Towards a choice of gestural constraints for instrumental performers

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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.

This paper 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.

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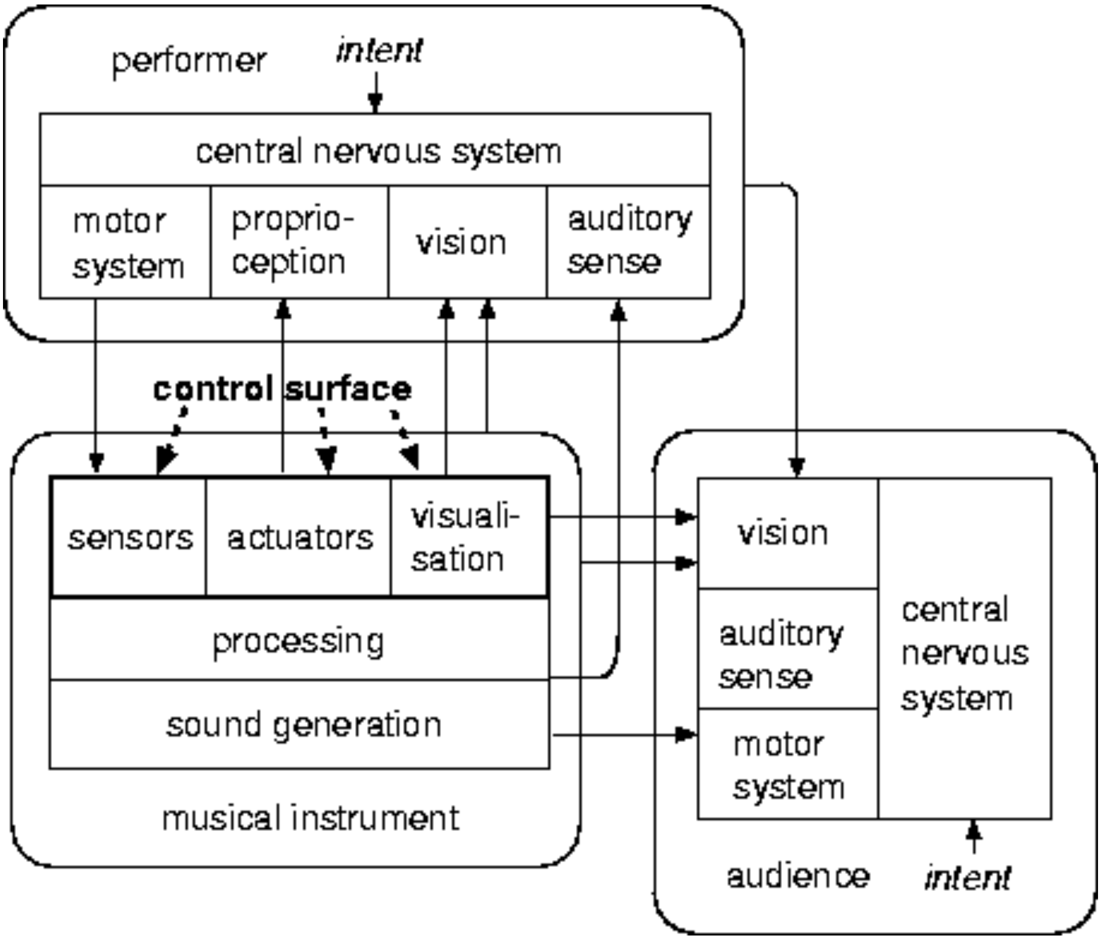

Fig. 1. A model of musical performance.

Drawing from Pressing [37], 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 1. Visual and proprioceptive feedback (tactile and force feedback) and communication are included. For the sake of giving humans credit for being so terribly 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.

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. In prosaic and poetic literature, gesture is often used to express an initiation or conclusion of some human-human interaction, where no human movement may be involved. 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,

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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.

