systems are capable of changing the electrical signals, first as *analogue electronic* systems (using vacuum tubes, later transistors) and later as *digital electronic* systems (eventually based on integrated circuits).

The essence of a *computer* is that it can change function under the influence of its programming. Although there have been programmable mechanical systems and analogue electronic computers, the digital computer has had the biggest impact on society and therefore forms a separate category.

What can be seen in this historical development is a decrease in visibility: Everything becomes smaller and less tangible, while at the same time complexity increases. This contradiction urges developers to pay more attention to the design of the interface. A whole field of research and design has emerged in the last few decades, offering us methodological and structured approaches in human-computer interaction.

Musical Instrument Classification

The oldest artifacts that are identified as musical instruments are flutes made of hollow bird bones. The simplest form of musical instrument—pieces of material that sound when hit—must have been first employed much earlier. Such instruments are *objects.* Examples of instruments in this category are still widely used: percussion instruments from drums and cymbals to the marimba.

Most instruments in classical music are *passive mechanical* systems; movements of the player are transported and converted

Fig. 1. The adjustable Hands for Basel, 1988. (Photo © Bert Bongers)

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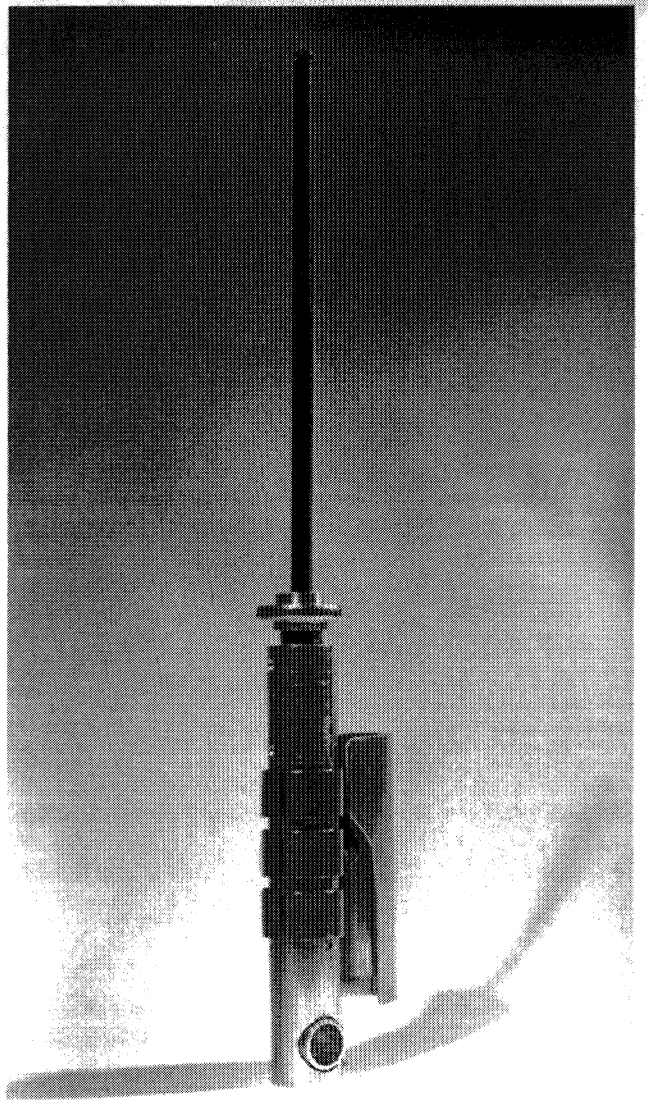


Fig. 2. The first MIDI-Conductor "baton." (Photo © Ernst Bos)

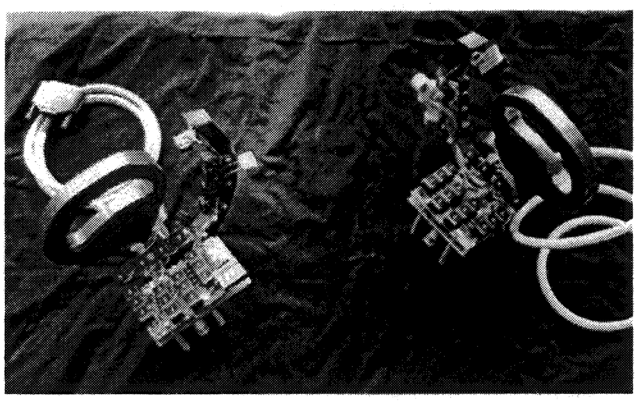


Fig. 3. Michel Waisvisz's Hands II, 1991. (Photo © Bert Bongers)

into part of the instrument. Examples are the mechanics of a flute or saxophone and the mechanical systems in the piano. The pneumatic organ is an example of an *active mechanical* system (driven by an added power source).

