AN ALTERNATIVE MIDI CONTROLLER

Brad Cariou
Industrial Design Program
Faculty of Environmental Design

National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

ISBN 0-315-88495-9

THE UNIVERSITY OF CALGARY

FACULTY OF ENVIRONMENTAL DESIGN

The undersigned certify that they have read, and reccomend to the Faculty of Environmental Design for acceptance, a Master's Degree Project entitled AN ALTERNATIVE MIDI CONTROLLER submitted by BRAD CARIOU in partial fulfillment of the requirements for the degree of Master of Environmental Design.

Supervisor Dr. R. Wardell, Faculty of Environmental Design

Professor D. Gadbois, Faculty of Environmental Design

Dr. D. Eagle, Faculty of Fine Arts, Music Department

Dr. J. Love, Faculty of Environmental Design

Date May 31, 1993

Acknowledgments

I would like to thank my committee members: Dr. Ron Wardell for his continual encouragement, insightful recommendations, and valued comments; Dr. David Eagle for his boundless enthusiasm, spirited debates about the design, critiques of the project, and access to the electronic music studio in the Faculty of Music, and Prof. Denis Gadbois for his comments, recommendations and guidance.

I would like to thank the Faculty of Environmental Design for providing funding in the form of Graduate Research Scholarships and busaries. I would also like to thank the shop staff, namely John Kopala and Bob Fisher, for their help and advice in building my model.

I would also like to thank Graduate Research Services for providing funding for the construction of my model and travel to the 1992 International Computer Music Conference, enabling me to present my project before individuals with a particular interest in such things.

'Thank you' does not begin to describe the debt I owe to my life partner, Sandra Sawatzky, who has stuck by me (for better and for worse) for nearly 20 years! She has always believed in me and my project unconditionally, and has tolerated my many moods, the long hours, and my occasional mental, if not physical, absence with good humour and grace.

I would like to thank my father and Sandra's mother and father for their encouragement and support throughout my education. I could not have done it without them and am deeply in debt to them.

Last, but not least, I would like to thank my fellow students for their support through my time here. I would like to thank Greg Olsen for the philosophical debates and advice. I would especially like to thank Geoff Gosling for convincing me I have the abilities to be a designer and not to doubt myself.

Abstract

MIDI (**M**usical **I**nstrument **D**igital **I**nterface) controllers allow an individual to control a wide variety of sound synthesizers (and other devices such as CD-ROM and video disc players) using the same physical interface. The diversity of musical and other tasks to which a MIDI controller might be applied argues for a general-purpose controller having multiple means and dimensions of control. The utility of such a controller is increased when integrated with a personal computer and software that allows the musician to define the connections between the controller and device under control.

This project is the design of a MIDI controller and associated software. The physical interface of the controller is designed to provide a variety of means of control and 9 dimensions of control. Software running on a personal computer allows the musician to adapt the controller to different sound synthesizers or other pieces of equipment, or to different tasks through a graphical interface.

The primary focus is on the human factors influencing the design. Models of the musician's task, musical instruments, human information processing and human-machine interaction are used to develop a foundation for the design of MIDI controllers. Ergonomic and anthropometric considerations affecting the design of the physical interface are presented and the secondary issues of aesthetics and production materials and methods are briefly discussed.

Keywords

Computer Music, Electronic Musical Instruments, Human Factors, Human-Computer Interaction, Industrial Design, Interface Design, MIDI controllers

Table of Contents

page

Introduction **1**

Objectives 1
Terms 2
Alternative MIDI Controllers 3
Transmogrification 5
Instruments as Systems 6

PART I: BACKGROUND **7**

1.0: Defining Music **9**

1.1 Definitions of Music 11
1.2 The Nature of Music 12
1.3 Music and Instruments 13
1.4 Summary 13

2.0: A (Very) Brief History of Electronic Instruments **15**

2.1 Early Electronic Instruments 15
2.1.1 The Theremin 15
2.1.2 The ondes Martenot 12
2.1.3 The Electronic Sackbut 18
2.2 Voltage-Control Synthesis 19
2.3 Introduction of Microprocessors 20
2.4 The MIDI Specification 20
2.4.1 MIDI Instruments and Controllers 21
2.4.2 Alternative MIDI Controllers 21
2.5 Summary 24

3.0: The Musician's Task **27**

3.1 Performance as Task 27
3.2 Interpretation and Expression 29
3.3 The Nature of Performance 30
3.4 Perception of Gesture 31
3.5 Making Music 33
3.6 Summary: The Musician's Task (Reprise) 33
Levels of Control 34

4.0: Modelling Musical Instruments 35

4.1 An Instrument Model 35
4.1.1 Input Structures 36
4.1.2 Output Structures 37
4.1.3 Mapping 37
4.1.4 Mapping Interactions 38
4.2 Instrument Analysis 39
4.2.1 Application to Musical Instruments 44
4.2.2 MIDI Keyboard Controllers 45
4.2.3 Application To Electronic Instruments 45
4.3 Summary 47

5.0: Musician-Instrument Interaction 49

5.1 Gesture and Interface 49
5.1.1Musician-Instrument Model 49
5.2 Man-Machine Interaction 51
5.2.1 Signals, Signs and Symbols 55
5.2.2 Interaction Models 56
Direct Manipulation 56
Indirect Manipulation 56
Remote Manipulation 58
Remote Process Control 58
5.3 Application to Musical Instruments 59
5.4 Controllers Modelled on Acoustic Instruments 61
5.5 Summary 63

PART 2: DESIGN 65

6.0: Controller Design 67

6.1 Project Objectives 67
6.2 Target User Group 68
6.3 Design Criteria 68
6.4 Design Constraints 69
6.5 Design Solution 70
6.5.1 Chord Keyboard 71
Fingering Possibilities 75
Velocity Sensing 77
Modes of Operation 78
Channel and Key Pressure (Aftertouch) 79
Pitchbend 80
Key Simultaneity 80

6.5.2 Joystick 82
Pressure Sensing
(Z dimension of control) 85
Finger Touch-strip 86
Joystick Switches 86
Thumb Switches 87
6.5.3 Switch Array 88
6.3 Additional Considerations 90

7.0: Electronic Hardware 93

7.1 Proof of Concept Model 93
7.2 Design Electronics 94
7.3 Summary 98

8.0: Software 99

8.1 The MAX Programming Language 99
8.2 Graphical Interface 99
8.2.1 aXiØ Window 100
8.2.2 Transmogrifier Window 101
8.2.3 Joystick Window 102
8.2.4 Joystick Switch Window 106
8.2.5 Keyboard Window 107
8.2.6 Switch Array Window 108
8.2.7 User Patcher Window 109
8.2.8 Monitor Window 110
8.2.9 Tools Window 111
8.2.10 Preferences Window 111
8.2.11 Help Window 111
8.3 Summary 111

9.0: Form and Fabrication 113

9.1 Form 114
9.1.1 Human Factors Issues 114
9.1.2 Aesthetic Issues 117
9.1.3 Perception of Form 120
9.2 Fabrication 121
9.2.1 Electronics 121
9.2.2 Chord Keyboard 122
9.2.3 Joystick 123
9.2.4 Switch Array 123
9.2.5 Support Leg 123
9.2.6 Spine 124
9.2.7 Body Coverings 124

9.2.8 Rack-mounted Unit 124
9.3 Summary 124

10.0: Conclusion 125

10.1 Controller Analysis 125
10.2 Future Considerations 127
User Testing 127
Force Feedback 127
10.3 Summary 128

Appendix A The MIDI Specification 129

Appendix B Instrument Analysis Chart 131

Appendix C Dimensioned Drawings 133

Appendix D Fingering Charts 141

Appendix E Keyboard Electronics 143

Appendix F MIDI Implemetation Chart 151

References 153

page

FIGURES

2.0: A (Very) Brief History of Electronic Instruments

Figure 2.1 Clara Rockmore, playing the Theremin ... 16
Figure 2.2 Operation of the ondes Martenot ... 16
Figure 2.3 1977 concert Ondes Martenot ... 17
Figure 2.4 Timbre controls for the Electronic Sackbut ... 18
Figure 2.5 Electronic Sackbut left hand controls ... 19
Figure 2.6 The Mathew's/Boie Radio Drum ... 22
Figure 2.7 Rubine and McAvinney's Video Harp ... 23
Figure 2.8 Buchla Thunder controller ... 24

3.0: The Musician's Task

Figure 3.1 Model of performance from a score ... 28

4.0: Modelling Musical Instruments

Figure 4.1 Components of a musical instrument ... 36
Figure 4.2 Input to output mapping of a piano ... 38
Figure 4.3 Partial diagram of the input-output mapping of a cello ... 38

5.0: Musician-Instrument Interaction

Figure 5.1 Musician-instrument model ... 52
Figure 5.2 Skill-, rule-, and knowledge-based model ... 53
Figure 5.3 Behaviour continuum ... 53
Figure 5.4 Direct manipulation of objects ... 57
Figure 5.5 Indirect object manipulation ... 57
Figure 5.6 Remote process control ... 58

6.0: Controller Design

Figure 6.1 Design space of the project ... 67
Figure 6.2 Key layout ... 72
Figure 6.3 Keyboard layout ... 73
Figure 6.4 Sketch of chord keyboard ... 74
Figure 6.5 Possible key layout ... 74

