Design of Virtual Three-dimensional Instruments for Sound Control

by

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Abstract

An environment for designing virtual instruments with 3D geometry has been prototyped and applied to real-time sound control and design. It enables a sound artist, musical performer or composer to design an instrument according to preferred or required gestural and musical constraints instead of constraints based only on physical laws as they apply to an instrument with a particular geometry. Sounds can be created, edited or performed in real-time by changing parameters like position, orientation and shape of a virtual 3D input device. The virtual instrument can only be perceived through a visualization and acoustic representation, or sonification, of the control surface. No haptic representation is available.

This environment was implemented using CyberGloves, Polhemus sensors, an SGI Onyx and by extending a real-time, visual programming language called Max/FTS, which was originally designed for sound synthesis. The extension involves software objects that interface the sensors and software objects that compute human movement and virtual object features. Two pilot studies have been performed, involving virtual input devices with the behaviours of a rubber balloon and a rubber sheet for the control of sound spatialization and timbre parameters.

Both manipulation and sonification methods affect the naturalness of the interaction. Informal evaluation showed that a sonification inspired by the physical world appears natural and effective. More research is required for a natural sonification of virtual input device features such as shape, taking into account possible co-articulation of these features. While both hands can be used for manipulation, left-hand-only interaction with a virtual instrument may be a useful replacement for and extension of the standard keyboard modulation wheel. More research is needed to identify and apply manipulation pragmatics and movement features, and to investigate how they are co-articulated, in the mapping of virtual object parameters. While the virtual instruments can be adapted to exploit many manipulation gestures, further work is required to reduce the need for technical expertise to realize adaptations. Better virtual object simulation techniques and faster sensor data acquisition will improve the performance of virtual instruments.

The design environment which has been developed should prove useful as a (musical) instrument prototyping tool and as a tool for researching the optimal adaptation of machines to humans.

Acknowledgments

First of all I want to thank Tom Calvert. His indefatigable support and encouragement concerning the research presented in this dissertation have been crucial for its success and exceptionally generous. If it weren't for Tom, this research might never have happened.

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Sidney Fels, with whom I closely collaborated in Japan, needs special mention. It was his true partnership and passion for the project that made the difference. Way to go Sid ! Let's keep moving this project into the next century.

Among the many people who have helped me with various important, urgent, difficult, interesting or other things during this PhD process I would like to address special thanks to Lyn Bartram, Parveen Bawa, Leslie Bishko, Jean Blackall, Gail Brow, Armin Bruderlin, Frank Campbell, John Dickinson, Tameyuki Etani, Mel Frank, Koujiro Fujii, Dave Goodman, Martin Gotfrit, Evan Graham, Yumiko Honjo, Kana Itoh, Chris Ivens, Sandra Johnson, Rieko Kadobayashi, Laurie Klak, Kaoru Kobayashi, Maria Lantin, Roberto "Gulliver" Lopez, Sang Mah, Frank Manuel, Rob Ballantyne, Ron Marteniuk, Shona McLean, Ted Milner, Kazzushi Nishimoto, Miho Nishimura, Haruo Noma, Yasuyuki Sumi, Yugo Takeuchi, Glen Tibbits, Naoko Tosa, Owen Underhill and Dan Weeks. Thank you all for your help, suggestions and guidance.

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Chapter 1

Introduction

Most people assume that learning to play a musical instrument requires a commitment for many years to develop the motor skills necessary to elicit the desired sounds as well as to develop an intuition and understanding of the musical structures and idiom of the musical style of interest.

The research presented in this dissertation is concerned with identifying ways to turn part of the above assumption around: allowing musical instruments to be adapted to the motor skills a performer already may have, may prefer or may be limited to. This approach to the relation between performer and instrument should lead to a greater freedom for the performer to choose and develop a personal gestural “vocabulary” and, if the performer can already express these gestures skillfully, a shorter time to musical performance proficiency.

The realization of this approach has been hindered by the physical implementation of current musical instruments, whether they are acoustic or electronic. Changes in the layout of keys, valves and sliders of these instruments cannot be brought about easily by a performer. In the case of acoustic instruments, such changes are also limited by the sound generating principles around which the instrument is designed.

Electronic musical instruments enabled the separation of the control surface (e.g. keys, sliders, valves etc.) from the sound generating device (e.g. speakers). This separation lead to the development of a plethora of “alternate controllers” like the Theremin and the Dataglove. The latter “hands-free” controllers do not physically restrict hand motion in any way and hence allow for the implementation of imaginary or virtual control surfaces of almost unlimited size and of any type of shape.

While this opened up the use of formalized gestures used in sign languages as well as less formalized gestures often called gesticulation for the control of sound, such gestures, as they are intended for conveying structured symbolic information, are best applied during musical tasks for the control of musical structures, as can be seen in conducting. Where it concerns the control of sound represented as a multidimensional space of continuous parameters such as in many synthesis models, manipulation gestures applied to a visually represented control surface appear more appropriate because these gestures are intended for controlling multiple continuous variables.

However, the constraints, if any, on the control surface of these “hands-free” controllers do not facilitate a visualization of the control surface in terms of familiar physical object features. Generally speaking, to make virtual control surfaces visualizable it is necessary to maintain a level of continuity from the physical world.

This limitation lead to the notion of a Virtual Musical Instrument (VMI) - a musical instrument without a physical control surface, but instead a virtual control surface that is inspired more or less by the physical world. It is the virtual control surface, not any physical device or sensor that is the focus of attention for any performer. As a VMI is entirely defined by software any changes to the control surface are a matter of programming, which is in many cases much easier and forgiving than changing hardware components.

This dissertation presents a design environment for modifying and creating VMIs that use a sculpting metaphor in its literal sense. Thus, the interaction with these VMIs during performance, in composing or for sound design is called sound sculpting.

Dissertation Outline

Chapter 2, drawing from work in music, engineering and ergonomics identifies in detail (in)compatibility issues between performer and instrument. Chapter 3 subsequently carves out a path to close the gap between the two: what boundary conditions for the system design can be defined based on human behaviour, human perception and engineering experience ? It is in chapter 4 that we get down to the details: how is the design environment actually implemented and what VMI prototypes have been explored. Chapter 5 discusses the results of this design experiment - the conclusion in chapter 6 places a summary of this evaluation in the larger context of the fields drawn from in chapter 2, as well as outlines future work.

This dissertation is available on the world wide web [55]. For more information related to this dissertation and for links to other publications by the author look up
http://www.cs.sfu.ca/~amulder/personal/vmi.

Chapter 2

Performer and Instrument

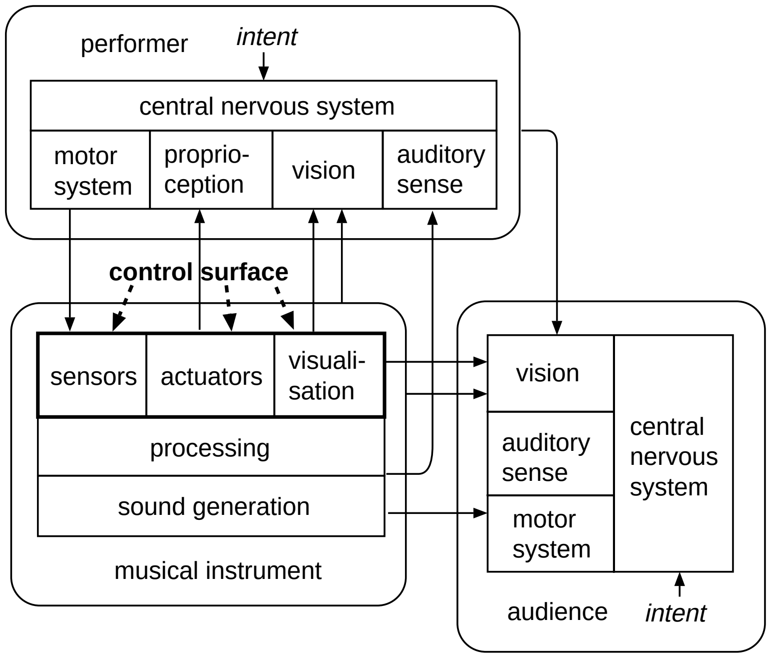


Figure 2.1: A model of musical performance.

2.1 Analysis of Performer and Instrument

Drawing from Pressing [71], a simple model of the interaction during musical performance between performer and instrument that results in audible effects perceived by an audience is given in figure 2.1. Visual and proprioceptive feedback (tactile and force feedback) and communication are included. For the sake of giving humans credit for being so unpredictable, intent is indicated. The fact that musical performance can be represented in different ways must be taken into account when modeling musical performance. Reference to an auditory process as "hearing", for instance, implies a different representation than does reference to the same process as "listening". Similarly with respect to the motor system, the terms "moving" and "gesturing" reflect different representations of the performance process. Two performance forms, conducting and instrumental performance represent the two extremes in terms of abstraction. The performance form of conducting, i.e. the control of musical structures, is often described in terms of symbolically structured gesturing, while instrumental performance, i.e. the control and processing of sounds through the manipulation of physical materials, is often described in terms of simultaneous continuous motions of multiple limbs.

2.1.1 Defining Gesture

The word gesture has been used in place of posture and vice versa. The tendency however, is to see gesture as dynamic and posture as static. The notion of a musical gesture that at the time it occurs involves no actual human movement but merely refers to it is quite common. Obviously, musical expression is intimately connected with human movement, hence the existence of such an idiom. In the following, a hand gesture and hand movement are both defined as the motions of fingers, hands and arms. Hand posture is defined as the position of the hand and fingers at one instant in time. However, hand posture and gesture describe situations where hands are used as a means to communicate to either machine or human. Empty-handed gestures and free-hand gestures are generally used to indicate use of the hands for communication purposes without physical manipulation of an object.

2.1.2 Defining Control Surface

The control surface, when visualized, is a physical or virtual surface that, when (virtual) forces are applied with body parts like the hands, identifies all the human movements the instrument responds to. In more practical terms, it consists of sensors for human movement capture, actuators for tactile as well as force feedback yielding a haptic representation and last but not least a visual representation. The control surface outputs data that represents the movements and gestures. These data are turned into sound variations after processing.

The control surface may change shape, position or orientation as a result of the application of these forces. For example, the control surface can be such that it requires a set of touching movements such as used for piano playing or constrained reaching movements such as used in Theremin performance (see section 2.2.2). Note that, as in the case of the Theremin, the control surface visualization may not be visible either as physical matter or virtually, on a graphical display. Also, as is the case with the Theremin, the visualization of the control surface does not need to be identical to the visual representation of the musical instrument. In the case of conducting, the visual representation of the instrument would be the orchestra or ensemble, which representation is very different from the control surface. In conducting, the control surface is very difficult, perhaps impossible to visualize.

2.1.3 Performer-Instrument Compatibility

Due to the configuration of the control surface, currently available musical instruments require the learning of specific gestures and movements that are not necessarily compatible with the preferences and/or capabilities of the performer. Moore defined compatibility between performer and instrument as "control intimacy": "Control intimacy determines the match between the variety of musically desirable sounds produced and the psycho-physiological capabilities of a practiced performer" [53].

Research to improve this compatibility has resulted in many new musical instrument designs, many of which make use of alternate means of controlling sound production - alternate controllers - to connect forms of bodily expression to the creation of sound and music in innovative ways. There are however two shortcomings common to all traditional and new musical instruments:

- **Inflexibility** - Due to age and/or bodily traumas the physical and/or motor control ability of the performer may change, or his or her gestural vocabulary may change due to personal interests, social influences and cultural trends. Unless the instrument can be adapted (and the technical expertise to do so is available), accommodation of these changes necessitates switching to another instrument. Acquired motor skills may be lost in the transition, while new learning or familiarization will need to take place. The capability of currently available musical instruments to adapt to these types of changes can be greatly expanded [2].

- **Standardization** - Most musical instruments are built for persons with demographically normal limb proportions and functionality. The availability of different sizes of the violin is an exception that confirms the rule. The capability of musical instruments to accommodate persons with limb proportions and/or functionality outside the norm is relatively undeveloped. It is safe to say that many musical instrument designs do not fully exploit the particular or preferred capabilities of the performer, so that persons whose skills are outside the norm need more time to learn to play a given instrument if they are able to play it at all.

It follows that there is a need for musical instruments with gestural interfaces that can adapt by themselves, through "learning" capabilities, or be adapted by the performer, without specific technical expertise, to the gestures and movements of the performer.

2.1.4 Human Factors Context and Gestural Communication Context

Human factors research addresses subjects like ergonomy, human interfacing, human-machine communication, human computer interaction, motor control, etc. Gestural communication research addresses subjects like sign language, non-verbal communication, etc. Human factors researchers have studied the compatibility between performer and instrument as interface "naturalness" [65] leading to "transparency" of the interface. Interface aspects that constitute naturalness are understood to be consistency of the interface (in terms of its method of operation and appearance) and adaptability (either autonomously by the instrument or by the user) of the interface to the user's preferences [84]. For multidimensional control tasks it has been shown that the separability (or integrality) of the dominant perceptual structure of the task, i.e. whether a user will use dimensions separately and sequentially to reach an endpoint in control space, should be reflected by the input device [32]. The research on performer instrument compatibility performed in this context has generally aimed at improving the usability of the interface [93], [94], for which estimation Shackel [81] provides four criteria: user learning, ease-of-use, system flexibility and user attitude. The focus of research performed in this context is on finding a new control surface configuration or control method that reduces the motor and cognitive load applicable to either specific groups or all humans, usually by generalizing from experimental research.

2.1.5 Music and Performing Arts Context

The research performed in the context of music and performing arts has generally viewed compatibility between performer and instrument from the point of view of the listener, focusing first on the sounds to create the artistic image that needed to be projected onto the audience and then on suitable and possible gestural control strategies. Due to the uniqueness of any artistic piece much of the work on alternate controllers resulted in highly unique and idiosyncratic controllers. The notion of "effort" ([48] and later amongst others [79]), deemed by some to arise from a level of performance uncertainty [75], contrasts with the goal of human factors researchers to increase the "ease-of-use". It has been suggested that increasing the "ease-of-use" leads to a loss of expressive power because less effort is required to perform easier, i.e. less refined, motions [95]. As such, from an artist point of view, increasing the "ease-of-use" has no value other than changing the performance boundary defined by the gestural and musical constraints of the instrument. Many artists strongly believe that it is impossible to perform original sound material and to convey a sense of the performer's emotions, without the effort necessary for challenging the performance boundary, regardless of where it may be [40], [33]. However, each performer may have preferences as to the precise definition of the performance boundary, so as to convey a more personal artistic statement. This observation lead to the development of musical instruments adapted to the individual performer, with a performance boundary often uniquely challenging to that performer [105], [110], [46], [108].

2.2 Review of Related Research

Given the different goals of research carried out within the two clusters of fields outlined above, research to improve the compatibility between performer and instrument focused on either or both of the following topics:

- **Gestural Range** - Some research aims to expand the gestural range of existing instruments, to exploit unconventional gestures or movements or unused aspects of conventional gestures, so that the range of adaptation can be expanded, despite the fact that it would still be limited due to physical laws.
- **Adaptability** - Some research aims to find specific methods to make the musical instrument as easily adaptable (performer implements change) or adaptive (instrument

implements change) as possible.

This research has resulted in the development of a wealth of alternate controllers [67], [72], [30], [61], [8], [92], either completely new or extrapolated from traditional musical instruments (e.g. hyperinstruments [46]). To realize larger and larger gestural ranges, alternate controllers have evolved from those requiring contact with some physical surface fixed in space to those without almost any such physical contact requirements. In the latter case the implementation of a suitable haptic representation is very difficult. Unfortunately the integration of various different controllers is often hindered by physical form and size as well as MIDI protocol limitations. The I-Cube System (figure 2.2), a modular, user-configurable sensing environment [103], was inspired by this approach. However, its coverage of the human gestural range is incomplete as yet. Also, users are required to physically assemble a controller matching their needs, which often requires significant engineering skills.

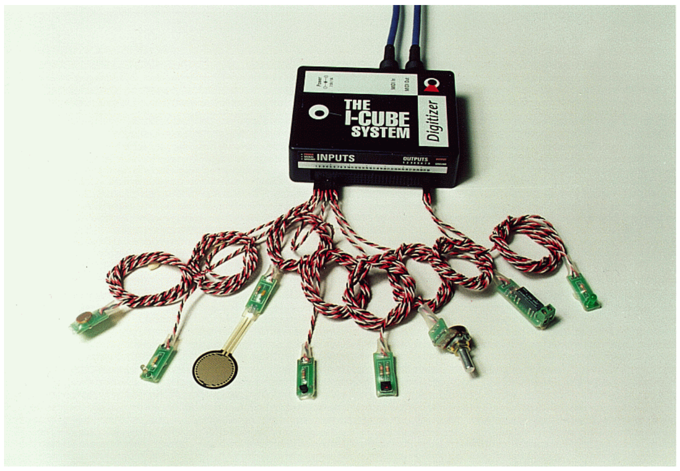


Figure 2.2: The I-Cube System Digitizer and a few sensors. Courtesy Infusion Systems Ltd. [103].

To provide an insight in the range of research carried out, in the following a variety of controllers will be discussed, varying from touch controllers, to expanded range controllers, to immersive controllers which impose few or no restrictions to movement but provide no suitable haptic feedback as yet. Immersive controllers are subdivided in three different types: internal, external and symbolic controllers.

2.2.1 Touch Controllers

Most alternate controllers that expand the gestural range still require the performer to touch a physical control surface, usually fixed in space but sometimes carried around. Although any of these controllers can be adapted to meet the specific gestural needs or preferences of an individual performer, such adaptation is limited by the particular physical construction of the controller. Adaptation beyond these limits requires not only very specific technical knowledge, but is usually also time consuming. An important advantage of touch controllers is their ability to provide a haptic representation.

aXiO

A typical example of an alternative controller requiring physical contact is the aXiO (figure 2.3), an ergonomic physical control surface consisting of knobs, sliders and buttons [16]. Despite the fact that it was developed within a human factors context and could be designated an ergonomic controller, the ergonomic features are only evident given a specific gestural "vocabulary" and posture. Also, any adaptation of this controller would be technically challenging and time consuming.

2.2.2 Expanded Range Controllers

These controllers may require physical contact in only a limited form, or may not require physical contact but have a limited range of effective gestures. Despite their expanded gestural range compared to touch controllers, the performer can always "escape" the control surface and make movements without musical consequence. The haptic representation of these controllers is reduced or even absent due to less physical contact.

The "Hands"

At STEIM in the Netherlands a number of alternate controllers amongst others the "Hands" (figure 2.4) were developed [3]. The "Hands" allow the hands to move almost freely in space - finger motions are restricted to button press motions. Only distance between the hands is sensed ultrasonically. Also, no visualization of the control surface was implemented. Therefore it is a hybrid of a controller like the Theremin (see section 2.2.2) and alternate controllers requiring physical contact like the aXiO.

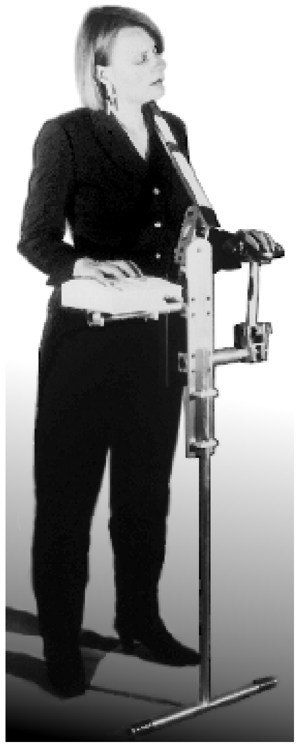


Figure 2.3: The aXiO. Courtesy Brad Cariou [16].

