Gestural Control of Music

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Abstract

Digital musical instruments do not depend on physical constraints faced by their acoustic counterparts, such as characteristics of tubes, membranes, strings, etc. This fact permits a huge diversity of possibilities regarding sound production, but on the other hand strategies to design and perform these new instruments need to be devised in order to provide the same level of control subtlety available in acoustic instruments. In this paper I review various topics related to gestural control of music using digital musical instruments and identify possible trends in this domain.

1 Introduction

The evolution of computer music has brought to light a plethora of sound synthesis methods available in general and inexpensive computer platforms, allowing a large community direct access to real-time computer-generated sound.

Both signal and physical models have already been considered as sufficiently mature to be used in concert situations, although much research continues to be carried on in the subject, constantly bringing innovative solutions and developments [8] [88] [64].

On the other hand, input device technology that captures different human movements can also be viewed as in an advanced stage [63] [7], considering both non-contact movements and manipulation[1]. Specifically regarding manipulation, tactile and force feedback devices for both non-musical[2] and musical contexts have already been proposed [12][3].

Therefore, the question of how to design and perform new computer-based musical instruments – consisting of gesturally controlled, real time computer-generated sound – need to be considered in order to obtain similar levels of control subtlety as those available in acoustic instruments.

This topic amounts to a branch of knowledge known as *human-computer interaction (HCI)*[4]. In this context, various questions come to mind, such as:

- Which are the specific constraints that exist in the musical context with respect to general human-computer interaction?
- Given the various contexts related to interaction in sound generating systems, what are the similarities and differences within these contexts (interactive installations, digital musical instrument manipulation, dance-music interfaces)?
- How to design systems for these various musical contexts? Which system characteristics are common and which are context specific?

1.1 Human-Computer Interaction and Music

Gestural control of computer generated sound can be seen as a highly specialized branch of human-computer interaction (HCI) involving the *simultaneous control of multiple parameters*, *timing*,

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[1] With the exception of extreme conditions, such as 3-dimensional whole-body acquisition in large spaces

[2] For a survey on haptic devices, check the Haptics Community Web page at: *http://haptic.mech.mwu.edu/*

[3] Even so, many users still use the traditional piano-like keyboard as the main input device for musical interaction. This situation seems to be equivalent to the ubiquitous role played by the mouse and keyboard in traditional human-computer interaction (HCI).

[4] For general information on human-computer interaction, the reader is directed to general textbooks, such as [25] or to the ACM SIGCHI webpage at: *http://www.acm.org/sigchi/*

rhythm, and *user training* [62]. According to A. Hunt and R. Kirk [39]:

> In stark contrast to the commonly accepted choice-based nature of many computer interfaces are the control interfaces for musical instruments and vehicles, where the human operator is totally in charge of the action. Many parameters are controlled simultaneously and the human operator has an overall view of what the system is doing. Feedback is gained not by on-screen prompts, but by experiencing the moment-by-moment effect of each action with the whole body.

Hunt and Kirk consider various attributes as characteristics of a real-time multiparametric control systems [39, pg. 232]. Some of these are:

- There is no fixed ordering to the human-computer dialogue.
- There is no single permitted set of options (e.g. choices from a menu) but rather a series of continuous controls.
- There is an instant response to the user's movements.
- The control mechanism is a physical and multi-parametric device which must be learned by the user until the actions become automatic.
- Further practice develops increased control intimacy and thus competence of operation.
- The human operator, once familiar with the system, is free to perform other cognitive activities whilst operating the system (e.g. talking while driving a car).

1.1.1 Interaction Context

Taking into account the specificities described above, let me consider the various existing contexts[5] in computer music[6].

These different contexts are the result of the evolution electronic technology allowing, for instance, a same input device to be used in different situations, e.g. to generate sounds (notes) or to control the temporal evolution of a set of pre-recorded notes. If traditionally these two contexts corresponded to two separate roles in music – those of the performer and the conductor, respectively – today not only the differences between different traditional roles have been minimized, but new contexts derived from metaphors created in human-computer interaction are now available in music.

One of these metaphors is *drag and drop*, that has been used in [104] with a graphical drawing tablet as the input device, a sort of gesturally controlled sequencer, whereas in [80] and in [102] the same tablet was used in the sense of a more traditional instrument.