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, which data is 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. 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.

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" [26].

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 [1].

- 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.

Human Factors and Gesture Communication Context

Human factors research addresses subjects like ergonomy, human interfacing, man-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" [34] leading to "transparency" of the interface. Interface aspects that constitute naturalness are understood to be

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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 [47]. 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 [14]. The research on performer instrument compatibility performed in this context has generally aimed at improving the usability of the interface [52], [53], for which estimation Shackel [44] 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.

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" ([21] and later amongst others [42]), deemed by some to arise from a level of performance uncertainty [40], 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 [54]. 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 [17], [15]. 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 [63], [62], [20], [64].

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 [35], [38], [13], [32], [5], [51], either completely new or extrapolated from traditional musical instruments (e.g. hyperinstruments [20]). 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), a modular, user-configurable sensing environment [60], 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.

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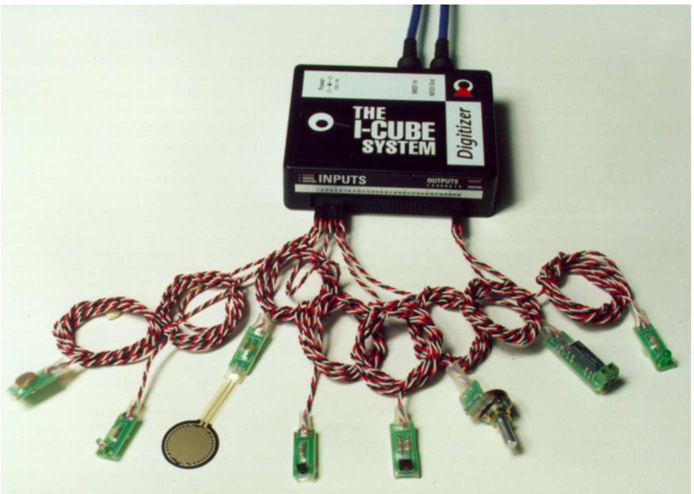

Fig. 2. The I-Cube System Digitizer and a few sensors. Courtesy Infusion Systems Ltd. [60]

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

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 3), an ergonomic physical control surface consisting of knobs, sliders and buttons [6]. 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.

Fig. 3. The aXiO. Courtesy Brad Cariou [6].

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 4) were developed [2]. 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 below) and alternate controllers requiring physical contact like the aXiO.

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Fig. 4. The "Hands". Courtesy Michel Waisvisz [65].

Lightning

Buchla's Lightning™ (figure 5) 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 [58]. 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 [19] applied neural networks to implement an adaptable mapping of conducting gestures to musical parameters.

Fig. 5. The Lightningt™ II. Courtesy Buchla and associates [58].

Radio Drum

Mathews and Boie's Radio Drum (figure 6) [22], 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 [43], [15].

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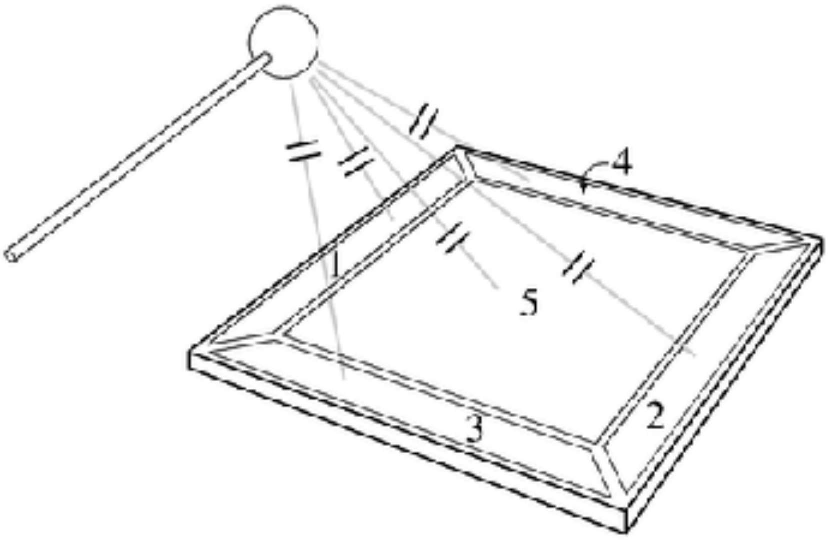

Fig. 6. The Radio Drum. Courtesy William Putnam and R. Benjamin Knapp. [41].