Lightning

Buchla's Lightning^{tm} involves a hand-held unit which tracks hand motion in a two-dimensional vertical plane through infra-red light scanning. The hand motions are subsequently represented as MIDI signals and available for control of sounds [104]. Due to the fact that the hands need to hold the infrared transmitting unit hand shape variations are restricted. It is comparable to the "Hands" in this analysis. Given these limitations, Lee [44] applied neural networks to implement an adaptable mapping of conducting gestures to musical parameters.

Radio Drum

Mathews and Boie's Radio Drum (figure 2.5) [49], involves two drum sticks with coils at the far ends that each emit an electrostatic field with different frequency. Both fields are picked up by four electrodes placed in a horizontal plane beneath the sticks. The 3D position of each stick end can be measured as the detected signals vary correspondingly. Again, hand shape could not be used for performance control, while no visualization was provided of the control surface [80], [33].

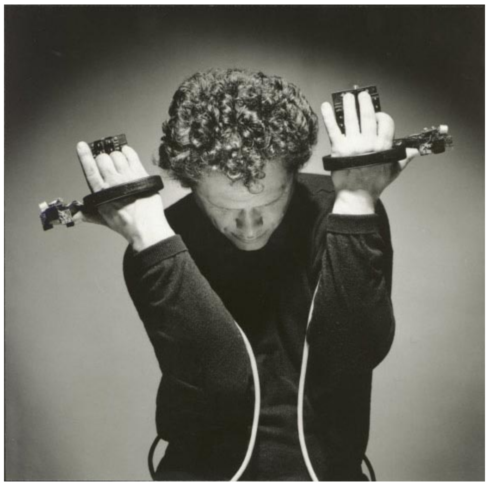


Figure 2.4: The "Hands". Courtesy Michel Waisvisz [111].

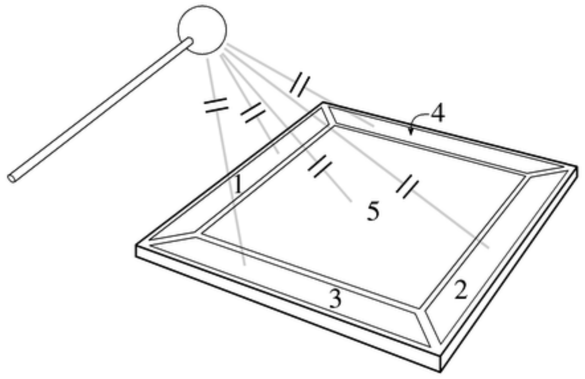
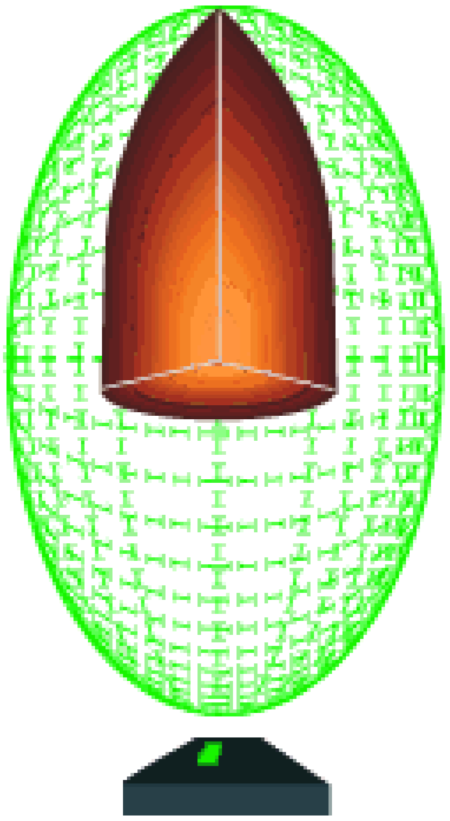


Figure 2.5: The Radio Drum. Courtesy William Putnam and R. Benjamin Knapp. [76].

Theremin and Dimension Beam

The Theremin (figure 2.6a) is a well-known alternate controller [19], [50]. The Theremin uses two antennas to detect human body mass within a certain range of proximity, which results in the production of only two control signals traditionally used for pitch and volume. Gestures are effective only within the range of the sensing field, while the control surface does not exploit the full dexterity of the hands, because the gestural expression is reduced to only two variables. The electric field technology used for the Theremin has been used in various other controller designs [68], [96], including a method to extract a more detailed hand geometry [86]. Using infrared tracking within an egg-like sensing field yielding one dimension of control, the Dimension Beam^{tm} (figure 2.6b) [102] has similar limitations as the Theremin.

(a) A Theremin - the right antenna controls pitch, the left antenna controls volume. Courtesy Jason B. Barile [109].

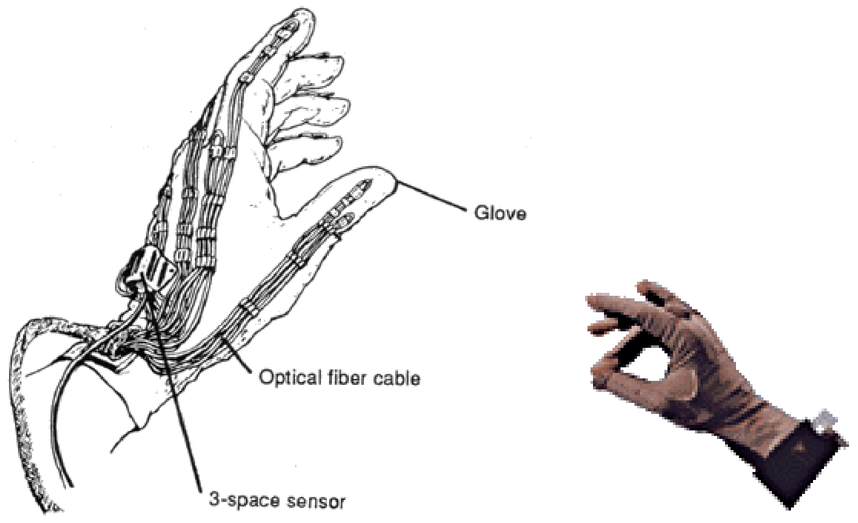


(b) The sensing field of the Dimension Beam^{tm}. Courtesy Interactive Light Inc. [102].

Figure 2.6: The Theremin and the Dimension Beam^{tm}.

2.2.3 Immersive Controllers

The alternate controllers with few or no restrictions to the movements are best suitable for adaptation to the specific gestural capabilities and needs of a performer. They often rely on the use of a Dataglove (figure 2.7) or Datasuit to track (nearly) all human movements of interest so that the feeling of immersion is created - the performer is at all times in the sensing field [60]. For immersive controllers, touch feedback and/or force feedback can only be provided in very limited form, if at all, with current technology [29], [6], [82], [83]. These types of feedback are generally deemed necessary to achieve a reasonable timing accuracy as well as a higher level of refinement in the motions. The bandwidth of such feedback enables control of timing within a few milliseconds, matching perceptual capabilities for detecting timing differences [17].



(a) Drawing of the Dataglove, as originally made by VPL. Courtesy IEEE [54].

(b) The CyberGlove^{tm}. Courtesy Virtual Technologies [101].

Figure 2.7: Examples of Datagloves.

Immersive controllers can be loosely grouped as follows:

- **Internal Controllers** - Controllers with a control surface the visualization of which is the physical shape of the human body itself. Limb features like joint angles are mapped in a one-to-one fashion to sound or music parameters.

- **External Controllers** - Controllers with a control surface the visualization of which is so different from the physical shape of the human body that it can be visualized by the performer as separate from his or her own body, although the visualization may be impossible to implement as a physical shape. Limb features may be complex (e.g. derived features like distance between two finger tips) and/or these features are mapped in a complex (e.g. non-linear or many-to-one) way to sound and/or music parameters.

- **Symbolic Controllers** - Controllers with a control surface that is, due to its complexity, (almost) impossible to visualize or can only partially be visualized and which requires formalized gesture sets like sign language and forms of gesticulation such as used in conducting to operate. Gestural patterns are mapped to structural aspects of the music.

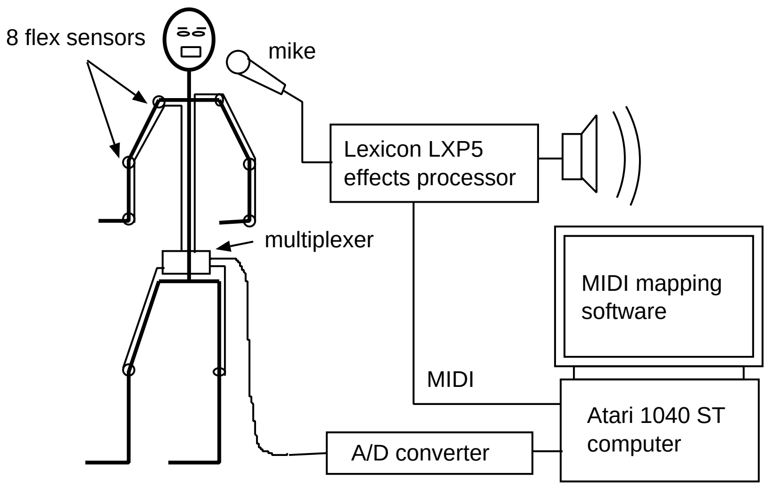


Figure 2.8: Functional diagram of the bodysuit system.

Internal Controllers

The following describes a preliminary design experiment for the work described in this dissertation. To experiment with controlling sound effects through whole body movements, a tightly fitting garment intended for use by dancers was made [58]. The bodysuit incorporated eight sensors to capture wrist flexion, elbow flexion, shoulder flexion and knee flexion which were mapped to MIDI messages controlling a sound effects device processing the voice of the performer (figure 2.8). This controller did not impose any restrictions on the gestural range, but did not capture all aspects of the movements either, so that effective gestures were somewhat limited. Nevertheless, immersion was achieved in the sense that the performer felt most movements had an effect. The control surface was the performer's body, each joint controlling a synthesis parameter like a slider on a synthesis control panel. This mapping appeared to be very difficult to learn. First of all, human movements often involve the simultaneous movement of multiple limbs. So, when the intent was to change one or more specific parameter(s), often other synthesis parameters were co-articulated, i.e. also changed unintentionally. Perhaps more importantly, the mapping did not encourage use of any familiar movements like manipulation gestures or simple symbolic gestures or signs. Instead, the performer was required to learn to move single joints only. An easier way to deploy this control surface would seem to be to have another performer move the bodysuit wearer's body through manipulation gestures.

The Biomuse [38] implements a relation between muscle tension and musical sound by capturing myo-electric voltages off the human skin with EMG electrodes. The dimensionality of the control surface is dependent on the number of EMG electrodes used. When sufficient electrodes are used this approach results in an immersive controller. The controller requires the performer to focus attention on the tension in the sensed muscles [90], unless a control surface would be designed that can be visualized with a different shape than the performer's body. Otherwise, as with the musical bodysuit, the control surface is (a part of) the performer's body and the control surface would seem to be easier to learn if another performer would move the Biomuse wearer's body (the Biomuse wearer will have to resist movement to create muscle tension).

External Controllers

Hartono et al [27] mapped movement parameters captured by a Dataglove to a multi dimensional sound parameter space using neural networks. An adaptation was implemented using active learning capabilities of the neural networks. This method alleviated the common problem of requiring the user to provide the entire gesture - sound data set each time a part of the mapping is changed or expanded. Although the instrument could be adapted almost entirely to the needs of the performer, no control surfaces were implemented requiring that a performer had to start from scratch designing a control surface. No visualizations of control surfaces were provided, so that gestures were limited to simple manipulation gestures or spatial trajectories.

Fels [21], in his implementation of a gesture to speech system (figure 2.9) used neural network technology and a variety of movement tracking technologies, including a Dataglove.

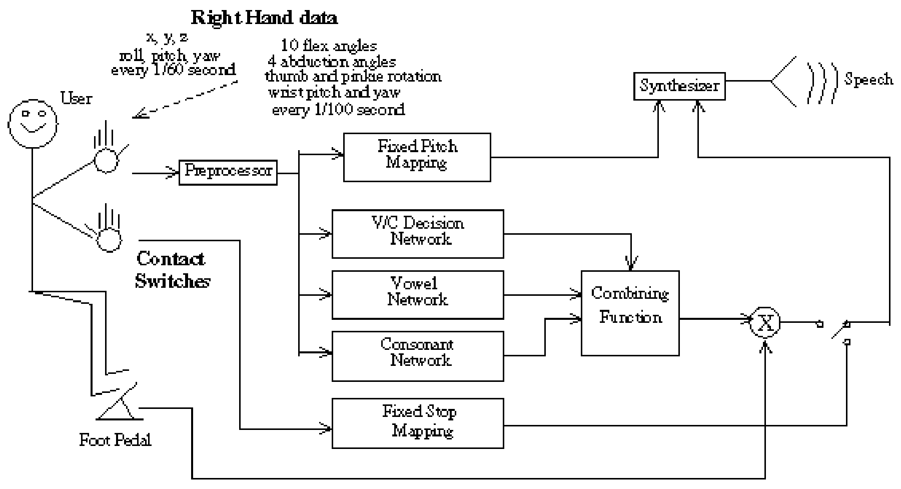


Figure 2.9: Functional diagram of the GloveTalk II system. Courtesy Sidney Fels [21].

The neural networks were used to enable the implementation of a specific, non-linear mapping that enabled the production of speech through hand gestures. The mapping could be learned to an acceptable level in about 100 hours, perhaps because the control surface enabled the use of familiar manipulation-like gestures and simple spatial trajectories, yet was not easily visualized. A graphical display of the sound generating mechanisms of speech would most likely confure rather than facilitate control because the gestures such a visualization provides do not correspond with the gestures defined by the control surface. However, a graphically displayed visualization of the control surface, clearly indicating how to gesture, might have shortened the learning time.

Symbolic Controllers

The following describes another preliminary design experiment for the work described in this dissertation. To experiment with symbolic controllers a Dataglove was used to implement a drum set that could be operated by performing one of a predefined set of hand signs while making a sudden motion with the wrist [58]. Figure 2.10 shows the functional diagram of the application. Hand sign recognition was implemented by processing 10 values representing the hand shape with a backpropagation neural network with one hidden layer of 15 nodes and three outputs which allowed encoding of 7 different MIDI note-on pitch values. Each

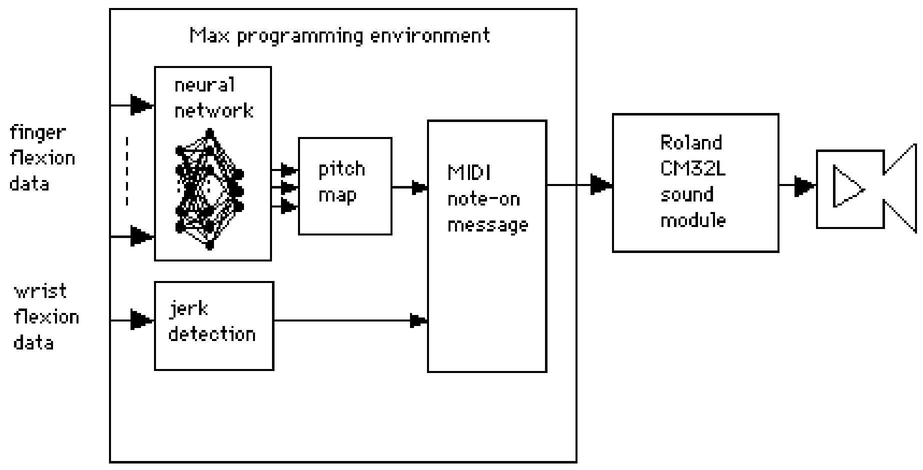


Figure 2.10: Functional diagram of the sign-drum.

note-on pitch value represented a percussive sound. Sounds could be assigned to gestures according to the user's preferences, but, as no active learning was implemented, the entire set had to be specified each time a change was made to the set, which was time consuming. The use of hand signs did not help to visualize a control surface for the various sounds. It would seem that the use of a set of manipulation gestures used for a specific familiar shape would have been a better choice - the variation in the set would have to correspond to the variation of the sounds.

The Miburi (figure 2.11) [107] is a musical instrument that translates specific body postures and gestures (measured with flex sensors attached to the body) and key presses (through buttons attached to the hands) to triggers for musical sounds. The performer is required to learn the specific postures and gestures, i.e. adaptability is limited to the set of postures and gestures.

A virtual orchestra was implemented by Morita et al [54]. The system controlled an electronic orchestra with a complex performance database through common conducting gestures captured with a CCD camera and a Dataglove. Adaptation was possible though required significant technical expertise. It is one of the more complete controllers involving formalized gestures. Its success is based on the use of an existing gesture set for an existing performance paradigm, i.e. conducting.

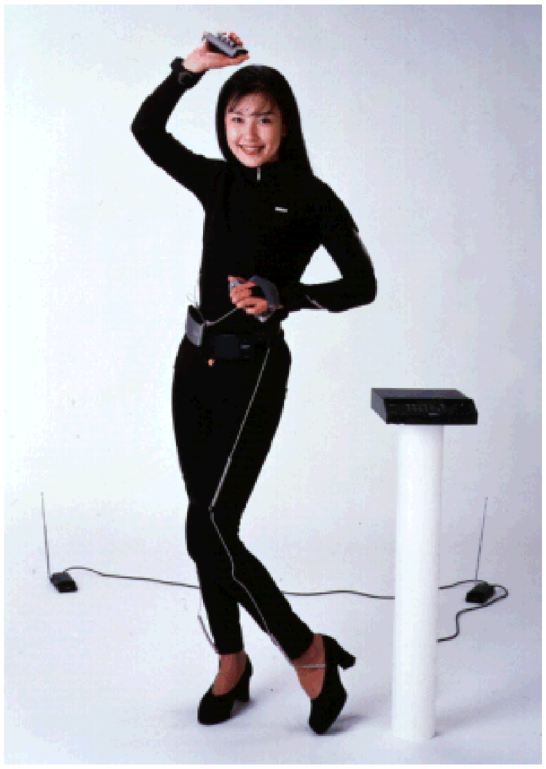


Figure 2.11: The Yamaha Miburi^{tm}. Courtesy Yamaha Corp. [107].

2.3 Design of Gestural Constraints for Musicians

2.3.1 Current Methods

Physical and Sensing Limitations

As stated above adaptation of touch controllers, requiring contact with a physical control surface that is fixed in space, to an individual performer's range of gestures is currently limited by the physical implementation of the musical instrument. Any adaptation beyond these limits requires specialized technical expertise and is generally time consuming. The idea of creating from scratch a gestural interface for a musical instrument based on the specific gestural and movement capabilities and needs of the performer seems rather far-fetched due to these limitations and is only available to those performers with substantial technical expertise or those affiliated with research institutes. Some controllers were designed with fewer constraints resulting from physical contact and an expanded gestural capturing range, but still limited or hindered hand movements considerably.