Therefore, the same term *interaction in a musical context* may mean [100]:

- *instrument manipulation* (performer-instrument interaction) in the context of real-time sound synthesis control.
- *device manipulation in the context of score-level control*, e.g. a conductor's baton used for indicating the rhythm to a previously defined computer generated sequence [51] [3] [48]. Wessel and Wright use the term *dipping* to designate this context [104].
- *other interaction contexts related to traditional HCI interaction styles*, such as *drag and drop*, *scrubbing* [104] or *navigation* [90].
- *device manipulation in the context of post-production activities*, for instance in the case of gestural control of digital audio effects[7] or sound spatialisation.
- *interaction in the context of interactive multimedia installations* (where one person or many people's actions are sensed in order to provide input values for an audio/visual/haptic system).

But also, to a different extent:

- *interaction in the context of dance* (dance/music interfaces) [15].
- *computer games*, i.e., manipulation of a computer game input device [22].

although in these two last cases the generation of sound is not necessarily the primary goal of the interaction.

1.1.2 Music as Supervisory Control

Another way to consider the different contexts in music is to relate them to supervisory control theory. For instance, Sheridan [81] makes a parallel to supervisory control theory, where the notions of

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[5] Sometimes called metaphors for musical control [104].

[6] A detailed analysis of different interaction contexts has been proposed in [100], taking into account two points of view: system design (engineering) and semantical (human-computer interaction).

[7] Several papers on the control of digital audio effects are available from the DAFx site, at: *http://echo.gaps.ssr.upm.es/COSTG6/goals.php3*

zeroth, *first* and *second order control* correspond to different musical control levels, i.e., *biomechanics* (performer gestures and feedback), *putting notes together*, and *composing and conducting the synchronization of musicians*.

2 Gestural Control of Sound Synthesis

I will now focus on the the main interest of this paper and analyze the situation of performer-digital musical instrument interaction[8]. The focus of this work can be summarized as *expert interaction by means of the use of input devices to control real-time sound synthesis software.*

The suggested strategy to approach this subject consists in dividing the subject of gestural control of sound synthesis in four parts [98]:

- Definition and typologies of gesture
- Gesture acquisition and input device design
- Mapping of gestural variables to synthesis variables
- Synthesis algorithms

The goal is to show that all four parts are equally important to the design of new digital musical instruments. This has been developed in detail in [96].

Due to space constraints, I will focus here on item 2, gesture acquisition and input device design. Item 1 has been studied in collaboration with Claude Cadoz in [14] and item 3 in collaboration with Andy Hunt and Ross Kirk in [40]. Synthesis algorithms have been explored in various articles and textbooks, including [8], [72] and also in the perspective of real-time control in [18].

3 Digital Musical Instruments

In this work, the term *digital musical instrument* (DMI)[9] is used to represent an instrument that contains a separate gestural interface (or gestural controller unit) from a sound generation unit. Both units are independent and related by mapping strategies [34] [56] [76] [79]. This is shown in figure 1.

The term *gestural controller*[10] can be defined here as the input part of the DMI, where physical interaction with the player takes place. Conversely, the sound generation unit can be seen as the synthesis algorithm and its controls. The mapping layer refers to the liaison strategies between the outputs of the gestural controller and the input controls of the synthesis algorithm[11].

This separation is impossible in the case of traditional acoustic instruments, where the gestural interface is also part of the sound production unit. If one considers, for instance, a clarinet, the reed, keys, holes, etc. are at the same time both the gestural interface (where the performer interacts with the instrument) and the elements responsible for the sound production. The idea of a DMI is analogous to ”splitting” the clarinet in a way where one could separate these two functions (gestural interface and sound generator) and use them independently.

Clearly, this separation of the DMI into two independent units is potentially capable of extrapolating the functionalities of a conventional musical instrument, the latter tied to physical constraints. On the other hand, basic characteristics of existing instruments may be lost and/or difficult to reproduce, such as tactile/force feedback.

3.1 Gesture and Feedback

In order to devise strategies concerning the design of new digital musical instruments for gestural control of sound synthesis, it is essential to analyze the characteristics of actions produced by expert instrumentalists during performance. These actions are commonly referred to as *gestures* in the musical domain. In order to avoid discussing all nuances of the meaning of gesture, let me initially consider *performer gestures* as *performer actions produced by the instrumentalist during performance*. A detailed discussion is presented in [14][12].