Figure 6.6 Velocity maps 77
Figure 6.7 Polyphonic mode amplitude envelope 78
Figure 6.8a Typical mono-retrigger mode amplitude envelope 79
Figure 6.8b Typical mono-legato mode amplitude envelope 79
Figure 6.9 Pitchbend amount vs. MIDI value 80
Figure 6.10 'Ski-pole' joystick concept 83
Figure 6.11 Palm rest joystick 84
Figure 6.12 Range of movement of palm rest 85
Figure 6.13 Thumb roller switches 88
Figure 6.14 Switch array layout 89

7.0: Electronic Hardware

Figure 7.1 Block diagram of model electronics 93
Figure 7.2 Block diagram of system electronics 95
Figure 7.3a Front panel of rack-mounted unit 95
Figure 7.3b Rear panel of rack-mounted unit 96
Figure 7.4 High speed serial data path 97

8.0: Software

Figure 8.1 aXiØ window and menu bar 101
Figure 8.2 Transmogrification window 102
Figure 8.3 Joystick window 103
Figure 8.4 Joystick X-axis sub-window 104
Figure 8.5 User table #1X open 105
Figure 8.6 Joystick Switch window 106
Figure 8.7 Keyboard window 107
Figure 8.8 Pitchbend window 108
Figure 8.9 Switch array window 109
Figure 8.10 Monitor window display 110
Figure 8.11 Help window 112

9.0: Form and Fabrication

Figure 9.1 General layout of controller (front view) 115
Figure 9.2 Rotation of switch array arm (side view) 116
Figure 9.3 Optimal work area overlap 116
Figure 9.4 Sitting and standing playing positions 117
Figure 9.5 Visual geometry of the controller form 118
Figure 9.6a-f Computer generated views of controller 119
Figure 9.7 Internal electronics and loudspeakers 122

TABLES

1.0: Defining Music

Table 1. Definitions of music 12

4.0: Modelling Musical Instruments

Table 2. Controller Characteristics 42

There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.

Niccolo Machiavelli

Harnessing the sound power of a synthesizer to a keyboard is like using a team of oxen to pull a Porsche.

Jim Aikin, 1990[1]

Electronic music synthesizers are usually played using a physical interface based on an organ- or piano-type keyboard, or some other acoustic musical instrument such as a guitar or saxophone. These interfaces make it easy for many people to play electronic synthesizers, but make it difficult if not impossible to fully exploit the ways in which electronically generated sounds can be controlled.

MIDI (Musical Instrument Digital Interface) controllers allow an individual to control a wide variety of sound synthesis engines (and other devices such as CD-ROM and video disc players) using the same physical interface. The diversity of musical and other tasks to which a MIDI controller might be applied argues for a general-purpose controller having multiple means and dimensions of control. A personal computer can increase the utility of a controller by allowing the user to define and manipulate the data generated by the controller as it passes to the device under control; the data can be modified to suit the task at hand. A computer can also support a graphical user interface to this data manipulation. Such a controller could be used to 'play' sounds in ways conventional interfaces such as those mentioned above cannot.

OBJECTIVES

The primary objective of this project is to design an alternative MIDI controller and construct a proof-of-concept model. The controller is intended to function as part of an electronic musical instrument system, and includes software running on a Macintosh computer. The software has a graphical interface and many aspects of the controller's operation are programmable.

A secondary objective is to summarize the investigation of a model of musical instruments and human-machine (or, in this case, musician-instrument) interaction that can be applied to the design of MIDI controllers. The purpose of this is to provide a basis for the design of alternative MIDI controllers or other specialized input devices for computer-based products in general.

The project focuses on the human factors aspects of design, in particular human-machine and human-computer interaction. Given this focus, aesthetic

[1] in "The Light Touch.", Keyboard, Vol. 16, No. 6, June, 1990.

issues and issues related to manufacturing are addressed only briefly. These issues are, of course, important aspects of industrial design but can only be dealt with adequately after development of the electronic hardware and user testing is completed.

The presentation is divided into two sections. The first section deals with the relevant design issues such as task analysis, the modelling of musical instruments, and interaction between musicians and their instruments. The second section deals with the design of a controller based on the ideas developed. Ergonomic issues related to the physical aspects of the design are also introduced.

TERMS

Defining some of the terms used herein will help the reader understand this project and clarify the difference between an electronic musical instrument and a MIDI controller.

A **musical instrument**, electronic or acoustic, encompasses a means of producing sound and a means of 'playing' that sound. The strings within a piano are 'played' using the piano's keyboard.

MIDI (Musical Instrument Digital Interface) is a protocol developed by the musical instrument industry that allows communication between pieces of electronic equipment. The MIDI specification is discussed briefly in Appendix A. One significant consequence of the industry-wide adoption of MIDI as a standard is that electronic musical instruments can be broken into separate components more easily than before; the means of producing a sound can be separated from the means of playing that sound.

MIDI data is not limited to controlling sound modules. Signal processors, tape recorders, lighting equipment, video disc players, and other types of equipment now send and receive MIDI data.

A **MIDI controller** is a device that senses and translates physical actions into MIDI data that can be understood by another MIDI device. A single MIDI controller can be connected to a number of MIDI modules simultaneously. A controller by itself is not a musical instrument for it has no means of producing sounds.

Most MIDI controllers are based on acoustic instruments. These include piano and organ keyboards, stringed instruments (guitars, violins, cellos, etc.) wind and valve instruments (the saxophone and trumpet, respectively) and percussion instruments (drums and mallet instruments such as the vibraphone).

The term **synthesizer** has, in general, come to mean an electronic instrument consisting of an electronic sound generator connected to a piano-or organ-type keyboard. Nearly all synthesizers manufactured today respond to MIDI data.

A **sound module** is a self-contained electronic sound source that responds to MIDI data coming from a MIDI controller, a computer, or some other MIDI device.

In this paper the term **synthesis engine** will mean any device (a synthesizer, sound module, plug-in board, etc.) that responds to MIDI data to produce sounds.

ALTERNATIVE MIDI CONTROLLERS

Existing MIDI controllers have been used to compose and perform a great deal of music in all sorts of styles. However, an increasing number of composers and performers find that MIDI controllers modelled on acoustic instruments do not provide the kind or degree of control they desire. Aikin points out the problem with this approach:

> *Unfortunately, most of these controllers* [based on acoustic instruments]... *suffer from the limitations imposed by their ancestry, even though these limitations are largely needless in an electronic instrument.*
>
> Aikin, 1991

The value of alternative controllers not based on acoustic instruments is evident in a discussion of one such controller developed by Max Mathews, the father of computer music, with Bob Boie and Andy Schloss. They write:

> *The results* [of using this controller] *are so clear that we suspect that the usual 'synthesizer timbre' is caused by limitations in traditional control devices — keyboards, footpedals, and knobs — and not by inherent limitations in sound synthesis hardware.*
>
> Boie, Mathews and Schloss, 1989

Nicolas Collins is a composer and performer who uses electronics extensively. Collins expresses the need for new controllers and electronic instruments when he explains why he builds his own controllers and instruments:

> *I build instruments because I have to — because my interests, needs and desires seem forever out of sync with the market.*
>
> *Building and programming are time-consuming processes, but I have ended up with instruments that have a distinctly personal*
>
> continued

character, ... and that are much more powerful — if specialized — than anything available commercially. Most importantly, buried in the mechanics of instrument design can be the seeds of music.

Collins, 1991

Alternative MIDI controllers are a means of establishing new paradigms for the creation and performance of music through the use of new sets of gestures for the control of sound. Electronic instruments allow the paradigm of a sound source being inseparable from its means of control to be left behind. MIDI allows this separation to be accomplished with relative ease.

Different methods of sound synthesis and signal processing often have distinct sonic characteristics. New electronic instruments can be realized by connecting a MIDI controller to modules employing different methods of synthesis or signal processing. Alternative controllers may be used to take advantage of some of the unique characteristics of these modules.

Michel Waisvisz discussed the role of alternative MIDI controllers in musical performance and composition in an interview:

> *... I consider the creation of a specific electronic musical instrument as being part of the compositional process due to the high*[ly] *modular* [and] *flexible setup of MIDI instruments... . The way a sound is created and controlled has such an influence on its musical character that one can say that the method of translating the performer's gesture into sound is part of the compositional method.*
>
> in an interview with Krefeld, 1990

Musical instruments offer composers and performers opportunities for expression. The form of that expression is a function of both the instrument and the imagination of its user. Insisting that electronic instruments replicate every facet of the behavior of acoustic instruments before exploiting their unique strengths is to ignore many possibilities for musical expression. Craig Harris, a composer and multimedia artist, explains:

> *... this new technology offers an opportunity to develop fundamentally different instruments and musical resources. Unlike instruments with fixed acoustical properties and playing methods (strings, brass, etc.), computers* [used as electronic musical instruments] *have no inherent sounds or musical processes. This technology lets us design the instruments and the way of working with them dynamically, i.e., as we need them for a specific context. In this sense, restriction resides largely in the limitations of our imagination, whether we are designing and building the instruments, or whether we are using them to make music.*
>
> Harris, 1990

As Harris observes, part of the new paradigm of electronic instruments is that nearly all such instruments are in fact computers in disguise. New possibilities begin to emerge when we start to think of these instruments as computers. An alternative controller then becomes a new kind of computer interface.

TRANSMOGRIFICATION

An idea borrowed from the field of human-computer interaction can supply part of the conceptual framework for an alternative controller. Chen and Leahy (1990) describe a two-part model for interacting with computer input devices. The first part of the model is based on the concept of physical and logical devices as developed by Foley, Wallace and Chan (1984). Physical devices are the means by which a user interacts with a computer. Joysticks, keyboards, mice, etc. are types of physical devices. Logical devices are the means of interpreting events supported by a computer's software. Each logical device has a natural prototype or associated physical device. As well, any physical device is able to simulate any of the defined logical devices, depending on the implementation of the devices. For example, text can be entered using a mouse to select individual letters from a displayed alphabet.