Visualization of the Control Surface

Although with current technology a suitable haptic representation is very difficult to implement for immersive controllers, they are capable of capturing the entire gestural range with sufficient accuracy and resolution. Immersive controllers were subsequently used for musical control tasks. However, in the case of internal controllers confusion arises as the object acted upon is also the acting object. In the case of external controllers thus far the visualization of the control surface has been (too) complex or the visualization was unavailable, making the use of manipulation gestures more difficult to learn and possibly limiting the use of such gestures. While a skilled musician does not need to rely on a graphically displayed control surface visualization, almost all musicians have learned to manipulate the control surface of their instrument by studying the visual and haptic representation of the control surface and its behaviour [85]. Hence it can be argued that, if manipulation gestures are to be used, it should always be possible to visualize and/or imagine the haptic "feel" of a control surface. If gestures other than manipulation are to be used a visualization might not be necessary and symbolic controllers may be applicable. While the extraction of symbolically structured information from formalized gestures like signing is still non-trivial [59], symbolic controllers are thus far most successful in terms of deploying the maximum gestural range while being maximally adaptable. But these controllers are not well-suited for the simultaneous control of multi-dimensional continuous parameter spaces such as used for the description of sound, because signing involves mainly selection and structuring of discrete and discontinuous events represented as symbols [51].

Real World Continuity

If the need is to simultaneously control multiple continuous sound parameters, manipulation gestures may be better suited than gestures for communication of symbol structures. But the immersive controllers implemented thus far do not facilitate the use of manipulation gestures. These gestures are much easier executed with respect to a visualization and haptic representation of the control surface that is reminiscent of physical objects. What is needed is the ability to create and adapt multidimensional control surfaces that are readily visualizable and responsive to manipulation gestures. In other words, what is needed is the ability to create and adapt multidimensional control surfaces that are not too different from most shapes we handle in day-to-day life.

2.3.2 Virtual Musical Instruments

The afore going reasoning leads to the following possible solution. The limitations imposed by physics can be overcome by using sensor technology that tracks the entire hands such as that used for immersive controllers and virtual environments. Then, in a virtual environment musical instruments can be created that exist only as software. With good user interfaces, it will be much easier for performers to program this software and design their own controller than when faced with the requirement to assemble a controller from (modular) hardware controller parts. All aspects of such a controller will be programmable and no constraints will be imposed by acoustic or other physics principles and the performer will not be required to hold physical components, so it will be maximally adaptable to the needs and capabilities of an individual performer.

But in order to allow for the effective use of manipulation gestures and similar movements, these instruments must provide a form of continuity with respect to the real world with a readily visualizable control surface, including a suitable haptic representation. Thus, the shapes or contours of these musical instruments should be copies of or inspired by the physical shape or contours of objects in our day-to-day life, yet the mapping to sound parameters may be very different from acoustic instruments. Such musical instruments are defined as Virtual Musical Instruments (VMI) [61].

In other words, and from the point of view of a human interacting with a computer, the idea is to extend the user interface for musical and sound synthesis environments from a 2D interface (or what is sometimes called $2\frac{1}{2}$D due to the presence of a 3D mouse represented as a 2D pointer on a 2D screen) to a 3D interface where visual and haptic representation and control space are superimposed.

Prior Art

A lot of work has been done on $2\frac{1}{2}$D virtual musical instruments, but very little on 3D virtual musical instruments. This work has not aimed for a maximally adaptable or adaptive instrument or an environment in which to design such instruments, but instead has focused mostly on the creation of fixed virtual instantiations of familiar musical instruments like drums [7], flutes [63], guitars and even a Theremin [7], with all the familiar limitations of the control surface of the original instrument. In a very few cases researchers or artists like Lanier [43] have been able to develop their own variation of a VMI inspired on traditional musical instruments. Choi et al [18] developed a virtual environment in which 3D spatial paths were visualized. Tracing these paths (a form of movement closely related to manipulation gestures) resulted in sound variations. Similar to the work presented in this dissertation, Modler [52] has recently implemented "behaving virtual musical objects", simple 3D graphical objects with which the user can interact using 3D hand movements with musical results.

2.3.3 Research Objectives

The goal of the work presented in the following chapters was to implement a prototyping environment for Virtual Musical Instruments, without haptic representation because of technical limitations, and thereby to gain insight into the following areas:

- **Manipulation** - What kind of manipulation gestures would be used and what kind of gestural analysis computations would need to be implemented ?
- **Sonification** - What recommendations can be made with respect to relating shape, position and orientation variations to sound and music variations ?
- **Visualization** - How "real" should the control surface visualization appear and how should it change in response to manipulation and other gestures by the performer ?
- **Adaptation** - How should the environment be implemented to enable a maximum of adaptation of a VMI to/by any performer ?
- **Engineering** - What engineering feats in terms of sensing, computing and display need to be accomplished in order to achieve real-time performance with a VMI ?

Chapter 3

VMI Design

Rubine has examined in some detail the performer's sensori-motor and auditory perception capabilities so as to formulate requirements for musical instruments given engineering constraints [78]. Similarly, following the discussion in the previous chapter, the question arises of what should be the capabilities of a virtual musical instrument. Any treatise of this subject will be necessarily incomplete, and it also does not fall within the scope of this dissertation to achieve completeness. Hence, this chapter serves to outline a basis for implementing a VMI design environment by discussing some of the known boundaries that delimit the design space of virtual musical instruments without providing a classification method for VMIs in the same way that Card et al has done for computer input devices [15] and Nigay et al for multi-modal systems [64].

3.1 System Analysis

The aim is to build musical instruments that allow performers to start learning any given (traditional or new) form of gesturing in a musical performance setting while they may later prefer or need to incorporate other forms of gesturing.

3.1.1 Task Analysis

Music involves the simultaneous control of many parameters, the changes in which have to be precisely timed in order for the music to be considered expressive and aesthetically pleasing. The activities music composition and sound design are not constrained temporally. Normally a composition is first written out, after which a performance of the piece may occur. For sound design, sound parameters may be adjusted after which the sound may be generated for evaluation. Thus, based on Sturman [89], the task of performing and composing music and designing sound can be characterized as follows:

- **Degrees of freedom** - Musical performance, composition and sound design involve the control of many parameters. The precise number of degrees of freedom depends on the type of musical activity. Traditionally they have been pitch, loudness, timbre (which in itself can involve a few degrees of freedom), expression related parameters like vibrato and musical structure related parameters like tempo, dynamics and meter. This list has expanded considerably due to electronic sound synthesis and processing techniques.

- **Task constraints** - The musical parameter changes, in some musical styles more so than others, have to be timed down to milliseconds. Music composition and sound design are not constrained temporally. Aesthetically, musical activities are highly constrained, although it is a socio-culturally defined constraint. Instrumental performance traditionally imposes a physical constraint as to how and where the performer can move to achieve musical results. The aim of the research presented in this dissertation is to let performers define this constraint according to their desires and/or needs.

- **Coordination** - To compose or perform a musically expressive piece or design the right sound, many parameter changes have to be coordinated. For example, in classical music to indicate a climax a pitch increase is accompanied by an increase in loudness decrease and an increase in vibrato. In sound design, envelope parameter changes may have to be accompanied by changes in the spectrum of the sound. Instrumental performance traditionally requires a high level of coordination. For example, in wind instruments, the opening and closing of multiple valves has to occur at the same time as changes in reed vibration. As the coordination of certain limbs may be more difficult for certain performers than for others, the research presented in this dissertation may lead to a reduction of the need for difficult forms of coordination.

- **Resolution** - Resolution is dependent on human perception. Depending on the musical or sonic context, perception resolution may vary greatly. Given the right conditions, pitch variations can be perceived as low as 2 cents and loudness variations as lows as 0.25 dB. In terms of timing resolution, two clicks can be heard as separate clicks when they are at least 2 ms apart [78].

- **Speed** - Music is a timed series of audible events. The audible events do not have to be performed as fast as possible, but simply on time. For music composition or sound design there is no speed requirement.

- **Repeatability** - The repeatability of musical performances is dependent on musical style. For example in jazz music improvisations repeatability is low, while in classical music repeatability is very high.

3.1.2 Requirements

Although the aim as stated above implies that VMIs should be able to respond to *any* specific movement or gesture the performer desires it to respond to, the research can be limited to hand movements. This limitation can be implemented without compromising the objectives of the research significantly, while greatly reducing time and resources necessary to complete the research.

Given the above considerations, the following requirements can be summarized for any VMI:

- **Manipulation** - The performer has to be able to interact with the control surface using common manipulation pragmatics.

- **Sonification** - Performer gestures affecting the control surface have to result in perceptible changes of sound and music parameters.

- **Visualization** - The performer has to be able to visualize the control surface, i.e. the control surface has to be similar to or inspired by real world objects.

- **Adaptation** - As many aspects of the controller as possible have to be adaptable/adaptive through an easy-to-use programming interface.

- **Sensing** - As many hand movements and gestures as possible have to be captured.

- **Computing** - The VMI has to compute within real-time, i.e. hand actions have to correspond with visual and auditory changes without any perceptible time delays. Only if the task is to design a sound or compose music, not to perform it, auditory changes may be delayed, but visual changes should still be occurring in real-time in order to be able to manipulate the virtual object effectively.
- **Display** - The control surface visualization has to be graphically or otherwise visually displayed, whereas the sonification has to be audibly "displayed".

3.2 The Performer

The requirements on manipulation warrant an excursion into the body of knowledge on human gestural capabilities and behaviour. There are many excellent overviews of human hand gestural capabilities and behaviour e.g. [34]. The human hand is the most dextrous of the human limbs and has, at the anatomical level of description, 29 degrees of freedom which are operated through 39 muscles.

3.2.1 Hand Movements

Human hand movements can be classified according to two categories:

- **Prehension** - MacKenzie et al define prehension as the application of functionally effective forces by the hand to an object for a task given numerous constraints [47], i.e. hand movements involving tactile and force feedback. Since prehension involves an external object it always involves target oriented movements. In almost any prehensile behaviour, opposition of some part of the hand to the rest of the hand is essential [31].
- **Gesturing** - This can take the forms of gesticulation and signing, amongst other things. All forms of gesturing can involve tactile feedback (aside from skin stretching due to movement) but very often do not. Similarly, they may involve target oriented movements, but very often do not. Kendon defined gesticulation as idiosyncratic spontaneous movements of the hands and arms during speech and signing as the use of a set of gestures and postures for a full fledged linguistic communication system [36]. Kendon observed that in going from gesticulation to language-like gestures to pantomime to emblems to signing, gesticulation is the least structured as a language and signing the most structured as a language.

Musical Performance Movements

Musical instrument performance including sound mixing during live performance involves prehension, as forces are applied by the fingers to valves, strings, keys or sliders with the aim to control some aspect of the sound. In the case of string instruments, tactile and force feedback in the form of string motions may inform the performer how to adjust his or her finger positions to achieve the desired sounds. Cadoz differentiated excitation gestures (initiating an acoustic event) from modulation gestures (changing an ongoing acoustic event) [13]. This differentiation is useful in identifying the goal of the movements, but does not identify which specific motions were performed. The instrumentalist's movements may also serve to convey a visible result of the performance to the audience.

Conductors use signing and some gesticulation to communicate instructions to the orchestra and/or choir. The conductor's baton is an instrument to this purpose. The conductor's signing and gesticulation also serve to communicate a visible result of the performance to the audience.

Control Dimensionality

The highest number of control dimensions are provided by prehensile behaviour, such as that used for changing object shape (i.e. sculpting) and other forms of object manipulation, in which the shape, position and orientation of the hand is changing simultaneously. If no tactile or force feedback is involved we can call such prehensile movements manipulation gestures. Such gestures provide the highest dimensionality of control especially when two hands are involved in the manipulation. If well designed, two-handed manipulation increases both the directness and degree of manipulation of the interface [35], [10], thereby reducing the motor and cognitive load.

Fewer control dimensions are provided by dynamic signs (hand shape is constant, but hand position and/or orientation is changing) and the least by static signs, which are mainly useful for selection tasks and the communication of symbolic information such as in sign languages. The use of such gestures requires some form of gesture recognition. In previous work on gesture interfaces (such as [22]), it has been noted that, since most humans do not normally reproduce their gestures intended for conveying symbolic information very precisely, natural gesture recognition is rarely sufficiently accurate due to classification errors and segmentation ambiguity. Only when gestures are produced according to well-defined formalisms, such as in sign language, will automatic recognition have acceptable precision and accuracy.

3.2.2 Pragmatics

Object manipulation can be defined as the grasping, holding and changing of position, orientation and shape of an object. These actions normally occur within a certain spatial region or workspace [69] and are preferably centered around the body of the performer [89].

Holding

The pragmatics of holding objects involves a number of specific grips [91]:

- **Platform grip** - While the hand is flat, the object is resting on the whole or part of the palmar surface.
- **Pinch grip** - The object is held between at least two pads of the hand. Some of the main pinch grips are:
  - Thumb-finger grip - Also known as the precision grip, objects are held between the thumb, in opposition, and one or more of the other fingers.
  - Interdigital grip - Objects are held sideways between two fingers, without thumb opposition.
  - Digitopalmar grip - Objects are held between fingers and palmar surface.
  - Whole hand grip - Also known as the power grip, objects are held by wrapping the entire hand around the object.

Moving

The pragmatics for the application of position and orientation changes consists of two praxes. One praxis consists of the usage of one of the grips identified above for holding objects followed by a movement of the hand. The other praxis consists of applying force to the object with some part of the hand without holding the object.

Sculpting

An analysis of the methods employed by humans to edit shape with their hands, i.e. sculpting, leads to the identification of four different stereotypical methods [57]:

- **Claying** - The shape of objects made of material with low stiffness, like clay, is often changed by placing the object on a supporting surface and applying forces with the fingers of both hands.
- **Carving** - The shape of objects made of material with medium stiffness, like many wood materials, are often changed by holding the object in one hand and applying forces to the object using a tool like a knife or a file.
- **Chiseling** - The shape of objects made of material with high stiffness, like many stone materials, are often changed by placing the object on a supporting surface and applying forces to the object using a tool like a chisel held in one hand and a hammer held in the other.
- **Assembly** - Using pre-shaped components, a new shape is created or an existing shape is modified. One hand may be used for holding the object, while the other hand(s) place a pre-shape component.

3.3 The Instrument

3.3.1 Sensors and Display

There are many sensors for capturing hand movements, but only a few capture most degrees of freedom and even fewer capture these with a minimum of time delays and inaccuracies [60]. Instrumented gloves, or Datagloves, are most frequently used to achieve immersion with respect to the hand. Currently available Datagloves are rather cumbersome to put on and off as well as inconveniently tethered to an interface. Visual and auditory display should provide no significant engineering problems, as the technology is readily available.

3.3.2 Intelligent Computing

To implement a mapping, some form of intelligence is required in the form of mapping functions and methods, and adaptation techniques. For example, many movement parameters can be mapped to one sound parameter through a summing function or one movement parameter can be mapped to many sound parameters through a variety of functions [77]. Sturman distinguishes between "direct" (hand motions result in kinematically similar motions of the controlled device), "mapped" (hand motions are interpreted abstractly, e.g. finger flexion as a slider or a specific posture as a button click) and "symbolic" (gestures and postures are interpreted as streams of tokens for sign-like language communication) [89]. Also, both sound and human movement can be represented at various abstraction levels [14]. Although it is hard to identify sharp boundaries between levels of abstractions, a mapping may be faster to learn when movement features are mapped to sound features of the same abstraction level.

This intelligence may consist of implicit and/or explicit knowledge. Explicit knowledge requires the user to know and specify to the instrument how parameters should be mapped. Implicit knowledge requires the instrument to deduce from examples to know how parameters should be mapped. Implicit knowledge can be implemented with neural networks, which require that the user "teach" the system which hand movements it should map to the sound parameters of interest [21].

Whether the mapping is implicit or explicit, an intelligent system can be adapted to the user's preferences. The implicit method does not provide any guidelines when designing a mapping, which may be an advantage in situations where the user already has an idea of how a sound should change when making a movement but a disadvantage in other situations where guidelines for the design of a mapping are desired or when presets needed. In the latter case explicitly provided knowledge may be useful, although the user interface to configure the VMI may require more design work to achieve the same ease-of-use as in the case of an implicit mapping which would not require the user to specify as much detail. Visual programming interfaces like Max [106] may provide an easy to use method to reconfigure or adjust the VMI.

3.3.3 Real-time Computing

Music performance requires "real-time" operation of the instrument. Although humans can hear timing differences between click sounds as low as 2 ms, full perception of complex sounds can take as much as 60 ms. Thus, depending on the aspect of the sound or music that is being controlled "real-time" translates into a time delay created by the instrument that, to be imperceptible, may have to be in the order of milliseconds. However, it should be noted that when a click sound is generated through a movement, the knowledge of the time when the click should be heard must rely on a perceptual system with a high bandwidth like the tactile sense. Otherwise such timing precision cannot be achieved and hence not known. Therefore, unless tactile or force feedback is implemented, it is safe to assume that "real-time" can be achieved within the order of 10 ms. Visual perception takes at least 100 ms up to about 200 ms, so that "real-time" here means a maximum time delay of 200 ms.

3.3.4 Sonification

Sonification has been defined as the use of data to control a sound generator for the purpose of monitoring and analysis of the data [39]. Sonification in the context of this dissertation concerns the use of virtual object features as sound and music controls. Sonification is very new as a field and applicable research is extremely sparse [39]. Guidelines for sonification are especially useful considering that computer controlled electronic sound synthesis has given rise to an enormous increase in the number of parameters available to represent sound and music, so that the possibilities for mapping are endless. As a starting point, from a composer's point of view a need for methods to organize these parameters in musically meaningful ways has been recognized [20], [80]. To facilitate the use of such organizations a variety of methods have been developed to visualize sound and music, usually through a 2D or 3D projection on a 2D screen. These methods may inspire the design of VMIs as they provide a way of interacting with sound and music composition environments through a visual interface.

Visualizations of sound often consist of a time-frequency-amplitude graph if 3D (projected) display is available. Some have experimented with such visualizations on a 3D interactive display [5], [1]. These visualizations may require 3D input but they have not exploited the dexterity of the whole hand. In 2D visualizations time-amplitude or frequency-amplitude (or spectral) graphs are often used, although other variables are also used [62].

Sometimes sound is visualized as the shape of a physically modeled vibrating object [11]. In all these cases, thusfar the gestural controls made available to the user are limited due to the use of keyboard and mouse interfaces.

Visualizations of musical structure traditionally consists of classical sheet music notations displaying the acoustic events over time. Some have tried alternative forms of displaying the musical flow [37], [26], related pitch sequences to colour [25], [28] or transformed entire musical compositions into one painting [66]. All these visualizations were developed solely for visual aesthetic purposes, not for providing a method to control or create music. Data flow software programs such as Max [106], patchwork [4], synthbuilder [70] etc. provide an algorithmic visualization where the musical or sound generating process is visualized through graphical boxes or otherwise shaped objects. All these visualizations are limited due to the use of keyboard and mouse interfaces.

Chapter 4

VMI Implementation

An environment for developing virtual instruments for the control of spatial and timbral sound parameters was created based on the pragmatics of sculpting [58], [56]. In this environment a 3D virtual object, as a visualization of the control surface, is used as input device for the editing of sound - the sound artist literally “sculpts” sounds using a 3D virtual sculpting computer interface [24], of which early 2D precursors can be found in Krueger’s work [41]. Thus, by changing virtual object parameters such as shape, position and orientation sound and music parameters are changed in real-time. In this environment the object is virtual, i.e. the object can only be perceived through its graphics display and acoustic representations, and has no tactile representation.

Although sculpting in the physical world is most effective with touch and force feedback, it was assumed that these forms of feedback can be replaced by acoustic and visual feedback with some compromises. The motivation to make such assumptions is based on the fact that the generation of appropriate 3D touch and force feedback, while exploiting the maximum gestural capability in terms of range of motion and dexterity, is currently technically too challenging in a 3D virtual object manipulation task.

