Physical Interfaces in the Electronic Arts

Interaction Theory and Interfacing Techniques for Real-time Performance

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Introduction

This paper takes two approaches to describe aspects of physical interfaces in the electronic arts. One approach takes a Human Factors point of view of the different interactions that can take place in electronic art, and the other more practical approach describes sensor technologies (and a sensor categorisation) to make the physical interaction possible.

In this introduction the historical development of the ergonomic aspects of the design of instruments are described.

Because the earliest examples of the usage of electronic media to make art can be found in music, and because music has a long tradition of performance and of a precise and intimate relationship between human and technology, this paper often takes electronic musical instruments as a starting point. From there, the paper aims to describe the general field of art forms using electronics (visual arts, installations, architecture, network, music).

Humans have always been making music by using objects and artefacts. Every known way of generating sound, using strings, bells, reeds etc. has been used to make musical instruments. In all stages of engineering (manual / mechanical / electromechanical / electronic / digital) the technology was reflected in the instruments. The nature of the sound generating process traditionally dictated the design of the instrument. Take for instance bowing a string. On a violin the strings are short and therefore fit on an instrument that is held under the player's chin. Longer strings to reach lower registers called for a bigger instrument, for instance the cello that rests with a pin on the ground and is held between the player's knees. Even longer and thicker strings for bass notes demands such a big instrument that the player has to stand next to it and embrace it. In instruments that use electricity in any form this relationship is often less clear.

The Ergonomics of Electronic Instruments

Soon after electricity was discovered people started to use this new medium to generate sound. When the electrical sciences became more serious and the grasp of humankind on this new medium enabled the building of all sorts of devices for communication, the electrical instruments became more sophisticated and in the first half of the 20th century a lot of new instruments sprung up. Most of them where based on a keyboard, which had proven to be a versatile interface since it can be found for centuries on a variety of instruments like the piano, harpsichord, organ, etc. There were interesting exceptions of course, like the well known Theremin which operates with gesture-sensitive antennas changing pitch and volume of a tone generated by an oscillator [Martin, 1995]. Another example is the Trautonium, which works with a touch sensitive strip. Of the instruments that did use the keyboard as their main interface part, like the ondes

Martenot (France) [Ruschkowski, 1990] and the Electronic Sackbutt (Canada) [Young, 1984], most used a variety of additions to enhance the sensitivity. A good overview of the early days of electronic music (and the business aspects of it) can be found in Joel Chadabe's book [1997].

Instrument designers like Leon Theremin, Maurice Martenot, Oskar Sala and Hugh Le Caine seemed to exploit the freedom of design offered by the new medium, which imposed far less on the design of the shape and dimensions of the instrument than the traditional instruments did. They could take the properties and possibilities (and limitations) of the human being as a starting point for the design[1]. At the same time a lot had to be developed on the sound synthesis side, and also the invention and usage of the record player and later the tape machines in electronic music led to the field turning away from real-time music performance.

The Ergonomics of Digital Instruments

For many years, the keyboard and a number of knobs were the standard interface objects for making electronic music. Today there is a wide (if not to say wild) variety of sensors available. Virtually any real-world action can be translated into electrical energy and therefore serve as a control signal for an electronic (analog or digital) sound source.

Although the advent of digital technologies brought us even more ways of synthesizing sounds (and sampling as a convenient way of recording, manipulating and playing back sounds), the distance between controller and that which is controlled became even bigger. The introduction of the MIDI protocol around the mid-eighties detached the control device (the interface or instrument) from the sound source, which widened the gap even further but also introduced new possibilities. It became possible to develop alternative MIDI-controllers, which could be entirely new forms based on humans rather than on the technology. In a way, one could argue that it is only the most obvious thing to do - devise instrument forms especially for this medium. Michel Waisvisz was an early example, inventing his "Hands" around 1983 [Waisvisz, 1985, 1999], and he still emphasises that in fact the piano keyboard should be regarded as the alternative controller for electronic instruments. [Steinglass, 1999].

MIDI controllers also became available in many known instrument forms (like the guitar and several wind instruments) to enable musicians already proficient on these traditional instrument forms to use their skills and playing techniques. Hybrid forms came about as well. In this paper these categories will be described and illustrated with examples of instruments and installations built and / or developed by the author.

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1. This was even before Ergonomics or Human Factors was established as a serious field of research around 1950!

The question of how to deal with the total freedom of being able to design an instrument based on the human (in)capabilities instead of a traditional instrument form, has not been answered yet. A suggested approach is to look at the most sensitive effectors of the human body, such as the hands and the lips, which also have the finest control, and look at the gestures and manipulations that humans use in traditional instruments or in other means of conveying information.

Tactual Feedback

Due to the decoupling of the sound source and control surface, a lot of *feedback* from the process controlled was lost. In electronic musical instruments, the main sense addressed is the auditory through the sounds produced. Visual feedback of more analytic parameters is often displayed on LCD screens. But the touch feedback from the sound source is hardly used, the feel of a key that plays a synthesized tone will always be the same irrespective of the properties of the sound (the device can even be turned off entirely!).

Some work has been carried out (partly borrowing from the research fields of Human-Computer Interaction (HCI) and Virtual Environments) on addressing the sense of touch, to restore the relationship between that which is felt and the sounds produced. This is an important source of information about the sound, and the information is often sensed at the point where the process is being manipulated (at the fingertips or lips). This can be described as articulatory feedback.

Conclusion

This paper consist of two parts. The next chapter outlines a general framework to classify interaction in the electronic arts, and the last chapter describes techniques and technologies (the nuts and bolts) of how to build these interactions. Throughout the paper examples are used of instruments I have built, or projects I was involved in. It is therefore work in progress, I intend to keep updating the paper with knowledge I acquire after this publication.

With the technologies described in this chapter the design of electronic musical instruments and development of interfaces for visual arts can be based on human beings rather then on the technology. This way, we hope to achieve maximum sensitivity along many dimensions (or degrees of freedom), with profound feedback addressing many sensory modalities.

Interaction in Performance Arts

There are many interactions possible between performer, (electronic) system and audience, involving various modes of communication. In this chapter, a concise overview and theoretic framework based on research mainly carried out in the field of HCI (Human-Computer Interaction) is described. The approach described focuses on the physical interaction between people and systems, rather then the interactive behaviour as a result of machine cognition.

Interaction between a human and a system is a two way process: *control* and *feedback*. The interaction takes place through an interface (or instrument) which translates real world actions into signals in the virtual domain of the system. These are usually electric signals, often digital as in the case of a computer. The system is controlled by the user, and the system gives feedback to help the user to articulate the control, or feed-forward to actively guide the user. Feed forward is generated by the system to reveal information about its internal state.

In this chapter the interaction between humans and electronic systems is described in general, and then interaction is grouped and described in three categories: performer - system (e.g. a musician playing an instrument), system - audience (e.g. installation art), and performer - system - audience. The direct interaction between the performer and audience can always be present, but this paper focuses on the interaction mediated by an electronic system. The interaction between multiple performers as in an ensemble or band, even when it is mediated by a system (for instance The Hub or the Sensorband network concerts [Bongers, 1998b]), is not addressed in this paper.

The categories will be illustrated by projects where the author was involved as an instrument builder or interaction researcher.

Human-Machine Interaction

The diagram below illustrates the classic human-machine interaction loop (by personal definition the machine is square and the human is round). The system, or 'machine' in the diagram, is defined very wide. It can consist of several linked elements or devices, as is often the case with computers through networks and protocols like MIDI (the language through which synthesizers, computers etc. can communicate). The 'system' can also refer to a musical instrument.

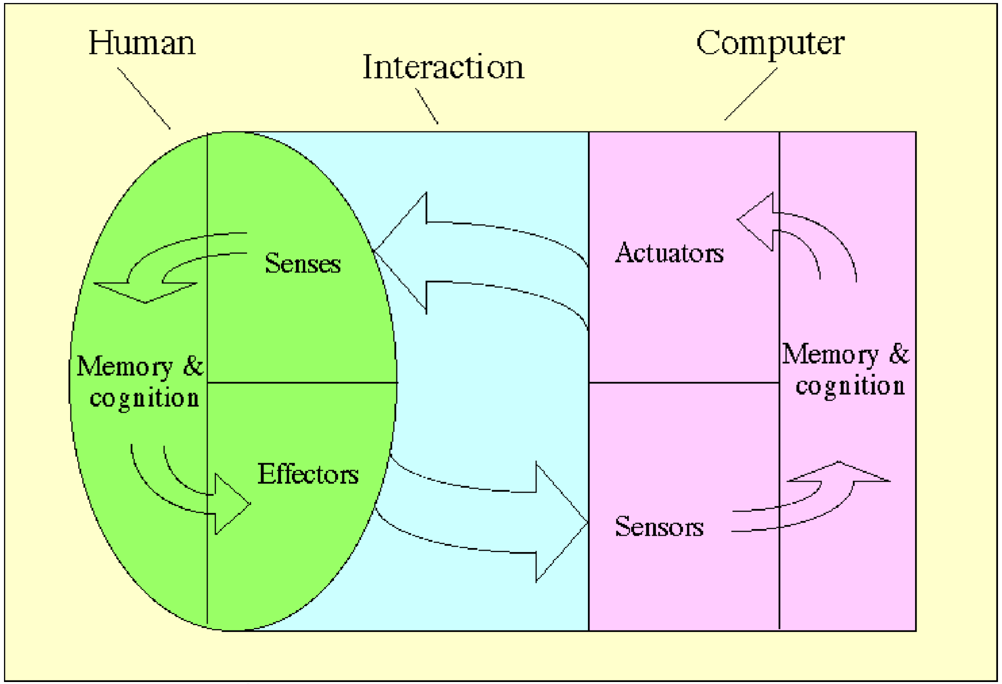

Fig. 1. Human-Machine Interaction.

An interaction-'loop' may start when the user wants to activate the system. The system is controlled by a user through its inputs, it processes the information, and displays a result. For instance, when the user presses a key on a computer keyboard, a character is displayed on the screen. Or, in the case of an electronic musical instrument, a sound is displayed through the loudspeakers after a key is pressed. The human perceives the information from the system, processes it and controls again.

Note that in some cases only parts of the loop can occur, for instance when the cognition is left out on one side or the other this part rather *reacts* than *interacts*. Many interactive systems in new media arts are in fact reactive systems. Ideally, interaction between a human and a system should be mutually influential.

The systems communicates with its environment through *transducers*, devices that transduce (translate) real-world signals into machine-world signals (*sensors*) and vice versa (*actuators*).

Sensors are the sense organs of a machine. Through its sensing inputs, a machine can communicate with its environment and therefore be controlled. A sensor converts any physical energy (from the outside world) into electricity (into the machine world). There are sensors available for all things perceivable by human beings, and more. For instance, kinetic energy (movement), light, sound, but also properties unperceivable for human beings can be sensed such as electromagnetic fields and ultrasonic sound. Sensors are described in the next part of this paper.

Machine output takes place through *actuators*. Actuators are the opposite of sensors, i.e., they convert electrical energy from the machine world into other energy forms for instance those perceivable by human beings. For instance, a loudspeaker converts electricity in changes in air pressure perceivable by the human ear, a video display shows images perceivable by the eye, motors or vibrating piezo elements may address the sense of touch. The interaction usually takes place by means of an interface (instrument). Following the definitions of the diagram, the interface is part of the system or machine and consists of the sensors and actuators.[2]

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[2] This notion is challenged by the SciFi term 'cyborgs' (Cybernetic Organism), where interfaces become part of the human body. This work is carried out in scientific research, as well as in the arts (e.g. the Australian performance artist Stelarc).