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[8] Due to space constraints, other important and interesting modalities of human-computer interaction in music will not be studied here. An electronic publication (CDROM), *Trends in Gestural Control of Music*, co-edited by the author and by M. Battier [97], may present useful guidelines for the study of other modalities not discussed here.

[9] The term *digital musical instrument* [2] will be used instead of *virtual musical instrument - VMI*[57] due to the various meanings of VMI, such as for example in the software package *Modalys*, where a software-defined instrument is called a virtual instrument, without necessarily the use of an input device. This is also the common usage of the term in the field of physical modeling [88]. On the other hand, various authors consider a VMI as both the synthesis algorithm *and* the input device [56] [24] [35], although in this case the digital musical instrument is eventually much more real or tangible and less virtual.

[10] The term *gestural controller* is use here meaning *input device* for musical control.

[11] Details of each module of figure 1 will be considered in the rest of this document.

[12] I will use the term *performer gesture* throughout this document meaning both actions such as prehension and manipulation, and non-contact movements.

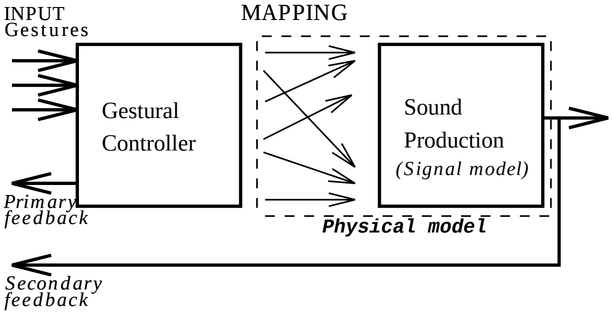

Figure 1: A Digital Musical Instrument representation.

3.1.1 Performer Gestures

Instrumentalists simultaneously execute various types of gestures during performance. Some of them are necessary for the production of sound [11], others may not be clearly related to sound production [23] [99], but are nevertheless present in most highly-skilled instrumentalists' performances.

One can approach the study of gestures by either analyzing the possible functions of a gesture during performance [69] or by analyzing the physical properties of the gestures taking place [17]. By identifying gestural characteristics – functional, in a specific context, or physiological – one can ultimately gain insight into the design of gestural acquisition systems.

Regarding both approaches, it is also important to be aware of the existing feedback available to the performer, be it visual, auditory or tactile-kinesthetic. Feedback can also be considered depending on its characteristics, as:

- *Primary/secondary* [92], where primary feedback encompasses visual, auditory (clarinet key noise, for instance) and tactile-kinesthetic feedback, and secondary feedback relates to the sound produced by the instrument.

- *Passive/active* [7], where passive feedback relates to feedback provided through physical characteristics of the system (a switch noise, for instance) and active feedback is the one produced by the system in response to a certain user action (sound produced by the instrument).

Tactile-kinesthetic, or *tactual* [6] feedback is composed by the tactile and proprioceptive senses [75].

3.2 Gestural Acquisition

Once the gesture characteristics have been analyzed, it is essential to devise an acquisition system that will *capture* these characteristics for further use in the interactive system.

In the case of performer - acoustic instrument interaction, this acquisition may be performed in three ways:

- *Direct acquisition*, where one or various sensors are used to monitor performer's actions. The signals from these sensors present isolated basic physical features of a gesture: pressure, linear or angular displacement, and acceleration, for instance. A different sensor is usually needed to capture each physical variable of the gesture.

- *Indirect acquisition*, where gestures are isolated from the structural properties of the sound produced by the instrument [1] [44] [68] [26] [61]. Signal processing techniques can then be used in order to derive performer's actions by the analysis of the fundamental frequency of the sound, its spectral envelope, its power distribution, etc.

- *Physiological signal acquisition*, the analysis of physiological signals, such as EMG [45] [65]. Commercial systems have been developed based on the analysis of muscle tension and used in musical contexts [85] [5] [86] [49] [105]. Although capturing the *essence* of the movement, this technique is hard to master since it may be difficult to separate the meaningful parts of the signal obtained from physiological measurement.

Direct acquisition has the advantage of simplicity when compared to indirect acquisition, due to the mutual influence of different parameters present in the resulting sound (i.e. instrument acoustics, room effect and performer actions). Nevertheless, due to the independence of the variables captured, direct acquisition techniques may underestimate the interdependency of the various variables obtained.

3.2.1 Direct Acquisition

Direct acquisition is performed by the use of different sensors to capture performer actions. Depending on the type of sensors and on the combination of different technologies in various systems, different movements may be tracked.