The second part of Chen and Leahy's model is event transmogrification.[2] Events are the data generated by the physical input devices. Transmogrification allows one physical device to mimic a variety of logical devices. Chen and Leahy propose a means of transmogrification that is transparent to users (and programmers). An event generated by a physical device that is not understood by an application is automatically converted into an event that can be understood.

The concept of transmogrification can be applied to electronic music systems. MIDI controllers can be considered the physical input devices for synthesizers and sound modules. The data generated by these physical devices can be transmogrified into the logical devices desired for control of the synthesizers or sound modules. The computer placed between the controller and the sound engine is the means of transmogrification.

Such transmogrification cannot be automated at the present time. In practice such automation may not be desirable, as each musician or composer, or the musical situation in which they are working, may require a unique transmogrification.

An ideal controller suitable for all musical applications cannot exist. Each physical interface has strengths and weaknesses making it suitable for different applications. Although some controllers span a greater range of applications and are therefore more generally useful than other controllers, they cannot cope with every possibility. A controller puts a variety of

[2] Transmogrification is the metamophosis or transformation of one thing into another.

resources at the disposal of the musician; it is up to the musician to take advantage of those resources and use them creatively. The 'deeper' these resources are, the more useful the controller will be.

INSTRUMENTS AS SYSTEMS

The idea of treating an electronic musical instrument as a system comprising a control surface, a computer and a synthesis engine is not new. The earliest implementation of this concept is probably that of Max Mathews' Groove system developed in 1969 (Mathews and Moore, 1970). The Groove system consisted of a computer, analogue sound synthesis modules and a set of input devices such as knobs, switches, sliders, and other controls. The input devices were connected to the computer, which in turn was connected to the synthesis modules. Data generated by the manipulation of the controls was processed in different ways using the computer. This system provided new kinds of control over the production of sounds.

The introduction of the MIDI standard in 1982 and its rapid and wide-spread acceptance encouraged this approach. A wide variety of MIDI controllers have been developed, some of which are described in Chapter 2. Several of these controllers are specifically designed to be connected to a computer. The computer is, in turn, connected to a synthesis engine.

This approach has several advantages. The electronics of the controller can be relatively simple and need only generate a fixed set of data. (This need not be in the form of MIDI data.) The computer can be used to process and route this data in different ways, store data for future use, provide visual feedback and add complex functions that would be difficult to achieve economically otherwise. In effect, the instrument's operating system is software-based and can be updated and modified easily in comparison to the more commonly used ROM-based operating system.

Some of the advantages of this approach are less concrete in nature and more concerned with the interaction between the composer/performer and their instrument. David Zicarelli (1991a) describes the advantages of an electronic instrument system; "Music environments... coupled with flexible controllers, allow performance systems to drift and evolve as the performer's interests and skills change."

Zicarelli (1991b) also points out the potential in 'communicating with meaningless numbers'. MIDI messages have specific meanings; for example, MIDI note-on messages are generally treated as specifying a particular note with an associated velocity, not as magnitudes generated by an array of impact-sensitive switches that can be used for a variety of control purposes. Zicarelli believes interactive programming environments allow one to see past the supposed meaning of MIDI messages and that when these messages lose their meaning, their potential for control applications increases significantly. Ideally, a controller would generate streams of 'meaningless' numbers, to which the user could assign a desired meaning (transmogrifying the numbers). This concept is used within the *MAX* programming environment for the Mathews/Boie Radio Drum and for interfacing with a Mattel PowerGlove®.

Xavier Chabot is a composer of electronic music and multimedia performer. Echoing Michel Waisvicz's idea of the relationship between gesture interfaces, performance and role of electronic musical instrument systems, Chabot states:

> *Gesture interfaces reintroduce in music a concern for physicality. Composition and execution, while remaining clearly two different activities, share characteristics of performance. First, the composer performs the act of creation when interfacing with programmers, performers and machines; second the use of electronic instruments, especially gesture interfaces, implies the explicit composition of the performance itself.*
>
> *This is why we must look for music making environments which stress creation through interaction and progressive refinement of prototypes. A music environment becomes truly interactive if it features tools to access, modify and represent in various ways all musical entities involved in the piece.*

Chabot, 1989

Part 1

BACKGROUND

Who wrote this fiendish 'Rite of Spring',
What right had he to write the thing,
Against our helpless ears to fling
Its crash, bash, cling, clang, bing, bang, bing?

From a review of Stravinsky's "Rite of Spring"
printed in the Boston Herald, 1924[1]

In order to properly understand the nature of musical instruments, one should first understand what it is that composers and performers do with musical instruments. One of the intentions of the following brief discussion is to remind the reader of the range and scope of the art of music. Electronic instruments have extended music into areas never before possible.

DEFINITIONS OF MUSIC 1.1

Most of us feel we know music when we hear it; defining music is another matter. Music and musical tastes, as with any art form, are continually changing in response to cultural, societal, political and technological influences. Stravinsky's Rite of Spring, initially unpalatable to the tastes of many people, is now a popular and respected piece of music enjoyed by many. As well, our own experience of music influences how we hear it. Even though we might listen to a piece of music over and over, we hear it with a different and increasing history of experience and in a different context each time. We might become aware of a new and different aspect of the piece and as a result develop a new understanding of it each time we listen to it.

Lewis Rowell expresses the diversity of musical definitions in the form of a chart illustrated in Table 1. Rowell (1983) invites readers to select the combination of words that most accurately represents their own view of music. He does caution that this is not an exhaustive list of statements to be used to define music.

[1] Quoted in John Booth Davies' The Psychology of Music, pp. 216.

Subject	Verb	Object
Music or a musical event	means	a feeling
	expresses	emotion
	represents	a mood
	evokes	an image
	imitates	a thing
	signifies	nothing
	symbolizes	a process
	resembles	human qualities
	points to	another musical event
	refers to	a type of motion

Table 1.
Definitions of music (from Rowell, 1983).

THE NATURE OF MUSIC 1.2

The American composer Aaron Copland (b. 1900 – d. 1990) feels we listen on three planes simultaneously. These planes are the sensuous plane, the expressive plane, and the musical plane (Copland, 1957).

On the sensuous plane, we take pleasure in the musical sound itself. A single note or chord sounded on an instrument having a rich tone quality (a cello or a piano, for example) can be a pleasing sensation in itself. However, music is not always made up of only pleasing sounds. Copland points out that consonance and dissonance are relative to the listener's experiences, the time in which the music is composed, and the place they hold in the music.

Listening on the expressive plane reveals the meaning behind the notes or the emotional content of the music. The idea that music has any meaning beyond itself is somewhat controversial. Copland suggests the idea that music has no deeper meaning springs from the inadequacy of words in describing what a piece of music might be about. Music and the sounds of music have great suggestive powers and can bring to mind waterfalls, trains, the passage of time, or nearly anything an ingenious composer might wish to convey. Copland feels the meaning of music is not so specific or concrete as some people might believe, but a more general concept expressing some shade of emotion or a mood. Research by Clynes and Netthiem (1982) connecting specific emotions to corresponding musical gestures lends credence to Copland's view.

On the musical plane we listen to the materials of music. These materials are the rhythms, melodies, harmonies, forms, tone colours, and other devices employed by the composer to communicate his or her idea to the listener. Musical instruments are used to express these elements within a composition.

The three musical planes have a synergistic relationship; each plane reinforces the others. Expression can be conveyed on the sensuous and musical planes just as expression reveals the materials of the musical plane. The most satisfying musical experiences are built on a foundation of synergistically related planes.

MUSIC AND INSTRUMENTS 1.3

Copland's explanation of music shows musical instruments are used to create a sensual, emotional and intellectual experience for a listener. Each aspect of the listening experience is a result of the combination of the sounds of the instruments used, the arrangement of these sounds, the intent of the composer and how that intention is transmitted by the performer. These aspects also influence each other in significant ways.

We can see that individual musical instruments have different characteristics. These characteristics make different instruments suitable for different purposes. Musical instruments have varying degrees of effectiveness on the sensuous and musical planes of music. Striking a single note on a grand piano produces a rich and sensuous sound, but expression is limited to striking the piano key with varying degrees of force, producing louder or softer tones.

Many listeners might find notes sounded on a saxophone to be not as rich or sensuous as notes sounded on a piano. The saxophone note, however, can be manipulated in ways the piano note cannot. Vibrato, tremolo, volume changes and timbre changes can be used to infuse a note with emotional meaning. This ability makes the saxophone more immediately expressive than the piano.

The polyphonic capabilities of a piano (many notes can be sounded at once) make it suitable for working with different materials of the musical plane (such as harmonies or simultaneous musical lines) in a solo situation. The saxophone is monophonic, able to sound only one note at a time, and thus cannot access the same musical materials as the piano.

SUMMARY 1.4

Electronic musical instruments often have sufficient flexibility to be used in more situations than conventional instruments. Nevertheless, just as conventional instruments have characteristics and limitations, so do electronic instruments. The current generation of electronic instruments excel at dealing with the formal, quantitative and objective aspects of sound. While these instruments can produce a wide range of sounds, the physical interface limits the control the player has over the sound. The sounds produced can often be quite sensuous, but the interface falls short in dealing with the manipulation of sensual qualities of the sound.