Modalities

Several interaction *modalities*, or communication channels, can be distinguished. Modalities are closely related to perception and motor control: the visual input modality for seeing things, the auditory input modality for hearing things, or the manual output modality where the human physically controls things.

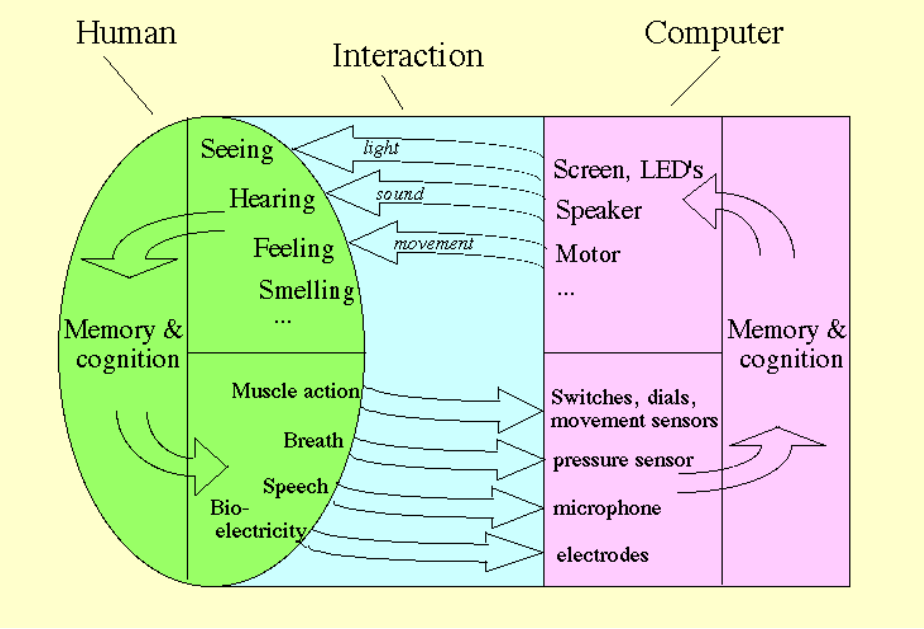


Fig. 2. Examples of modalities.

Other examples of *sensory modalities* are: smell, taste and touch. Within each sensory modality other (sub)modalities can be distinguished, for instance the visual modality can be used for reading text, reading a musical score or watching a movie.

The human sense of touch (tactual perception) differs in an important way from our other senses in that it gathers most information about the outside world mainly by active explorations. In contrast to sound for instance, which is very hard for us to even neglect, we perceive object dimensions and properties often only by reaching out and touching them, and moving around the surface. Understanding the sense of touch is important for the work on physical interaction as described in this paper. The sense of touch actually consists of three main senses, which are often difficult to separate. Tactile perception receives its information through the *cutaneous* sensitivity of the skin, when the human is not moving. *Proprioceptors* (mechanoreceptors that sense forces in the muscles, tendons and joints) are the main input for our kinaesthetic sense, which is the awareness of movement, position and orientation of limbs and parts of the human body. Haptic perception uses information from both the tactile and kinaesthetic senses. The movement sensed by the kinaesthetic or haptic sense can be a result of actions from the human (active touch, which involves the perception of the signals the brain sends to the muscles), or from forces outside the body (passive touch).

Active haptic perception, when actively gathering information about objects outside of the body, is the main sense that can be applied in interfaces.

The tactile, kinaesthetic and haptic perception together, is called *tactual perception* as defined by Loomis & Leederman [1986] building on the seminal work of J.J. Gibson in the fifties.

Human *output modalities* mainly involve the motor system; muscles are used to move things around but are also used for finer tasks such as handwriting and speech. A special case is bio-electricity, such as electromyographic signals (EMG) as measured on the skin which are related to muscle activity, and electroencephalographic signals (EEG) related to brain activity (e.g. alpha waves). These signals can be can be measured by electrodes and used to control a system, a good description can be found in a paper by Tom Zimmerman et al, [1995] and Hugh Lusted and Benjamin Knapp [1996]. Bio-electricity is used for musical performance for instance by Atau Tanaka of Sensorband [Tanaka, 1993], [Bongers, 1998b] [Editors' note: see the article by Tanaka in this volume].

Michel Waisvisz was an early pioneer, using galvanic skin response (the changing electrical resistance of the skin) by sticking his fingers into (analog) electronics directly, resulting in the well-known Crackle boxes [Krefeld, 1990].

Some activities or interactions can be *multimodal*, in fact, most activities in everyday life involve multiple modalities. For instance, eating may involve a combination of *taste* (the four tastes of sweet, bitter, sour or salt), *smell* and *touch* (texture, form, softness).

Virtuality

In addition to the diagram above, it is relevant to emphasise the distinction between *active* and *passive* system feedback. For instance, when pressing a button on an electronic device, one may feel and hear the mechanical 'click' regardless of the state of the device. The device can even be turned off and still the feedback is perceived. This key click can be called passive or inherent feedback, i.e. not generated by the system. In the case of a synthesizer, the sounds produced by the system as a result of the user action are active, i.e. generated by the system (controlled by the performer). Synthesized experiences are also called *virtual*, as opposed to real (mechanical, inherent or passive) experiences [Robinett, 1992]. An electronic system (often a computer) interface generates things that, through its output devices, can be perceived by humans. These are virtual, because they are not really there but can be perceived and experienced. For example, one can listen to sounds generated by a system (synthesized, or sampled and played back). Other examples are computer generated images, or touch.

In order to synthesize a more convincing experience, multiple senses of the human could be addressed. These multimodal interfaces [Schomaker et al., 1995], [Bongers et al, 1998a] enable users to hear, see and feel the virtual world and influence it in many ways including for instance speech.

The importance of the sense of touch in traditional musical instruments, as well as in tools used for other art forms, is well known. Due to the de-coupling of control and feedback in electronic systems, this form of information about the process is often lost. Ultimately, the 'feel' has to be synthesized artificially, just as the sounds and images are synthesized by such a system. This is described in another paper [Bongers, 1998c].

Performer - System

The most common interaction in the electronic arts is the interaction between performer and the system. This can be the musician playing an electronic instrument, a painter drawing with a stylus on an electronic tablet, or an architect operating a CAD (Computer Aided Design) program.

Electronic Musical Instruments

The communication between a musician and the instrument is often intimate and precise. This has been the case with traditional (acoustic) instruments, and developers of electronic instruments often strive for the same level of intimacy and precision.

Electronic versions of traditional instruments

Early examples of the electric guitar, invented by Leo Fender around 1950, are the Fender Telecaster and Stratocaster and the Gibson Les Paul. These instruments offer new possibilities for playing, as pioneered by Jimi Hendrix and Jaco Pastorius (on the electric bass guitar, an instrument invented by Fender), and new playing techniques are still discovered. Another example is the Fender Rhodes, an electric piano. *Electric* instruments use the same sound production as their acoustic counterparts, but are electrically amplified. *Electronic* instruments are based on electronic sounds sources such as oscillators.

Many early attempts to make electronic musical instruments were based on copying traditional instruments forms. Yamaha, Roland and Syntaxxe pioneered with electronic guitars, Akai brought out the EWI (Electronic Wind Instrument, a saxophone) and the EVI (Electronic Valve Instrument, a trumpet). Other examples of the electronic saxophone are the Yamaha WX7 and the Lyricon (which worked with an analog synthesizer). Not to mention the keyboard, which falls in this category as well.

These instruments were to different extents incredibly limited in sensitivity and expressiveness compared to their acoustic (and electric!) counterparts, but this can be seen as a trade-off against the enormous range of different sounds. For a while, people were thrilled by the possibility of being able to play organ sounds on a trumpet, or flute sounds on a keyboard. This is a mixed blessing of course, because the relationship between the controlling device and the sounds produced is distorted, a mismatch which can result in lack of expressiveness.

Alternate controllers

As stated earlier, it is possible to design instruments in entirely new forms. Several gestural controllers were invented, and instruments that (still) have to be touched. The Theremin is the earliest example of an gestural controller, and the Thunder by Don Buchla is an example of an alternate controller that had to be touched through a touch-control surface that reflects the human hand.

People started using electronic gloves, inspired by the success of the VPL Dataglove [Zimmerman et al, 1987] for use in virtual environments (the popular term is Virtual Reality [Rheingold, 1991]). Often the Mattel Powerglove, a cheaper version intended for computer games [Gold, 1992] that came out in 1989, was used for these applications.

An example of a musical glove is the Lady's Glove, built for Laetitia Sonami from Oakland (Calif.) in 1994. She uses a glove fitted with a variety of sensors to enhance control (see the picture below, middle) [Chadabe, 1997, pp.229 - 230]

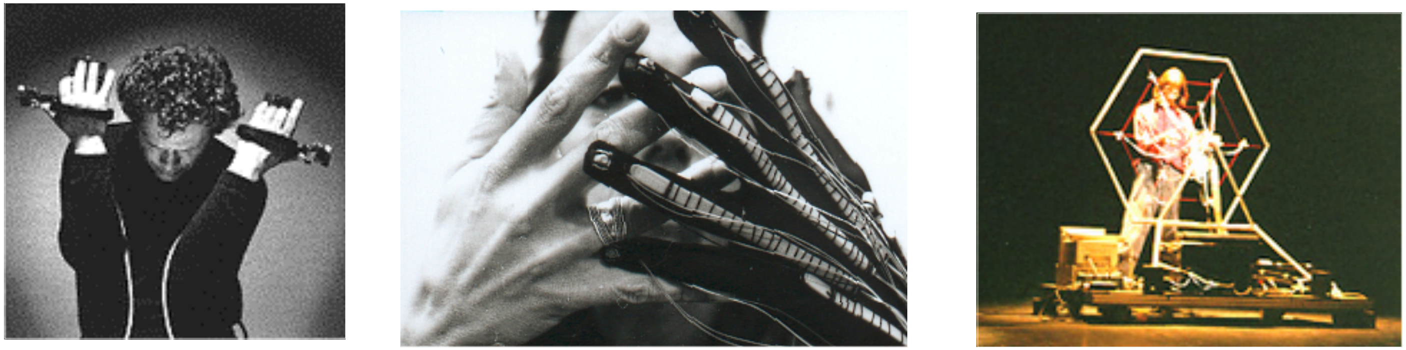


Fig. 3. Alternate controllers.

In the Netherlands, Michel Waisvisz, director of STEIM (Studio for Electro-Instrumental Music) devised instruments like The Hands and The Web (as pictured above) to explore the possibilities of new instrument forms for improved gestural and sensitive control over the sounds produced [Bongers, 1994].

Another example is the English composer and performer Walter Fabeck, who plays his Chromasone, and Sensorband [1999], [Bongers, 1998b], a trio of musicians all playing on novel instruments.

Hybrid instruments

Musicians using traditional instruments have often extended the instruments, for instance preparations of the piano. Electronic extensions are a logical step, also because it enables an instrumentalist to use the proficiency in playing acquired after many years of training.