An example of an *electric* instrument is the electric guitar. The mechanical vibrations of the string are translated into electrical signals by a pickup (a coil of copper wire around a magnetic core). This signal is further amplified and processed by electronics. The earliest synthesizers are examples of *analogue electronic systems*, and later *digital electronic* synthesizers as well as samplers were introduced [2]. The possibility of recording sounds and playing them back had a great impact on musical development, from player pianos and musique concrète to DJs and sampling [3].

The computer is an omnipresent tool in electronic music, for both the generation and manipulation of digital sound, as well as for composing and even as a generative system of algorithmic composition.

As most instruments are combinations of (successive) technologies, it is not easy to classify them. Not only the sound source is important, but so is the way it is controlled and in some cases the way the signal is transduced. Instruments are often also grouped by their appearances, particularly of their means of control (their interfaces). Thus, there are keyboard instruments (organ, piano, harpsichord, synthesizer), plucked instruments (guitar, lute, electric guitar), etc.

Existing Organologies

The common system for categorizing musical instruments does not place the electric, electronic and further developed instruments very well. In the Hornbostel-Sachs model, from 1914 [4], instruments are divided by their way of producing sound into *idiophones*, *membranophones* (these two fit in the class of "objects"), *chordophones* (based on strings) and *aerophones* (based on vibrating air) (the passive mechanical technology). To cover this new class of instruments, the Hornbostel-Sachs model was extended with the *electrophones* in 1961, and Hugh Davies discerned the combinations of *electronic*, *electro-mechanical* and *electro-acoustical* [5]. However, I think the distinction between electrical and electronic is important, with the further development of digital and computer-based instruments with their inherent freedom for the design of the interface.

Musical instruments are often compounds of various technologies. The "electric guitar" is therefore actually much more than just the guitar; with all its extensions it is a compound instrument that includes many technological categories: The instrument itself is *passive mechanical*, the transducing of the vibration of the string is *electric* (coil and moving field of the magnetized string) and the amplification and effects machines were first *analogue*, later *digital electronic*. I think the essence of the instrument is the way the vibration is

Fig. 4. Wart Wamsteker playing a SonoGlove, 1992. (Photo © Bert Bongers)

picked up, which is electric, and which influences the way it can be played, including various extended techniques.

New Electronic Musical Instruments

The interaction between player and instrument is partially determined by the technological category. Mechanical systems are directly influenced by the player's actions; the musical instrument is a unity of sound source and interface. Electronic systems need a translation in order to be mechanically manipulated by humans. Of course it is possible to interact directly with the circuits, as in an electric fence, for instance, or connect directly to the electrical signals of the human brain and nervous system. Generally, however, an interface is needed, one designed in such a way that it enables and facilitates a rich and profound interaction (two-way by definition). In electronic and computer systems, the system and interface are separated. This can be clearly seen in electronic musical instruments, in which the instrument is technically and conceptually split in two: sound source and interface.

The instrument should be designed as a whole. In traditional instruments these two elements are often one part and tightly coupled. Although in mechanical instruments in some cases the sound source is remote, such as in a church organ, or touched indirectly, such as with the bow of a cello, with electronic instruments the interface can in some cases be developed entirely independently. The interface would communicate with the sound generating electronics through control voltages (CV) in the case of analogue electronic instruments and through MIDI in the case of digital electronic instruments.

In this section I will describe some instruments [6] in the category of digital electronic technology, based on my experiences as a designer of such interfaces since 1987. In the final section I will reflect and discuss the general experiences.