A (Very) Brief History of Electronic Instruments 2.0

What I try to do is persuade as many people as possible... to look on the possibilities of the electronic family as a legitimate family of musical instruments and not as an imitation or a bastard... . We should have the same variety of approaches in the electronic family as any other family.[of instruments].

Donald Buchla, 1983[1]

A brief review of the history of electronic musical instruments will serve two purposes. It will familiarize readers new to this relatively specialized field with some of the developments that lead to current state of the art. It will also show that the issues surrounding real-time performance using electronic instruments have been a continuing concern in the development of new controllers. This review is extremely brief and is in no way a comprehensive look at the history of making music using electronics.

EARLY ELECTRONIC INSTRUMENTS 2.1

The first electronic musical instruments were developed in the 1920s. Sound recording technology was in its infancy and had significant limitations. As a result, the instruments of that time were designed for live performance purposes. Two instruments in particular, the *Theremin* and the *ondes Martenot*, generated significant interest in the music world.

The Theremin 2.1.1

The Theremin is considered the first truly electronic musical instrument; it's sound is generated by electronic rather than electro-mechanical means. Leon Theremin invented the instrument in Russia about 1920. The instrument is monophonic and is played by moving one's hands in the proximity of two antennae. One antenna controls the pitch and the other controls the loudness of the tone. The Theremin is characterized by its pure, smooth, gliding tones.

The instrument generated enough interest that a number of composers, including Edgard Varèse and Joseph Schillinger, wrote music specifically for the instrument. Interest in it faded as other electronic instruments with a wider range of sounds (such as the ondes Martenot) became available. People have become virtuoso players, and the instrument continues to enjoy some popularity in Russia. Figure 2.1 shows the Theremin virtuoso Clara Rockmore in performance.

---

[1] in "An Interview With Donald Buchla." by John K. Diliberto in Polyphony, Vol. 8, No. 5, August, 1983.

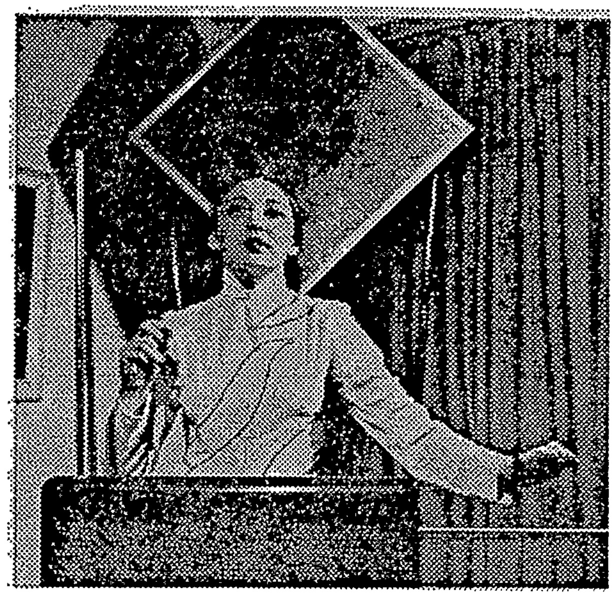


Figure 2.1
Clara Rockmore, playing her Theremin, ca. 1945 (from Rhea, 1984).

The Ondes Martenot 2.1.2

In 1928 the ondes Martenot was introduced in France, when its inventor, Maurice Martenot, performed a piece written for the instrument. Martenot's intent was to design a musical instrument that would be accepted as another member of the family of symphonic instruments. The instrument uses the same basic principle of sound generation as the Theremin. Martenot's contribution was to add a means of playing traditionally notated keyboard music. The instrument's pitch is controlled with a sliding ribbon that moves back and forth over an illustration of a conventional keyboard, using a plastic ring attached to the ribbon. The ribbon, in turn, rotates a variable capacitor that changes the frequency of one of the oscillators. Figure 2.2 illustrates the operation of the ondes Martenot.

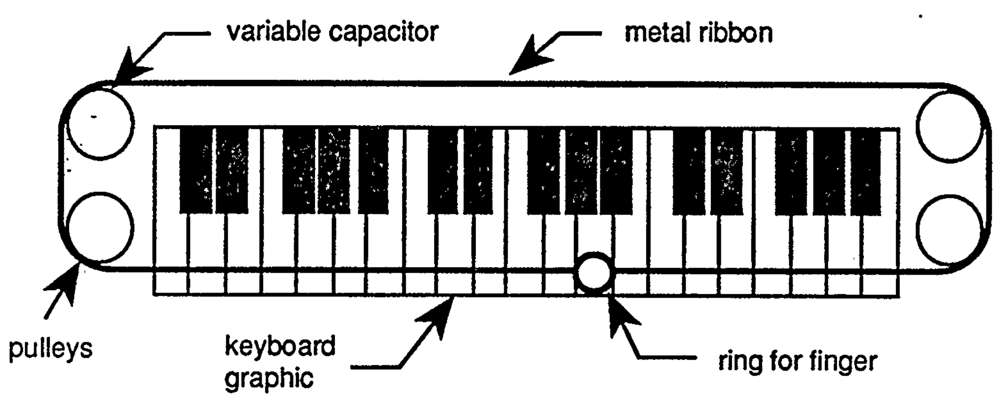


Figure 2.2
Operation of the ondes Martenot.

This means of selecting pitch also makes it possible to play micro-tonal music (music where the octave is divided into more than 12 tones). This particular feature made the instrument attractive to a number of composers. Several controls for the left hand alter the timbre, and a single pressure sensitive key controls the loudness of the notes. When this key is fully released the instrument is silent; increasing pressure makes the sound louder. This key gives the player control of the attack of each note and also permits the glissando (produced by moving the ribbon from note to note) to be heard or silenced. The ability to control the glissando was considered a great improvement over the Theremin.

The various improvements made to the ondes Martenot over time included the addition of a keyboard with moving keys and helped to make it the most successful of the early electronic instruments. To date, more than three hundred composers have contributed to the sizable repertoire of the instrument. This includes chamber works, operas, symphonic works, numerous ballets, and over five hundred incidental scores for film and theatre (Holmes, 1985).

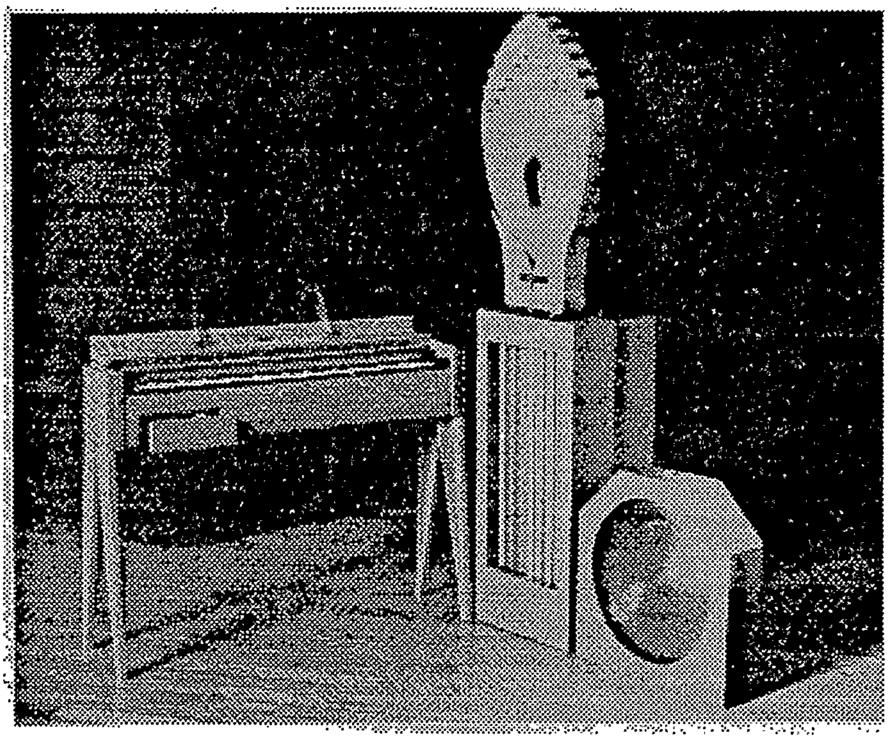


Figure 2.3
1977 concert Ondes Martenot (from Manning, 1985).

One of the most promising of the early electronic instruments originated in Canada. Hugh Le Caine designed and built a prototype instrument he called the Electronic Sackbut in 1945. In developing the Sackbut, Le Caine's sought to design an instrument that "would be as satisfying musically as a violin with the same detail and nuance in the sound". He concentrated on controlling the sound, and felt "the subtle shading of the elements of the sound would lead to greater expressivity," (Young, 1989).

The Electronic Sackbut was a monophonic instrument, intended for use in live performance. Le Caine felt monophonic instruments were the starting point for all musical thinking, and polyphonic instruments were an expedient brought about by the difficulty of gathering together a sufficient number of monophonic instruments and performers.

To realize the control of nuance he desired, Le Caine designed the keyboard to be sensitive in two dimensions. In the vertical dimension the keyboard was pressure sensitive, allowing the player to determine the attack and decay characteristics of each note. Movement in the horizontal dimension affected pitch, allowing the player to add vibrato to a note. The left hand was used to operate controls affecting the timbre of the sounding note. Movement of the index finger in a two dimensional matrix controlled the waveform being produced while the thumb and other fingers operated controls that affected the harmonic spectrum of the tone and different types of frequency modulation. (see Figures 2.4 and 2.5) Despite the touch sensitive keyboard and continuous controls for pitch and timbre, the instrument was not a commercial success. Several attempts were made to manufacture the Electronic Sackbut, but the instrument was never mass produced (Young, 1989).