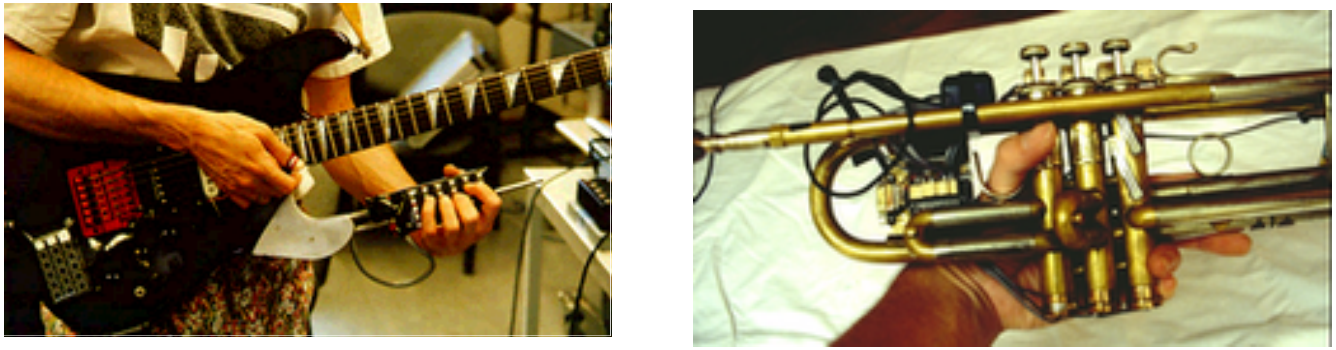


Fig. 4. Hybrid instruments.

The pictures above show some examples, an extended guitar built for the Israelian Sonologist Gil Wasserman in 1995, and the "Meta-trumpet" developed in 1993 for Jonathan Impett [1994a, 1994b, 1996].

Visual Arts

Computers have been used for drawing and editing of pictures and video. This became more common after the introduction of the Graphical User Interface (GUI) and Desktop Publishing (DTP) in the mid eighties, developed first at Xerox PARC with the Star computer and further developed by Apple with the Lisa and the Macintosh. Often the interface consisted of the common elements: virtual objects on the computer screen (icons and buttons) controlled by the mouse and keyboard. However, the two degrees of freedom of movement the mouse offers is severely limiting expression compared to the amount of DOF's the human hand has. A more suitable tool is the graphic tablet, one could say the electronic brush for the painter. Current day versions such as developed by Wacom are quite sensitive, the (wireless) pencil offers five degrees of freedom. It measures position in the 2D plane, pressure at the tip, and the angle (2 DOF) relative to the plane. Software such as Adobe Illustrator and Macromedia Freehand works in consort with this, but still as a physical interface the tablet is not nearly as sensitive as the far more expressive possibilities of the real brush and paint.

System - Audience

In the case of an installation work (or a CD-ROM or Web site-based work), one could say that the artist communicates to the audience *displaced in time*. An extreme example of this is a CD, where the performer instead of playing notes directly to the listener records it first. The audience then listens to it at another time. The artist's actions, intentions and ideas are *built in* the system, therefore the artist is left out of the interaction diagram below.

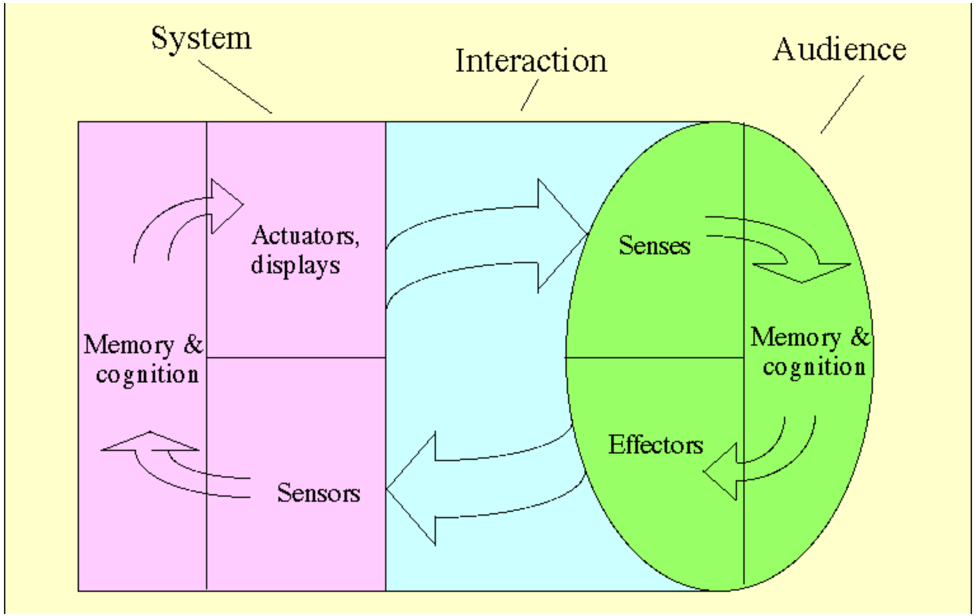


Fig. 5. The interaction between audience and installation.

Interaction between the work and the audience can take place in several ways or modalities. Usually a viewer pushes buttons or controls a mouse to select images on a screen, or the presence of a person in a room may influence parameters of an installation. The level of interactivity should challenge and engage the audience, but in practice ranges from straight-forward reactive to confusingly over-interactive.

The picture below on the left shows a prototype of The Global String, an installation by Atau Tanaka and Kasper Toeplitz which aims to take the interaction quite a bit further away from the computer and the mouse. A virtual string will be set up through the internet between gallery / performance spaces in Paris and in Tokyo. The string in the picture is the (prototype of the) real world part of the installation, and forms the end of the virtual string. This string can be played by performers, coupled to the other end of the string at the other side of the world. [Tanaka, 1999]

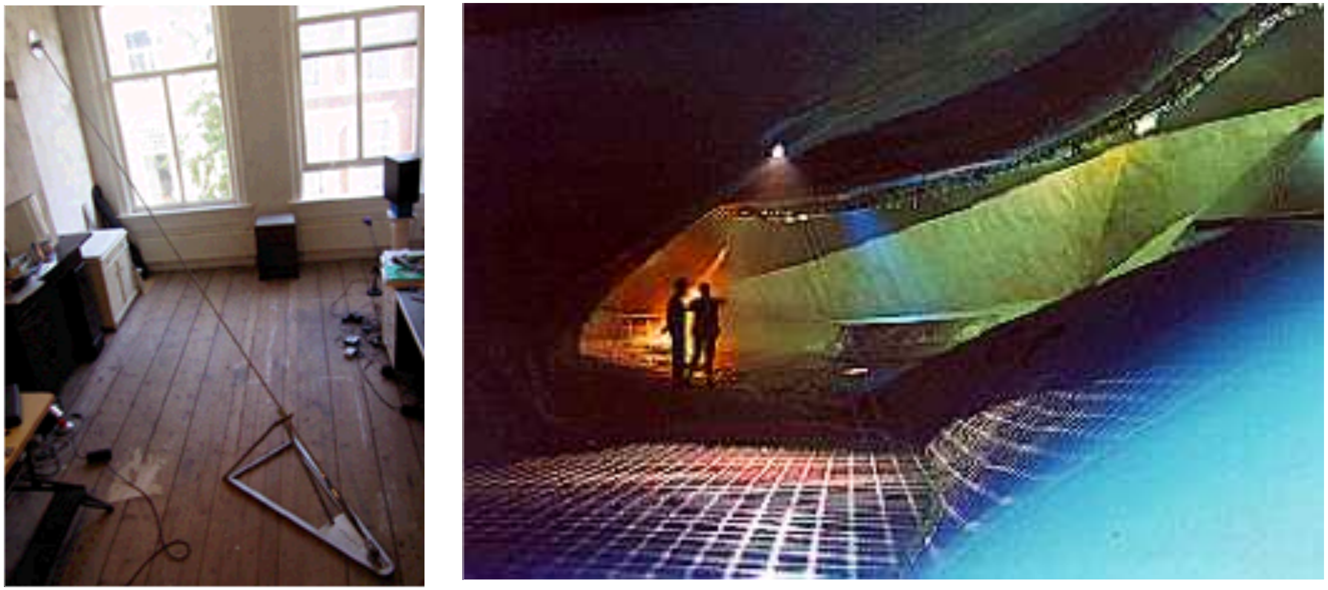


Fig. 6. Two examples of installation work.

The picture on the right shows part of the interior of the Water Pavilion in Zeeland, The Netherlands. This is an interactive building, designed by architects Kas Oosterhuis and Lars Spuybroek (the part shown in the picture). The audience can interact with the architecture by pushing against walls, entering hotspots, pulling ropes and other ways. Sounds will change (also position) and projections (such as the grid visible in the picture) change as if they were directly touched by the audience [Schwartz, 1997].

Another example is the electronic coffee-table book with built-in sensors I made for a research group at the University of Amsterdam. This book plays music continuously (a rather annoyingly melody through a little microchip as used in wishing cards), except when placed on the shelf or read up side down. When turning to page 105, the music stops so that the audience can read a poem (about accessibility) [de Jong, 1991].

Performer - System - Audience

Real interaction is a living two-way process of giving, receiving and giving back. In a traditional performance set up the audience is passive, the performer active. The increasing use of "audience participation" in a traditional concert setting acknowledges the need but does not address the issue in any depth - typically the situation created is one of "reaction" not "interaction". A situation can be created where the audience and performer meet, each influencing the other, as if conversing, while maintaining the quality of the performance at a high level.

In (musical) performance, there can be two active parties: the performer(s) and the audience. The audience can (and often does) participate by (even subtle and non-verbal) communication directly to the performer(s), which may influence the performance. Apart from this direct interaction between the parties, performer and audience can communicate with each other through the system. The system may facilitate new interaction channels, and this is the subject of this paragraph. The two kinds of interaction with an electronic system as distinguished in the previous paragraphs (the interaction between the performer and the system, and the interaction between the audience and the work performed through the system) can take place at the same time through one system. The performer communicates to the audience through the system, and the audience communicates with the performer by interacting with the system.

The diagram in the figure below shows the possible communications, both the interaction through the system as well as direct interaction in the real world (the large arrow below in the diagram).