Furthermore, although the aim is to make musical instruments, it can be argued that when no control is provided for note onset, duration and pitch, the performer is not making music but controlling sound. Traditionally the difference between music and sound is determined by the presence or absence of structure indicating the passage of time, using these parameters. However, in the present times many composers create pieces that would not traditionally be considered music because the structuring parameters are not limited to note onset, duration and pitch but may for instance only be timbral and spatialization parameters. In the following the definition of a VMI should be interpreted in this context.

4.1 Environment

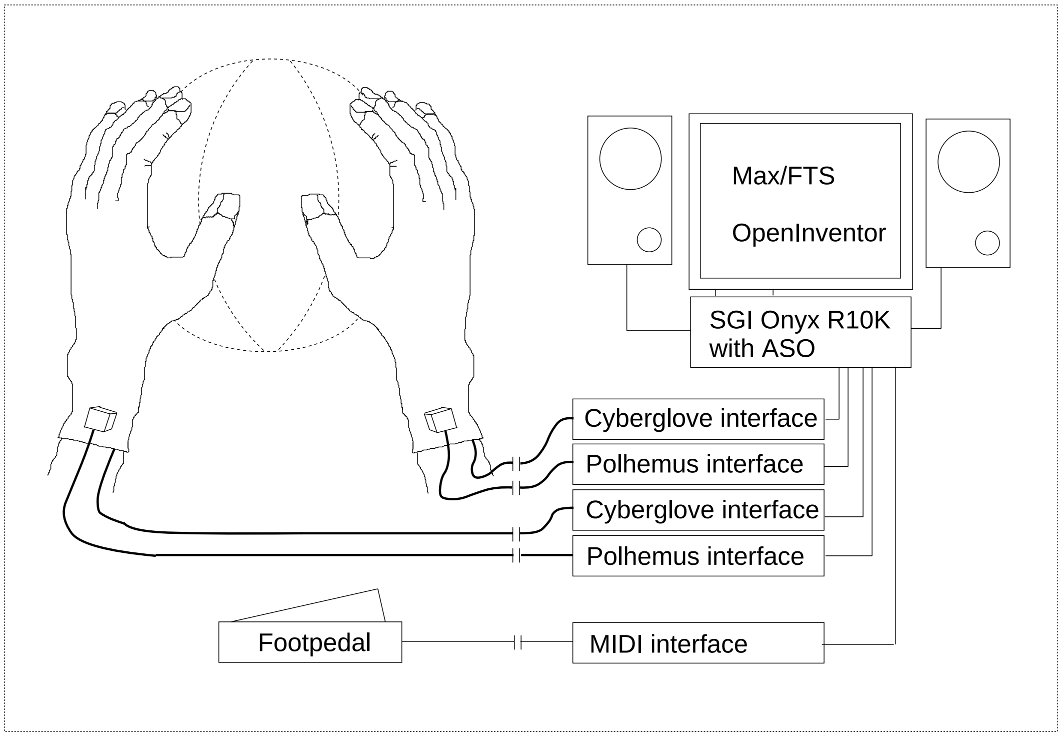


Figure 4.1: Devices used for the VMI environment. The dotted lines represent a 3D virtual surface which the sound/music composer or performer manipulates.

Figure 4.1 illustrates the devices used for the environment.

4.1.1 Sensors

Two Virtual Technologies CyberGloves^{tm} (instrumented gloves that measure hand shape, see figure 2.8) and Polhemus Fastrak^{tm} sensors (a sensor for measuring position and orientation of a physical object, such as the human hand, relative to a fixed point) were used to capture hand movements [60]. The sensors were interfaced at 38.4 KBaud. A footswitch, interfaced using MIDI (31.25 KBaud), enabled "grabbing and holding" the virtual object.

4.1.2 Computing Platform

All computations were performed on an SGI Onyx with 4 R10000 processors and audio/serial option (6 serial ports) to interface the sensors and connect with a MIDI interface. The MIDI interface was not used to send messages to a sound synthesizer as the software synthesizer provided by Max/FTS (see below) was used. Instead the MIDI interface allowed the interfacing of a footpedal. To facilitate quick prototyping and experimentation with a multitude of gestural analysis methods, a set of software objects were created that facilitate the computation of various gesture features and parameters similar to Wexelblatt's gestural analysis environment [99]. To implement this, a visual, interactive programming environment for real-time sound synthesis and algorithmic music composition called Max/FTS was used [73], [74]. Max/FTS consists of two software programs and was chosen because FTS provided a software development platform, while Max provided an appropriate user interface. FTS is designed for real-time computation and has built in software sound synthesis tools without requiring special sound cards. Max has visual programming capabilities and includes various synthesis models implemented as editable patches. FTS functionality is extended by linking in at run-time dynamic shared objects (DSO), containing the code for new software objects.

4.1.3 Display

The hands and virtual object were graphically displayed (2D projections of 3D models) using OpenInventor software. After trials with line drawings of the virtual objects it was found that fully rendered graphical models provide much clearer information about the status of the virtual object. Sound was either amplified through a pair of speakers or through a headphone.

4.2 Computations

4.2.1 Method

The mapping relied on the use of virtual object parameters to relate manipulation gestures to spatialization and timbral variations of the sound at various levels of abstraction (figures 4.2 and 4.3). Hand features, computed from the acquired hand shape, hand position and hand orientation data, are mapped to virtual object parameters of a similar abstraction level.

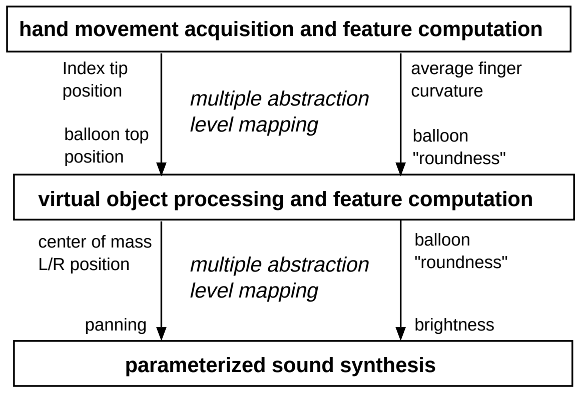
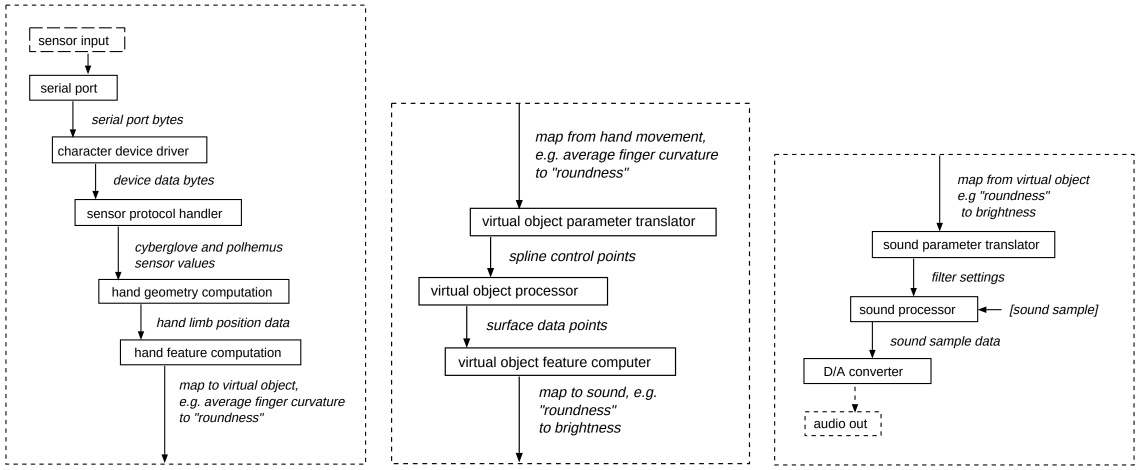

hand movement acquisition and feature computation
Index tip position
balloon top position
multiple abstraction level mapping
average finger curvature
balloon "roundness"
virtual object processing and feature computation
center of mass L/R position
panning
multiple abstraction level mapping
balloon "roundness"
brightness
parameterized sound synthesis

Figure 4.2: Functional diagram of hand movement to sound mapping. Virtual object features are used as a means to relate hand movement features to sound features.

If a virtual object parameter is specified at a different abstraction level than the parameters of the virtual object processor, it will need to be translated to the parameter space of the virtual object processor. A virtual object processor is an algorithm that computes surface data points from virtual object parameter values. The simplest virtual object processor is the identity, i.e. it takes surface data points as virtual object parameters and outputs surface data points describing the same surface. If the hand feature computation and virtual object parameter translation are also taken as the identity, the 3D positions that represent the hand will also specify the virtual object surface. In other words, the hands are then continuously "touching" the virtual object. A virtual object feature is computed from surface data points and represents an abstraction of the virtual object (e.g. surface curvature). Virtual object features are subsequently computed and mapped to sound parameters.

Examples

In terms of relating the parameters of a virtual object to sound, a mapping based on the real, physical world may be easy to understand, but will not easily provide suggestions for the control of abstract, higher level sound parameters. Nevertheless, if the object were taken as a sound radiating object, a simplified mapping of the virtual object's position and orientation to sound parameters could involve mapping left/right position to panning, front/back or depth position to reverberation level, angle of the object's main axis with respect to the vertical axis to reverberation time and virtual object volume to loudness.


sensor input
serial port
serial port bytes
character device driver
device data bytes
sensor protocol handler
cyberglove and polhemus sensor values
hand geometry computation
hand limb position data
hand feature computation
map to virtual object, e.g. average finger curvature to "roundness"
map from hand movement, e.g. average finger curvature to "roundness"
virtual object parameter translator
spline control points
virtual object processor
surface data points
virtual object feature computer
map to sound, e.g. "roundness" to brightness
map from virtual object e.g "roundness" to brightness
sound parameter translator
filter settings
sound processor
[sound sample]
sound sample data
D/A converter
audio out

(a) Functional diagram of hand movement acquisition and feature computation.

(b) Functional diagram of virtual object processing and feature computation.

(c) Functional diagram of sound synthesis.

Figure 4.3: The diagrams show mapping at the feature abstraction level, but mapping at other levels is equally possible.

Mapping virtual object shape parameters to timbral parameters is less easily based on the physical world, but could involve mapping the length of the main, i.e. longest, axis to flange amplitude, transverse surface area or object width to chorus depth and curvature or “roundness” to brightness as defined by Wessel [98].

4.2.2 Implementation

The strong data type checking of Max/FTS was used to introduce new data types such as *position* and *orientation* for geometric and kinematic computations as well as a *voxel* and *hand* data type. This way the user is made aware of different abstraction levels or methods of representation which do not necessarily map linearly but may require more complicated functionality.

Based on the mapping method and the new data types, a number of Max/FTS software objects were programmed enabling quick and easy prototyping of various gestural analysis computations and allowing for application of the computations to different body parts. They are listed below with reference to figures 4.2 and 4.3. See the Max/FTS object reference appendix for a more detailed description.

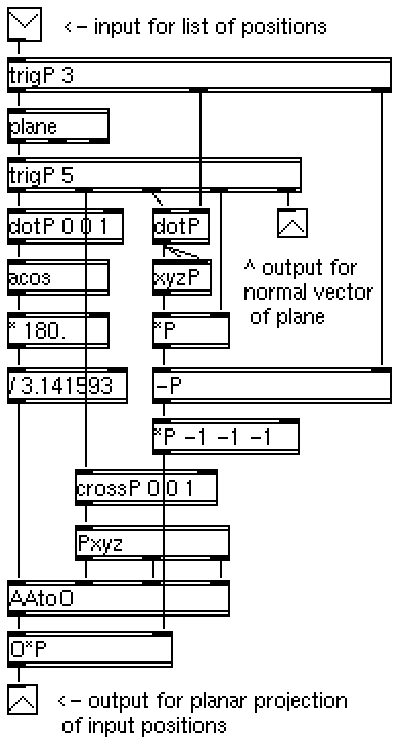
- **Unix character device drivers** - Objects for interfacing peripheral devices that communicate using one of the SGI's serial ports (*serial*), and for communication between Max and other processes using TCP sockets (*client*) or shared memory with semaphores (*sms* and *smr*). The *sms* object was used to communicate data to an OpenInventor 3D graphics server to display the acquired hand shape, hand position and hand orientation data as a graphic hand as well as to display the virtual object graphically. The *sms* and *smr* objects also enabled real-time performance because they allowed for rapid data exchange between two Max/FTS applications, one for sound synthesis and the other for remaining computations. It was found that TCP communication was too slow to enable real-time performance.

- **Sensor interfaces** - These objects are peripheral (character) device interfaces that implement a specific protocol, such as for the CyberGlove and Polhemus sensors (*cyberglove* and *polhemus*).

- **Geometric computation** - New data types *position* (x, y and z position as floats in one data structure) and *orientation* (a data structure containing a rotation matrix, Euler angles and angle-axis representations of orientation) were defined for this group of objects to facilitate computations such as distance between points ($+P$, $-P$), scaling ($*P$), dot product ($dotP$), cross product ($crossP$), norm ($normP$), magnitude ($\|P$), rotation ($O * P$ and $*O$), frame of reference switching (TO) etc. and their derivatives (see figure 4.4).

- **Geometric structure computation** - At this level of abstraction the computations do not involve just points with a position and an orientation but involve volume elements (represented as a new data type *voxel*). Voxels may be ordered and linked in a specific manner so as to represent for instance human anatomical structures or otherwise shaped objects. A new data type *hand* is used to represent a human hand. The object $geoHand$ computes an ordered list of *voxels*, packed as a *hand* that are relative to the Polhemus transmitter from CyberGlove joint data and Polhemus receiver position and orientation data. This computation could also be done using the geometric computation objects in a patcher, but it would be computationally more expensive.

- **Hand feature computation** - Objects for the computation of hand features such as



<– input for list of positions
trigP 3
plane
trigP 5
dotP 0 0 1
dotP
acos
xyzP
* 180.
*P
/ 3.141593
-P
*P -1 -1 -1
crossP 0 0 1
Pxyz
AAtoO
O*P
^ output for normal vector of plane
<– output for planar projection of input positions

Figure 4.4: Typical example of geometric computing using the new Max/FTS *position* and *orientation* objects. This Max patcher takes a list of *positions*, projects these on the plane that best fits them, then rotates the plane (with projected *positions*) and eliminates z. This patcher enables subsequent fitting of 2D parametric curves to the x-y coordinates (e.g. the x-y coordinates computed from the *positions* marking the thumb and index fingers).

the distance between thumb and index fingertips and the distance between left and right hand palm are easily calculated using the above geometric computation objects in a patcher. Objects were also made for computation of the orientation of a plane (*plane*, see figure 4.4) such as the palm, the average position of a selected number of points of the hand (*avgP*) and for computation of features based on the path of a selected point of the hand (*bufP*). Other objects for the computation of features such as finger and hand curvature using a curve fitting algorithm, estimated grip force using a grasping taxonomy etc. would be useful but have not been programmed.

- **Virtual object processing** - The *sheet* object implements a physical model of a sheet of two layers of masses connected through springs (see figure 4.5 and 4.6) [23].

The four corners of the sheet act as the control points and can be stuck, or clamped to the index and thumb tips of both hands for example. Similarly, *balloon* implements a physical model of a single layer of masses positioned in sphere-like form (see figure 4.7 and 4.8).

- **Virtual object feature computation** - Many of the geometric computation objects and some of the hand feature objects can be used to compute virtual object features. Other types of virtual object feature computations involve superquadrics, a mathematical method to describe a wide variety of shapes with two parameters specifically related to virtual object (vertical and horizontal "roundness" or "squareness") and 9 others for size, orientation and position of the virtual object. "Roundness" is an abstract feature which might map well to abstract sound features such as "brightness" [98]. Based on [87] a *superquadric* object was programmed that fits a virtual object described in terms of superquadric parameters to a set of *positions*. As the fitting process is iterative, it is computationally expensive (order of 100 ms). A simpler approach was implemented in a feature computation object *ellipsoid* which fits only a virtual object described in terms of ellipsoid parameters (i.e. three size parameters) to the list of *positions*. For 2D curve fitting the *polynomial* object, which approximates a list of *positions* by a polynomial of at most second degree, was programmed. The *kappa2D* object computes the curvature of a 2D curve, whereas the *kappa3D* object computes the curvature of a 3D surface.

4.3 VMI Prototypes

Two types of VMI prototypes were created, one using a virtual object with a behaviour of a rubber sheet and another using a virtual object with a behaviour of a rubber balloon (see the appendix on Operating Instructions for pictures of the Max/FTS patches which were used).

Chronologically, an attempt was first made to implement the balloon, but then found too slow, so that the simpler model of the sheet was implemented. It was then reasoned that by computing hand curvature from the average bending of the hand instead of fitting a superquadric to the shape of the hands, the balloon model could still be implemented as the computation and display of a superquadric requires far less computing time than the fitting computations.

The manipulation gestures for sculpting were based on the pragmatics of claying. The virtual object could be manipulated either while it was "held" by (a selected number of) joints and subsequent hand motions moving or changing the shape of the object or it could be manipulated by "touching" it. A footswitch enabled selection of either manipulation method.

To control parameters of the sound that define the spatial properties of the space in which the sound is generated, position and orientation of the virtual objects were mapped as if the virtual object was a sound radiating object. Thus, the virtual object's position and orientation were simply mapped as follows: left/right position to panning, front/back or depth position to reverberation level, angle of the object's main axis with respect to the vertical axis to reverberation time and virtual object volume was mapped to loudness.

Mapping virtual object height to pitch could be "intuitive". However, due to human inaccuracy in moving the hands to absolute positions without tactile or force feedback and only (delayed) acoustic and visual feedback, in combination with a high sensitivity for perceiving pitch changes, controlling pitch in this way was ineffective. Thus, the pitch of the sound was either fixed at one frequency, or was pre-programmed as a sequence. Instead the virtual object height was mapped to mid-pass filter amplitude.

The remaining available sound parameters in the synthesis model used were timbral parameters attack time, release time, flange index, chorus depth, frequency modulation index, and low/mid/high-pass filter amplitude and filter frequency.

The virtual objects were displayed graphically in real-time as 3D projections on a 2D screen, against a black background, together with line drawings of the hands.

4.3.1 Rubber Sheet

To implement a virtual object with a behaviour of a rubber sheet, the object *sheet* was used to compute the virtual object *voxels*. The object holding pragmatics involved a pinch grip. The *voxels* of the tips of the index and thumb fingers were used as the *voxels* of the four corners of the virtual sheet. Thus, rotating, but not moving, the finger tips would result in bending of the virtual sheet. Stretching, widening, positioning and orienting the sheet was a direct consequence of moving the index and thumb fingers and/or the hands.

The fingertips of both hands or one hand only could be clamped to the corners of the sheet (figure 4.5). If only one or none of the hands was clamped, the other hand or both hands could manipulate the sheet by "touching" it (figure 4.6). Manipulation with the

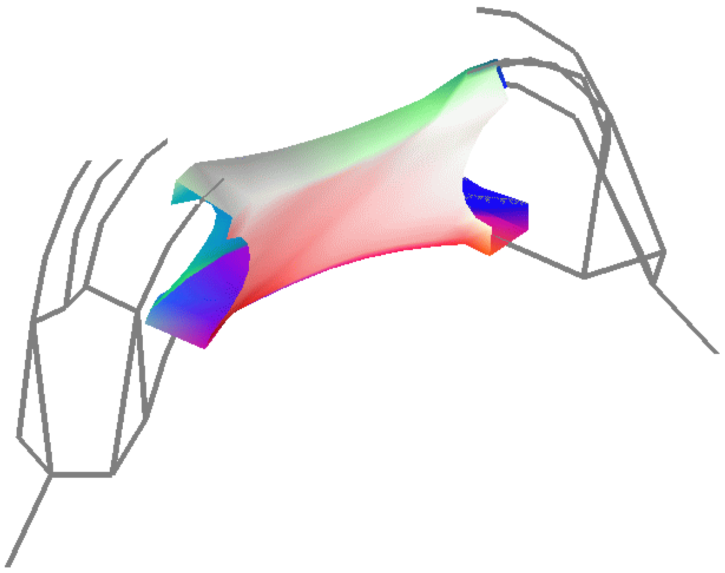


Figure 4.5: Example of the sheet clamped to the index and thumb tips of both hands.

left hand only resulted in a virtual input device similar to manipulation of the familiar keyboard modulation wheel but with increased functionality. This was implemented with the left corners of the sheet clamped to the left hand index and thumb and the right corners of the sheet fixed in space.