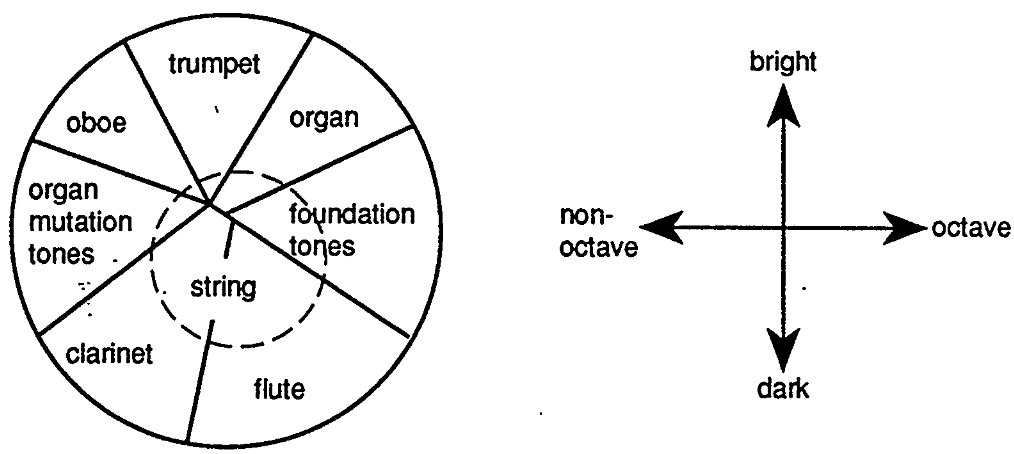


Figure 2.4
Timbre controls for the Electronic Sackbut (from Young, 1989)

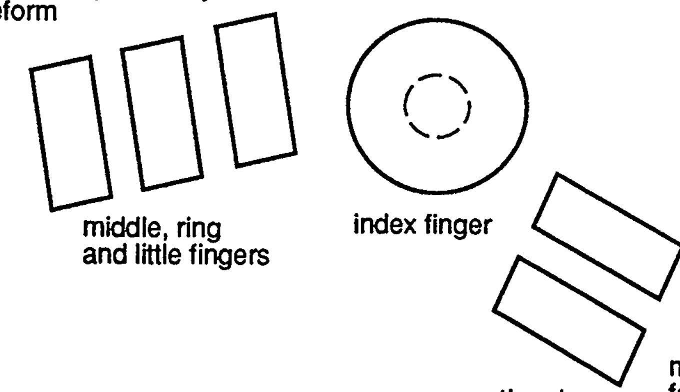


Figure 2.5
Electronic Sackbut left hand controls (from Young, 1989).

VOLTAGE-CONTROL SYNTHESIS 2.2

The introduction of voltage-controlled synthesis in 1964 by Moog and Buchla initiated a change from electronic musical 'instruments' to re-configurable electronic music 'systems'. The modules of a voltage-controlled system have different functions such as oscillators, filters, envelope generators, amplitude modulator, low frequency oscillators and mixers. Patch cords are used to connect the modules in different configurations. This approach allows many 'instruments' to be made with the same set of modules. The knobs and switches of these synthesizers provide additional real-time control of the sound.

Synthesizers consisting of a collection of permanently configured modules connected to an organ-type keyboard soon became readily available. These instruments were affordable for many musicians and the elimination of patch-cord connections made them easier to understand than the modular synthesizers. This first generation of synthesizers was monophonic, sounding one note at a time. The organ keyboard functioned simply as a row of on-off switches to select pitches from the chromatic scale. Additional performance controls were generally limited to two modulation controls, usually wheels or levers activated with the left hand. One control was typically dedicated to altering the pitch of the note, and the other controlled the modulation level of a low-frequency oscillator to add vibrato to a note.

The early synthesizers manufactured by Donald Buchla used touch-sensitive plates in place of the organ-type keyboard and usually incorporated a sequencer (later models offered a keyboard as an option). Each touch-plate could initiate an entirely different sonic event. The sequencer allowed a series of events to be pre-programmed and triggered automatically. These features attracted composers consciously seeking to avoid a keyboard-oriented approach to electronic music. Schwartz (1989) states "the very appearance of the touch-board [on the Buchla synthesizers] radically changes the psychology of one's approach to the instrument, for it simply cannot be treated like a keyboard instrument."

INTRODUCTION OF MICROPROCESSORS 2.3

Microprocessors began to be used in mass produced synthesizers in the mid-1970's. Manufacturers were quick to recognize the capabilities microprocessors could add to synthesizers. Initially, microprocessors were used to manage voltage controlled synthesis modules and primarily served to store 'patches' (the settings of the controls and routing of the cords used for different sounds).

Microprocessors were soon used to extend the capabilities of an organ-type keyboard in many ways. Polyphony, key velocity, the assignment of different sounds to specific ranges of keys, alternate tuning systems and many other functions are now commonly available on microprocessor-based instruments. Perhaps the most significant development resulting from the use of microprocessors was the MIDI specification (discussed in the following section). Microprocessors are used for the actual generation of sounds and virtually every commercially available instrument is now 'digital'.

Manufacturers also realized that a microprocessor would allow a reduction in the number of physical variable controls on an instrument and thereby reduce manufacturing costs. By using a LED or LCD display and a number of switches, a single variable control could replace many controls. Typically, most of the switches are 'soft' switches, performing double or triple duty. A desired parameter is selected using menu selection buttons and the value is changed using increment/decrement buttons, a free-spinning dial, a slide control, or a data entry keypad.

The economies realized in manufacturing costs have been at the expense of the human interface of these instruments. Usually only a small amount of information can be displayed at one time and often only one parameter at a time can be adjusted. This kind of interface often has several modes of operation, and the controls can have different functions depending on what mode the instrument is in. Learning to navigate through the screens of information can be difficult. Most significantly, the ability to control parameters in real-time is greatly reduced.

THE MIDI SPECIFICATION 2.4

The MIDI specification was developed in 1983 by a group of American and Japanese musical instrument manufacturers as a means of interconnecting their products. (See Appendix A for an overview of the specification.) The initial intention was to allow one keyboard to control the sound generating components of other synthesizers. The MIDI specification is intentionally an open-ended specification and changes reflecting the needs of MIDI users and the capabilities of new technologies continue to be made. People quickly realized that MIDI data could be handled by personal computers, and many MIDI programs have been developed.

Manufacturers have also adapted many different types of equipment for MIDI control. Audio mixers, tape recorders, signal processors and even lighting control systems are among the devices that can now be controlled using MIDI.

Recently, programs such as *Sybil* (GHS Music Products), *HMSL* (*H*ierarchical *M*usic *S*tructure *L*anguage, Frog Peak Music) and *MAX* (Opcode Systems, Inc.) have brought interactive performance capabilities to MIDI instruments. These kinds of programs allow the manipulation of MIDI data in real-time using a personal computer. Musicians can set up situations where their musical or physical gestures will interact with previously established musical structures or events. For example, a program may accompany a musician, in effect 'hearing' the notes being played, and respond by 'playing' the appropriate accompaniment.

MIDI Instruments and Controllers 2.4.1

One of the most significant changes brought about by the adoption of the MIDI specification is the ability to separate sound generating mechanisms from control mechanisms. Many 'sound' or 'expander modules' are now available. These modules retain the sound producing and editing capabilities of a synthesizer but do not have a keyboard or other 'performance' interface; they are intended to be controlled using MIDI data.

The MIDI controllers that are currently available are usually modelled on existing instruments including the saxophone, trumpet, guitar, and percussion instruments such as drums and the vibraphone. As well, actual instruments such as pianos, violins, cellos and electric guitars have been adapted to act as MIDI controllers.

Alternative MIDI Controllers 2.4.2

New MIDI controllers are continually being developed. The reader is referred to Rothstein and Metlay (1990) for a comprehensive discussion of the history and development of musician-machine interfacing for electronic music performance, emphasizing MIDI controllers.

The following brief descriptions focus on several alternative MIDI controllers. One can see the diversity of approaches taken as well as the common concerns of the designers.

The Hands

The Hands are a set of controllers developed by Michel Waisvisz for the real-time control of synthesizer parameters (Waisvisz, 1985). The Hands are (appropriately enough) worn on the hands and sense the flexing of fingers, touching of the palms, rotation of the hands, and waving of the arms through the use of a variety of sensors. Waisvisz admits that the Hands are difficult for other people to play not only for ergonomic reasons (the Hands were designed to fit his hands), but also because of his unique conceptions of timbre and how one should manipulate timbre (Krefeld, 1990).

The Radio Drum

The Mathews/Boie Radio Drum (see Figure 2.6) is a percussion-type instrument developed by Max Mathews and Bob Boie, and consists of a rectangular sensing surface played with mallets. The heads of the mallets contain short-range radio transmitters tuned to different frequencies. A special radio receiver in the playing surface continuously senses the positions of the mallets in three dimensions. The mallets can be used to trigger events and for making control gestures. Trigger signals are typically generated when a mallet crosses a plane parallel and close to the surface of the playing area. The position of the mallet is continuously scanned by the instrument's computer, so the velocity of a stroke as well as the position can be determined. Control gestures are made by waving a mallet above the horizontal surface.