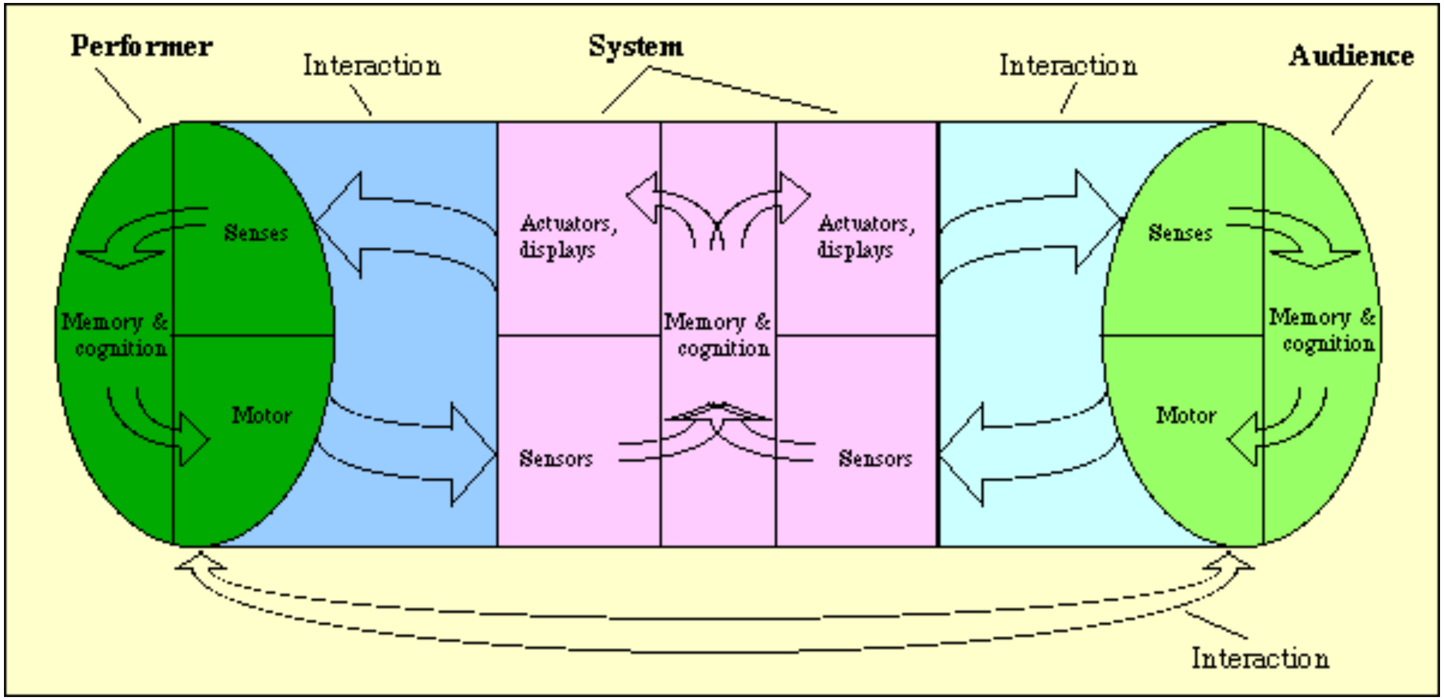


Fig. 7. The interactions between performer, system and audience.

An example of this is The Interactorium (described in more detail in another paper [Bongers, 1999]), a project which will research these issues and aims to be presented at the Nerve festival at the ICA (Institute for Contemporary Art) in London in October 2000. The project described here is undertaken in conjunction with performer, composer, and inventor of the Chromasone instrument Walter Fabeck, and visual artist and composer Yolande Harris from England. The Chromasone is an electronic musical instrument, a gestural controller based on a pair of datagloves and a keyboard-like template. The figure below shows Fabeck and his instrument, which is further described in an article [Young, 1997] and on the web site [Fabeck, 1999]

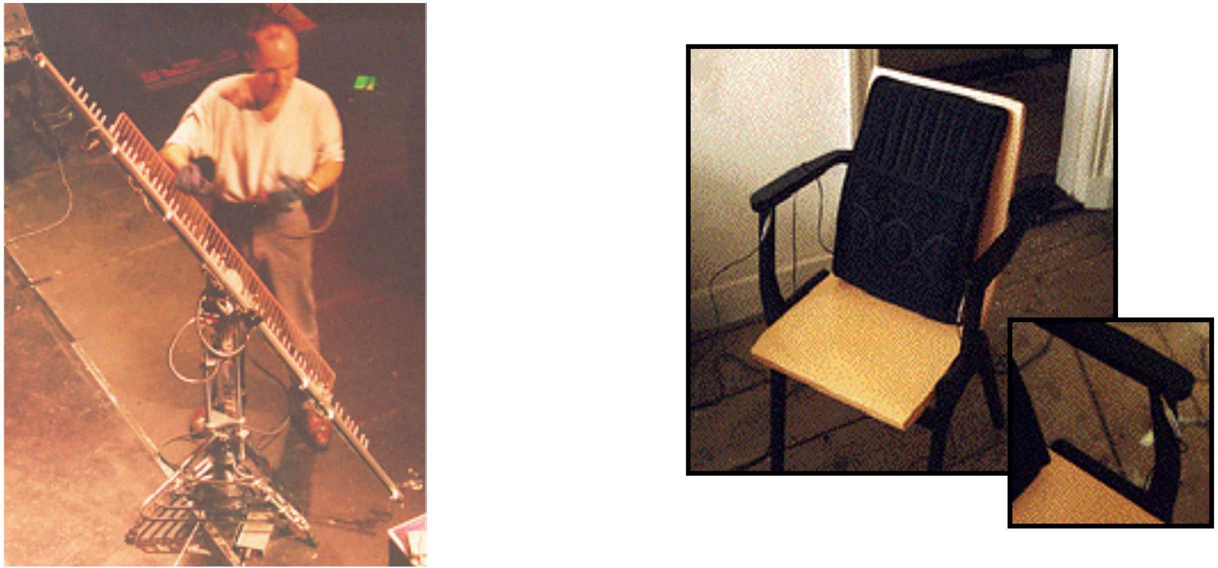


Fig. 8. The Chromasone (left) and the Interaction Chair (right).

The audience will be experiencing not only sound and visuals, but also tactual experiences through active cushions in their chairs. To provide the audience with ways to directly interact with the system, their chairs will also be equipped with sensors. The picture above shows a prototype of the Interaction Chair, with the cushion and a close up of the pressure sensor.

The actions of the audience will be displayed visually by a data-projector, and the images are interpreted by the performer. This way of audience participation, including the translation of the images to musical performance parameters is under exploration in the project.

Conclusion

In this chapter I have described the interaction between performer and instrument, the interaction between an audience and an installation, and mentioned the possibilities of work that combines these two interactions. The use of electronic media offers many possibilities for new ways of interaction, both in regarding modalities as well as activating parties previously playing a passive role. Further studies are needed to investigate how an audience experiences the interaction, as well as experimenting with new technologies.

The next chapter aims to take this theory to practice by describing sensing technologies.

Sensors

Sensors are the sense organs of a machine. Sensors convert physical energy (from the outside world) into electricity (into the machine world). There are sensors available for all known physical quantities, including the ones humans use and often with a greater range. For instance, ultrasound frequencies (typically 40 kHz used for motion tracking) or lightwaves in the ultraviolet frequency range.

Sensors are available to convert energy quantities like:

- kinetic (incl. pressure, torque, inertia);
- light;
- sound;
- temperature;
- smell;
- humidity;
- electricity;
- magnetism;
- electro-magnetism (radio waves).

Rather than summing up all these sensors categorised by the physical energy they measure, as is common in technical literature [Sinclair, 1988], [Horowitz & Hill, 1980] this chapter describe sensors based on the ways humans have to change the state of the world. These so called output modalities (as described earlier) are mainly related to muscle actions, resulting in for instance movement, air flow or sound. In this chapter, sensors are described which can be used to build a device that interfaces between a human and a machine (computer, electronic sound source etc.) illustrated with practical examples of instruments built by the author.

The following categorisation can be used, which takes the human output modalities as a starting point (with musical instruments in mind):

- muscle action (isometric / isotonic);
- blowing;
- voice;
- other: bio-electricity, temperature, blood pressure, heart rate, etc.

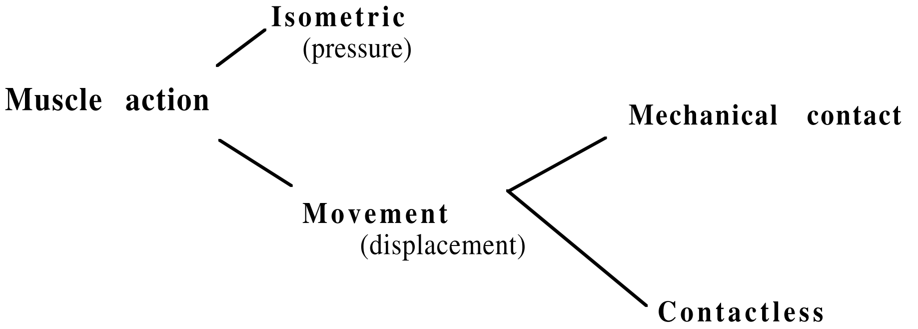
Blowing air and outputting sound by the voice are strictly speaking also the result of muscle action, but there are reasons for describing them separately. The "other" category contains changes in the state of the body, some of which are not under voluntary control but they can be very interesting. At the moment, in this chapter only the first category is described.

Muscle Action

Forces exist in two forms: dynamic and static e.g., movement and pressure (isometric force). This can have several degrees-of-freedom, referring to the position and orientation of an object in three-dimensional space.

Movements can be measured without contact (for instance with a camera) or with a mechanical linkage (with a potmeter for instance). A complex, multiple degree-of-freedom movement (as most movements are!) is often decomposed and limited by mechanical constructions.

In the diagram below a categorisation or *taxonomy* is shown which gives the various kinds of movements their place, from left to right. A movements starts with human *muscle action*, and is then distinguished into *isometric* (no movement, just pressure of pushing against something) or *movement* (when there is displacement). In the latter case, the movement can be sensed through *mechanical contact*, or free moving *contactless* measurement



Degrees of freedom (DOF's) is the term used to describe the position and the orientation of an object in space. There are three degrees of freedom to mark the *position* on the x, y and z axys of the three-dimensional space, and three degrees of freedom which describe the *rotation* along these axes. The terms usually used to describe the rotations, come from the robotics field[3], where *pitch* means rotation around the x-axis, *yaw* rotation around the y-axis and *roll* rotation to the z-axis.

The figure below shows the six degrees of freedom in the three-dimensional space.

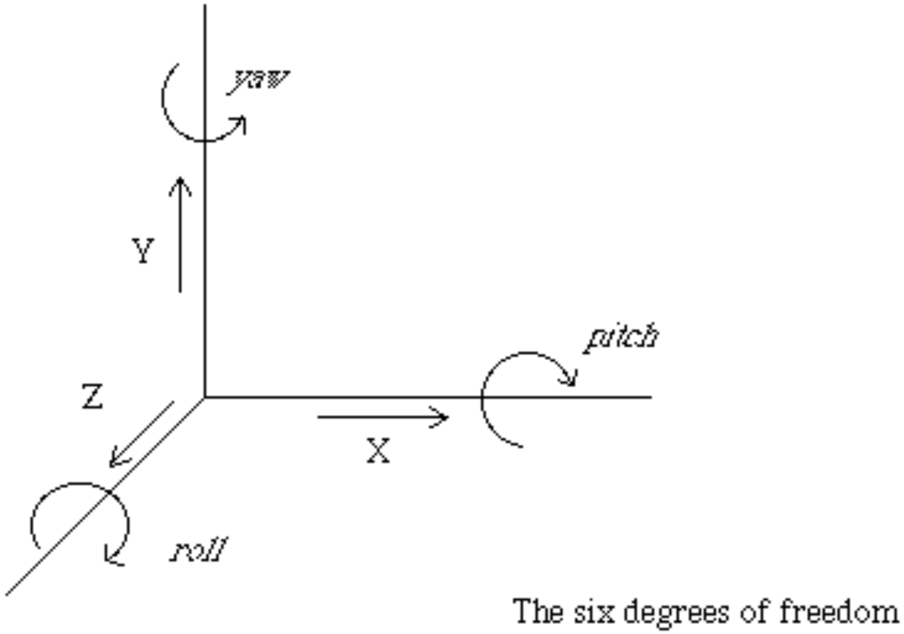


Fig. 9. The six degrees of freedom in the three-dimensional space.