The Hands

In the early 1980s Michel Waisvisz at STEIM (Studio for Electro-Instrumental Music) in Amsterdam realized that the standard interfaces for performing electronic music were not sufficient. The experiences with his development of the Crackle Synthesizers, which were played by touching the electronics of the analogue circuits directly with the hands, could not be applied for influencing digital electronic circuits. Through the MIDI protocol, however, the digital domain could be entered. Together with engineers at STEIM, Waisvisz started to experiment with aluminum plates strapped to the player's hands, mounted with various switches, dials and other sensors. A small microcontroller worn on the back converted the sensor signals into MIDI commands. The Hands are sensitive to gestures on different planes and scales, enabling an intuitive control of the sounds produced [7]. In the first years several versions were built, in an experiment to find the right form and layout of the switches and sensors. The difficult problem of how to design a new instrument's form and function was approached in a trial-and-error fashion, experimenting until a satisfying solution was found. Sometimes inventions were made by coincidence; for instance, the very useful "scratch mode" (in which every movement of the hand would re-trigger a sound) was discovered by accident, due to a loose wire and a programming error by one of the engineers. The engineer wanted to correct his "mis-

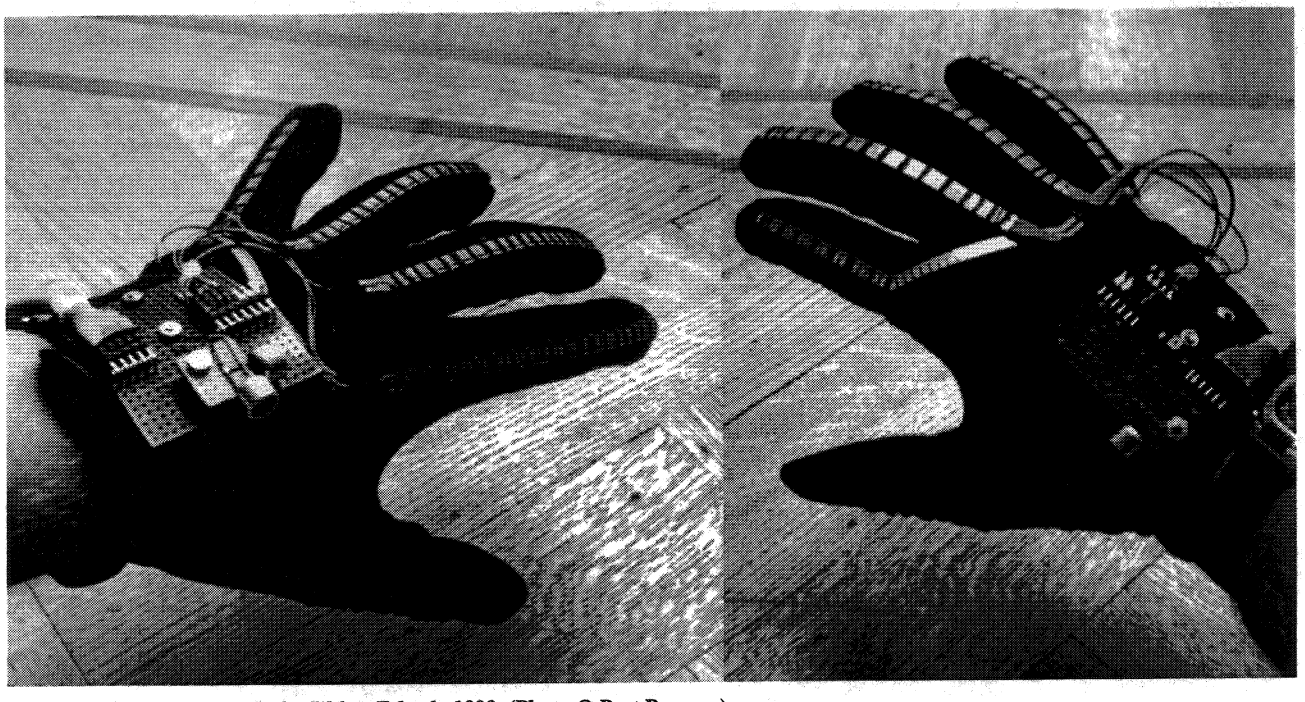
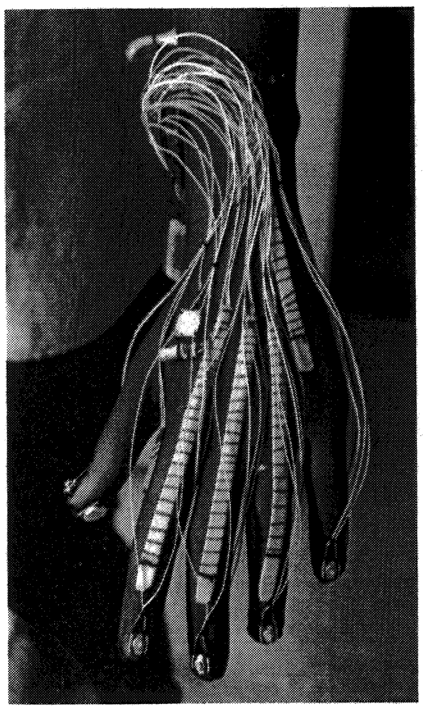