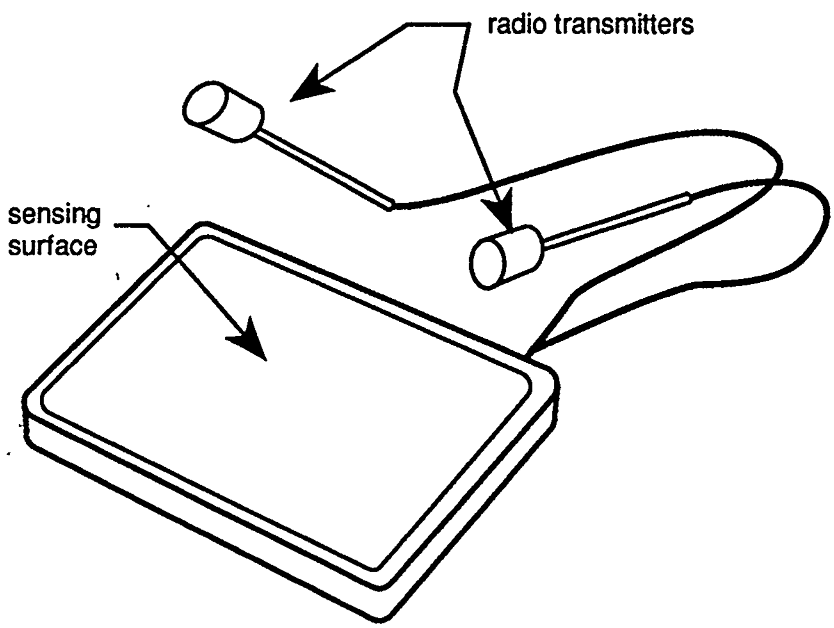


Figure 2.6
The Mathew's/Boie Radio Drum.

The Radio Drum is typically used in applications requiring a 'conductor mode'. In this mode of operation, the pitches of the notes of a musical composition are stored ahead of time as a sequence, and the player triggers each note individually. The player has no control over the pitch selection, but instead controls rhythm, tempo, and nuances such as the loudness and timbre of each note.

The Video Harp

The Video Harp (illustrated in Figure 2.7) uses a built-in light source to sense the position and motion of a player's fingers on a pair of flat, transparent acrylic surfaces (Rubine and McAvinney, 1988, 1990). The fingers of each hand break a light beam from a neon tube into light and dark bands, sensed by micro-chip.

At present the instrument does not sense finger velocity. The chief advantage of this controller is that a variety of different finger motions can be sensed, including those used to simulate bowing or strumming effects. The size of the contact area of the fingers and the angle of the fingers can also be sensed.

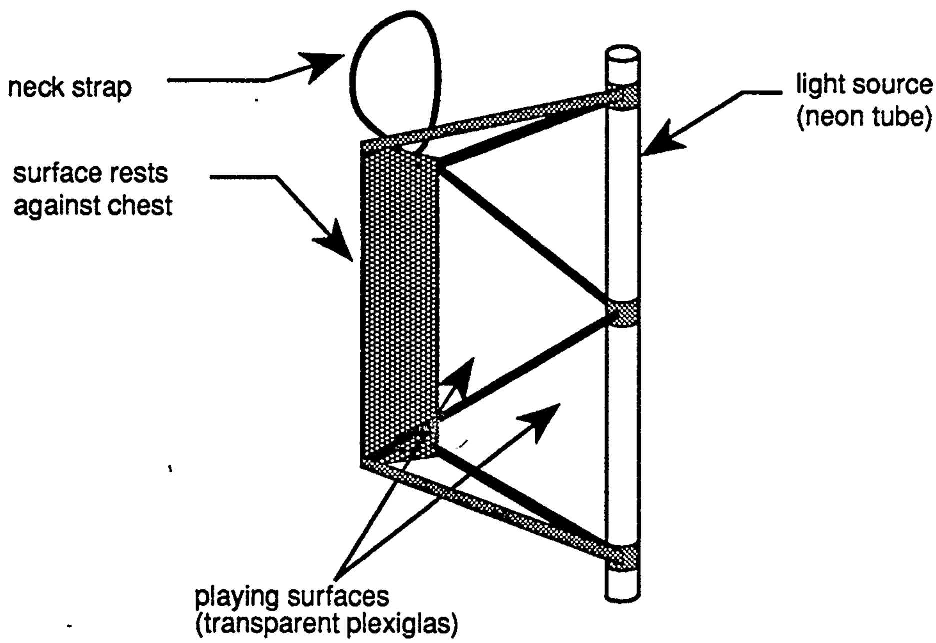


Figure 2.7
Rubine and McAvinney's Video Harp.

Thunder and Lightning

Donald Buchla has expanded on his notion of touch-plates to develop the Buchla Thunder (Figure 2.8), an advanced MIDI performance controller. Thunder is an array of 25 velocity- and pressure-sensitive touch-pads (fifteen of the pads also sense finger location) that can be programmed to send a wide variety of MIDI messages.

Buchla's Lightning controller is similar in function to the Radio Drum and senses the X-Y position of one or two infra-red transmitters. The position, velocity and direction of movement of the transmitters are used to generate MIDI data. The controller consists of a small box with a short wand attached that is held in the hand and a small box some distance away to detect the movements of the transmitters (the infra-red transmitter is at the end of the wand). The distance from the detector box is not sensed. The transmitters are also available in the form of rings worn on the fingers and embedded in a pair of drumsticks.

The Lightning controller has gained much attention and is frequently used to 'conduct' pieces of music in much the same way as the Radio Drum.

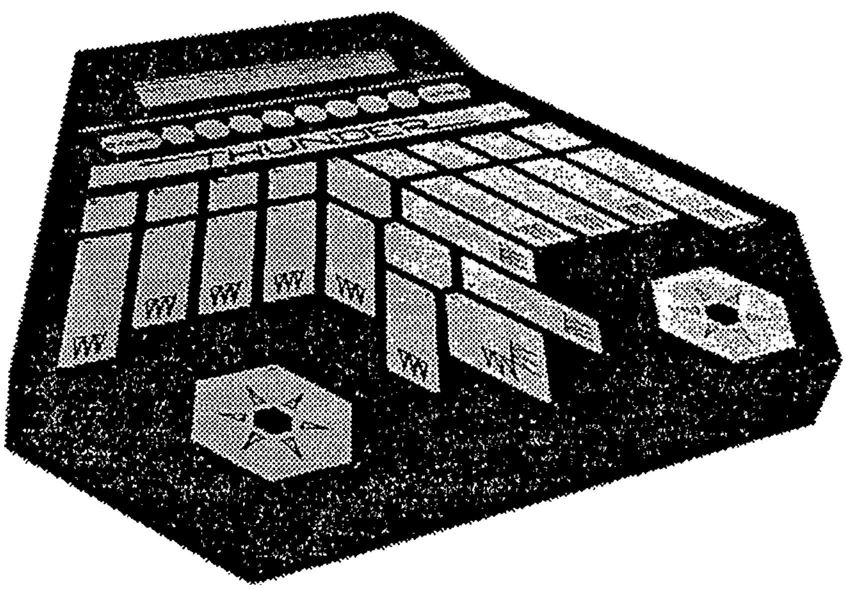


Figure 2.8
Buchla Thunder controller.

SUMMARY 2.5

Electronic musical instruments started as a family of unique performance instruments. As technology progressed electronic instruments became simultaneously more powerful and less performance oriented. The introduction of voltage-controlled synthesizers placed the means of electronically generating sound in the hands of many people, but did little to take advantage of the unique performance capabilities offered by electronic instruments.

The establishment of the MIDI specification allows a separation of the control interface and the sound generating mechanism and provides a means of dealing with data generated by performance. Separate performance controllers can be designed for connection to a variety of sound generating modules.

The modular approach fostered by MIDI has simplified the development of electronic musical instrument systems. Frequently such systems include a computer. In some instances, such as the Mathew's/Boie Radio Drum, a computer is an integral component of the instrument. The computer can be used for such things as sound generation and manipulation, score playback, or various kinds of information storage (sounds, patches, digital recording, etc.). The computer can also take a more active role and be intimately involved in performance situations, responding to a performer's actions in many different ways. An electronic musician can choose a controller, a sound generator and software, according to their needs or the requirements of a musical situation.

Although not explicitly discussed, a distinct culture exists around electronic musical instruments. Electronic instruments are very powerful, but that power has a price. Persons involved in this area of music cannot ignore the high-tech aspects of the instruments they have chosen to work with. At the simplest level this means dealing with cables and cords for power and signals, and hooking up amplifiers and loudspeakers. The other extreme is dealing with computer crashes, software bugs, indecipherable manuals, and hardware that is virtually obsolete by the time it is manufactured. The learning curves associated with the equipment and software are often long and steep. Dealing with these things is the cost of realizing a particular artistic vision.

The Musician's Task 3.0

Man, if we could play the piano we wouldn't have to move them.

O.J., of Green Lines Movers, after a
particularly difficult piano-moving job,
in Pomona, New York[1]

The musician's task is complex, and involves more than simply the development of the physical skills necessary for playing a musical instrument. Playing music often includes an element of creative expression or interpretation that is difficult to define.

PERFORMANCE AS TASK 3.1

Kurkela (1991) develops a model of the act of performing from a score as a goal-directed activity divided into levels of interpretation and execution. This model is illustrated in Figure 3.1. The interpretive level concerns the understanding of the materials of the music and the composer's intention (this corresponds to Copland's musical and expressive planes). The execution level concerns the ability of the musician to produce the sounds of the music (Copland's sensuous plane).