Average length of the sheet, along the axis between left and right hand was mapped to flange index. Width (i.e. axis between index and thumb) of the sheet was mapped to chorus depth. A measure of the average curvature, computed with $kappa3D$, was mapped to the frequency modulation index. The angle between left and right edge of the sheet was mapped to vibrato.

4.3.2 Rubber Balloon

A virtual object with a shape and behaviour of a rubber balloon was created by using the *balloon* object. Manipulation of this virtual object occurred through the movement of any of the *voxels* that make up a hand. Thus the pragmatics of "holding" the object involved manipulation gestures varying between a platform grip and a whole-hand grip or power grip.

When the virtual object was clamped to the hands, a superquadric shape was fitted to the *positions* of these *voxels*. When switching from clamping to "touching", the virtual

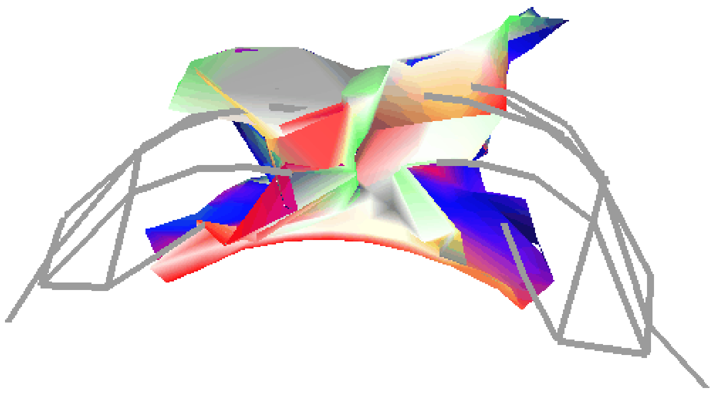


Figure 4.6: Example of touching the sheet with both hands.

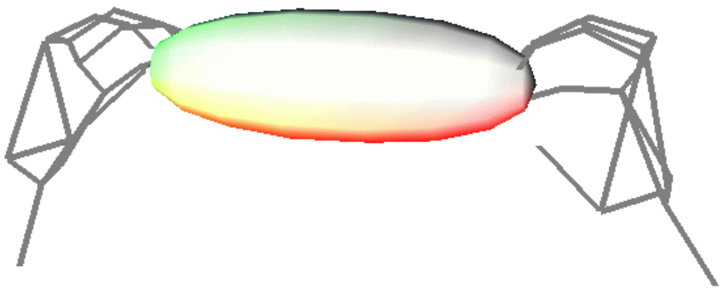


Figure 4.7: Example of the balloon clamped to both hands.

object surface *positions* were used as the starting positions for a physical simulation of a rubber balloon. Joints of both hands or one hand could be clamped to surface points of the balloon (figure 4.7).

If no hand or only one hand was clamped, the other hand(s) could manipulate the sheet by "touching" it (figure 4.8). As in the case of the sheet, manipulation of a virtual mod wheel, using the left hand only, was implemented with the balloon clamped to all positions used to represent the left hand.

The object *ellipsoid* was used to compute virtual object features. The length of the main, i.e. longest, axis of the balloon was mapped to flange index and the cross-sectional surface area was mapped to chorus depth. The "roundness" of the object was not computed using the *superquadric* object due its computation time but was estimated using the bending of

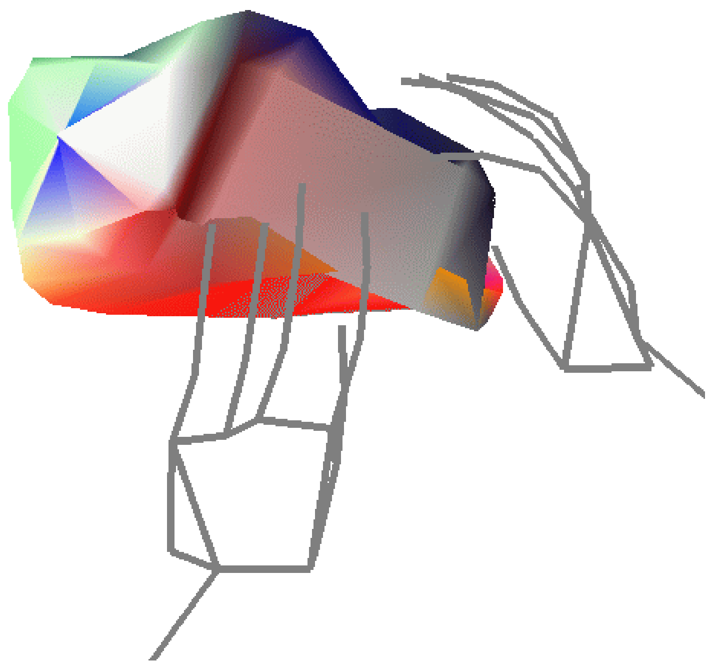


Figure 4.8: Example of touching the balloon with both hands.

the fingers. The “roundness” was mapped to the frequency modulation index.

Chapter 5

VMI Evaluation

There are a number of methods to evaluate the VMI environment described in chapter 4. Heuristic evaluation by experts is difficult because there are no expert users of the VMI implemented environment and expertise specifically in VMI design is unavailable. Model based evaluation is only partially useful due to the fact that applicable models only apply to a limited number of aspects of the VMI environment and are difficult to integrate due to their origin in different disciplines. A comprehensive model of musical performance is unavailable.

In the following sections, based on informal live user observation and analysis of video material, the VMI environment and prototypes will be discussed in terms of the research objectives listed in chapter 2 and the requirements specified in chapter 3, with a focus on manipulation.

5.1 Data Acquisition

Due to time and resource limitations, the VMI environment was informally tested by the author and research colleagues only, with the CyberGloves calibrated to the author's hands. This group of approximately 15 test users included 3 amateur musicians. Usage consisted of performance of 3 MIDI sequences (two bossa nova style songs and one rock style song) and single tone experimentation (single pitch was automatically turned on and off, allowing evaluation of timbral and spatialization changes).

Documentation

Some of the use of the environment by the author was videotaped:

- 2-handed balloon performance (29 min)
- 1-handed balloon performance (4 min)
- 2-handed sheet performance (14 min)
- 1-handed sheet performance (8 min)

The appendix includes an edited version of this video material together with a description of the system.

5.2 Manipulation

The design goal was to allow the performer to interact with the control surface using common manipulation pragmatics. Moving and rotating the virtual object while "holding" it was mostly effortless, as it was virtually identical to the manipulation of physical objects.

Touching the virtual object to move, rotate or shape the virtual object, required effective feedback of the contact between the hands and the virtual object. As no tactile feedback or force feedback was available, the performer had to rely on the visual feedback generated from the hand movements affecting the virtual object or the performer had to rely on changes in the sound. This method proved not so effective, probably because of a lack of suitable depth cues and because the absolute location of the virtual object had to be kinesthetically remembered (instead of being able to rely on tactile feedback when collision of the hand with object occurred) each time the hands moved without affecting the virtual object surface.

Most test subjects informally felt more comfortable working with the balloon than with the sheet given the sonifications used. Further testing is needed to verify whether this preference was due to the sonification of balloon features or to the type of manipulation the balloon afforded. Differences between the two prototypes are outlined below.

5.2.1 Rubber Sheet

The control of virtual object position and orientation took no time to get used to as it was similar to manipulation of physical objects. As for shape, it was found that control of curvature was limited by the fact that only the four corners of the sheet could be manipulated using the pinch grip. Normally, one positions fingers or fingertips in various ways on the surface to control the curvature. For example, to create a curved sheet, movements had to be exaggerated. Also, it was not possible to create a sheet with double bending in one direction. This limitation resulted sometimes in unwanted co-articulation of shape parameters, i.e. it was difficult to accept the limited control of curvature and not affect other shape features with the exaggerated movements. Some co-articulation of shape and position and/or orientation features was unavoidable, but could, with careful attention, be kept to a minimum. The length was easiest to control, then the width and the angle between left and right edge of the sheet.

Using the sheet as a virtual modulation wheel allowed left hand gestures to be more expressive than typical keyboard modulation wheel gestures and hence provided for a more dramatic performance effect. In addition, the reference point (the right corners) could easily be moved, so as to accommodate rapid changes in the zero-point of any modulations given different musical context, by clamping the right corners to the right hand temporarily.

5.2.2 Rubber Balloon

The “holding” of the virtual object was somewhat unnatural, as parts of the hand sometimes passed through the surface of the virtual object during manipulations.

It was unclear how to infer “roundness” of the virtual object accurately from the performer’s movements, due to the fact that normally the hand is only partially touching an object’s surface. Any sphere-like object can be held with anywhere from a few finger tips to the entire hand to change the shape using claying pragmatics. This problem made “roundness” difficult to control and resulted, as in the case of the sheet, in unwanted co-articulation of shape parameters. When the cross-sectional surface area was increased the balloon would also become more rectangular or ellipsoid if the performer would unintentionally extend or flex the fingers. In addition, due to errors in the estimation of finger bending sometimes jitter occurred, i.e. the virtual object would at times jump from cube-like to ellipsoid without any significant hand motions. As with the sheet, some co-articulation of shape and position and/or orientation features was unavoidable, but could, with careful attention, be kept to a minimum.

Manipulation using the left hand only, with the balloon entirely clamped to the hand was not as natural as in the case of the sheet, most likely due to a missing reference point (the rightmost corners in the case of the sheet - in hindsight, the balloon could also have been fixed in space at one end) and hence more difficulty in manipulating the shape of the balloon with one hand. Nevertheless manipulation of the position and orientation of the virtual object was effective, but the same sound effects might have been achieved without the presence of the virtual object. In terms of shape manipulations, balloon length was easiest to control, then cross sectional surface area and then “roundness”.

5.3 Sonification

The design goal was to create a sonification of the control surface that is responsive (i.e. results in perceptible changes of sound and music parameters) to performer gestures. This was not an easy task. For example, it was found that when mapping a virtual object feature to a sound parameter, offsetting and scaling the value of the virtual object feature required some arbitrary heuristics based on workspace dimensions etc. A solution without such heuristics would be preferred. In addition, undesired co-articulation of shape parameters required that virtual object features were chosen carefully for sonification. Due to the available manipulation methods certain virtual object features could only be controlled together, so they should not be mapped to sound parameters that may need to be controlled independently. However, the main challenge was to create a sonification that had similar expressive qualities as the gestures themselves, so that control would appear natural.

As mentioned in section 5.1, most test subjects informally felt more comfortable working with the balloon than with the sheet given the sonifications used. Both for the rubber sheet and for the balloon the mapping of virtual object position and orientation worked equally well and cost no effort to learn. Informal evaluation showed the mapping of virtual object shape to work sufficiently well. In the case of the balloon, due to jitter (i.e. the virtual object would at times jump from cube-like to ellipsoid without any significant hand motions), occasionally unpredictable sound variations occurred. Possibly this can be circumvented by algorithm and patch adaptations.

5.4 Visualization

The appearance and behaviour of the control surface was sufficiently similar to common physical objects to allow performers to immediately use the VMIs. It was not so easy to perceive the depth of the graphical environment and the absolute position of the virtual object, necessary for "touching" manipulations. The lighting and coloring were effective, and helped in cases when the surface folded through itself or turned partially inside out.

5.5 Adaptation

The design goal was to allow as many VMI aspects as possible to be adaptable and/or adaptive through an easy-to-use programming interface. The use of Max/FTS proved effective for this purpose, although the version of Max/FTS used in the VMI environment suffered from a poorly designed graphical interface. For example, the making of patches was often tedious due to difficulty in connecting objects to other objects via "wires"and an increasing difficulty in comprehending a patch the higher the number of "wires". The ease-of-use could definitely have been better. A new version of Max/FTS called jMax may improve this aspect.

The addition of FTS objects allowed for quick prototyping of gestural analysis computations, and an almost unlimited number of possibilities for adaptation. Small adjustments could easily be implemented, even while a performer was using the environment. In terms of adaptability, the library of FTS objects was not tested for its usefulness for making VMIs relying on sign-like languages.

5.6 Engineering

For musical performance, the VMI has to operate within real-time, i.e. hand actions have to correspond with visual and auditory changes without any perceptible time delays. Only if the task is to design a sound or compose music, instead of performing it, auditory changes may be delayed, but visual changes should still be occurring in real-time. The main delays were incurred by the sensor data acquisition (approximately 60 ms) and the physical modeling computations (approximately 8 ms).

The sensor data acquisition delay could not be reduced to the theoretically possible minimum. Probably the long serial cables (approximately 30 m) connecting the computer in one room with the serial interfaces in another room prohibited use of higher baudrates (56K and 115K). The computations could be completed in real-time if a suitably low (order of 100) number of virtual masses of the physical models was chosen. The computation of sound synthesis parameters and sound generation occurred in approximately 2 ms, so that acoustic feedback occured within approximately 70 ms, which is very close to real-time (60 ms) given the type of sound changes. The OpenInventor software displayed the graphics within three frames (i.e. 50 ms on a 60 Hz refresh rate monitor), so that the visualization was displayed within at most 120 ms, i.e. within real-time (200 ms).

The combination of CyberGlove and Polhemus sensors captured almost all possible hand movements and gestures. While the CyberGlove is probably one of the most accurate means to register human hand movements, accurate measurement of thumb movement was still difficult due to the fact that the sensors intended for the thumb did not map to single joints but to some of the neighbouring joints at the same time. Nevertheless, with the hand model used it was possible to reach acceptable accuracy for the purpose of this research, but the calibration was somewhat tedious as well as individual specific. Each joint had to be separately calibrated by setting the gain and offset of each joint flex sensor. No patch was implemented that allowed a user to execute a standard set of postures and/or gestures to provide calibration settings. Last but not least, the tethering of the sensors was inconvenient.

At the beginning of this research a graphical display was not deemed a high priority, but during development the graphical display of hands and virtual object proved to be very useful as a method to verify that hand and shape modeling were operating correctly and it also proved a simple way to show new users what to do. Its likely that even with experienced users the graphical display will have some value to finetune their motions.

5.7 Summary

Based on informal testing by the author, a handful or research colleagues and video material of the author's use of the environment, the evaluation of the VMI environment can be summarized as follows:

- **Manipulation** - The control of virtual object shape often required some effort to master due to the need for exaggerated movements and/or the need to learn limitations to the control of shape. Due to these limitations to manipulation, unwanted co-articulation of virtual object features could occur. While it is possible that such co-articulation can be used to the performers advantage in certain tasks, in the real world the virtual object features used can be controlled separately. The "touching" of virtual objects was difficult due to a lack of tactile and force feedback, or suitable depth clues.

- **Sonification** - The mapping of position and orientation to spatialization parameters proved easy to use. The mapping of virtual object shape to a variety of timbral parameters offered no obvious analogy to the physical world to the user. Thus, learning was required to obtain desired acoustic feedback in a natural way using the manipulation methods. Forced co-articulation of some shape features prohibited independent control of the sound parameters they were mapped to. Scaling and offsetting of virtual object features for mapping to sound parameters was somewhat arbitrary.
- **Adaptation** - Although adaptation of VMIs was possible in many diverse ways, the user interface to implement these adaptations was not so easy to use without significant technical expertise.
- **Engineering** - While acceptable real-time performance capturing almost all hand gestures, was achieved, expensive technology is required to implement it.
- **Interaction** - Different types of interaction were tried out. The left-hand-only manipulation method could provide a useful alternative to the standard keyboard modulation wheel in situations where the right hand is needed for pitch control using e.g. a keyboard. The naturalness of the interaction is affected by both the manipulation methods afforded by the virtual object and the sonification of the object and appears natural if inspired by the physical world.

5.8 Recommendations

Based on the experience with the implemented VMI environment the following recommendations and ideas can be listed for continuation and extension of the work:

- **Pragmatics** - There is a need to identify and address manipulation pragmatics in more detail, which should make manipulation of the virtual musical instrument easier because it will make a better use of already established movement patterns, while in some cases undesirable co-articulation of virtual object features may be avoided.

- **Manipulation vs. Signing** - The distance between the virtual object and the performer's hand(s) can perhaps be used to interpret hand movements that occur far from an object in terms of symbols, i.e. as gesticulation and/or signing (depending on the formalization), while hand movements in close proximity to an object can be interpreted as multidimensional continuous parameter changes, i.e. manipulation gestures.
- **Touch/Force** - Touch and force feedback will make the control of timing aspects of musical performance available, and also enable finer control of the virtual musical instrument.
- **Simulation** - To improve the behaviour of the virtual object in response to the manipulation by the performer more accurate and detailed (physical) models of 3D surfaces are needed.
- **Motion** - Virtual objects may have mass and hence gain momentum from manipulations, making autonomous motions or shape changes.
- **Fuzzy Boundary** - Force fields or fuzzy boundaries surrounding an object can be programmed to enable multiple objects to affect each other. Useful when different objects have intersecting motion paths.
- **Zones** - Spatial zones can be defined that alter the sound (e.g. sound effects are applied) when the object is placed in or moved through it.
- **Sonification** - A significant amount of work needs to be done to identify suitable methods to visualize sound in terms of features of a 3D virtual object. In addition, co-articulated virtual object features, whether desired or not, should be sonified such that they do not force the user to make unusual movements.
- **Real-time** - The speed of sensor data acquisition needs to increase while computational efficiency needs to improve in order to enable higher detail and tighter control of the sound parameters.
- **Wireless** - Wireless connections will make the CyberGlove and Polhemus sensors much easier to use.

- **Display** - For a better perception of the absolute position of the virtual object, useful for more accurate "touching" manipulations, a patterned background with depth clues as well as a 3D display may be helpful.
- **Multi-object** - An expansion of the environment where multiple virtual musical instruments, each representing an auditory stream such as notes and/or speech, can be accessed and controlled will enable a conductor and orchestra performance configuration.
- **Multi-user** - The environment can be expanded to a configuration where multiple (remotely networked) performers control each their own virtual musical instrument or together one virtual musical instrument.
- **Other Domains** - The developed interaction methodology may be applied to other domains, such as the editing of texture, color and lighting of graphical objects.

Chapter 6

Conclusion

What can be learned from the musical instrument design experiment involving advanced human movement tracking technology described in this dissertation ?

The main result of the research is that a prototype of an environment for design of virtual instruments with 3D geometry has been successfully implemented, allowing real-time performance in 3D and adaptation to exploit many manipulation gestures.

While this result is encouraging, the preliminary evaluation of the environment showed that for a natural interaction to take place the user or performer should be able to:

- 1. apply manipulation methods used in everyday life to change shape, position and orientation of the virtual object
- 2. believe that the sonification of the virtual object is qualitatively and directly related to the variations in virtual object shape position and orientation.