Citing B. Bongers, a well-known alternate controller designer [7]:

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

3.2.2 Sensor Characteristics and Musical Applications

Some authors consider that most important sensor characteristics are: *sensitivity*, *stability* and *repeatability* [83]. Other important characteristic relates to the linearity and selectivity of the sensor's output, it's sensitivity to ambient conditions, etc. P. Garrett considers six descriptive parameters applicable to sensors as [32]: *accuracy*, *error*, *precision*, *resolution*, *span*, and *range*.

In general instrumentation circuits, sensors typically need to be both precise and accurate, and present a reasonable resolution. In the musical domain, it is often stressed that the choice of a transducer technology matching a specific musical characteristic relates to human performance and perception: for instance, mapping of the output of a sensor that is precise but not very accurate to a variable controlling loudness may be satisfactory, but if it is used to control pitch, its innacuracy will probably be more noticeable.

Various texts describe different sensors and transducer technologies for general and musical applications, such as [32] and [33] [7] [28], respectively. The reader is directed to these texts for further information.

3.2.3 Analog to MIDI Conversion

For the case of gesture acquisition with the use of different sensors, the signals obtained at the sensors outputs are usually available in an analog format, basically in the form of voltage or current signals. In order to be able to use these signals as computer inputs, they need to be sampled and converted in a suitable format, usually MIDI (Musical Instrument Digital Interface) [42] or more advanced protocols [29].

Various analog-to-MIDI converters have been proposed and are widely available commercially. The first examples have been developed already in the eighties [95] [84].

3.2.4 Comparison of Analog-to-MIDI interfaces

Concerning the various discussions on the advantages and drawbacks of the MIDI protocol and its use [55], strictly speaking, nothing forces someone to use MIDI or prevents the use of faster or different protocols. It is interesting to notice that many existing systems have used communication protocols other than MIDI in order to avoid speed and resolution limitations. One such system is the TGR (*transducteur gestuel réctroactif*, from ACROE [13].

I compare here six *commonly available* models of sensor-to-MIDI interfaces in order to provide the reader an idea of their differences[13]. Their basic characteristics are seen in table 1.

One can notice that interface characteristics may differ to a significant amount, but most models present comparable figures. As already pointed out, the limiting factor regarding speed and resolution is basically the specifications of the MIDI protocol, not the electronics involved in the design.

3.2.5 Indirect Acquisition

As opposed to direct acquisition, *indirect acquisition* provides information about performer actions from the evolution of structural properties of the sound being produced by an instrument. In this case, the only sensor is a microphone, i.e., a sensor measuring pressure or gradient of pressure.

Due to the complexity of the information available in the instrument's sound captured by a microphone, different real-time signal processing techniques are used in order to distinguish the effect of a performer's action from environmental features, such as the influence of the acoustical properties of the room.

Generically, one could identify basic sound parameters to be extracted in real-time. P. Depalle, cites four parameters [98]:

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[13] I have developed an extended comparison of nine commercially available models, including technical characteristics and general features, based on information provided from manufacturers and/or owner manuals/manufacturer's web pages. This comparison is available from the *Gesture Research in Music* home-page at *http://www.ircam.fr/gesture*

Interface	ADB I/O	AtoMIC Pro	Digitizer (I-Cube)	MIDIBox	Midicreator	Sensorlab
Manufacturer	BeeHive	Ircam	Infusion Systems	NOTAM	York Elect. Centre	STEIM
Platform	Macintosh	Any	Any	Any	Any	Any
Max. SR [Hz]	< 90	1000	200/225 (12/8 bits)	Approx. 400	120	250
Analog IN	4	32	32	8	8	32, 2x3 Usound
Digital IN	4/6/8	8	-	16	8	8x16 key
Input Res.	8 bits	10/ 8 bits	12/ 8 bits	8 bits	8 bits	8/14bits Usound
Outputs	max 8	8 + 4 MIDI	8 switch + MIDI	6 + MIDI	MIDI	MIDI
Size(HWD)[mm]	29x122x65	38x165x225	34x121x94	20x100x100(PCB)	41x227x166	35x200x100

Table 1: Comparison of 6 Analog-to-MIDI commercial interfaces.

- *Short-time energy*, related to the dynamic profile of the signal, indicates the dynamic level of the sound but also possible differences of the instrument position related to the microphone.