The steps of the process are carried out sequentially with different skills required for each step. Musicians typically read and understand a written part in a score (using notational competence and semantic understanding), and artistically interpret what they have understood. A musician might play a piece of music from memory, follow a part in a score, improvise, or use some combination of means of performance. This stage produces a conception of what must be done to realize the performance. Kurkela notes that this is the logical order of the interpretive process, and in reality the output may be a result of reflection over a period of time where the two phases are tightly entwined.

The next stage is one of preparation for the act of playing. Kurkela suggests this may be more a process of automatic or proceduralized application of previously learned skills than a conceptualized process. At this stage the performer must be aware of his or her own physical and psychic state, the properties of the instrument, the acoustic environment, and other factors that might be affecting the process at that moment.

After the execution strategy has been calculated the actions are carried out, resulting in a performance. Attempts to improve a performance are based on

[1] Quoted in EAR, Magazine of New Music, Vol. 16, No. 2, May, 1991.

motor-kinesthetic and auditory feedback. (Criticism from an objective listener an also improve a performance.) Skills can be developed in performance by using this feedback to modify or 'fine-tune' both the interpretation and execution of the music; changes on the interpretive level are reflected in the execution. Feedback can affect the performance on a note-by-note level, or on a level that considers the piece of music in its entirety.

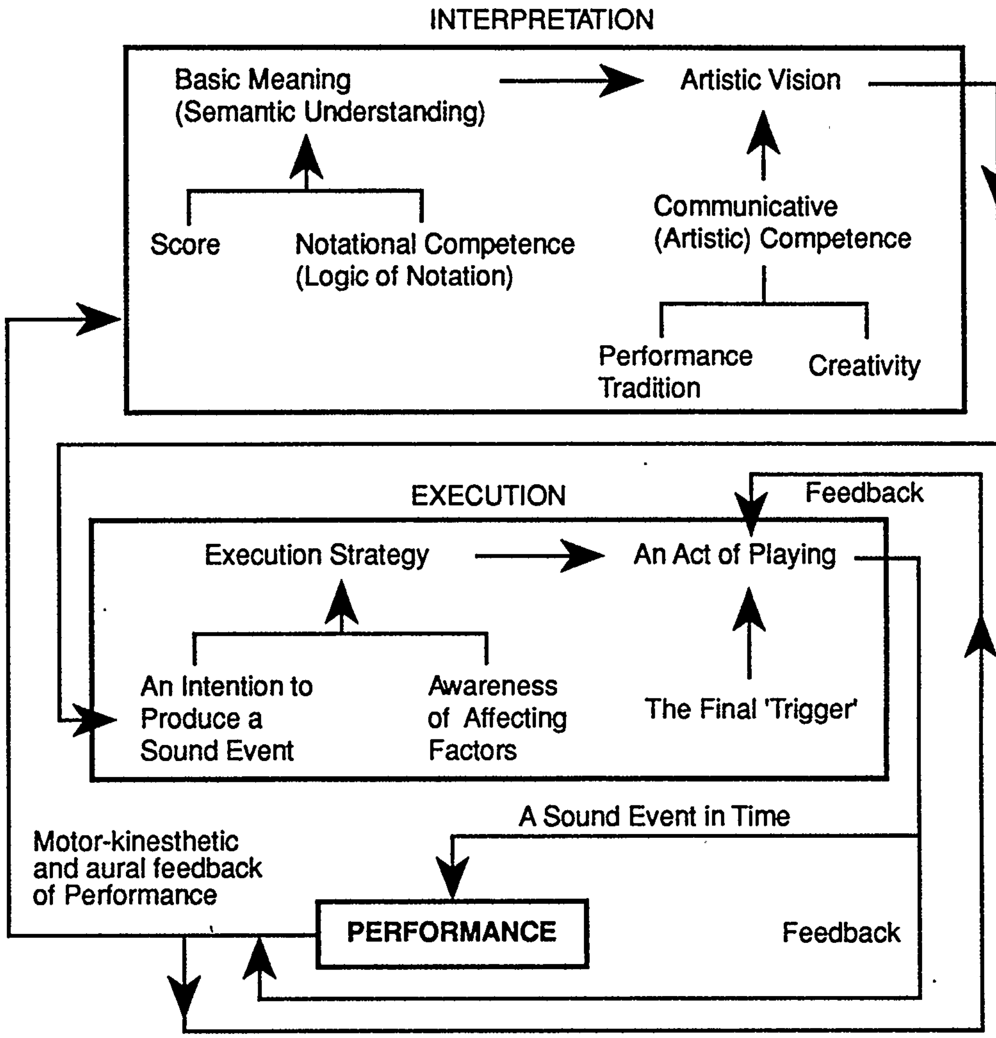


Figure 3.1
Model of performance from a score (from Kurkela, 1989).

Kurkela's model assumes performance from a written score. However, not all musicians rely on a score; musical improvisation skills are highly valued in jazz and other forms of music. In all but the most adventurous improvisation, the musician has an internal conception of the form of the music, and in effect has a memory of their part of the 'score' in mind when performing.

According to Clarke (1988), interpretation is a structural and expressive coding of music. Musical compositions are subject to different structural interpretations, and Clarke feels the primary role of expression is to limit the resulting ambiguity by emphasizing one structural interpretation.

Clarke lists three factors influencing the choice of expressive options. The first is the resources of the instrument. As previously discussed, different instruments have different expressive capabilities, according to the resources they present to the musician. Second is the style of performance. Styles of performance expression change with history, geography, and can also be linked to the changing technology of musical instruments. Individuals often develop strong personal styles of performance as well. The third factor is the manner in which the musician chooses to perform; a musician would likely use a style of performance for a ballad different from that used for a national anthem.

The musician, then, has two major tasks; interpreting the written music, followed by execution of that interpretation. Interpreting music requires as much skill as the execution and can involve an element of creativity (the Artistic Vision in the Kurkela's model). One musician's rendition of a piece of music might move us more than another, even though both possess similar physical skills in playing their instruments.

Clarke sums up his discussion of interpretation and expression with a statement reflecting the difficulty in determining the appropriateness of any particular design solution for a musical instrument relative to the musician's task.

> *If communication is the primary aim, then it is not too difficult to prescribe a successful configuration of the expressive principles outlined* [in this article]. *If, on the other hand, artistry is the primary aim, then prescription is both impossible and inappropriate. The essential characteristic of artistic activity (and aesthetic objects) is a radical form of ambiguity and creativity, and while the expressive resources may be outlined, their precise disposition on any occasion can be accounted for only in retrospect, not predicted. Were this not the case, and our curiosity in these ambiguities and possibilities not boundless, we might all have given up going to concerts long ago.*
>
> Clarke, 1988

It must be pointed out that creative expression and/or interpretation on the part of the musician are very often not desired; in many instances a composer has very specific ideas about the execution of a piece of music in mind and spells these out in the score. In these instances the musician's task is to execute the music as accurately as possible and performances by different musicians should be virtually identical. The creativity and expression in such pieces is strictly the province of the composer.

THE NATURE OF PERFORMANCE 3.3

Baily (1985) turns to the field of ethnomusicology to explore the nature of musical performance. Baily reasons that the field of ethnomusicology has access to the cross-cultural data needed to distinguish between musical activities specific to a culture and those activities that are universal in nature. He summarizes the research of several leading ethnomusicologists and lists four points regarding musical performance. Those points are:

1.) There is a recognition of the importance of studying the movement patterns used in playing an instrument. A musical instrument is a transducer, converting movement patterns into sound patterns. The exact nature of the sound pattern depends on the characteristics of the movement pattern.

2.) When a body of works for an instrument is analyzed, common elements may emerge at the level of movement. This suggests that performance is, in some sense, based on a vocabulary of movements or gestures.

3.) The physical characteristics of an instrument influence, to some degree, the form of the music played on it in a way that those aspects of the music may be said to be a function of the instrument. Alternatively, an instrument may be constructed to suit particular movement patterns in order to fulfill certain musical requirements.

4.) In musical performance, the cognitive representation in terms of which the performer operates may be a movement representation rather than an auditory one.

Baily finds the notion that the spatial properties of an instrument may influence the form of the music played on it emerging from his review. He suggests the relationship between an instrument and its music must be examined in terms of the human sensorimotor system, and that it is necessary to look closely at the interaction between the structures of the human body and the structure of the instrument in order to understand this relationship.

According to Baily, musical instruments have an inherent connection between the physical interface and the structure of the music produced. This connection[2] plays a significant role in determining the music made with that instrument. The physical interface determines the patterns of movement possible and thus such things as the combinations and sequences of notes possible on a musical instrument. Extending Baily's hypothesis to electronic

[2] This connection (called a 'mapping') is discussed in greater depth in the next chapter.

instruments, a physical interface modelled on an existing acoustic instrument cannot take full advantage of the unique capabilities of an electronic sound generating mechanism. The patterns of movement are established by the model instrument determining, to a certain extent, the musical forms available to the player.

Baily's hypothesis also recognizes that an instrument has an associated set of repeatable physical gestures used to produce corresponding specific musical events. Musicians can spend a lifetime developing these physical skills. In contrast to acoustic instruments, the nature of MIDI controllers is to translate performance gestures into data, and a fixed correspondence between gesture and sound is not necessary. This allows the individual using such a controller to establish their own 'voice' or set of gestures with corresponding sonic or musical events. Performers are thus able to express themselves in a more personal manner. The flexibility of MIDI controllers also encourages experimentation and diversity, although, as pointed out above, controllers modelled on existing instruments can be somewhat restricted in this area.