Theremin and Dimension Beam

The Theremin (figure 7a) is a well-known alternate controller [9], [23]. The Theremin uses two antennas to detect human body mass within a certain range of proximity, which results in the production of two control signals for pitch and volume. Gestures are effective only within the range of the sensing field, while the actual control surface is two-dimensional only.

The electric field technology used for the Theremin has been used in various other controller designs [36], [55], including a method to extract a more detailed hand geometry [49]. Using infrared tracking within an egg-like sensing field yielding one dimension of control, the Dimension Beam™ (figure 7b) [57] has similar limitations as the Theremin.

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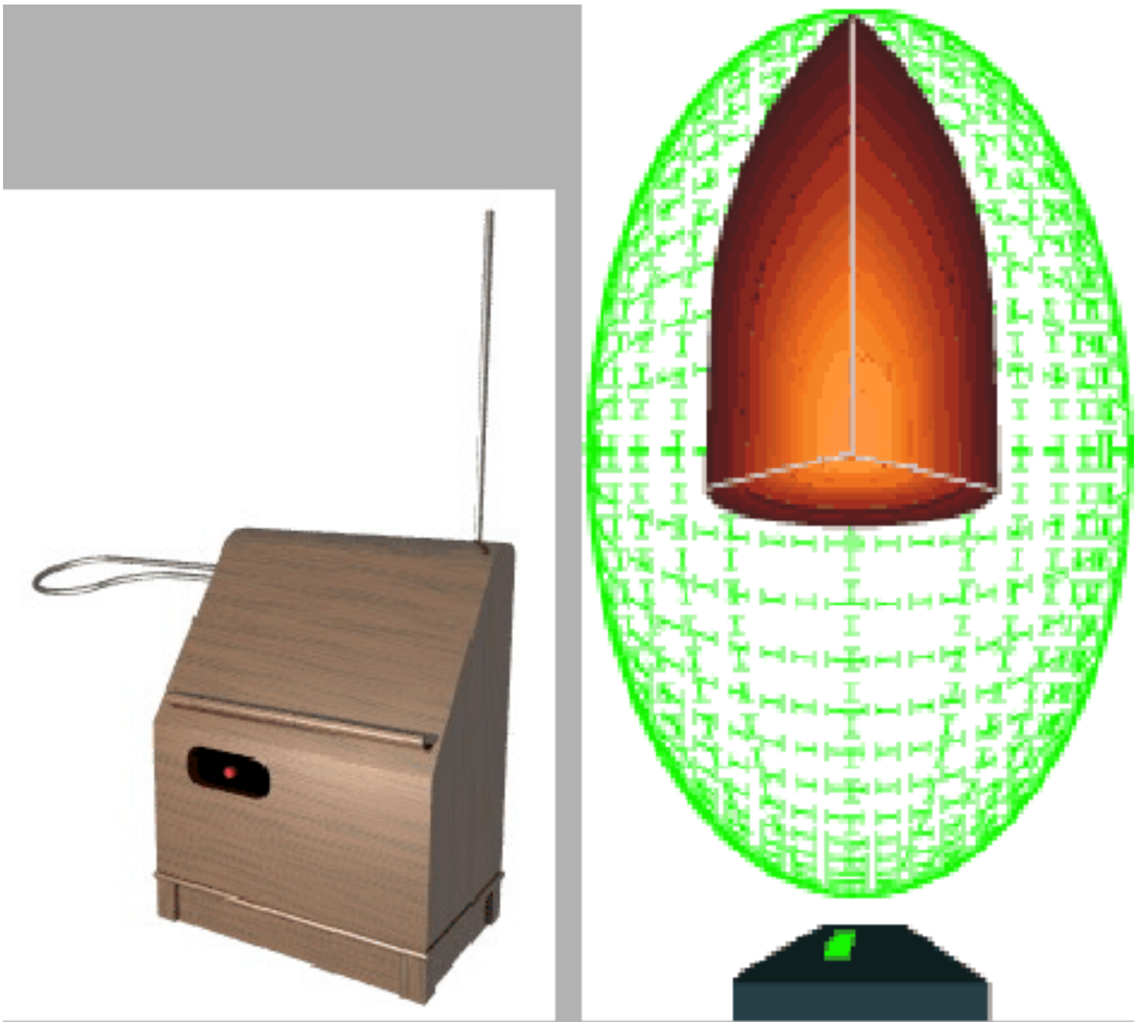
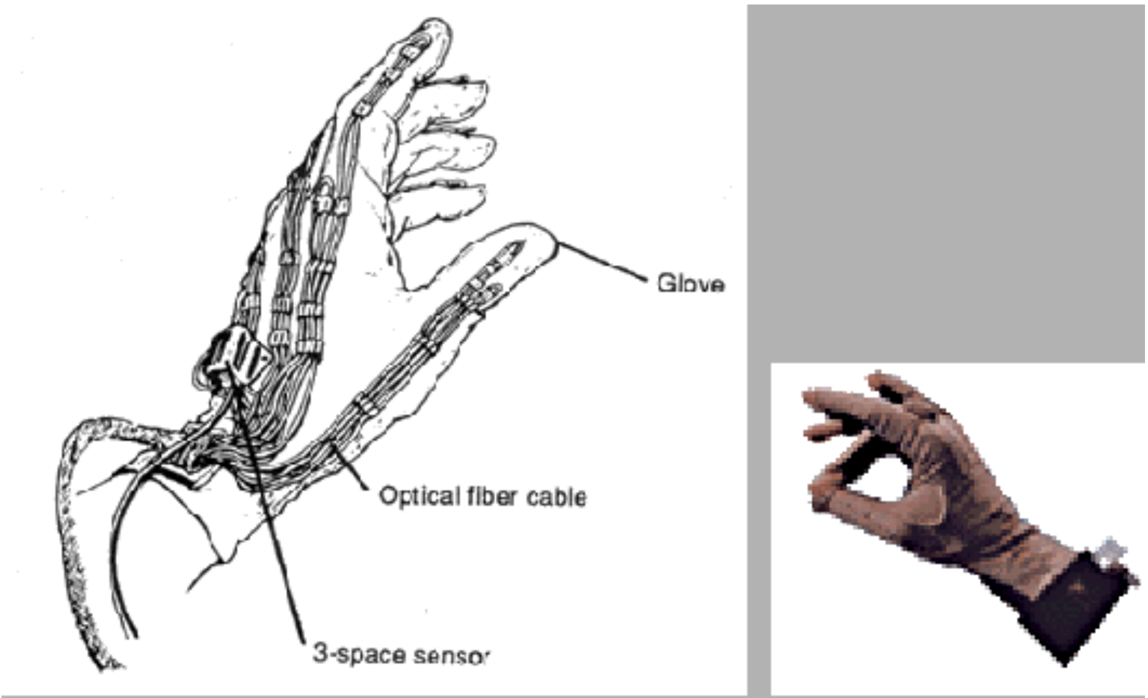


(a) A Theremin - the right antenna controls pitch, the left antenna controls volume. Courtesy Jason B. Barile [61].

(b) The sensing field of the Dimension Beam^{tm} . Courtesy Interactive Light Inc. [57].