- *Fundamental frequency*, related to the sound's melodic profile, gives information about fingering, for instance.

- *Spectral envelope*, representing the distribution of sound partial amplitudes, may give information about the resonating body of the instrument.

- *Amplitudes, frequencies and phases of sound partials*, that can alone provide much of the information obtained by the previous parameters.

Obviously, in order to perform the analysis of the above or other parameters during indirect acquisition, it is important to consider the correct sampling of the signal. According to the Nyquist theorem, this frequency needs to be at least twice as big as the maximum frequency of the signal to be sampled.

Although one could reasonably consider that frequencies of performer actions can be limited to few hertz, fast actions can potentially present higher frequencies. A sampling frequency value typically proposed for gestural acquisition is 200 Hz [50]. Some systems may use higher values, from 300 to 1kHz [13]). Recently, researchers considered the ideal sampling frequency to be around 4 kHz [30] [29]. As a general figure, one can consider 1 kHz as sufficient for most applications.

Several works on indirect acquisition systems have already been presented. They include both hybrid systems (using also sensors), such as the *hypercello* [46] and pure indirect systems, such as the analysis of clarinet performances [68] [26] and guitar [61].

3.3 Gestural Controllers

Once one or several sensors are assembled as part of a unique device, this device is called an input device or a *gestural controller*[14].

As cited above, the gestural controller is the part of the DMI where physical interaction takes place. *Physical interaction* here means the actions of the performer, be they body movements, empty-handed gestures or object manipulation, and the perception by the performer of the instrument's status and response by means of tactile-kinesthetic, visual and auditory senses.

Due to the large range of human actions to be captured by the controller[15] and depending on the interaction context where it will be used (cf. section 1.1.1), its design may vary from case to case. In order to analyze the various possibilities, we propose a three-tier classification of existing controller designs as [98] [7]:

- *Instrument-like controllers*, where the input device design tends to reproduce each feature of an existing (acoustic) instrument in detail. Many examples can be cited, such as electronic keyboards, guitars, saxophones, marimbas, and so on.

  A sub-division of this class of gestural controllers would be that of *Instrument-inspired controllers*, that although largely inspired by existing instrument's design, are conceived for another use. One example is the *SuperPolm* violin, developed by S. Goto, A. Terrier, and P. Pierrot [66] [35], where the input device is loosely based on a violin shape, but is used as a general device for the control of granular synthesis.

- *Augmented Instruments*, also called *Hybrid Controllers*, are instruments augmented by

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[14] Called *input device* in traditional human-computer interaction.

[15] According to A. Mulder, a *virtual musical instrument* (here called *digital musical instrument*) *is ideally capable of capturing any gesture from the universe of all possible human movements and use them to produce any audible sound* [56].

the addition of extra sensors [4] [46]. Commercial augmented instruments included the Yamaha Disklavier, used in for instance in pieces by J.-C. Risset [71] [70]. Other examples include the flute [67] [107] and the trumpet [21] [41] [89], but any existing acoustic instrument may be instrumented to different degrees by the additions of sensors.

- *Alternate controllers*, whose design does not follow an established instrument's one. Some examples include *the Hands* [95], graphic drawing tablets [80], etc. For instance, a gestural controller using the shape of the oral cavity has been proposed in [60].

For instrument-like controllers, although representing a simplified (first-order) model of the acoustic instrument, many of the gestural skills developed by the performer on the acoustic instrument can be readily applied to the controller. Conversely, for a non-expert performer, these controllers present roughly the same constraints as those of an acoustic instrument[16], technical difficulties inherent to the former may have to be overcome by the non-expert performer.

Alternate controllers, on the other hand, allow the use of other gesture vocabularies than those of acoustic instrument manipulation, these being restricted only by the technology choices in the controller design, thus allowing non-expert performers the use of these devices. Even so, performers still have to develop specific skills for mastering these new gestural vocabularies [95].

4 An Analysis of Existing Input Devices

A reasonable number of input devices have been proposed to perform real-time control of music [73] [63], most of them resulting from composer's/player's idiosyncratic approaches to personal artistic needs. These interfaces, although often revolutionary in concept, have mostly remained specific to the needs of their inventors. Four examples of gestural controllers are shown in figures 2 and 3.

The advantages and drawbacks of each controller type depends mostly on the user goals and background, but unfortunately systematic means of evaluating gestural controllers are not commonly available.