Contribution in Context

If we examine the results in the context of the discussion in chapter 2, the contribution of this research appears tiny, as the implemented VMI prototypes appear such rudimentary musical instruments, unable to withstand any comparison with traditional, real acoustic instruments. While adaptation is virtually unlimited within the VMI environment, such adaptations still require a significant amount of technical expertise. Nevertheless, in comparison, similar adaptations of physical instruments not only require an equal or greater amount of technical expertise but are also limited by the laws of physics. On the other hand, physical instruments offer the musically very useful tactile and (usually) force feedback.

In terms of human factors and gestural communication research, the work has shown the feasibility and usefulness of 3D interactive virtual input devices in a sound control task - further work is needed to demonstrate usefulness in other application domains. The value of the VMI environment as a virtual input device prototyping tool should not be underestimated. More on the theoretical side, different forms of sculpting pragmatics were identified.

In terms of music and performing arts research, exciting new possibilities for musical performance have been identified and shown to be technically feasible (though costly). A research and development path to realize these new performance possibilities has been identified. The virtual modulation wheel, although much work is needed to find an appropriate implementation, is one of the many examples of new virtual controllers that can be prototyped in the VMI environment. Last but not least, it would easily be overlooked that Max/FTS, a state of the art sound and music programming environment, has been extended with a gesture analysis library of software objects.

Future Work

Future work should address an important question that arose from this research:

To what extent do performers really want their musical instruments adapted during their career, if they were given unlimited freedom to require such adaptation ?

This question can be answered by experimentation with a musical instrument design environment as was implemented for the research presented in this dissertation. While the current environment focusses on hand movements, future work may also address other types of human movement.

Furthermore, while chapter 5 includes detailed recommendations for how the current prototype can be expanded and improved, more generally future research on VMI's should concentrate on the identification of manipulation pragmatics, and their derived forms which are present in gesticulation and sign languages, as well as how movement features are co-articulated. Equal effort should be spent on identifying methods to visualize sound in terms of features of a 3D virtual object. While chapter 3 is a first attempt to cover some of these issues within the context of (virtual) musical instrument design, a more comprehensive understanding of these two elements is needed. This understanding will contribute to the creation of useful, effective and enjoyable new interaction methods. Engineering efforts should concentrate on the implementation of virtual object simulation techniques and faster sensor data acquisition, while whole-hand tactile and force feedback are most desirable for realization of more refined and immediate interaction.

Appendix: Operating Instructions

The Sound Sculpting application consists of two Max/FTS applications and one OpenInventor-based application that are all run on one multi-processor SGI machine with audio-serial option to connect to CyberGlove, Polhemus and footpedal. In the following sections the various components and options are explained and detailed. See the appendix "Max/FTS object reference" for details on the added functionality to Max/FTS.

Equipment

Equipment list:
1 SGI R10K multiprocessor such as an Onyx with audio-serial option (ASO)
1 Virtual Technologies left hand CyberGlove instrumented glove with serial interface
1 Virtual Technologies right hand CyberGlove instrumented glove with serial interface
3 Polhemus Fastrak 6 DOF sensors with one serial interface
1 RS232 to RS422 converter (Roland Sound Canvas 55 mkII can be used as such)
1 MIDI foot pedal or 1 Infusion Systems I-Cube Digitizer with TapTile sensor [103]
1 MIDI keyboard
headphones or sound amplifier with speakers
MIDI cables

Software:
IRCAM Max/FTS version 1.5.3 - real-time, graphical programming language
ssView - OpenInventor-based graphics command server

MIDI installation

MIDI can be operated on any of the 6 serial ports (usually tty72) of an SGI with ASO by typing "startmidi -n midiPort1 -p aso232 -d /dev/ttyd72". The name of the port will be "midiPort1", and a RS232 capable MIDI hardware interface, such as the Roland Sound Canvas 55 mkII, or an RS232 to RS422 converter in conjunction with an RS422 based MIDI interface should be used.

Max/FTS installation

To operate Sound Sculpting Max/FTS version 1.5.3 requires the shared objects libicube.so and libss.so to be linked at boot time. A file named .ftsbootload should be present in the directory /homedir and it should contain the lines:
ss /homedir/ss/fts/lib/irix6.2/libss.so
icube /homedir/ss/fts/lib/irix6.2/libicube.so

Hand Modeling and Virtual Object Processing

Max startup script "/homedir/ss/Max-hand" starts up Max/FTS with small audio buffers and MIDI (internal and via the serial port). The patch "handControl" is automatically opened.

Commands for hand.pat:
`reset` - button to initialize hand.pat (this takes about 11 seconds)
`point` - button to obtain one dataset from hand.pat
`stream` - switch to turn on/off continuous sampling from hand.pat
`draw` - switch to turn on/off sending out of drawing commands (make sure ssView is running first)

Commands for sheet.pat:
inlet 0 - expects 0 or 1 from switch to turn computation of the sheet on/off
inlet 1 - expects bang from button to initialize sheet.pat
inlet 2 - expects 0 or 1 from switch to turn on/off sending out of drawing commands (ssView

is required to display the graphics)
inlet 3 - expects 0 or 1 from switch to turn on/off clamping
inlet 4 - expects 0 or 1 from switch between holding left edge of sheet with left hand or entire sheet with both hands
inlet 5 - expects 0 or 1 from switch between only corners or entire fixing of the sheet
inlet 6 - switch to turn on/off touching the sheet with finger tips

Commands for graphicsS.pat:
`open` - button to open a shared memory buffer with key 1
`closeServer` - message to close ssView (if it is open in the first place, shared memory buffer with key 1 will still remain open)

Commands for balloon.pat:
inlet 0 - expects 0 or 1 from switch to turn computation of the balloon on/off
inlet 1 - expects 0 or 1 from switch to turn on/off sending out of drawing commands (ssView is required to display the graphics)
inlet 2 - expects 0 or 1 from switch to turn on/off clamping
inlet 3 - expects 0 or 1 from switch between holding balloon with left hand or with both hands
inlet 4 - expects 0 or 1 from switch between no fixing or entire fixing of the balloon
inlet 5 - switch to turn on/off touching the balloon with any finger joints

Commands for sheet-snd.pat:
inlet 0 - switch to turn computation and mapping of sheet features on/off

Commands for balloon-snd.pat:
inlet 0 - switch to turn computation and mapping of balloon features on/off

Commands for soundS.pat:
`send` - button to enable writing to shared memory buffer with key 2

Commands for note-color.pat:

`draw` - switch to turn on/off mapping of incoming MIDI notes to color of graphically displayed surface

Sound Synthesis

Max startup script "/homedir/ss/Max-sound" starts up Max/FTS with large audio buffers to avoid any clicks and both internal MIDI as well as serial port MIDI. The patch "soundControl" is automatically opened.

Commands for polySynth.pat:
`trig` - trigger a 10 second (duration can be set from within polySynth.pat) note from polySynth.pat
`beat` - switch to turn on/off pulsed sound from polySynth.pat
`intern` - button to increment MIDI channel for receiving MIDI notes (channel can also be set using the number box below it) from internal (to SGI) MIDI sources for polySynth.pat
`keyb` - button to increment MIDI channel for receiving MIDI notes (channel can also be set using the number box below it) from MIDI keyboard for polySynth.pat
`notes off` - button to turn off receiving any MIDI notes (channel is set using the number box beside it) from any MIDI source for polySynth.pat
slider - slider to set volume for any MIDI notes (channel is set using the number box beside it) from any MIDI source for polySynth.pat

Commands for soundR.pat:
`receive` - button to enable reading of shared memory buffer with key 2
(this buffer should be opened by starting up the Max-hand application, see below/above)

Max/FTS patches for Sound Sculpting

Below follows a brief description of the Max/FTS patches used to run the sound sculpting application. All these patches can be found in /homedir/ss/.

graphicsS.pat sets up and writes to the shared memory buffer with key 2 (the key number can be changed with the patch), which is read by ssView. In order to see the graphical hand and surface this patch is necessary.

hand.pat (figure 6.1) handles all the interfacing with the Polhemus and CyberGlove sensors, computes the 23 voxels of the hand model and sends drawing commands for drawing the hand (left hand is blue, right hand is red) to ssView. The gloves are calibrated for the hands of Axel Mulder. Sampling rate is default 40 Hz.

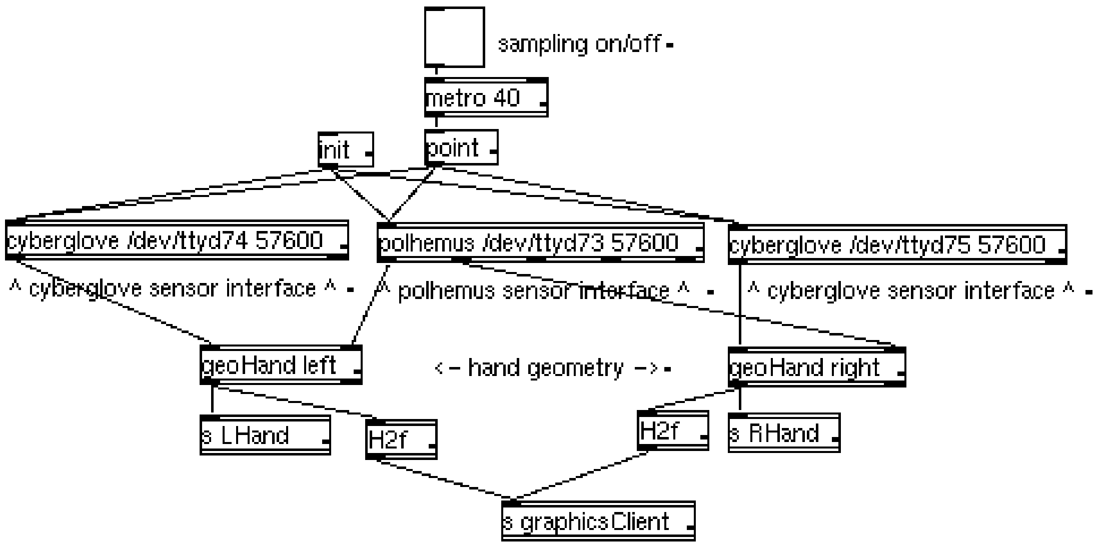

sampling on/off
metro 40
init
point
cyberglove /dev/ttyd74 57600
polhemus /dev/ttyd73 57600
cyberglove /dev/ttyd75 57600
^ cyberglove sensor interface ^
^ polhemus sensor interface ^
^ cyberglove sensor interface ^
geoHand left
<– hand geometry –>
geoHand right
s LHand
H2f
H2f
s RHand
s graphicsClient

Figure 6.1: The Max/FTS patch hand.pat for capturing hand shape, position and orientation (calibration capabilities omitted for clarity).

sheet.pat (figure 6.2) physically models a surface of two layers of masses connected through damped springs, in clamp mode attached to either both or only the left hand, and sends drawing commands for drawing the sheet to ssView. In touch mode the surface can be touched-up by “touching” with the indexes of the hand. All the sheet parameters can be set using this patch, default is a sheet of 10 (NW) x 10 (NL) nodes, with X0 = 2, Y0 = 2, Z0 = 4, K = 7.0, Q = 3.0, I = 15, DT = 0.05, FT = 0.05, R0 = 2.0 and IM = 10.

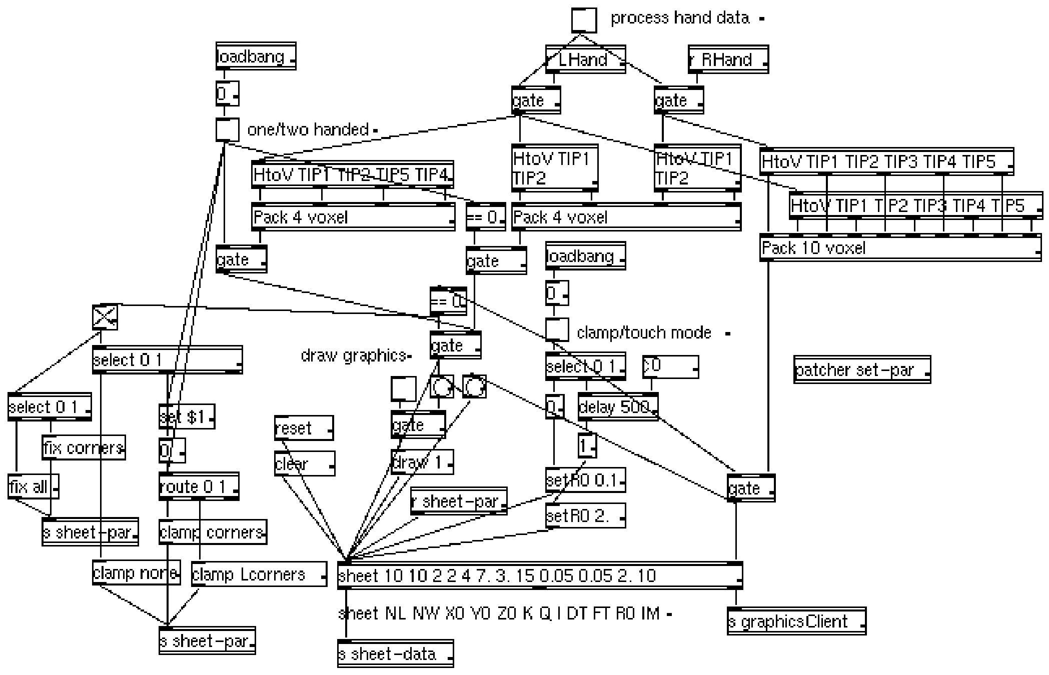


Figure 6.2: The Max/FTS patch sheet.pat for creating and controlling a physical simulation of a rubber sheet.

sheet-snd.pat (figure 6.3) computes features of the sheet computed with sheet.pat and maps the features to sound parameters. The features are average position of the sheet based on the position of the four corners (X value maps to reverb level, Y value maps to panning, Z value maps to vibrato), average curvature (maps to modulation index), average sheet width based on distances between corners (maps to high-pass amplitude), average sheet length based on distances between corners (maps to low-pass amplitude), angle between lines representing left edge and right edge of sheet calculated from the four corners, (maps to both attack and release time), average angle of the sheet with the vertical angle (maps to reverb time).

balloon.pat (figure 6.4), in clamp mode fits an ellipsoid to the hand data as acquired with hand.pat and estimates "roundness" for the surface to display based on finger bending using

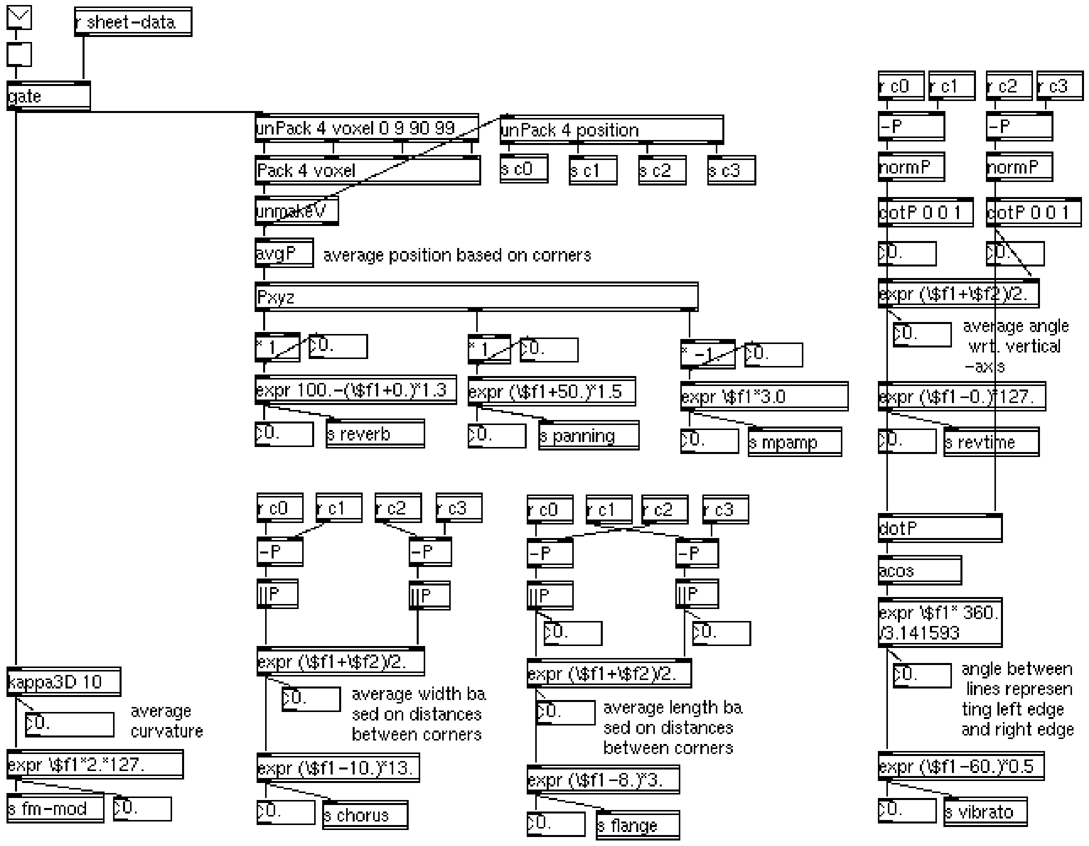


Figure 6.3: The Max/FTS patch sheet-snd.pat for mapping sheet features to sound parameters.

estE.pat (figure 6.5) and sends drawing commands for the resulting superquadric to ssView. In touch mode, the surface data computed last in clamp mode are used to initalize a physical model of a balloon-like surface of one layer of masses connected through damped springs, which surface can be touched-up by "touching" with any part of the hands. All the balloon parameters can be set using this patch, default is a sheet of 10 (NW) x 10 (NL) nodes, with X0 = 2, Y0 = 2, Z0 = 1, K = 0.9, Q = 0.6, I = 5, DT = 0.1, FT = 0.1, R0 = 4.0 and IM = 10.

balloon-snd.pat (figure 6.6) fits an ellipsoid to the surface data as computed with balloon.pat and maps the parameters to sound parameters. The computed parameters are center of mass

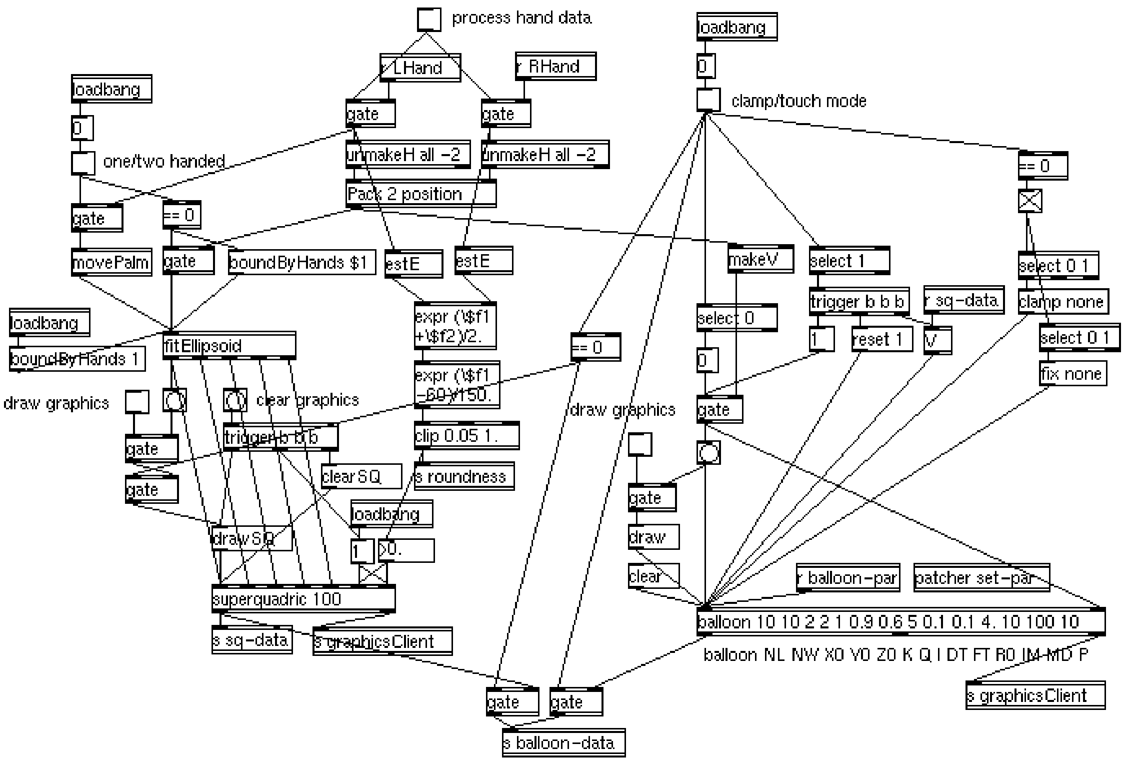


Figure 6.4: The Max/FTS patch balloon.pat for creating and controlling a physical simulation of a rubber balloon.