The next sections are organised in such a way that they follow the elements as outlined in the taxonomy, and the movements are further discerned in linear (the DOF's related to position) and rotational (the DOF's related to orientation).

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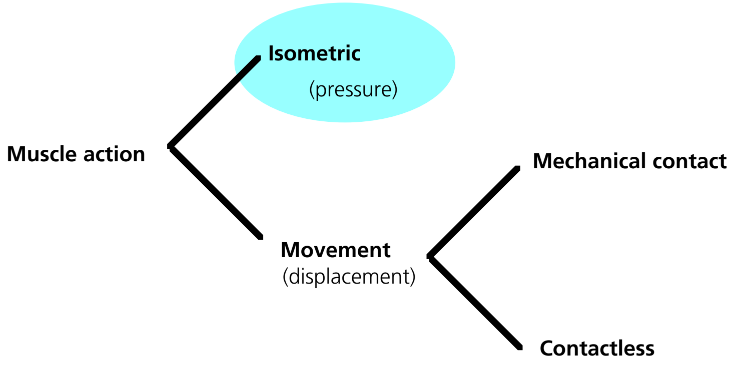
3. The terms are also common in avionics.

Isometric



Pressure sensors

These sensors measure pressure, for instance of a finger pressing on the sensor when there is no movement involved (and therefore called isometric).

A very common pressure sensor is the Interlink sensor, which is based on conductive ink technology. The picture below on the left show some of the shapes available, and on the right hand a small size applied on the Meta-trumpet of Jonathan Impett [Impett, 1994]. They are attached to the front valve, where the left hand index and middle fingers naturally rest.

Fig. 10. Interlink sensors.

The Interlink sensors are available in many shapes and sizes, also available sensing direction (in 1 or 2 dimensions and still including the third -isometric- dimension: pressure in the Z-direction) but these are described under the movement sensors.

These pressure sensors were also used in the 'Step' and 'Touch' sensors for the Water Pavilion as shown below. The pictures show (from left to right) the sensor frame, the inside with the actual sensor outlined, the final look (a yellow blob sticking out of the wall or floor) and the projection overlay which is influenced by pressing the object.

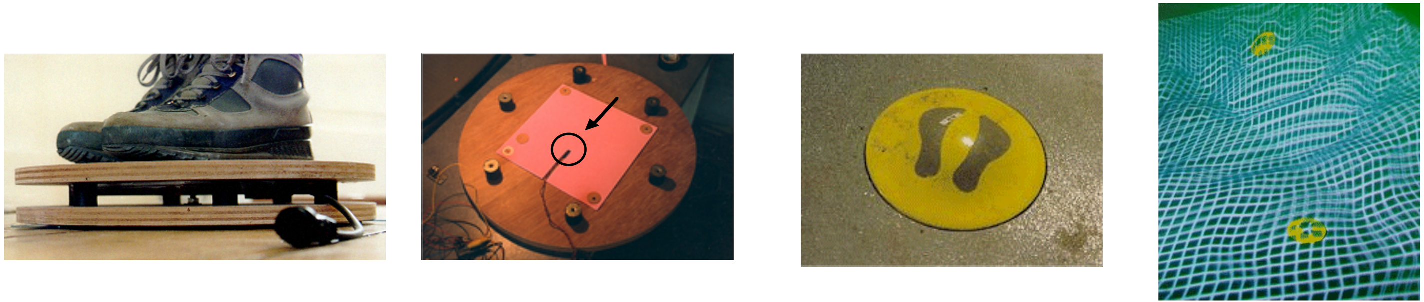


Fig. 11. Sensors for the Water Pavilion.

The electrical resistance of the sensors is infinite when no force is applied. When a force of a few grams is applied (a light touch of the fingertip) the resistance of the sensor starts to drop, from about 1MΩ to about 5kΩ when the full force of 20 kilograms is applied, a good range for hand pressure. For the sensors in the Water Pavilion which measure the full weight of a human body (around 80 kg.) a mechanical linkage was constructed with the rubber blocs (visible in the picture that shows the inside) to divert part of the force.

Another manufacturer of pressure sensors is Tekscan who make the FlexiForce sensors [Malacaria, 1998], as shown below.

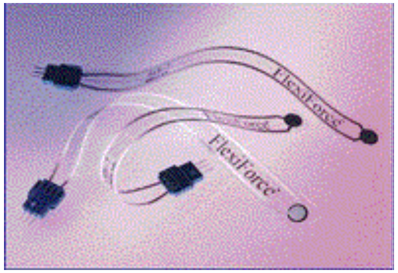


Fig. 12. FlexiForce sensors.

A cheap way of building pressure sensors is to use the black foam that is used to ship IC's in. This foam conducts electricity (to avoid static charges) and the resistance changes when compressed. Copper foil attached to both sides can be used to solder the leads to.

The part that senses aftertouch in a Yamaha DX7 synthesizer is based on this principle. It is a long and very flat strip, placed under the keys. It was often used as a touch sensor in electronic instruments, such as The Hands of Michel Waisvisz [1999] and the MIDI conductor [Bongers, 1994]. On these instruments the sensor was placed under the left hand thumb.

An isometric joystick (such as the little red pimple found on IBM notebook computers, the TrackPoint), measures two rotational degrees of freedom. The Sentograph, as used by Tamas Ungvary and Roel Vertegaal for musical applications, measures finger pressure applied to it in 3 degrees of freedom [Vertegaal and Ungvary, 1995]. It is based on the 2D pressure sensor of Manfred Clynes, which he used for research in human emotions [Ungvary and Vertegaal, 2000].

The SpaceOrb is a game controller with a ball slightly smaller than a tennis ball, which measures isometric pressure applied to it in all six degrees of freedom. It's cheaply available and interfaces directly with the serial port of a PC or Macintosh.

Switches

Following the terminology as described above, little button switches can be seen as pressure sensors too but with two discrete values (on/off) instead of continuous measurement. The picture below, on the left, shows some switches commonly used in instruments.

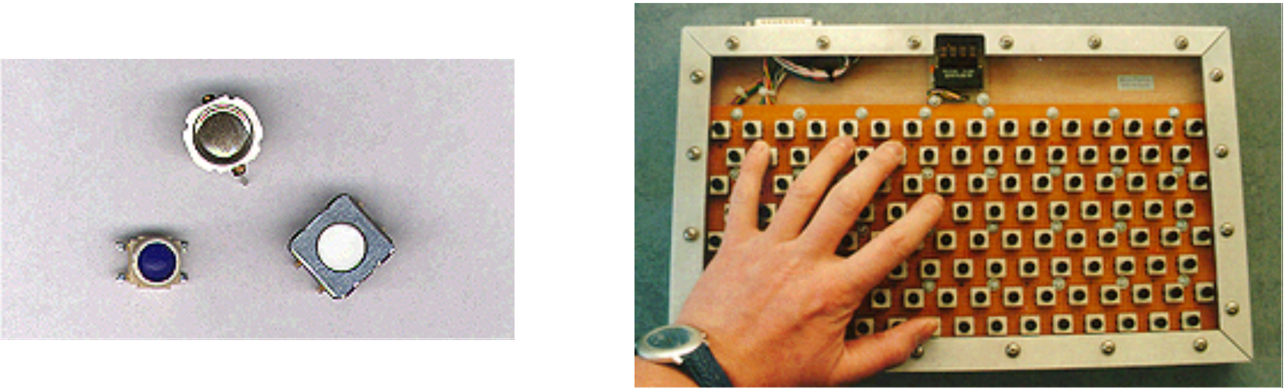


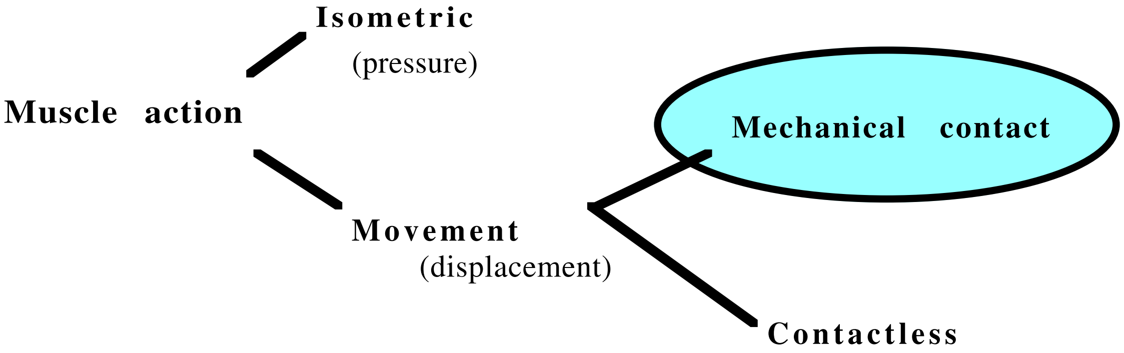
Fig. 13. Switches (left) and Clavette microtonal keyboard (right).

The picture on the right shows an application in the Clavette microtonal keyboard with 122 switches (each mapped to a pitch) built in 1994 at Sonology for Harold Fortuin [1999]

Movement

The acquisition of gestural data from a human performer is done with movement sensors, and as mentioned in the beginning of the chapter this can be categorised by whether there is a mechanical contact or not. Free moving, contactless sensing uses motion tracking sensors or cameras (with software such as STEIM's BigEye), which is not further described in this chapter.

Measuring the displacement through a mechanical contact requires the user to touch the sensing object. Both catagories are described in the next paragraphs, the sensors are again grouped by their degrees of freedom.



Rotation: Rotary pots, rotary encoders and goniometers

The potmeter is probably the most common sensor, this is the element that can be found behind the turning knobs of almost any electronic device. It rotates about 270° (but other angles exist, up to 360°), and changes electrical resistance. They are available in many shapes and sizes, almost any value of resistance. There are two main types: linear and logarithmic, referring to the curve of resistance change. Logarithmic pots are used for volume control in amplifiers, because our ears work logarithmically (ten times as much energy is perceived as two times as loud). Sometimes the logarithmic curve can be useful when measuring movements, to measure precisely the fine movements with the same sensor that measures gross movements less precise but often one may prefer to do this in software for greater flexibility. Potmeters are often applied in pitch bend wheels on commercial synthesizers.

Another type of rotational sensor is the rotary encoder which turns continuously, and outputs a sequence of digital pulses. An example of this can be found in the mouse, in the little wheels that track the movement (rolling) of the ball.

Because this type of sensor actually measures the change in *angle*, they are also called goniometers.

Rotation: Joysticks

A joystick is a device that, through mechanical linkage, divides a movement into two rotational degrees of freedom which are then tracked by individual potmeters. Usually, when held in the hand as in an aeroplane (or game simulation of that) it measures pitch and roll, but measurement of the rotation around the y-axis (yaw) is also possible.

Because the hands are often already in use when playing an instrument or interacting with a system, the movement of the *feet* can be tracked as well. An example is the 3-DOF foot joystick, which measures three rotational degrees of freedom of foot movement. It was originally built at Sonology for Harold Fortuin [1999], and its movement is shown in the movie below.

Fig. 14. Video excerpt. 3-DOF foot joystick.

In the pivot points potmeters are built in which measure the rotation around each axis. The pedals have adjustable stoppers to change the range of the movement, adjustable friction, and can be adjusted for foot size.