Fig. 5. The SonoGloves made for Walter Fabeck, 1993. (Photo © Bert Bongers)

take" immediately, but Waisvisz saw its musical potential and insisted on leaving it as a possible mode of playing—a good example of serendipity.

The Hands evolved and now include a small keyboard with 12 keys for each hand: four keys for special functions, four keys to modify the sound, a pressure sensor, four mercury tilt switches and a sensitive ultrasonic sensor to measure the distance between the hands.

Fig. 6. Laetitia Sonami's Lady's Glove, 1994. (Photo © Bert Bongers)



I got involved at STEIM in 1987 and added further control elements to the Hands prototypes based on the musical ideas (compositional and performative) of Waisvisz. These were the last additions, as Waisvisz realized that it would be best to stop changing the instrument and focus on the playing [8]. In 1988 at STEIM I designed and built a new set for the Musikhochschule (Music Academy) in Basel. This version was adjustable so that it could be fitted to various hand sizes, by moving the keys and other controls, and I painted the aluminum instrument and converter parts mint green (Fig. 1).

Since 1989, I have worked as an instrument developer at the Sonology Department of the Royal Conservatory of Music in The Hague, and Waisvisz and I have collaborated in the development of a new instrument called the MIDI-Conductor. This instrument was a simpler version of the Hands, and based on the metaphor of a conductor—the right Hand had the shape of a baton. We developed a series of six of these instruments, based on a wooden frame, which were used by students, teachers and others. Figure 2 shows a prototype of the right-hand controller, the actual "baton" made out of aluminum and brass; the final version was made of wood.

The wooden frames were made by Waisvisz, and he liked these so much that we decided that the next version of the Hands would be based on a similar shape and material. Functionally they were almost entirely the same as the old Hands with their metal frames. I built two sets of these Hands II, one pair as a backup in case the instrument would fail. They were used from 1990 to well past 2000 (Fig. 3).

Gloves

Using gloves as input devices for virtual-reality applications became popular in the mid-1980s. The cheap Mattel Power Glove was developed in 1989 to interface with the Nintendo game controller. The Power Glove used specially developed resistive strips as bend sensors, ultrasonic position and orientation sensors and a built-in microcontroller [9]. In the United States, several musicians and artists started to use the Power Glove to control sound generated by or through computers.

At Sonology, various composers developed an interest in using gloves to make music. We first took the Power Glove as it was, using the sensors and the plastic glove but replacing the electronics with the STEIM SensorLab sensor-to-MIDI converter. This way we were able to read the sensors with a much higher precision (8 bits instead of 2) and a larger range of movement, which was necessary for performing. Sonology student Wart Wamsteker used filters and feedback, controlling the filter parameters with the bend sensors and movement of the glove. Before developing the glove, Wamstecker

Fig. 7. Making of a Lady's Glove, 2003. (Photo © Bert Bongers)