From an engineering point of view, it is important to propose means to compare existing designs[17] in order to evaluate their strong and weak points and eventually come up with guidelines for the design of new input devices.

Some authors consider that new devices, designed according to ergonomical and cognitive principles, could eventually become general tools for musical control [93] [57] [87] [58][18].

4.1 Design Rationale: Engineering versus Idiosyncratic approaches

The use of pure engineering/ergonomical approaches can be challenged by the comparison with the evolution of input device design in human-computer interaction. In fact, researcher W. Buxton [10] considers HCI and ergonomics as *failed sciences*. He argues that although a substantial volume of literature on input device evaluation/design in these two areas has already been proposed, current available devices have benefit little from all this knowledge and therefore major innovations are not often proposed.

The problem with both points of view – *engineering* versus *idiosyncratic* – seems to be their application context. Although one can always question the engineering approach by stressing the role of creativity against scientific design [20], the proposition of scientific methodologies is also a key factor for *the evaluation* of existing gestural controllers.

Conversely, engineering methodologies, shall not prevent the use of creativity in design, although this can be a side effect of structured design rationales. But without a common basis for evaluation, the differentiation between input devices and simple gadgets turns out to be hazardous.

As stated before, the design of a new input device for musical performance is generally directed towards the fulfillment of specific and sometimes idiosyncratic musical goals, but is *always* based on an engineering corpus of knowledge. This technical background allows the choice of transducer technologies and circuit designs that implement the interface needed to perform the initial musical goals[19].

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[16] This fact can be modified by the use of different mapping strategies, as shown in [76].

[17] A similar situation occurs in others areas, such as haptic devices [36].

[18] On the other hand, other authors claim that effort demanding and hard-to-play instruments are the only ones that provide expressive possibilities to a performer [77] [78] [94].

[19] A description of several input device designs is proposed in [7], where Bongers review his work at STEIM, the Institute of Sonology (Den Haag) and in the Royal Academy of Arts in Amsterdam. Another good review of different controllers has been presented by J. Paradiso in [63]

Figure 2: *Left:* Joseph Butch Rovan holding a wx7, an *instrument-like* (saxophone) controller by Yamaha. *Right:* Suguru Goto and the SuperPolm, an *instrument-inspired* controller (violin).

Figure 3: *Left:* Marc Battier manipulating the Pacom, by Starkier and Prevot. *Right:* Jean-Philippe Viollet using the WACOM graphic tablet. Both devices are considered as *alternate* controllers.

Therefore, although the final development goals are musical and consequently any criticism of these goals turns into a question related to aesthetical preferences, their design is based on engineering principles that can, *and need*, to be evaluated and compared. This evaluation is essential, for instance, in the selection of existing input devices for performing different tasks [80], but it can also be useful in the identification of promising new opportunities for the design of novel input devices [16].

4.2 Gestural Controller Design

It may also be useful to propose guidelines for the design of new input devices based on knowledge from related fields, such as experimental psychology, physiology and human-computer interaction [62].

Taking the example of the research in human-computer interaction, many studies have been carried out on the design and evaluation of input devices for general (non-expert) interaction. The most important goal in these studies is the improvement of accuracy and/or time response for a certain task, following the relationship, known as the Fitts' law [47].

Also, standard methodologies for tests have been proposed and generally consist of pointing and/or dragging tasks, where the size and distance between target squares are used as tests parameters.

In 1994, R. Vertegaal and collaborators have presented a methodology, derived from standard HCI tests, that addressed the comparison of input devices in a timbre navigation task [90] [92]. Although pioneering in the field, the methodology used consisted of a pure selection (pointing and acquisition) task, i.e., the context of the test was a navigation in a four parameter timbral space [91], not a traditional musical context in the sense of instrumental performance.

In 1996, Vertegaal et al. [93] [87] proposed an attempt to systematically relate an hypothetical musical function (dynamic – absolute or relative – or static) to a specific sensor technology and to the feedback available with this technology. This means that certain sensor technologies may outperform others for a specific musical function. The interest of this work is that it allows a designer to select a sensor technology based on the proposed relationships, thus reducing the need for idiosyncratic solutions. An evaluation of this methodology is presented in [102].

Another attempt to address the evaluation of well-known HCI methodologies and their possible adaptation to the musical domain was presented in [62]. Although one cannot expect to use methodologies from other fields directly into the musical domain, at least the analysis of similar developments in better established fields may help finding directions suitable for the case of computer music.