position (X value maps to reverb level, Y value to panning and Z value to vibrato), orientation (angle with vertical axis maps to reverb time), longitudinal size dimension (maps to flange index), transversal surface area (maps to chorus depth), chorus depth and “roundness” (maps to frequency modulation index), .

soundS.pat and soundR.pat respectively write to and read from shared memory buffer with key 2 (the key number can be set with the patch) the sound parameters for polySynth.pat. These patches are required to send the sound parameters computed from the surface manipulated using Max-hand and ssView, to Max-sound.

synth.pat (figure 6.7) synthesizes polyphonic sound using multiple Voice patches (figure

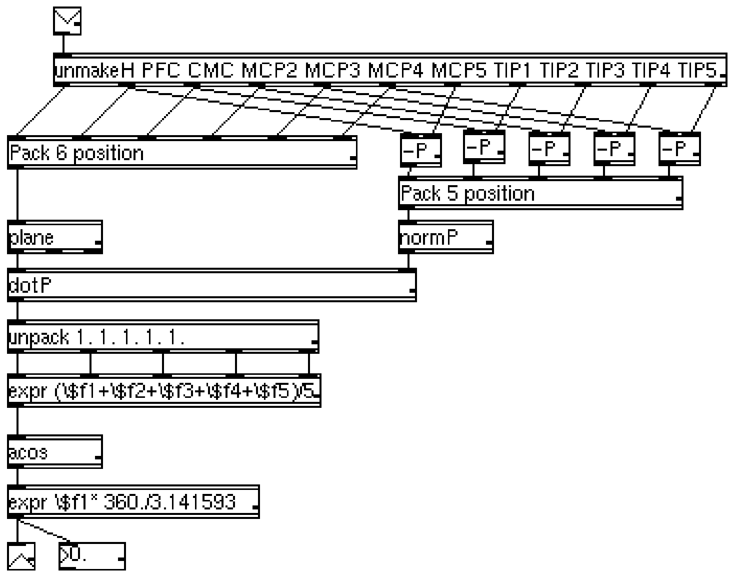


Figure 6.5: The Max/FTS patch estE.pat for estimating the hand curvature - used to set the "roundness" of the balloon.

6.9) in polySynth.pat (figure 6.8). Available parameters are note pitch, note velocity, note duration, vibrato, frequency modulation index, attack time, release time, low-pass amplitude, mid-pass amplitude, high-pass amplitude, flange index, chorus index, reverb level, reverb time, panning, master volume.

note-color.pat maps incoming single channel MIDI note pitch and velocity to RGB color values, perhaps useful when keyboard or MIDI file is used to set pitch and velocity values of the sound.

Graphics

When running the sound sculpting application as described above, the virtual object used as virtual input device can be graphically displayed using "/homedir/ss/ssView -k 1".

The command syntax is ssView -k keyNumber (when shared memory is used) or ssView

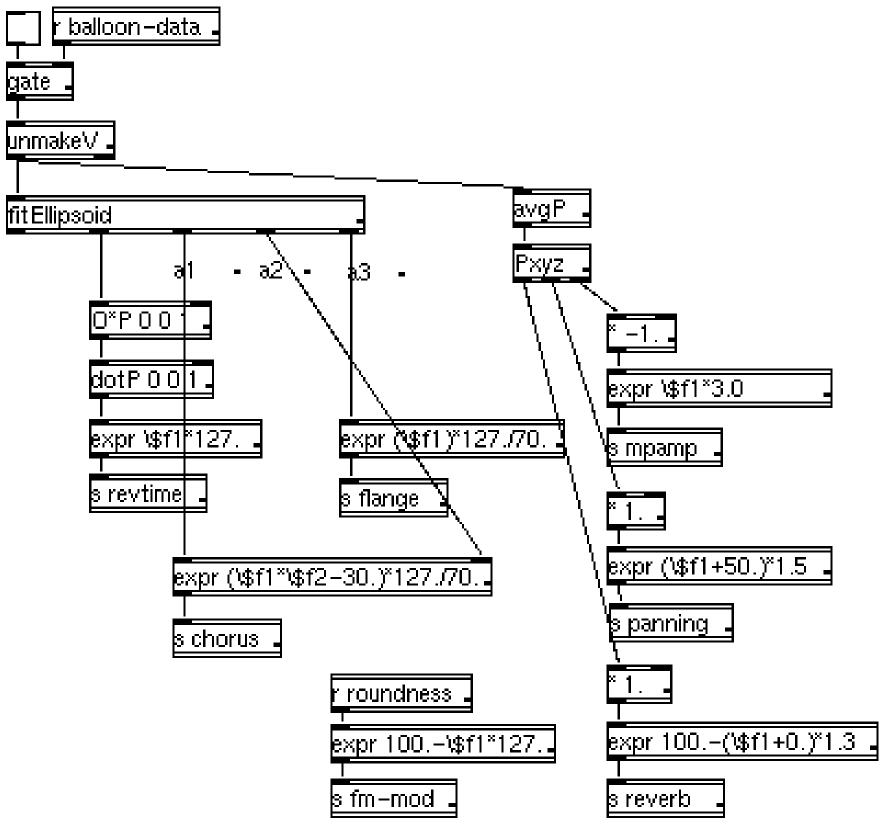


Figure 6.6: The Max/FTS patch balloon-snd.pat for mapping balloon features to sound parameters.

-p portNumber (when TCP sockets are used).

The graphics display program ssView accepts the following commands:

`closeServer` - close the graphics display program

`rotateCamera $1 $2 $3 $4` - rotate the camera of the graphics window using angle axis values x, y, z, theta respectively

`newLine $1 $2 $3 $4` - create a new line in the graphics window with name $1 and colors r, g, b (8 bit values) respectively

`deleteLine $1` - delete the line with name $1

`addToLine $1 $2 $3 $4` - add to the line with name $1 the coordinates $1 $2 $3

`clearLine $1` - clear the line with name $1
`super2D $1 $2 $3 $4` - draw a superquadric 2D curve with e1, a1, a2 and precision $4
`super2Dtrans $1 $2 $3 $4 $5 $6 $7` - transform (translate and rotate) the superquadric 2D curve using parameters x, y, z (translation) and angle axis parameters a1, a2, a3, theta
`super3D $1 $2 $3 $4` - draw a superquadric 3D virtual object with e1, a1, a2 and precision $4
`super3Dtrans $1 $2 $3 $4 $5 $6 $7` - transform (translate and rotate) the superquadric 2D curve using parameters x, y, z (translation) and angle axis parameters a1, a2, a3, theta
`handColor $1 $2 $3` - change the color of the hand stick figure to color r, g, b
`handCoords $1 $2 ..$70` - draw a hand stick figure of the left ($1 == 1) or right ($1 == 0) hand using the coordinates given in $2 ..$70 (coordinates of respectively CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR)
`sheetColor $1 $2 $3` - change the color of the sheet to color r, g, b
`sheetCoords $1 $2 $3 ..` - draw a sheet with $1 nodes in the length direction hand $2 nodes in the width direction, given the $1 * $2 coordinates specified as triplets $3 $4 $5 etc.

Bugs: Whenever Max/FTS crashes shared memory may be left open - closing ssView will not close the shared memory. Remove the shared memory by using “ipcs” (to see IDs of opened shared memory and semaphores) and ipcrm -m ⟨ memory ID ⟩ (to remove shared memory) and ipcrm -s ⟨ semaphore ID ⟩ (to remove semaphores)

The OpenInventor [97] source code for ssView can be found in /homedir/fts/dev/src/graphics/, files userIF2.c++, hand2.c++, serverLib.c, buffer.c, superQuad.c++, superQuad3D.c++, line.c++.

Running Sound Sculpting

Having read all of the above, you are now ready to startup sound sculpting. The procedure for starting up is:

connect and turn on all equipment
run “Max-hand”

initialize the Cyberglove and Polhemus sensors
run “Max-sound”
run “ssView -k 1”
now you can select various options from the two Max windows

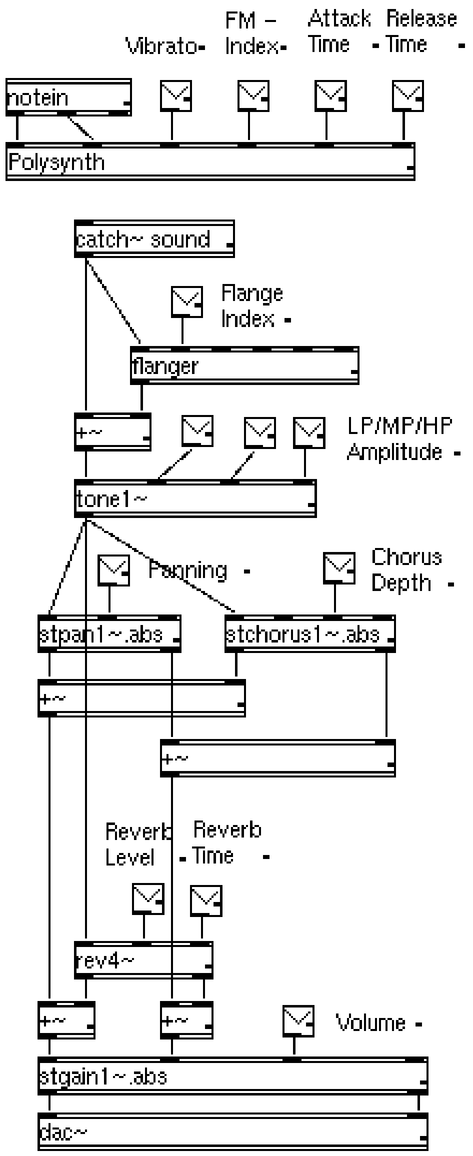


Figure 6.7: The Max/FTS patch synth.pat for polyphonic sound synthesis including all sound effect parameters. The polySynth object is shown in figure 6.8 as a patch.

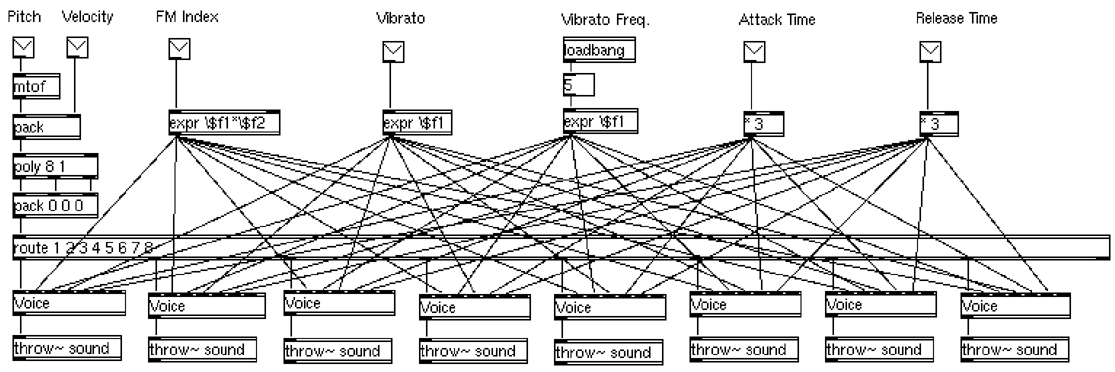


Figure 6.8: The Max/FTS patch polySynth.pat for polyphonic (8 voices) sound synthesis - each Voice object is the patch shown in figure 6.9.

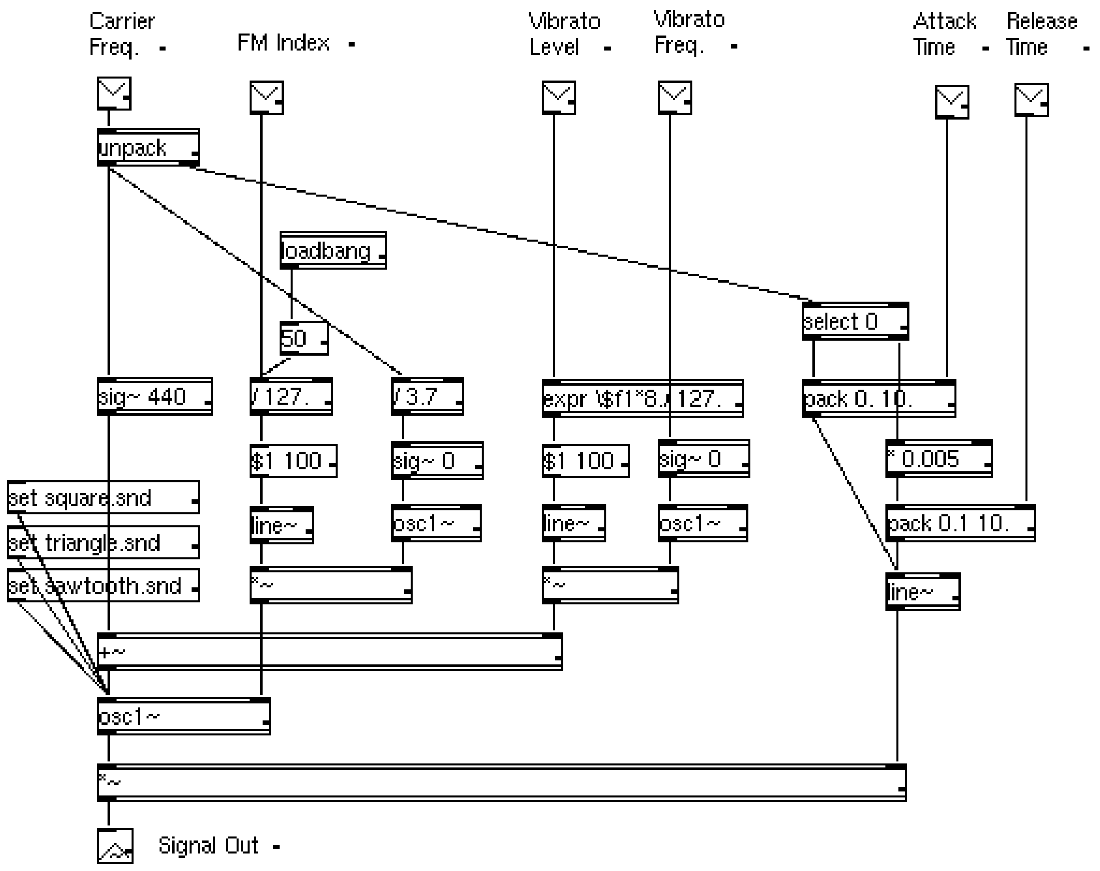


Figure 6.9: The Max/FTS patcher Voice for synthesis of a single voice. Different timbres could be created by using different waveforms for the oscillator.

Appendix: Max/FTS Object Reference

The following details the Max/FTS objects that were added to the Max/FTS environment specifically for the purpose of sound sculpting.

Communication

sms

Send data to other applications on the same machine or to the same Max/FTS (like standard send object) using shared memory with semaphores.

Object argument: default key (integer value)

Commands:
`openSmem $1` - sets up shared memory buffer with key $1
`closeSmem` - closes shared memory buffer opened with openSmem
`lowPrec` - cuts floats to only one decimal when writing in shared memory buffer
`printTime` - print time in ms required to write complete message in shared memory buffer
`printData` - show debug messages

Bugs: Whenever Max/FTS crashes shared memory may be left open. Remove the shared memory by using "ipcs" (to see opened shared memory) and ipcrm -m ⟨ memory ID ⟩ (to remove shared memory) and ipcrm -s ⟨ semaphore ID ⟩ (to remove semaphores)

Source code file: smem.c (shmemlib.c, buffer.c, ssutil.c)

smr

Receive data from other applications on the same machine or from the same Max/FTS (like standard receive object) using shared memory with semaphores.

Object argument: default key (integer value)

Commands:
`attachSmem $1` - attach to shared memory buffer with key $1
`closeSmem` - closes shared memory buffer opened with openSmem
`printTime` - print time in ms required to read complete message from shared memory buffer and send it out the outlet
`printData` - show debug messages

Source code file: serial.c (shmemlib.c, buffer.c, ssutil.c)

serial

Send and receive characters via the serial port using a Unix character device driver. Note that a message received in any of the inlets is immediately sent out, rather than usual waiting for a message in the leftmost inlet.

Object argument: number of serial ports to interface (on the Onyx at most 6)

Commands:
send it out the outlet
`open $1 $2 $3` - open serial device $1 at $2 baud on inlet and outlet $3 `close $1` - close device $1 `printTime` - print time in ms required to receive a complete message and
Source code file: serial.c (unixIO.c, ssutil.c)

client

Send and receive characters using TCP sockets using a Unix character device driver.

Object arguments: client name (e.g. "MaxClient"), machine name (e.g. "miris66"), machine port number (e.g. 2000)

Commands:
send it out the outlet
`connect` - connect as client name to the machine with name and port as specified in object argument
`disconnect` - disconnect from machine `addCR` - end each sent message with a carriage return
`noCR` - do not add a carriage return at end of message `printTime` - print time in ms required to receive complete message and
Source code file: client1.c (comtools.c, clientLib.1.c, ssutil.c)

Sensor Interfaces

cyberglove

Interface the Virtual Technologies Cyberglove instrumented glove via the serial port using a Unix character device driver. See also the Cyberglove manual.

Alternate object names: cg

Object arguments: serial device name (e.g. "ttyd1"), baud rate (upto 115200)

Commands: (with reference to the Cyberglove manual [101])
`point` - request one data set from Cyberglove
`stream` - set Cyberglove to continuously send data sets
`stop` - stop stream mode
`gain $1 ... $18` - set gain of all 18 sensors
`offset $1 .. $18` - set offset of all 18 sensors
`light $1` - turn on or off LED of Cyberglove

`rad` - output angles in radians
`deg` - output angles in degrees
`raw` - output angles in units as sent by Cyberglove (degrees)
`cal $1 $2 $3 $4 $5` - calibrate sensor $1 so that raw values $2 and $4 result in values $3 and $5 respectively
`calall $1 .. $72` - calibrate all sensors (sequentially named cmc_rot, mcp1_flex, pip1_flex, cmc_abd, mcp2_flex, pip2_flex, mcp3_flex, pip3_flex, mcp3_abd, mcp4_flex, pip4_flex, mcp4_abd, mcp5_flex, pip5_flex, mcp5_abd, palm_arch, wrist_flex, wrist_abd) as above in one fell swoop
`init` - initialize the Cyberglove
`reset` - reset the Cyberglove
`printTime` - print time in ms required to receive complete dataset
`printTTime` - print time in ms required to receive complete dataset and send it out the outlet
`printData` - show debug messages

Source code file: cg.c (unixIO.c, ssutil.c)

polhemus

Interface the Polhemus Fastrak 6 DOF sensor via the serial port using a Unix character device driver. See also the Polhemus manual.