Fig. 7. The Theremin and the Dimension Beam™.



(c) Drawing of the Dataglove, as originally made by VPL. Courtesy IEEE [27].

(d) The CyberGlove^{tm} . Courtesy Virtual Technologies [56].

Fig. 8. Examples of Datagloves.

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 8) 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 [31]. For immersive controllers, touch feedback and/or force feedback can only be provided in very limited form, if at all, with current technology [12], [3], [45], [46]. 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 due to the bandwidth of such feedback [7]. Immersive controllers can be loosely grouped as follows:

• Internal Controllers - Controllers with a control surface which visualization 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 which visualization 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.

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Internal Controllers

To experiment with controlling sound effects through whole body movements, a tightly fitting garment intended for use by dancers was made by the author [29]. 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 9). 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. 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.

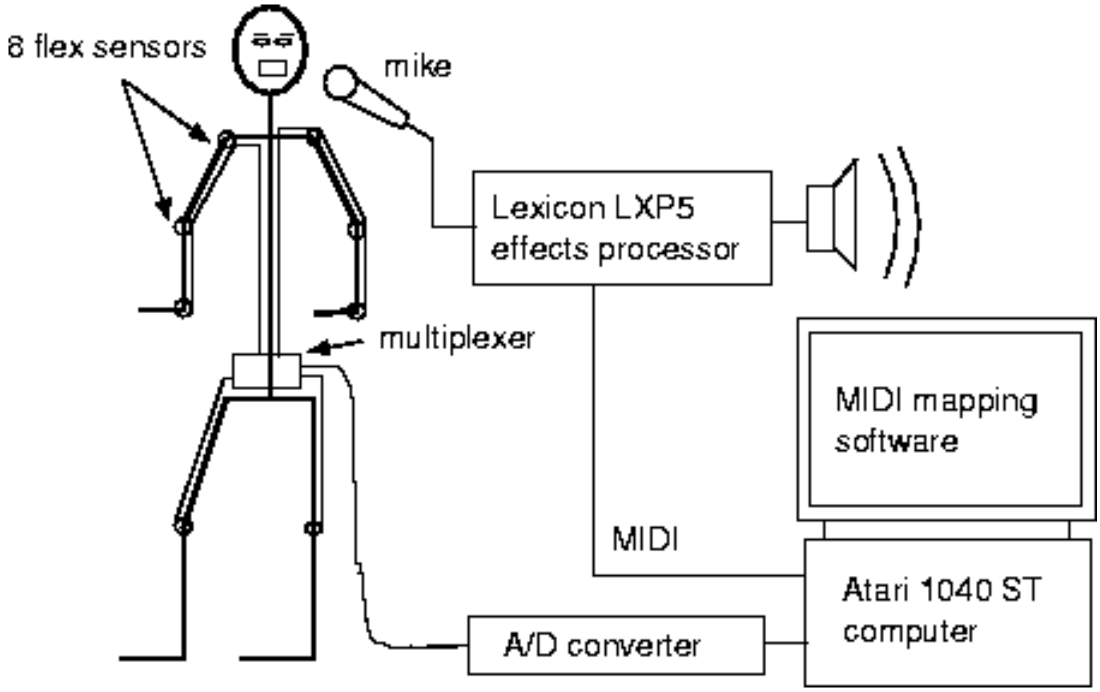

Fig. 9. Functional diagram of the bodysuit system.

The Biomuse [16] 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 [50], 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 [11] 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

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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 [10], in his implementation of a gesture to speech system (figure 10) used neural network technology and a variety of movement tracking technologies, including a Dataglove. 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. While a graphical display of the sound generating mechanisms of speech would most likely not facilitate but perhaps confuse control, a graphically displayed visualization of the control surface, indicating how to gesture, might have shortened the learning time.