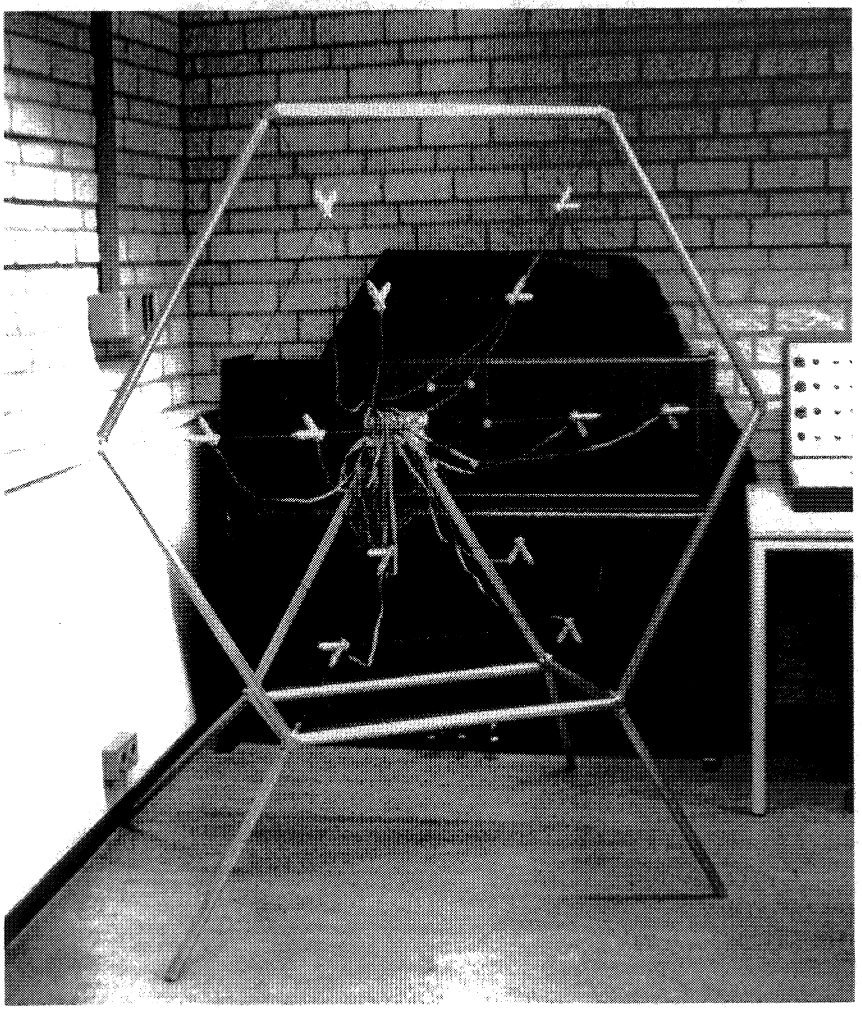


Fig. 8. The Web, made for Michel Waisvisz, 1992. (Photo © Bert Bongers)

used to play "no-input mixer," using the same principle of feeding back an output signal into the input of a mixing desk without further sound source. After an initial performance with this no-input mixer we realized that a dedicated interface was needed—the SonoGlove (Fig. 4).

This design was developed further for the Chromasone instrument for Walter Fabeck at Sonology in 1993. To reduce the restriction of finger movement to less than the thick plastic of the Power Glove, we used golf gloves (of a strong but thin blue suede leather) and sewed the bend sensors (taken from a Power Glove) on the outside (Fig. 5). Later I used "winter play" golf gloves, which had two layers, enabling us to slide the sensor between the layers. The electronics, connector and ultrasound sensors were mounted on the outside. To guide the movements through the air with the gloves, Fabeck had developed a keyboard "template" made of see-through plastic that swiveled on a stand. He has performed with the instrument in plays and other performances [10].

In 1994 STEIM commissioned me to build a new glove for Laetitia Sonami, based on her prototypes built after 1991 [11]. This Lady's Glove has three bend sensors on the main fingers, each with a center tap allowing the signal to be read in two areas relating to two different knuckles, a two-directional bend sensor on the wrist, little switches on the fingernails, a mercury tilt switch, sensitive accelerometer, ultrasound sensor for distance measurement of the glove in relation with the body and a foot, and continuous magnetic sensors on the fingertips activated by a magnet on the thumb. All sensors are sewn onto a thin, custom-made Lycra glove (Fig. 6). The idea was to then cover it with an outer glove of different colors and patterns. However the uncovered glove, with its colored wires and shrink-wrap of the several sensors, had such an interesting "cyber" look that the covering gloves were never used.