5 Mapping of Gestural Variables to Synthesis Inputs

Once gesture variables are available either from independent sensors or as a result of signal processing techniques in the case of indirect acquisition, one then needs to relate these output variables to the available synthesis input variables.

Depending on the sound synthesis method to be used, the number and characteristics of these input variables may vary. For signal model methods, one may have a) amplitudes, frequencies and phases of sinusoidal sound partials for additive synthesis; b) an excitation frequency plus each formant's center frequency, bandwidth, amplitude and skew for formant synthesis; c) carrier and modulation coefficients (c:m ratio) for frequency modulation (FM) synthesis, etc.

It is clear that the relationship between the gestural variables and the synthesis inputs available is far from obvious. How does one relate a gesture to a c:m ratio?

For the case of physical models, the available variables are usually the input parameters of an instrument, such as blow pressure, bow velocity, etc. In a sense, the mapping of gestures to the synthesis inputs is more evident, since the relation of these inputs to the algorithm already encompasses the multiple dependencies based on the physics of the particular instrument.

5.1 Systematic Study of Mapping

The systematic study of mapping is an area that is still underdeveloped. Only a few works have been proposed that analyze the influence of mapping on digital musical instrument performance or suggested ways to define mappings to relate controller variables to synthesis inputs. Examples of works include: [9], [43], [27], [106], [19], [54], [76], [59], [101], [38], [31], [39], [53], and [18].

A detailed review of the existing literature on mapping was presented in [14], and in [96]. Discussions have also been carried on on the role of mapping in computer music in the Working Group on Interactive Systems and Instrument Design in Music, at ICMA and EMF[20], where a complete bibliography on the subject is available, as well as suggestions on basic readings and links to existing research.

5.2 Mapping Strategies

Although simple *one-to-one* or *direct* mappings are by far the most commonly used, other *mapping strategies* can be used.

For instance, we have shown that for the same gestural controller and synthesis algorithm, the choice of mapping strategy may be the determinant factor concerning the expressivity of the instrument [76]. The main idea was to challenge the main directions in digital musical instrument design, i.e. input device design and research on different synthesis algorithms, and focus on the importance of different mappings using off-the-shelf controllers and standard synthesis algorithms.

Different mapping strategies were applied to the simulation of traditional acoustic single reed instruments using the controller, based on the actual functioning of the single reed. The three basic strategies were suggested: *one-to-one*, *one-to-many* and *many-to-one*, and were used in order to propose different mappings, from a simple one-to-one to complex mappings simulating the physical behavior of the clarinet's reed. This is shown in figure 4.

We could show, from the experience of single reed instrument performers that tried the system that the use of different mappings *did* influence the expressivity obtained during the playing, without any modifications in either the input device or the synthesis algorithm.

5.3 Mapping for General Musical Performance

The example above applying different mapping strategies to the simulation of instrumental performance has derived from the actual physical behavior of the acoustic instrument. But in the case of an alternate digital musical instrument, the possible mapping strategies to be applied are far from obvious, since no model of the mappings strategies to be used is available. Even so, it can be demonstrated that complex mappings may influence user performance for the manipulation of general input devices in a musical context.

An interesting work by A. Hunt and R. Kirk [37] [38] [39] presented a study on the influence over time of the choice of mapping strategy on subject performance in real-time musical control tasks. User performance was measured over a period of several weeks and showed that complex mapping strategies used with the multi-parametric instrument allowed better performance than simpler mappings for complex tasks (various parameters changing simultaneously) and also that performance with complex mapping strategies improved

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[20] *http://www.notam.uio.no/icma/interactivesystems/wg.html*