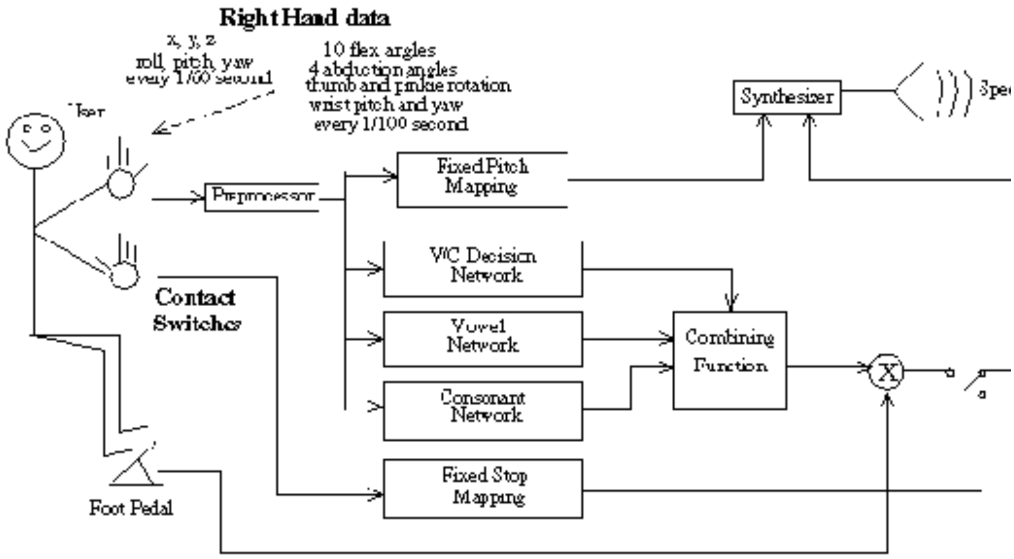

Fig. 10. Functional diagram of the GloveTalk II system. Courtesy Sidney Fels [10].

Video available in the original CD-Rom version. *Sound Sculpting*, by Axel Mulder, Sidney Fels and Kenji Mase. ATR MIC Research.

Symbolic Controllers

To experiment with symbolic controllers, the author used a Dataglove 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 [29]. Figure 11 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 seven different MIDI note-on pitch values. Each 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 seems 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.

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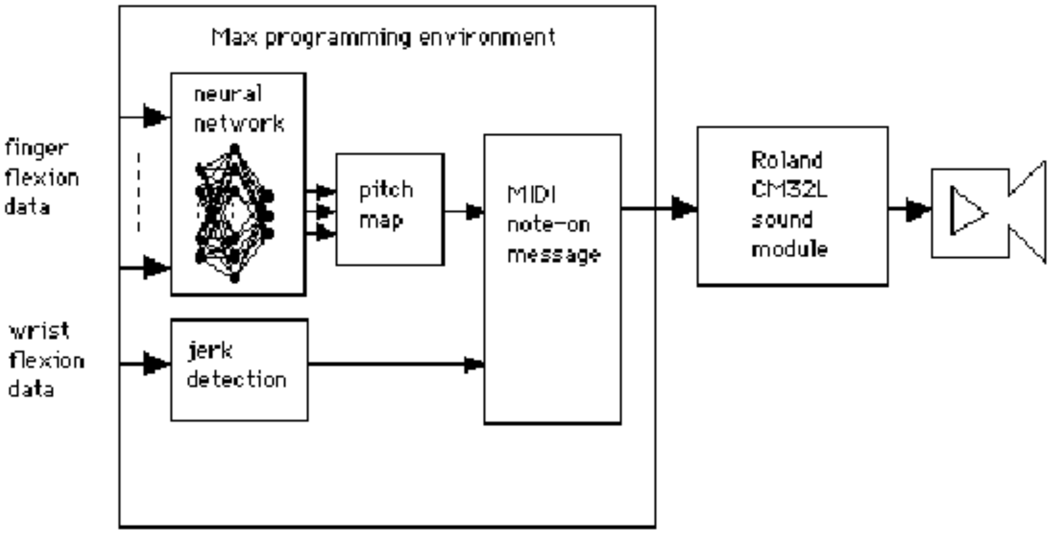

Fig. 11. Functional diagram of the Sign-drum.