Alternate object names: ph

Object arguments: serial device name (e.g. “ttyd1”), baud rate (upto 115200)

Commands: (with reference to the Fastrak manual [100])
`point` - request one data set from Fastrak
`stream` - set Fastrak to continuously send data sets
`stop` - stop stream mode
`boref $1 $2 $3 $4 $5` - see Fastrak manual
`bore` - see Fastrak manual
`unbore` - cancel `bore` command
`origin $1 .. $11` - see Fastrak manual

`unorigin` - cancel `origin` command
`metal` - correct for errors due to ferro magnetic materials in field of Fastrak emitter
`unmetal` - stop correcting for errors due to ferro magnetic materials in field of Fastrak emitter
`inch` - output data in inch
`cm` - output data in cm
`rad` - output angles in radians
`deg` - output angles in degrees
`binary` - set Fastrak to binary data format mode
`print` - print out current settings of Fastrak
`port $1 $2` - open Fastrak on serial device $1 at baudrate $2
`init` - initialize the Fastrak
`reset` - reset the Fastrak
`printTime` - print time in ms required to receive complete dataset `printTTime` - print time in ms required to receive complete dataset and send it out the outlet
`printData` - show debug messages

Source code file: ph.c (unixIO.c, ssutil.c)

Position Computing

P

Store and output the position(s) received in the inlet. When banged, output the last received position(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

+P

Add the position(s) received in left and right inlets. If the left inlet receives less positions than the right inlet, only as many positions as were received by the left inlet will be output.

If the right inlet only receives one position, all the positions received in the left inlet will use the position received in the right inlet as the other operand. When banged, output the last computed position(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

$-$P

Subtract the position(s) received in left and right inlets. If the left inlet receives less positions than the right inlet, only as many positions as were received by the left inlet will be output. If the right inlet only receives one position, all the positions received in the left inlet will use the position received in the right inlet as the other operand. When banged, output the last computed position(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

$*$P

Multiply the position(s) received in left and right inlets. If the left inlet receives less positions than the right inlet, only as many positions as were received by the left inlet will be output. If the right inlet only receives one position, all the positions received in the left inlet will use the position received in the right inlet as the other operand. When banged, output the last computed position(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

crossP

Compute the cross product of the position(s) received in left and right inlets. If the left inlet receives less positions than the right inlet, only as many positions as were received by the left inlet will be output. If the right inlet only receives one position, all the positions received in the left inlet will use the position received in the right inlet as the other operand. When banged, output the last computed value(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

dotP

Compute the dot product of the position(s) received in left and right inlets. If the left inlet receives less positions than the right inlet, only as many positions as were received by the left inlet will be output. If the right inlet only receives one position, all the positions received in the left inlet will use the position received in the right inlet as the other operand. When banged, output the last computed value(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

normP

Compute the norm of the position(s) received in the inlet. When banged, output the last computed value(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

||P

Compute the magnitude of the vector represented by the position(s) received in the inlet. When banged, output the last computed magnitude(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

avgP

Compute the average position of the positions received in the inlet. When banged, output the last computed position.

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

Pxyz

Output position(s) using the value(s) received in the inlets for x, y, z. When banged, output the last computed position(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

xyzP

Output x, y and z value(s) using the position(s) received in the inlets. When banged, output the last computed value(s).

Object arguments: initial values for x, y and z (float or integer values)

Source code file: position.c (ssutil.c)

bufP

Buffer positions received in the inlet. When banged, output the last received positions.

Object arguments: number of positions to buffer

Source code file: packPH.c (ssutil.c)

trigP

Output the position received in the inlet from left to right. When banged, output the last received position.

Alternate object names: tP

Object arguments: number of trigger outputs

Source code file: packPH.c (ssutil.c)

Orientation Computing

O$*$P

Compute the position(s) of the position(s) received in the right inlet re-oriented by the orientation received in the left inlet. When banged, output the last computed position(s).

Object arguments: initial values for x, y and z (float or integer values)

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: pos_orient.c (ssutil.c)

EtoO

Compute orientation(s) using the pitch, yaw and roll values received in the inlets. When banged, output the last computed orientation(s).

Object arguments: initial values for pitch, yaw and roll (float or integer values)

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

AAtoO

Compute orientation(s) using the angle axis value(s) (rotation angle theta and vector x, y, z) received in the inlets. When banged, output the last computed orientation(s).

Object arguments: initial values for rotation angle theta and vector x, y, z (float or integer values)

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

OtoAA

Compute the angle axis value(s) (rotation angle theta and vector x, y, z) using the orientation(s) received in the inlets. When banged, output the last computed angle axis value(s).

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

$*$O

Multiply the orientation received in left and right inlets. When banged, output the last computed orientation.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

O

Store and output the orientation received in the inlet. When banged, output the last received orientation.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

TO

Transpose the orientation received in the inlet. When banged, output the last computed orientation.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: orientation.c (ssutil.c)

Voxel Computing

makeV

Pack position(s) and orientation(s) input in either inlet into voxel(s).

Object arguments: default x, y, z for the position, pitch, yaw, roll for the orientation and x, y and z size parameters.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: voxel.c (ssutil.c)

unmakeV

Unpack voxel(s) into position(s) and orientation(s).

Object arguments: default x, y, z for the position, pitch, yaw, roll for the orientation and x, y and z size parameters.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: voxel.c (ssutil.c)

V

Store voxel(s) and output them when banged.

Object arguments: default x, y, z for the position, pitch, yaw, roll for the orientation and x, y and z size parameters.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: voxel.c (ssutil.c)

drawV

Output drawing commands to display the received voxel's data graphically.

Object arguments: default x, y, z for the position, pitch, yaw, roll for the orientation and x, y and z size parameters.

Commands:
`print` - print out in Max window all received and currently computed data

Source code file: voxel.c (ssutil.c)

Hand Computing

geoHand

Compute positions and orientations of all 23 joints of the hand model using Cyberglove and Polhemus data.

Alternate object names: worldcoordinates, wc, gh

Object arguments: handedness (i.e. "left", "right"), dataformat (i.e. "hand", "voxel", "position" or "float")

Commands:
`right` - compute right hand model
`left` - compute left hand model
`tune $1 $2` - set parameter $1 to value $2 ($1 = 0: adjust CMC orientation; $1 = 1: adjust MCP1 orientation; $1 = 2 and $1 = 3: adjust orientation of RCUC2, a virtual joint to create a more realistic palm)
`printTime` - print time in ms required to compute complete dataset
`printTTime` - print time in ms required to compute complete dataset and send it out the outlet

Source code file: wc.c (ssutil.c)

VtoH

Pack voxels received in the inlets into a hand data structure.

Object arguments: handedness (“left”, “right”) and subsequently at most 23 character strings (CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR) indicating which joints should be added in the hand datastructure and in which order they are received in the inlets

Source code file: packPH.c (ssutil.c)

HtoV

Unpack a hand data structure received in the inlet as voxels.

Object arguments: at most 23 character strings (CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR) indicating which joints should be output from the hand datastructure or the character string “all” to indicate that all joints should be output.

Source code file: packPH.c (ssutil.c)

makeH

Pack positions received in the inlets into a hand data structure.

Object arguments: handedness (“left”, “right”) and subsequently at most 23 character strings (CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR) indicating which joints should be added in the hand datastructure and in which order they are received in the inlets

Source code file: packPH.c (ssutil.c)

unmakeH

Unpack a hand data structure received in the inlet as positions.

Object arguments: at most 23 character strings (CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR) indicating which joints should be output from the hand datastructure or the character string "all" to indicate that all joints should be output (an additional integer value can be used to omit, counting from the end of the above list of joints, a specific number of joints)

Source code file: packPH.c (ssutil.c)

Hlist

Convert a hand data structure to a list message with first atom containing the symbol "handCoords", second atom containing 0 (right) or 1 (left) representing handedness and the remaining atoms the x, y, z value pairs of the joints.

Alternate object names: H2f, Hand2floats, Htof, Hmsg

Object arguments: at most 23 character strings (CMC, MCP1, PIP1, TIP1, MCP2, PIP2, DIP2, TIP2, MCP3, PIP3, DIP3, TIP3, MCP4, PIP4, DIP4, TIP4, MCP5, PIP5, DIP5, TIP5, PFC, RCUC, PHR) indicating which joints should be added to the list message (and in which order) or the character string "all" to indicate that all joints should be added

Source code file: packPH.c (ssutil.c)

Virtual Object Processing

superquadric

Compute surface voxels (left outlet) and output graphical drawing commands (right outlet) for a superquadric virtual object given the inlet data values for center position, orientation, size parameters a1, a2, a3 and shape parameters e1 and e2. A superquadric surface is defined by the 3-D vector

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_1 \cos^{\epsilon 1}(\eta)\cos^{\epsilon 2}(\omega) \\ a_2 \cos^{\epsilon 1}(\eta)\sin^{\epsilon 2}(\omega) \\ a_3 \sin^{\epsilon 1}(\eta) \end{bmatrix} \begin{array}{l} where \\ -\pi/2 \leq \eta \leq \pi/2 \\ -\pi \leq \omega < \pi \end{array}$$

Alternate object names: SQ

Object arguments: number of points to compute (not the same as number of points to draw)

Source code file: sq.c (ssutil.c)

sheet

Compute surface voxels (left outlet) and drawing commands (right outlet) using a physical model of a sheet consisting of two layers of masses connected through damped springs. The left inlet expects voxels as clamping voxels for the corners, the right inlet can be used to input voxels to “touch” the sheet. Each time a surface node is touched, the middle outlet outputs that surface node as a voxel.
Object arguments: number of nodes in length direction (NL), number of nodes in width direction (NW), distance between nodes in lenght (X0), distance between nodes in width (Y), distance between nodes in height (Z0), spring constant (K), damping constant (Q), number of iterations in settling (I), time interval (DT), force threshold (FT), minimum radius for a node to be “touched” (R0), maximum touching history length (IM) - note that setting these parameters requires some trial and error to obtain a stable surface

Commands:
`reset` - setup the sheet roughly according to the current voxels received in the left inlet
`clamp $1` - set clamp nodes to the input voxels each time they are received in the left

inlet ($1 = `none`: do not clamp anything, `corners`: clamp only corner nodes such that the surface extends from the fingers, `Rcorners`: clamp only right corner nodes such that the surface extends from the fingers, `Lcorners`: clamp only left corner nodes such that the surface extends from the fingers, `corners`: clamp only corner nodes such that the surface is perpendicular to the fingers)
`fix $1` - fix the sheet, i.e. nodes cannot move ($1 = `none`: do not fix anything, `all`: fix all nodes, `clamp`: fix only the clamp nodes, `corners`: fix only the corner nodes, `Rcorners`: fix only the right corner nodes, `Lcorners`: fix only the corner nodes)
`draw $1` - output drawing command `sheetCoords` to draw the surface (0 = top layer only, 1 = both layers)
`clear` - output drawing command `sheetCoords` with NW = 0 and NL = 0 to clear the graphics
`drawF $1 $2 $3` - output line drawing commands to draw the forces using a color specified by r g b values on the nodes
`drawTF $1 $2 $3` - output line drawing commands to draw only the forces of touched nodes using a color specified by r g b values (0 0 0 turns drawing off, use `clearF` to erase existing forces from the display)
`clearF` - output line drawing commands to clear all the drawn forces on the nodes
`setX0 $1` - set the value of X0 to $1
`setY0 $1` - set the value of Y0 to $1
`setZ0 $1` - set the value of Z0 to $1
`setK $1` - set the value of K to $1
`setQ $1` - set the value of Q to $1
`setI $1` - set the value of I to $1
`setDT $1` - set the value of DT to $1
`setFT $1` - set the value of FT to $1
`setR0 $1` - set the value of R0 to $1
`setIM $1` - set the value of IM to $1
`printTime` - print time in ms required to compute complete dataset
`printTTime` - print time in ms required to compute complete dataset and send it out the outlet

Source code file: sheet.c (ism.c, ssutil.c)

balloon

Compute surface voxels (left outlet) and drawing commands (right outlet) using a physical model of a balloon consisting of one layer of masses connected through damped springs and with internal pressure. The left inlet expects voxels as clamping voxels (set with `clamp`), the right inlet can be used to input voxels to “touch” and modify the sheet. Each time a surface node is touched, the middle outlet outputs that surface node as a voxel.

Object arguments: number of nodes in length direction (NL), number of nodes in width direction (NW), distance between nodes in lenght (X0), distance between nodes in width (Y), distance between nodes in height (Z0), spring constant (K), damping constant (Q), number of iterations in settling (I), time interval (DT), force threshold (FT), minimum radius for a node to be “touched” (R0), maximum touching history length (IM), maximum distance for finding node to clamp (MD), internal pressure (P) - note that setting these parameters requires some trial and error to obtain a stable surface

Commands:
`reset $1` - setup the balloon as a sphere roughly according to the current voxels received in the left inlet or, if $1 == 1 and the current number of input voxels is equal to the nuber of surface voxels, setup the balloon taking the input voxels as surface voxels
`clamp $1` - find the clamp nodes nearest to the current input voxels and subsequently set the clamp nodes to the input voxels each time they are received in the left inlet ($1 = `none`: do not clamp anything, `topbot`: clamp only one top and one bottom node, `all`: clamp all nodes)
`fix $1` - fix the balloon, i.e. nodes cannot move ($1 = `none`: do not fix anything, `all`: fix all nodes, `clamp`: fix only the clamp nodes)
`draw` - output drawing command `sheetCoords` to draw the surface
`clear` - output drawing command `sheetCoords` with NW = 0 and NL = 0 to clear the graphics
`drawF $1 $2 $3` - output line drawing commands to draw the forces using a color specified by r g b values on the nodes
`drawTF $1 $2 $3` - output line drawing commands to draw only the forces of touched nodes using a color specified by r g b values (0 0 0 turns drawing off, use `clearF` to erase existing

forces from the display)
`clearF` - output line drawing commands to clear all the drawn forces on the nodes
`setX0 $1` - set the value of X0 to $1
`setY0 $1` - set the value of Y0 to $1
`setZ0 $1` - set the value of Z0 to $1
`setK $1` - set the value of K to $1
`setQ $1` - set the value of Q to $1
`setI $1` - set the value of I to $1
`setDT $1` - set the value of DT to $1
`setFT $1` - set the value of FT to $1
`setR0 $1` - set the value of R0 to $1
`setIM $1` - set the value of IM to $1
`setMD $1` - set the value of MD to $1
`setP $1` - set the value of P to $1
`printTime` - print time in ms required to compute complete dataset
`printTTime` - print time in ms required to compute complete dataset and send it out the outlet

Source code file: balloon.c (ism.c, ssutil.c)

Feature Computation

fitEllipsoid

Compute the ellipsoid parameters (outlets output center position, orientation, size parameters a1, a2, a3) that best fit a list of positions as input in the left inlet.

Alternate object names: fitE, fe

Commands:
`boundByHands` - if the input data is a position list representing both hands, scale the size of the ellipsoid to be within the given positions
`printTime` - print time in ms required to compute complete parameter set
`printTTime` - print time in ms required to compute complete parameter set and send it out

the outlets

Source code file: fe.c (nrutil.c, ssutil.c)

fitSuperquadric

Compute the superquadric parameters (outlets output center position, orientation, size parameters a1, a2, a3 and shape parameters e1 and e2) that best fit a list of positions as input in the left inlet.

Alternate object names: fitSuperquad, fitSQ, fSQ, fsq

Commands:
`boundByHands` - if the input data is a position list representing both hands, scale the size of the ellipsoid to be roughly within the given positions
`printTime` - print time in ms required to compute complete parameter set
`printTTime` - print time in ms required to compute complete parameter set and send it out the outlets

Source code file: fsq.c (nrutil.c, ssutil.c)

fitPoly

Compute upto 3 polynomial parameters (outlets output the polynomial coefficients) that best fit a list of positions (only x and y data are used) as input in the left inlet.

Source code file: fpoly.c (nrutil.c, ssutil.c)

fitPlane

Compute the parameters of a plane (outlets output normal vector as a position, Zis and chi square) that best fit a list of positions as input in the left inlet.

Alternate object names: fp

Source code file: fp.c (nrutil.c, ssutil.c)

kappa3D

Compute the average curvature (left outlet) computed from a list of voxels representing a 3D surface with width NW as input (left inlet).

Commands:
`width $1` - set the NW to $1

Source code file: curv.c (nrutil.c, ssutil.c)

kappa2D

Compute the average curvature (left outlet) computed from a list of positions representing a 2D curve (left inlet).

Source code file: curv.c (nrutil.c, ssutil.c)

Miscellaneous

unpackcg

Unpack a list message coming from the cyberglove object as separate floats for each sensor.

Alternate object names: upcg

Object arguments: at most 18 character strings (cmc_rot, mcp1_flex, pip1_flex, cmc_abd, mcp2_flex, pip2_flex, mcp3_flex, pip3_flex, mcp3_abd, mcp4_flex, pip4_flex, mcp4_abd, mcp5_flex, pip5_flex, mcp5_abd, palm_arch, wrist_flex, wrist_abd) indicating which sensors should output (and to which outlet).

Source code file: packPH.c (ssutil.c)

unPack

Unpack a list of hand, voxel, position or orientation data structures as separate data structures.

Object arguments: number of outlets, data format (“hand”, “voxel”, “position” or “orientation”)

Source code file: packPH.c (ssutil.c)

Pack

Pack data structures received in the inlets into a list of hand, voxel, position or orientation data structures.

Object arguments: number of inlets, data format (“hand”, “voxel”, “position” or “orientation”)

source code file: packPH.c (ssutil.c)

sin, asin, cos, acos, tan, atan

Compute the geometric functions of the value(s) received in the inlet. When a bang is received the last computed value(s) are output.

Object arguments: initial output value
Source code file: math.c (ssutil.c)

count

Count the bangs in the left inlet modulo the maximum count (can be set with right most inlet), increase the count with 1 (default) or the value received in the middle inlet.
Object arguments: maximum count value
Commands: `up $1` - set the increment to 1 or $1
`down $1` - set the increment to -1 or $1
`up $1` - set the increment to 0 or $1

`jump $1` - add $1 to the count modulo the maximum count value

`max $1` - set the maximum count value to $1

`jump $1` - set the count to $1 modulo the maximum count value

Source code file: count.c (ssutil.c)

Appendix: Video Documentation

A video entitled "Sound Sculpting" was made, documenting and explaining the implemented system. The contents of the video are as follows:

- **Intro** - preliminary shots of the system used in performance and motivation of the research [0:00:14 - 0:01:42].
- **Development Environment** - Schematic diagram and description of the system components [0:01:45 - 0:02:39].
- **Manipulation** - Demonstration of manipulation methods as described in section implemented for the rubber sheet [0:02:43 - 0:04:09] and balloon [0:04:09 - 0:04:47] models.
- **Mapping** - Demonstration of sonification methods as described in section implemented for the rubber sheet [0:04:50 - 0:07:44] and balloon [0:07:47 - 0:10:02] models.
- **Show Time** - Performance of music defined by MIDI sequences, using two hands for manipulation of the rubber sheet [0:10:07 - 0:11:09] and balloon [0:11:12 - 0:11:48] models.
- **Show Time** - Performance of music defined by MIDI sequences using left hand only for manipulation the rubber sheet [0:11:51 - 0:12:36] and balloon [0:12:41 - 0:13:09] models.

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