Linear movement: Slide pots

The slide potentiometer can be found for instance in mixing desks. Travel ranges from a few millimetres to sixteen centimetres for normal commercial types. Like the rotary pots, the sliders are available as linear and logarithmic types, and various resistance values.

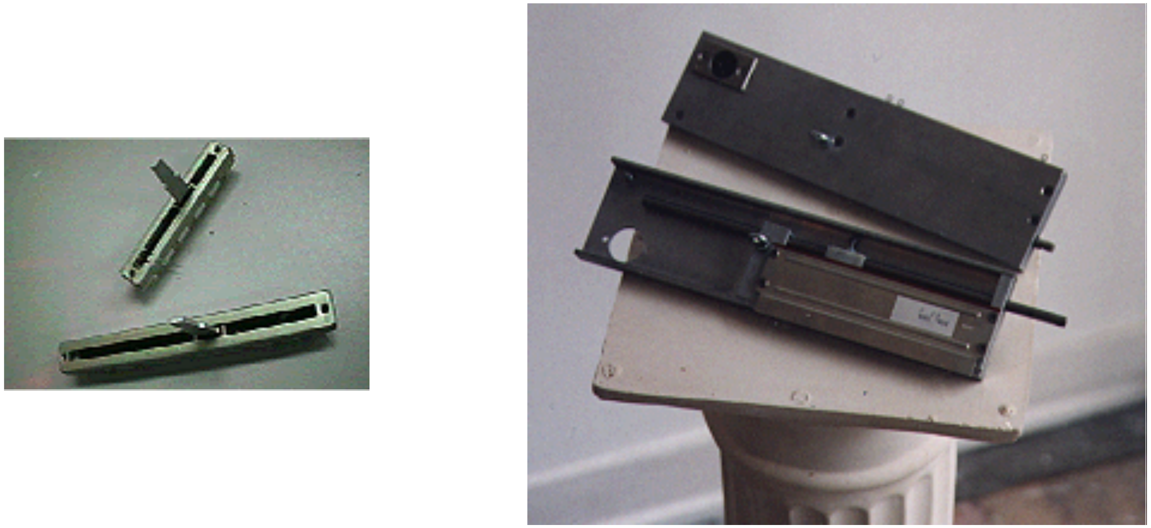


Fig. 15. Slide potmeters (left) and a pulling sensor.

In the picture on the left two small slide potmeters are shown. The picture on the right shows a bigger slider, a professional audio fader applied in a mechanical construction to create a pulling sensor. This one was measuring people bouncing on a big trampoline.

An even bigger version of this sensor was used as tension sensors for the Soundnet [Sensorband, 1999], [Bongers, 1998b].The picture on the right below show a picture of the members of Sensorband 'playing' the Soundnet, the picture on the left shows a detail of the sensor which is about 35 centimetres long and has an adjustable force range from 50 to 200 kilos.

Fig. 16. Soundnet performance and a tension sensor.

A similar sensor was used to measure differences in tension of the *Deep Surface* exhibition of Lars Spuybroek [1999], in a curved projection surface spanning the space. Each of the two sensors was connected to an oscillator and amplifier, all built together in one unit as can be seen in the pictures below (also showing the architectural drawings of the space).

Fig. 17. Pictures from the *Deep Surface* exhibition.

Linear movement: pads and ribbons

These are in fact pressure sensors (see above) which sense direction as well, and therefore described here. Trackpads devices as found in laptop computers (invented as a more cost effective and less space consuming alternative for the trackball) are a common example of this.

Two technologies are used to sense the movement of the finger: capacitive and resistive. The trackpad as found in the Apple PowerBooks is based on capacitive sensing. Under the surface there are two layers of fine electrical conductors, arranged in a grid, which create a surface electrical field. Due to the electrical conductivity of the human body, the fingertip distorts the electrical field at that spot, which is detected by scanning the grid. That's why they don't sense the movement of other objects than human.

The touchpad made by Interlink (the VersaPad or OEM parts, [Interlink, 1999]) operates with resistive (semiconductive) technology, and measures the position of a force applied to the surface. It is also touch sensitive (e.g. in the Z direction, isometric), and responds to other objects.

Linear movement: Drawing tablets

Tablets are flat surfaces, ranging in size roughly from A5 to A3. The user can control the cursor by moving a special stylus across the surface. Several technologies are used, mostly electromagnetic. Either the tablet or the pen operates as a transmitter coil, the signal being picked up by the receiver coil. In the older types, the pen was connected to the system with a wire but modern versions are untethered. Wacom for instance uses transponder technology: the pad transmits a (electromagnetic) pulse, forcing the pen to respond with a signal yielding the pen's position. The keys on the pencil are read in the same way (it changes the characteristics of the coil, which can be detected), as well as the orientation of the pen: holding it upside down activates an eraser mode. It is touch sensitive, and even the angle under which the stylus is held is detected (on two axes). Because of all these degrees of freedom this is a very sensitive tool for drawing artists. A good description of the technology can be found in an article in *Byte* [Ward and Schultz, 1993]

The musical application of tablets is described in a paper by Matt Wright [1997] [Editors' note: see the article by Dudas and Serafin in this volume].

Rotational: Bending

Bend sensors are useful to measure the bending (or abduction) of fingers. This is tracking the rotational movement of the joints of the fingers.

The most used bending sensor is the one in the picture below, also called the flex sensor. It's a flexible strip of plastic with conductive ink technology which changes resistance when bent (from 10 k when flat to 40 k when bent at 90°).

The sensors were originally developed by a company called AGE (Abrams / Gentile Entertainment in New York) for the Mattel PowerGlove [Gold, 1992], and for a long time the easiest way to get these sensors was to get the glove and remove the sensors. They are still a bit difficult to get, but Images Company sells them through the Web [Images Co., 1999] for ten dollars.

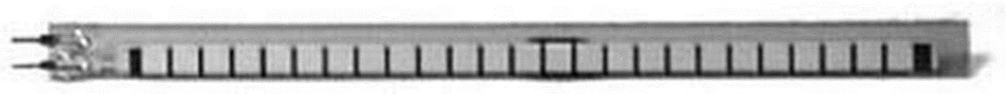


Fig. 18. Bend sensor.

These sensors are used in the Lady's Glove built in 1994 for Laetitia Sonami. The sensors are encapsulated in shrink wrap for protection, as can be seen in the picture below (the left one, with blue shrink wrap). On the wrist a double sensor is used, two sensors are shrink wrapped back to back to measure two directions of bending.

Fig. 19. Lady's Glove (left) and Walter Fabeck’s glove (right).

The glove originally built for Walter Fabeck at Sonology has the sensors sewn straight onto the outside of a glove, in such a way that the sensors can slide when the fingers bend. The gloves used are actually golf gloves (summer play) which appear very suitable for this purpose. The picture above on the right shows the glove with the sensors.

For the Laser Bass instrument for Florentijn Boddendijk at Sonology, this sensor was used to measure the bending of the middle finger, sliding through brass rings.

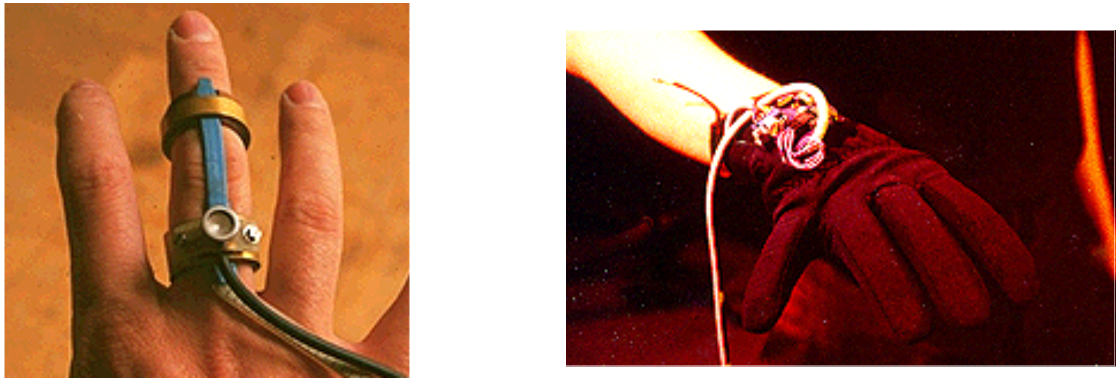
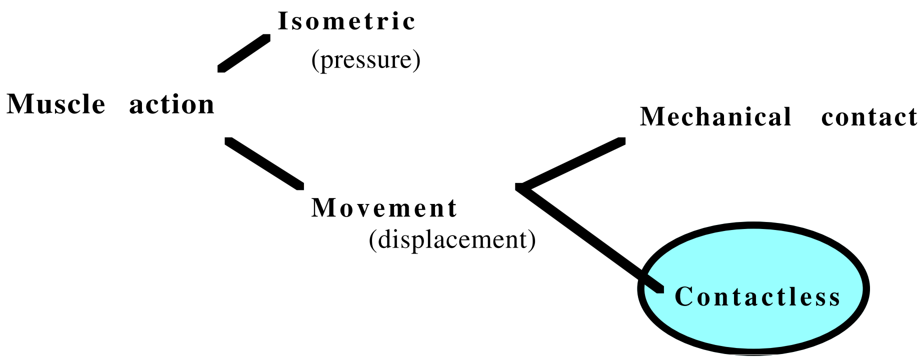


Fig. 20. Bend sensor for the Laser Bass, and glove built for Wart Wamsteker.

Pressure sensors, such as the Interlink sensors described earlier, can also be used as bend sensor because bending the material results in an increase of pressure in the sensitive area. The glove built for Wart Wamsteker at Sonology, to replace his worn out customised PowerGlove after about three years of intense usage, uses long strips of Interlink pressure sensors. In this case, the winter play model of the golf glove was used because the sensors slide conveniently between the outer fabric and thermally insulating inner part. The picture above on the right shows this glove.

Another way of sensing bending is to use optical fibre, which degrades the amount of light that it lets through when the fibre is bent. This can be measured and is then related to the amount of bending. The original Dataglove by VPL [Zimmerman et al, 1987], [Foley 1987] uses this technique, but the disadvantage is that it can be quite expensive. The technique works best with low quality fibre like the plastic ones, or fibres which have specially for this purpose damaged cladding.



Contactless measurement

A popular and cheap method of motion tracking is with ultrasonic sound (above the range of human hearing, i.e. > 20 kHz, typically 40 kHz). The system transmits an ultrasonic sound burst through an ultrasonic transducer (the speaker), usually a pulse train of about 10 square waves, and measures the time elapsed until the burst is received by another ultrasound transducer (the microphone). The delay time is proportional with the distance, this method is therefore known as time-of-flight tracking. The ultrasound system of the Mattel PowerGlove works this way, an L-shaped strip containing the receivers is put around the monitor and with the two transmitters on the glove the system is able to measure position in 3D space and rotation around the z-axis (roll) [Gold, 1992].

The picture below shows some of the ultrasound transducers, most of them are manufactured by Murata.

Fig. 21. Some examples of ultrasound transducers.

This technique is also used in gloves and The Hands, where the distance between the hands is measured by having the transmitter in one hand and the receiver in the other. The STEIM SensorLab [Cost, 1992] has built-in circuitry and software to use this technology on three separate channels, and needs only one (simple) circuit on the receiver side. The Sonology MicroLab [van den Broek, 1999] has one channel of ultrasound distance measurement built in, without the need of additional hardware.