The design illustrates the sensitivity of the device, getting so close to the skin of the human body, and how difficult it was to achieve mechanical reliability. The hand moves a lot, in many degrees of freedom, and wires and sensors have to move with it without restricting the movement and without breaking. The solution we found was to enable the electronic parts and the wires to move relatively freely and find their own way around the motions and postures of the hand. We used wire that was very thin and flexible, yet very strong, with a multi core and Teflon insulation, secured with sewing and glue around the soldering points where the cables are weakest. Another technique I developed for these applications was to bend the circuit boards by heating them (before the parts were put on) to better follow the human body and painting them to match the design. In 2003 in Barcelona I built a second glove with a different visual appearance with the help of Yolande Harris (Fig. 7).

The only way to get closer to the human body would be to connect directly to the (electrical) nervous system and brain. Sensors can be put inside the body or on the skin, measuring the small voltage changes of the nerve signals to the muscles [12,13]. At Sonology we experimented with this type of interface as well.

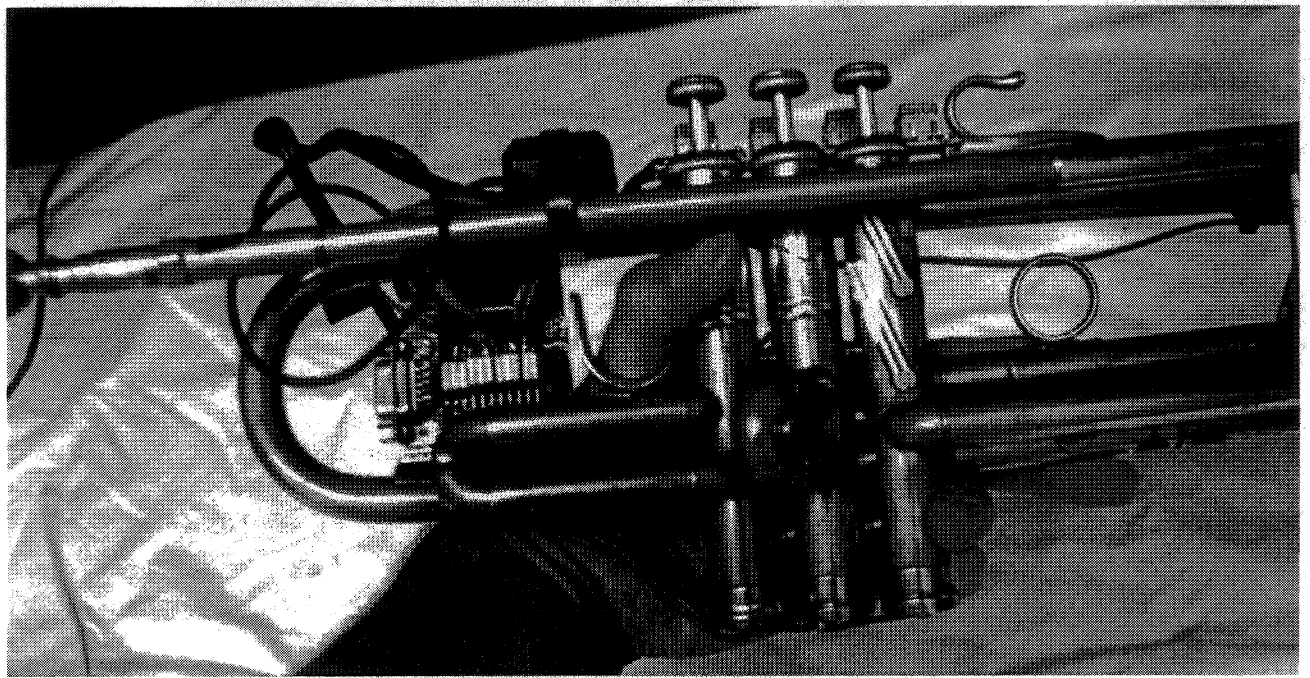
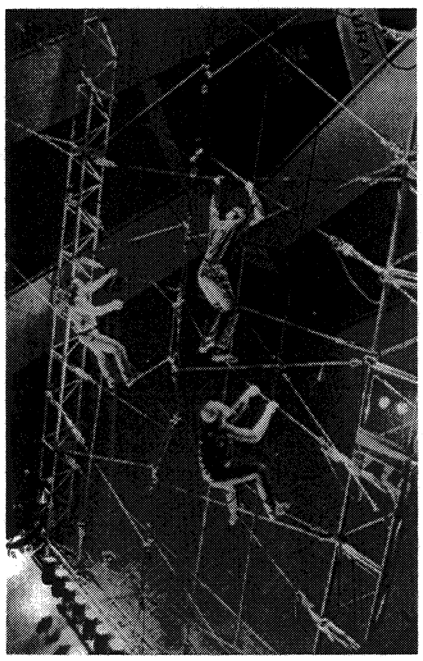