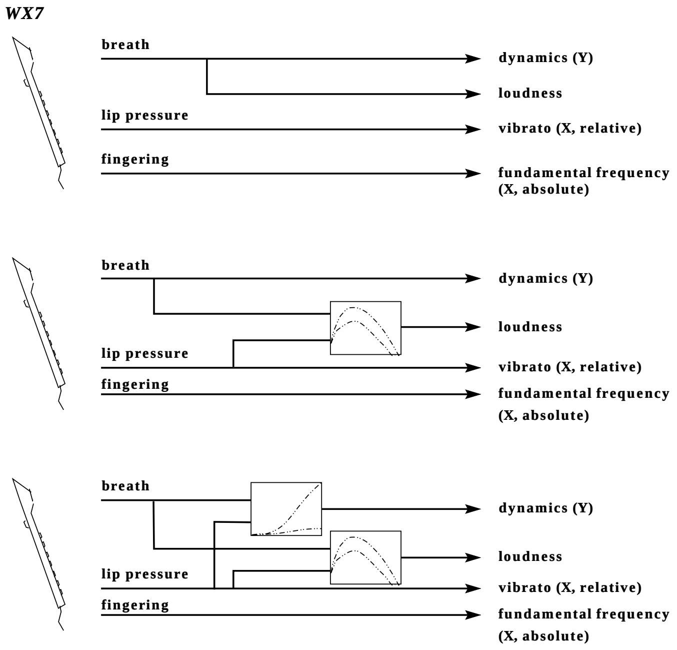

Figure 4: Examples of different mapping strategies for the simulation of instrumental performance [76].

over time.

5.4 A Model of Mapping as two Independent Layers

Mapping can be implemented as a single layer [9] [19]. In this case, a change of either the gestural controller or synthesis algorithm would mean the definition of a different mapping.

One proposition to overcome this situation is the definition of mapping as two independent layers: a *mapping of control variables to intermediate parameters* and a *mapping of intermediate parameters to synthesis variables* [101].

This means that the use of different gestural controllers would necessitate the use of different mappings in the first layer, but the second layer, between intermediate parameters and synthesis parameters, would remain unchanged. Conversely, changing the synthesis method involves the adaptation of the second layer, considering that the same abstract parameters can be used, but does not interfere with the first layer, therefore being transparent to the performer.

The definition of those intermediate parameters or an intermediate abstract parameter layer can be based on perceptual variables such as timbre, loudness and pitch, but can be based on other perceptual characteristics of sounds [103] [52] [31] or have no relationship to perception, being then arbitrarily chosen by the composer or performer [101].

6 Developments in Sound Synthesis Methods

On the other extreme of current trends regarding the digital musical instruments, various developments on sound synthesis methods have been proposed, among them methods for both physical and signal models.

Physical models are specially useful for a realistic simulation of a given acoustic instrument and today models of various instruments exist [82] and are commercially available. Disadvantages of physical models include the lack of analysis methods, difficulties regarding the continuous morphing between different models and most of all the complexity regarding the real-time performance using these models, that correspond to the difficulties encountered with the real acoustic instrument.

Signal models, specifically additive synthesis [74], present the advantage of having well-developed analysis tools that allow the extraction of parameters corresponding to a given sound. Therefore, the morphing of parameters from different sounds can lead to continuous transformations between different instruments. Although not necessarily reproducing the full behavior of the original instrument, the flexibility allowed by signal models may be interesting for the prototyping of control strategies since the mapping is left to the instrument designer.

7 Conclusions

This paper has critically commented on various topics related to real-time, gesturally controlled computer-generated sound.

I have discussed the specificities of the interaction between a human and a computer in various musical contexts. These contexts represent different interaction metaphors for music/sound control and cannot be underestimated since they define the level of interaction with the computer.

I have then focused on the specific case of real-time gestural control of sound synthesis, and presented and discussed the various constituent parts of a digital musical instrument.

I have claimed that a balanced analysis of these constituent parts is an essential step towards the design of new instruments, although current developments many times tend to focus either on the design of new gestural controllers or on the proposition of different synthesis algorithms.

8 Suggestions of Future Research Directions

Finally, I present suggestions of topics for future research directions that I believe can eventually lead to new directions on the design and performance of digital musical instruments.

- Concerning gestural acquisition, the use of indirect acquisition through the analysis of the sound produced by acoustic instruments may help the design of new gestural controllers. Although various works have been proposed in this direction, a general overview showing the current state of the research in this area was missing and was presented in [96]. It can serve as a basis for future developments in the field.

- The development of evaluation techniques for multiparametric expert user tasks is a difficult problem that may improve our knowledge of the actual motor behavior of performers in these circumstances. The definition of tasks taking into account different musical contexts may also help the comparison of existing devices and suggest design methodologies for the developments of new digital musical instruments.

- The study of mapping strategies is, in my opinion, quite underdeveloped. We have been pioneers in showing the isolated effect of mapping on digital musical instrumental design and another important work recently carried out at the University of York has pushed further our knowledge about general multiparametric control situations and the influence of mapping on performance. From these studies there seems to exist a huge unexplored potential on the definition of mapping strategies for different contexts.

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