The pictures below show the right hand (rings with the transmitter) and the left hand (with the receiver) of a smaller version of the Hands built at Sonology in 1993 for Stefan Bezoen.

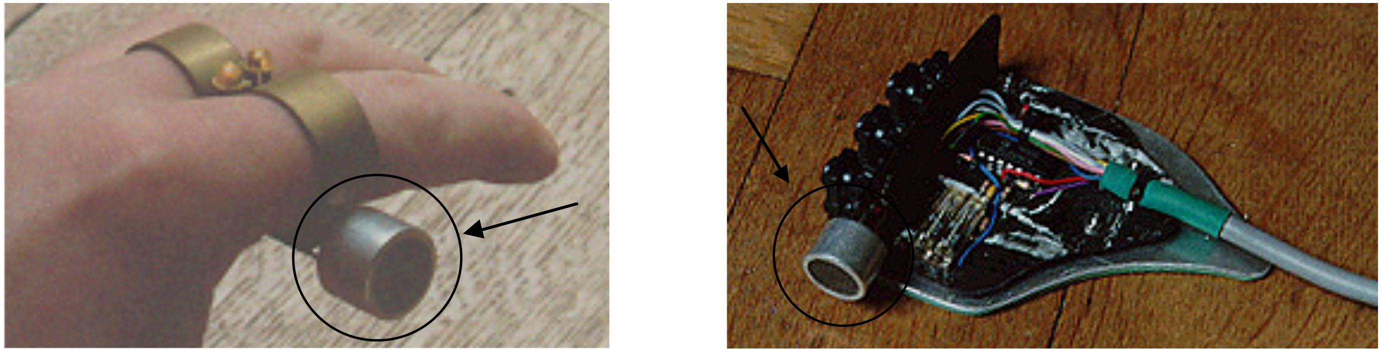


Fig. 22. The left and right hands parts of the MiniHands.

It is also possible to detect *reflection* of the sound, the well known Polaroid cameras operate on this principle. This may be less accurate because it is dependent on the reflective properties of the surface, but the detected object can be passive and therefore doesn't need a wired connection to the system. The polaroid transducer (in fact a speaker and microphone in one) works on an electrostatic principle as opposed to piezo and can operate on different frequencies (typ. 200 kHz).

Another way of achieving a wireless link is by transmitting a trigger pulse (which has to be synchronous) from the system via a radio signal or infrared link. The latter method is used to track movements of dancers in the *DanceWeb* installation [Camurri, 1996]. The transmitter and receiver need a line of sight connection, both the ultrasound and the infrared signals, which can be a disadvantage on the stage.

The Israelian company Pegasus manufactures a very cheap ultrasonic tracking system, called the FreeD system (formerly known as the Owl) [Pegasus, 1999]. The tiny transmitter unit can be worn on the finger and includes also two buttons. It is wireless, the switches emit infrared (RC5-like) signals and the ultrasound speaker is continuously emitting pulses. The pulses are picked up by three receivers in an L-shaped unit that fits on the computer monitor, and by two ASIC chips the signal processing and triangulation calculations are done in order to measure the position in 3D space. The working area is up to 90 cm, and the accuracy is 0,2 mm. It connects to the serial port of a PC, and costs about $80.

All these ultrasound systems remain crude compared to the sonar system of the average bat, however [Suga, 1990]. Bats emit ('shout') both constant frequencies and FM modulated frequencies, and by analysing the echoes in a special developed part of their auditory cortex they can detect position, angle and speed (by Doppler shifts) of objects. Future improvements in machine ultrasound tracking may therefore be expected.

Linear: magnetic field sensors

There are many ways to measure a magnetic field, the most common example is the pick up coil of an electric guitar. For sensing purposes however, the so called Hall effect sensor is the most useful one because it also measures slow changes in magnetic field (down to DC, unlike the coil which can only pick up AC signals). The name Hall-effect refers to the physics process of bending the flow of electrons through a semiconductor, perpendicular to the magnetic field lines. This bending of the flow results in a displacement of electron concentrations and therefore a voltage difference. The effect was named after the physicist Edwin H. Hall. It is related to the Gauss effect, which is the change in resistance due to the electron displacement, there are also sensors available based in this effect (Philips KTY series).

A nice and easy to use little sensor is the Allegro (formerly known as Sprague) UGN-3505 that operates off a 5 volts supply power, and delivers an output voltage range of about 2 volts around the neutral point of 2.5 volts. Depending on the direction of the magnetic field applied the output voltage will raise from 2.5 to 3.5 volts, or go down from 2.5 volts to 1.5 volts.

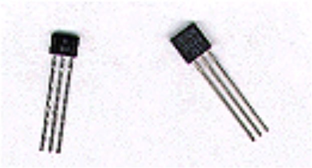


Fig. 23. Magnetic field sensors.

They operate with maximum sensitivity when powered by 6 volts. Sensitivity can be doubled by taking a pair of sensors glued back to back, and then measure the differential voltage between the two outputs. This can be done in software or in hardware.

It is recommended to use neodymium magnets, which are very strong and available in many shapes and sizes. These magnets are also available in an encapsulated version, where a mu-metal shield directs the magnetic field to one surface of the magnet disc only.

Although the sensor is linear, a trait of a magnetic field is that it decays in strength in a logarithmic way. Without a compensation for that, measuring movement will be very precise for the first few millimetres and become less sensitive for further distances (up to 6 centimetres, depending on the magnet used).

This sensing technique using Hall effect is used on the Lady's Glove of Laetitia Sonami. She has four sensors on the tips of the fingers, and a magnet attached to the thumb as shown in the picture below on the left.

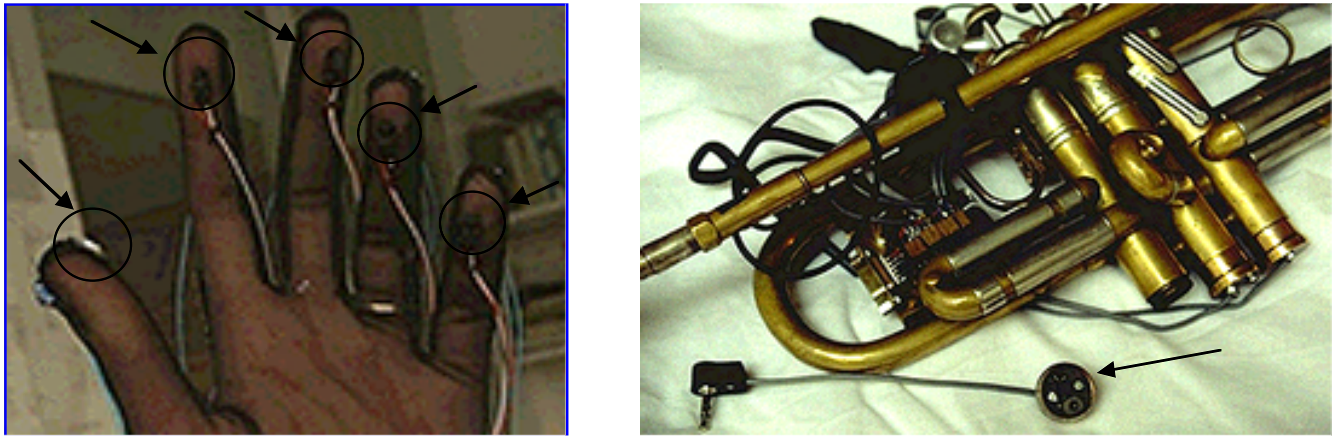


Fig. 24. Lady’s Glove sensors (left) and Jonathan Impett's metatrumpet’s sensors (right).

Another application of this sensing technique can be found in Jonathan Impett's metatrumpet [Impett, 1994] to track the movement of the valves, as can be seen in the picture above. The sensors are fixed in the bottom screws of the valve compartment on a round piece of PCB, and the magnets (encapsulated in mu-metal) are fixed to the moving part of the valve (not visible here).

The picture below shows the 'bridge' of the Global String instrument, the movement of the string is detected by Hall effect sensors mounted on the bridge (highlighted in the picture) through magnets attached to the string.

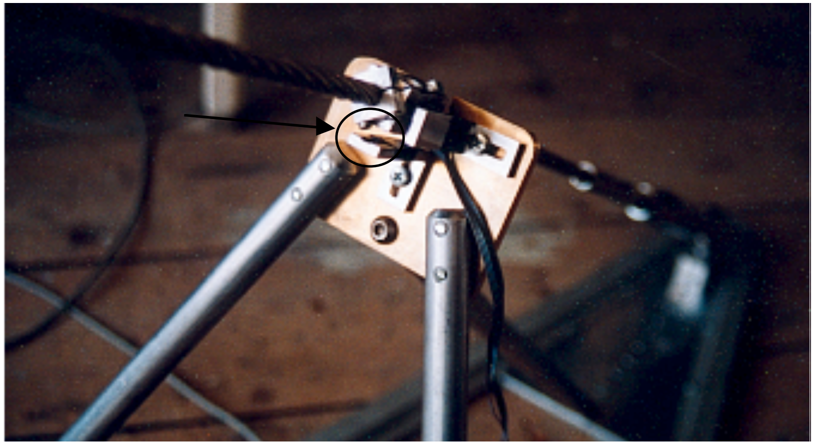


Fig. 25. The 'bridge' of the Global String instrument.

The picture below shows the pulling sensors used in The Web instrument devised by Michel Waisvisz [Krefeld, 1990] and built at Sonology in 1990. The change in string tension results in a movement of the magnet attached to the end of the string, which is sensed by the fixed Hall-effect sensor. Due to the logarithmic signal of the sensor, it was very hard to get a linear reading out of this set up.

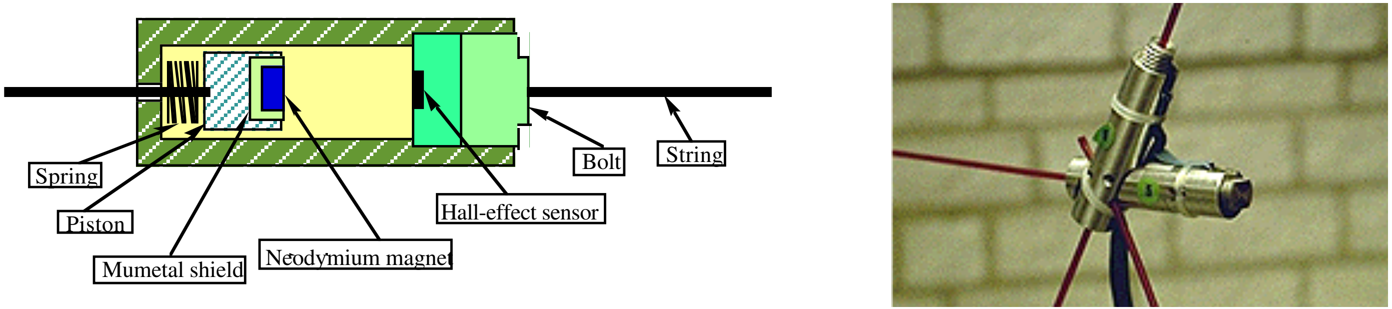


Fig. 26. Pulling sensors used in The Web.

Rotation: mercury tilt switches

Tilt or inclination sensors are very useful for measuring orientation of (parts of) the body. The most commonly used ones are glass mercury switches, and use gravity to move a little blob of mercury. Mercury switches are often designed to work with higher voltages, but some ones have special contacts so they operate well with the 5 volt range. The movie below shows how the mercury closes the contact by the movement of the sensor.