Fig. 9. The Meta-Trumpet, made for Jonathan Impett, 1993. (Photo © Bert Bongers)

The Hand in the Web

With many of these new instrument designs we were aiming for more continuous controls for manipulating sound, molding it like clay or "sonoputty." In the early 1990s Waisvisz came up with the concept of a spider's web, flexible and with all elements linked [14]. We designed The Web, an aluminum frame in an octagonal shape with a diameter of 1.2 m and consisting of six radials and two circles made with nylon wire (from the red C strings of harps). In 24 of the resulting string parts, the physical tension caused by the player was measured by custom-designed sensors (Fig. 8). The player thus has continuous, real-time, simultaneous control over 24 parameters of the sound, making The Web a good timbre controller compared with a standard keyboard, which would control in the most optimal case only three parameters (pitch, velocity and pressure). As in traditional instruments, these parameters are linked in a fixed configuration due to the web structure. The instrument was difficult to play in a traditional way compared with, for instance, a keyboard. Hitting The Web with, say, one finger in the middle would lead to a complex set of changes in many of the parameters of the sound. Hitting it again in exactly the same way would produce a slightly different set of changes. It might seem that we had produced the ultimate useless controller, giving a different output with exactly the same input. However, there is no such thing as exactly the same input. Due to slight variations of the movement of the hand, each time it hits The Web it does so slightly differently, which is translated into slight changes in the sound. For a human being it is impossible to make exactly the same gesture multiple times; there will always be variation ("noise," in engineering terms). I think that the beauty of the sound of traditional instruments has partially to do with the sensitivity of these instruments to these very variations of the player.

Fig. 10. Sensorband (Atau Tanaka, Edwin van der Heide and Zbigniew Karkowski) playing the SoundNet, 1996. (Photo © Bert Bongers)



The Web still exists; it is now part of STEIM's traveling exhibition Touch, but it now has fewer strings so it is easier to play.

Hybrid Instruments

Musicians using traditional instruments often extended the instruments by mechanical means, for instance preparations of the piano.

Adding *electronic* elements (sensors and interfaces) to the instrument leads to hybrid instruments or hyperinstruments [15]. With these hybrid instruments the possibilities of electronic media can be explored while the instrumentalist can still apply the proficiency acquired after many years of training.

Since 1992 I have worked with Jonathan Impett on developing his electronically extended trumpet, the Meta-Trumpet. Using semicircular brass base plates on which to mount the electronics and sensors, I made the additions look very much part of the original instrument. Another design consideration was that the additions should be easily removed, so that Impett could play baroque or classical music on it. (In practice this never happened.) We added several switches on the top of the instrument, pressure sensors on the outside of the piston tubes, motion sensors inside the pistons, mercury tilt switches, an accelerometer and a 2D ultrasound positioning system, enabling the instrument to be played as a gestural controller (Fig. 9). Generally the control parameters of the electronic extensions could be used independently of the original playing techniques. With this instrument Impett controls his algorithmic compositional computer system [16,17].

Another example is the Cello++, extensions built with Yolande Harris for Frances-Marie Uitti in 1999. We made soft pads (it had to be put on her precious ancient cello without damaging it) with switches, sliders and sensors, controlling processing in the computer.

From the Intimate to the Spatial

Inspired by The Web, the members of Sensorband [18] approached me in 1995 to help develop a web on an architectural scale. The SoundNet is about 10 m high and 6 m wide, to be played by the ensemble by climbing on it. To achieve this, we had to develop string-tension sensors to withstand a force of about 10,000 Newton. The rest of the instrument consisted of an aluminum frame and shipping rope chosen for its feel and strength. As the musicians climbed and bounced their way up and around the SoundNet, the sounds would change according to their actions (Fig. 10).