The Miburi (figure 12) [59] 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.

Fig. 12. The Yamaha Miburi™. Courtesy Yamaha Corp. [59].

A virtual orchestra was implemented by Morita et al [27]. 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.

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Design of Gestural Constraints for Musicians

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 moved away from the constraints of physical contact and expanded the gestural capturing range in some areas, 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. They 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 [48]. 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 [30], 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 [24].

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 are not very conducive for the use of manipulation gestures as these gestures are much better executed with respect to a visualization and a 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.

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) [32].

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 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.

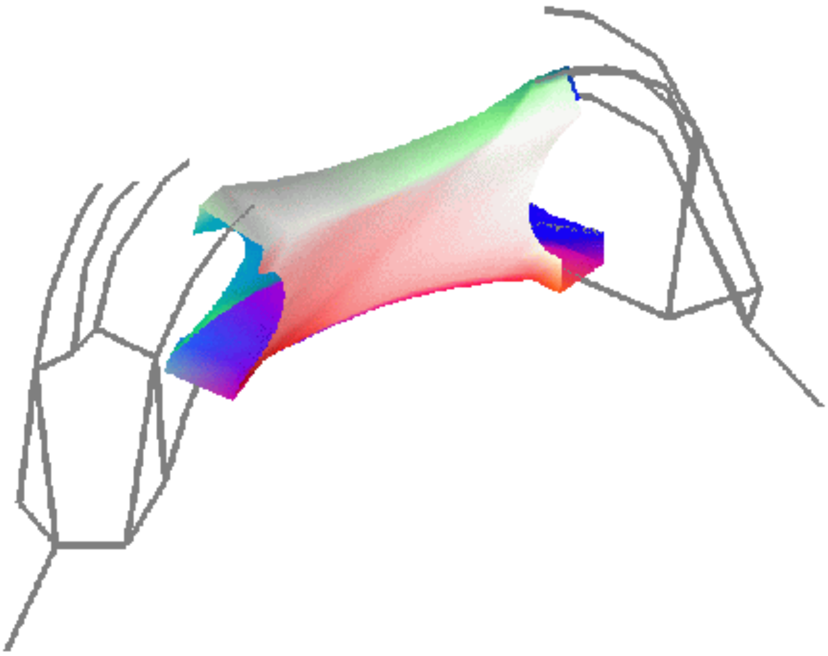

Fig. 13. Example of the sheet clamped to the index and thumb tips of both hands.

The Current State of the Art

A lot of work has been done on 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 [4], flutes [33], guitars and even a Theremin [4], with all the familiar limitations of the control surface of the original instrument. In very few cases researchers or artists like Lanier [18] have been able to develop their own variation of a VMI inspired on traditional musical instruments. Choi et al [8] developed a virtual environment in which 3D spatial paths were visualized [Editors' note: see the article by Choi," Manifold Interface...", in this volume]. 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 [25] has recently implemented "behaving virtual musical objects", simple 3D graphical objects with which the user can interact using 3D hand movements with musical results [Editors' note: see the article by Modler in this volume]. The author has prototyped an environment for the design of VMIs [28], allowing real-time sound editing and musical performance through manipulation of 3D virtual objects for now without haptic feedback due to technical limitations. The virtual objects used physical models to simulate shape variations, resulting in behaviours reminiscent of a rubber sheet and of a rubber balloon (figure 13 and 14). The virtual object position, orientation and shape variations were used to control sound timbre and spatialization parameters.

Fig. 14. Example of the balloon clamped to both hands.

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