Fig. 27. Video excerpt. Mercury tilt switch.

The ones used in The Hands are made by the German manufacturer Günther. By using four sensors in triangular setting (as a pyramid shape) 10 different inclinations can be measured: one neutral position with all the switches closed, four orientations of roll and pitch, clockwise and anticlockwise rotation, and four intermediate stages, and one more when the hands are turned upside down when all switches are open.

This configuration has been used in the Hands since they were developed at STEIM in the mid-eighties. The picture below shows the latest version (the Hands II) I built in 1991, also visible is that to protect the glass case from breaking (and spilling poisonous mercury) the sensors are built into a soft plastic tube.

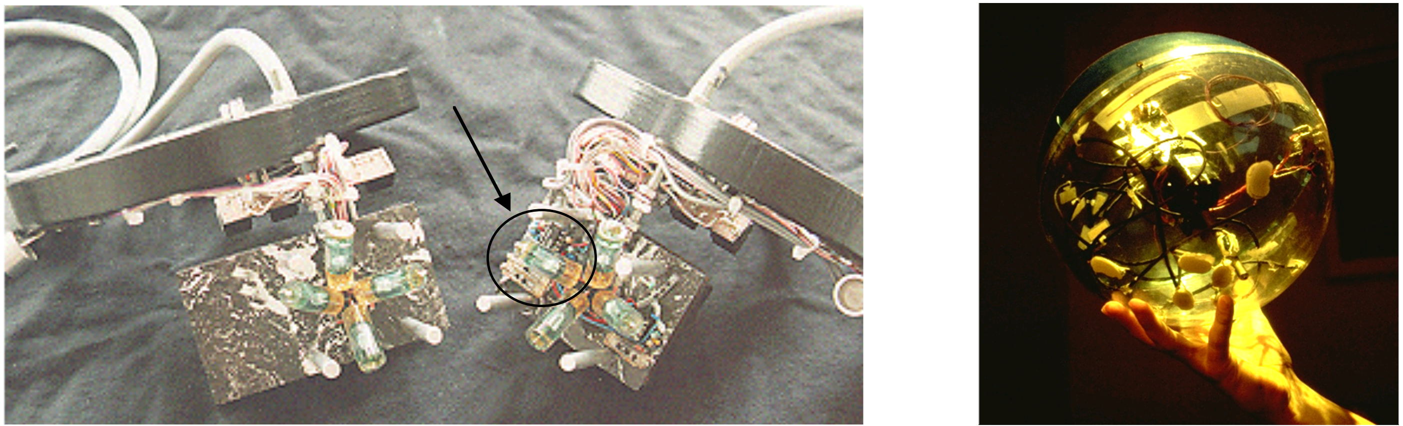


Fig. 28. Mercury tilt switches used in The hands II (left) and in a ball built for Ikaros van Duppen.

The picture above on the right shows another application, a number of these switches were built in a ball for Ikaros van Duppen at Sonology in 1993, to measure rotations of the object.

To avoid the risks involved in using glass switches it is better to use the sensor manufactured by Assemtech (CM13R-0) which is a lot smaller and has a metal case. The Assemtech CW1300-1 is a version without mercury, using a tiny gold plated ball inside which works well too. The picture below (right) shows a pair of these sensors, to detect two angles. It is part of the sensor experimenting kit I developed for the Dartington International Summer School in Devon, England [DISS, 1999].

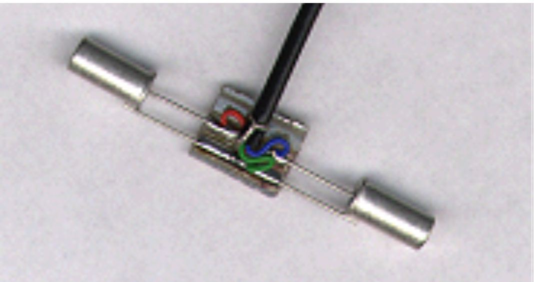


Fig. 29. A pair of tilt switches.

Assemtech makes a variety of sensors like this which can also be used as shock detector, as found in pinball machines (hence the phrase "op tilt slaan" in Dutch) and car alarms.

Inclination sensors also exist in continuous versions (as opposed to the switch action described here), but these are quite expensive and not very suitable for tracking swift movements. They operate with a small amount of special fluid in a cavity, the movement of which results in a change of the electric capacity.

Linear: accelerometers

Accelerometers measure acceleration (and deceleration, often a far richer source of information). Most sensors of this type are quite expensive, due to the high precision required in a common application for position detection (extracted from the direction and amount of acceleration over time measured) for car and avionics navigation systems. Nowadays another common application is shock detection in airbag systems in cars, and cheaper sensors are becoming available. They are little IC's (Integrated Circuits) that have a microscopic sized mass etched out of the silicon, which is suspended in little pieces of silicon that act as piezo-resistive sensors. An acceleration of the chip results in a relative movement of the little mass due to inertia, leading to a little change in voltage on the output.

To develop an accelerometer for musical applications, I used the ICSensors 3031-002 and developed a circuit around it on a tiny PCB with surface mount components (SMD). The most sensitive version available (+/- 2g) was found to be the most useful for musical applications, tracking even very slow waves of body parts. The sensor circuit (shown below, actual size) was developed in 1994 and is used for instance by Laetitia Sonami on the Lady Glove, by Jonathan Impett on his Meta-trumpet and by Joel Ryan for dance applications.

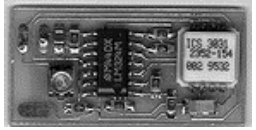


Fig. 30. The accelerometer circuit.

The recently introduced chip by Analog Devices, the ADXL105 series, has all the electronics built in, is still quite cheap and is much easier to use. This sensor is also available for simultaneous measurement of movement on two axes.

A cheap way of building an accelerometer is using the inner part of a panel meter, essentially a moving part (the needle) placed in a coil which moves the needle. This process can be reversed, the movement of the needle (due to inertia) will result in a voltage produced by the coil. This technique was applied in the Air Drums by Palm Tree Productions [Downes, 1987].

Rotational: gyroscopes

The gyroscope effect can be used for orientation sensing as well. Planes use gyroscopes to fly straight, mechanical devices that are very expensive again but these days cheap semiconductor versions appear as well. An example is the Murata ENC05E (or the ENC-05S), a little chip that outputs a voltage swing of a few volts proportional with the angular (rotational) velocity of the device. It operates on the principle of a vibrating triangular element, micromachined in silicon in the same way as the accelerometers, and the (tiny) forces operating on the suspension of the vibrating element when the object is turned (due to inertia) are translated into a voltage.

Linear: Photocells

Photocells are often found in every day life, for instance to detect people being caught between elevator doors. They operate by sending out a beam of light (often infrared) and detecting the obstruction of the light path, or reflection of the light. Operating distances vary from centimetres to tens of meters, and industrial rugged types are available. There are three types commonly available:

- A pair of one transmitter and one receiver
- One unit which is both transmitter and receiver, and detects the light path from a (passive) reflector
- One unit which is both transmitter and receiver, and detects the proximity of an object by the reflection off that object.

In the Water Pavilion interactive building the position of the audience was sensed with the latter type, of industrial water proof quality.

A small and quite useful sensor is the Honeywell HOA1397, containing a light transmitter and receiver and works very well as a (continuous) proximity sensor. It is shown in the picture below.

Fig. 31. A proximity sensor.

Without added electronics however it is also sensitive to changes in environmental light. In an enclosed space this is not a problem, and can then be used as a movement detector. An example of this is an interaction object in the Salt Water Pavilion, sensing rotational movements of a board manipulated by the audience. The board was mounted on a big rubber bloc which enabled it to move with three rotational degrees of freedom. The pictures below show (from left to right) the prototype of the board in the workshop, the final version (orange oval) as part of the sculpture (by Ilona Lénárd) manipulating the projections, the inside of the final version with four of the six HOA1397 sensors indicated (there were two for each degree of freedom to double the working range), and the foam outer walls of the unit.

Fig. 32. The interaction board in the Water Pavilion.

Linear: Photoresistors

Photoresistors are useful for detecting light changes, for instance in installations or movement sensing. The picture below on the left shows such an application, the movement of the leaf was sensed by a photoresistor in the interactive tree project by Dan Livingstone at the Dartington Summer Music School in 1999.

The picture on the right shows the LaserBass instrument, built for Sonologist Florentijn Boddendijk in 1994. It uses a photoresistor (in the circle on the ground) to detect the interception of a laser beam by the hand, played by Florentijn as shown on the picture. The circle on the top highlights the position of the laser diode (and the ultrasound receiver used for measurement of the vertical movement), an industrial diode laser but a laser pointer can be used as well.

Fig. 33. Florentijn Boddendijk playing the LaserBass (left), and a leaf being sensed.

Conclusion

With the work described in this paper, it is hoped that ideas for new instruments, installations and interactions in electronic arts are evoked. With the practical information supplied it is possible to build at least protoytpes to try out ideas, even for people without a background in electrical engineering. Most of the techniques and sensor parts are cheaply available and easy to use.

In the Interactive Electronic Music workshops at the Dartington Summer School in Devon, England participants unanimously agreed that being able to build their own instruments, from soldering to software programming, improved their understanding of the idiom.

As I mentioned in the introduction, this paper is a work in progress and I do intend to keep updating and expanding it. I therefore welcome all suggestions and comments, including severe criticism! The taxonomy or categorisation of sensors as presented in the beginning of the previous chapter is intended as a framework to fill in with knowledge acquired.

Acknowledgements

Most of the musical instruments developed and build at the Institute for Sonology at the Royal Conservatory in the Hague were the result of a team effort. This includes all the students and guests I mentioned throughout this paper who came in with their ideas, and my colleagues at the electronic workshop Jos Diergaarde and Jo Scherpenisse – who has been around in electronic music long enough to develop an ability to *see* electrons. I want to thank Jo also, as well as my successor at Sonology Lex van den Broek, for keeping me updated about recent developments and for their useful comments on earlier drafts of this writing. I (still) regard Paul Berg as my mentor in this field, and thank him again for the help with this paper.

I could never have build the instruments developed at or commissioned by STEIM in Amsterdam without Michel Waisvisz' vision and seminal ideas, the electronic skills of Peter Cost (in the early years) and the software developed by Frank Baldé and Tom Demeyer.

In the countless projects that involved mechanical engineering, a lot of work was done by Theo Borsboom who diverted his attention from (re-)building Harley Davidsons to reading my mind in order to create forms in aluminium and stainless steel from his lathe and milling machine. When the work involved welding, we were often helped by John Pauli, another Harley mechanic.

I want to thank Janwillem Schrofer, Director of the Rijksakademie in Amsterdam, for commissioning a substantial part of the writing of this paper.

The participants of the Dartington Summer School who did the course in interactive electronic music in the last two years served as willing guinea pigs for the soldering and tinkering as suggested in this paper.

The photographs and illustrations in this paper are all made by me, except for the picture of Laetitia Sonami and her glove in chapter 2 (by André Hoekzema), the picture of Michel Waisvisz and his Hands (by Carla van Thijn), and the pictures of the projections in the Water Pavilion (by Lars Spuybroek and Kas Oosterhuis).

I want to thank the editors of this book, Marcelo Wanderley and Marc Battier, for supporting and encouraging me to write this paper.

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