The scale was further extended in the Global String project [19], developed with Atau Tanaka and Kasper Toeplitz from 1998 to 2000. In two locations (DEAF festival in Rotterdam and Ars Electronica in Linz) we set up 10-m-long stainless-steel strings with various sensors played by the performers and connected to one another via the Internet. The network became part of the instrument, its parameters (for instance, the route that data packages took) influencing the sound.

Discussion and Conclusions

In this paper I have discussed traditional musical instruments as well as new electronic instruments developed in the last decades. They are examples of very sensitive interfaces that enable a rich interaction, using many modalities, including the tactual.

While traditional instruments are still being perfected and adjusted [20], the development of new instruments often occurs in an incremental, evolutionary way. For instance, Adolphe Sax, who invented the saxophone around 1850 in his workshop in Dinant, Belgium, was a renowned clarinet builder and developer of many wind instruments. His goal was to develop an instrument that would sound more like a string instrument, but without all the disadvantages present in string instruments at that time. He did not need to start from scratch but based his designs on existing knowledge of instruments. At the same time he made an instrument that enabled many techniques of expression beyond his knowledge. Sax could not possibly have had the music of Eric Dolphy or John Coltrane in mind when he invented the saxophone. Likewise, Leo Fender could not have predicted that Jimi Hendrix would play the Stratocaster, by the end of the 1960s, left-handed, using acoustic feedback and other effects to take the instrument to another level. These inventors created something that enabled new music and ways of playing to be discovered. I think this is relevant to emphasize because at present software tools are often developed with a much more narrowly defined goal or set of tasks in mind, inherently prohibiting kinds of use other than those intended by the designers. The goal is to design for possibilities, to design for inclusion rather than exclusion of tasks and functions—even those unknown.

Most of the new instruments presented in this paper were developed for expert players, often composers, enabling them to create their own idiosyncratic ways of music-making. I have shown that it is not a trivial task to generalize these instrument designs to be played by a wider audience. Traditional instruments are difficult to play and require years of dedicated training before they are mastered at a level such that full expression becomes possible. Instruments differ in their learning curves. However, the highest level of virtuosity that can be reached, such as is established by a sometimes centuries-long development of musical practice, is the same for every instrument because the player's musicality has to be developed too. With the freedom of design in the case of electronic instruments, the learning curve does not need to be steep, while at the same time the instrument should facilitate the development of virtuosic levels [21]. It is also possible to design different instruments for different target audiences, such as experts (who are or want to become virtuosic), generalists (with some music skills) and novices.

The difficulty of playing traditional instruments is related to the physical nature of the sound-making process. The process determines to a large extent the design of the instrument and therefore how it is controlled. With electronic instruments the form factor is free, so it becomes possible to take the human as a starting point and develop more ergonomically optimal instruments. Total freedom, however, is difficult to design from, as there is often no concrete function to dictate the form. The functions are abstract, so the form has to "follow the function" in other ways.

The development of musical instruments in their successive technological stages shows clearly how the instrument becomes more invisible, less physical, often "easier" to play, but harder for the player to use to express him- or herself. This is because *effort* is actually often a good thing. Musicians traditionally rely strongly on their sense of touch when playing acoustic instruments, which helps them to control and articulate the sounds produced. There are three sources of information for the player: kinesthetic, passive tactual and active tactual feedback. With electronic instruments, due to the decoupling of the sound source and control surface, the tactual feedback has to be explicitly built in and designed to address the sense of touch. It is an important source of information about the sound, often sensed at the point where the process is being manipulated (at the fingertips or lips). This immediate feedback supports the articulation of the sound [22].

Musical instruments facilitate a sensitive, multiple-degree-of-freedom, multimodal interaction. The interaction is traditionally on the intimate scale, but can extend to the spatial scale. Furthermore, instruments allow a high relative precision. My experiences in instrument design informed later work, such as the development of the Video-Organ, an instrument for audiovisual performance [23], the Meta-Orchestra multidisciplinary group performances [24,25] and general interface design research and teaching.

Acknowledgments

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