PERCEPTION OF GESTURE 3.4

Inherent in the notion of a musical performance is the idea that a musician does not engage in making music in isolation. Music is one of the performing arts, falling into the same category as dance and theatre. As one of the performance arts, music includes a visual element. An audience also plays an important role in performance, especially when music is considered to be a means of communicating a feeling or emotion.

While the gestures of playing need not be entirely visible to an audience, these gestures should be evident. It is not always possible to see the individual movements of a musician's fingers from the back of a concert hall but one usually has a sense of the gestures being used. Musicians in virtually all areas of music sometimes exaggerate their gestures while playing. Apparently, these exaggerated gestures allow them to feel more intimate with the music.

Research in psychoacoustics shows that our perceptual system does not process data from the senses in a direct fashion, but infers possible causes of the effect. Cadoz elaborates:

> *Moreover, even with a total absence of real gestural causality, as this can be achieved by sound synthesis, the ear has a tendency to look beyond the effective causality (the electronic process) for a possible evoked causality, at the same time relative to a producer object* [source of the sound] *and to an effector gesture.*

The instrument, in a general sense, and the instrumental gesture, have over and above the practical sound producing role, a function in the ontogeny of auditive perception...

Cadoz, 1988

Morthenson (1989) feels the lack of referents for electronic sounds is one of the aesthetic dilemmas of electronic music. He feels instrumental and vocal musics are based on 'natural' and familiar references, and that "... abstract patterns [such as the arrangement of a composition] as well as the expressive functions rest firmly on spatially and psychologically functioning orientation marks." Morthenson points out that many of these references (such as regular rhythms, well-tempered scales, etc.) are the result of convention, not nature. He also points out that the composer or performer of electronic music may use a familiar referent such as a keyboard, but listeners might not identify the resulting sound with the referent.

Simon Emmerson is a composer and theorist working in the field of electroacoustic music. He describes a performance he witnessed in a recent discussion of the role computers play in performance situations. Four performers sit behind computer monitors and react to what appears on their monitor screens by pressing keys on their computer's keyboard. Gesture had been reduced to a trigger/response mechanism. He points out that the use of computers has focused attention on the triggering of discrete musical 'events' rather than control within events. Emmerson feels a shift must be made in how computers are used in performance situations.

We must shift the emphasis away from this unmusical model of 'interaction' back solidly to the human performer. We need to evolve systems which give back to the performer a sensory relation with the result, one that he/she can monitor and control through this feedback in real-time — the expressive component...

The role of computer processing on the concert platform is...

a) to extend the human gestures of the composer and performer and their immediate choice of and control over: sonic materials, signal processing and treatments

b) to manage, under the control of the performer, score systems in the broadest sense including system configurations.

Emmerson, 1991

A recent review by Tom Darter (1991) of a performance of Bug-Mudra, an electroacoustic piece composed by Tod Machover, brings these points into focus. In performance Machover conducts using an Exos Dexterous Hand Master Controller to monitor the movements of one of his hands. These movements cause the sliders on an automated mixing console to move up and down, changing the volume of some sounds. Another person sits at a computer, making changes on his monitor screen. The other performers in the ensemble (primarily guitarists) also have their instruments connected to the computer, allowing them to trigger and shape notes and sequences in different ways. The ensemble is, in a sense, playing a single instrument.

Darter observes that the relationships between the actions of the performers and the resulting sounds are not immediately apparent and cause "major cognitive dissonance". The audience has difficulty making the connections between a gesture and the resulting sound, or associate the wrong sound with a particular gesture. To fully appreciate the performance, one must understand the concept of the hyperinstruments and realize that the gestures are having an effect on a level that is not visible or even necessarily audible.

MAKING MUSIC 3.5

The preceding discussion shows that performing music is a complex process. Kurkela's model of performance shows that making music involves more than just the physical activities of playing the instrument. Clarke argues that we cannot prescribe the activities of a musician that will result in an artistic performance, and that these activities are in fact different for each occasion. Analyzing an artistic performance and applying the extracted gestures to another performance will not result in artistry. Baily's research illustrates that a strong relationship binds together a musical instrument, the movement patterns used to play the instrument and music produced with that instrument. Cadoz and others show the importance of gesture in musical performance.

One can see that gesture and the perception of gesture are very important elements of musical performance, but that a task analysis on the gestural level is inappropriate if we want a musical instrument to be used for artistic expression and interpretation. Defining the gestures (the movement patterns) of an instrument and what those gestures do to the sound of the instrument also defines, to some extent, the music made with that instrument and prescribes the artistic aspects available to the musician.

SUMMARY: The Musician's Task (Reprise) 3.6

Pitch, loudness and timbre are three principle dimensions of sound, and the task of executing a musical performance involves control of these dimensions. This control is realized through physical contact with a musical instrument.

The musician's task is to play music. This is usually done by modulating the pitch, timbre and loudness of sounds, but is not limited to these variables. In some instances the notion of performance goes beyond playing notes and chords to involve more substantial changes to the fabric of the music. Specifics of the musician's task are related not only to the instrument, but also to the piece of music being performed. The specifics, or 'sub-tasks' (applying vibrato to notes, crescendos and decrescendos, etc.) that make an artistic and expressive performance, can only be described in retrospect. The musician's task, however, can be thought of as different levels of control over the materials of music rather than specific physical activities.

Levels of Control

Andrew Schloss, in discussing his use of the Mathews/Boie Radio Drum (an alternative controller described in Chapter 2), divides musical activity using electronic instruments into three broadly descriptive levels of control (Schloss, 1990). Schloss's division of musical activity provides a convenient means of categorizing the tasks of a musician and the corresponding functions of a controller without becoming so specific that artistry is impeded. His categorization also takes into account those functions of electronic instruments that are not possible with acoustic instruments. The three levels are described below:

1.) The *timbral* level is microscopic, in a sense 'within a note', and requires continuous control of synthesis parameters in a number of dimensions. This is the level where the pitch, timbre, loudness, and other acoustic properties of a sound are controlled.

2.) On the *note* level, the musician deals with selecting or triggering specific pitches. This level can be thought of as dealing with the 'melody' of a piece of music.

3.) Schloss conceives of the *musical process* level as macroscopic and having an abstract paradigm allowing the mapping of gestures to operations not available in acoustic instruments. He gives as an example the coupling of a controller to multimedia environments.

Passing through Canadian customs with his luggage, [jazz musician] *Bobby Hackett was stopped by a customs officer, who pointed to his trumpet case:*
"Is that a musical instrument?" *asked the officer.*
"Sometimes," *admitted Hackett.*

Bill Crow in Jazz Anecdotes

Musical instruments present opportunities for expression and, as a result, are in some ways defined by their users. The 'musicality' of an instrument resides in the user being able to express him- or herself using the instrument. Inventive musicians often find opportunities for expression that instrument designers did not anticipate. We can be sure that Leo Fender, the inventor of the electric guitar, did not anticipate what the sounds Eddie Van Halen makes with his instrument or that Adolf Sax could have imagined the sounds Ornette Coleman gets from the saxophone.

A conceptual model of how instruments function can help understand the nature of musical instruments and the properties that make electronic musical instruments different from acoustic instruments.

AN INSTRUMENT MODEL 4.1

Donald Buchla, a pioneer in the design of innovative electronic instruments and controllers, conceptually divides musical instruments into three components. These components are an input structure or physical control interface[1], an output structure or sound generator, and the connections or mapping between input and output. (Diliberto, 1983) Physical actions upon the input structure are mapped to the output structure, affecting different aspects of the sound produced. Figure 4.1 illustrates this model.

This conceptual model can be applied to both acoustic and electronic instruments. The components of an acoustic instrument are fixed and very tightly coupled. In contrast, each component of an electronic instrument can be varied. This variable nature gives electronic instruments their unique capabilities and distinguishes them from acoustic instruments.

[1] Robert Moog, inventor of the Moog synthesizer, describes the input structure of an instrument as "the tactile and visual reality of the instrument". (Moog, 1988)

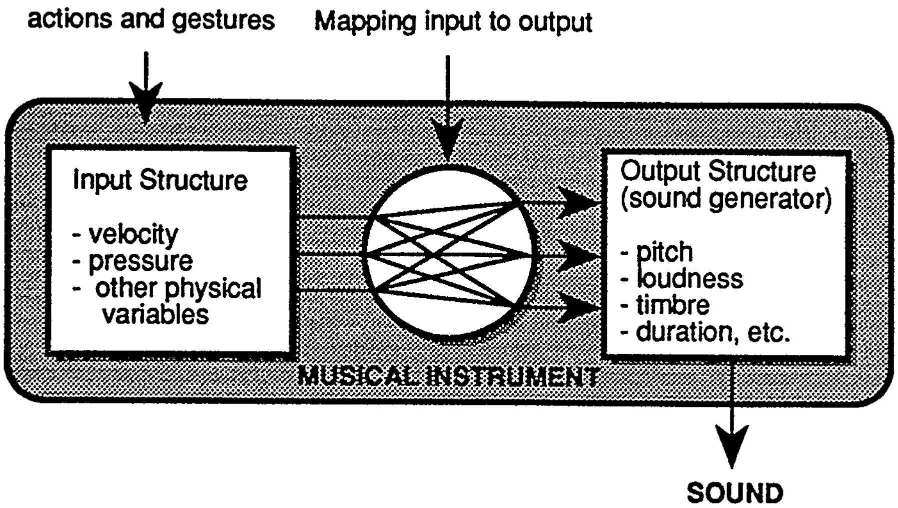


Figure 4.1
Components of a musical instrument. (after Pressing, 1988)

Input Structures 4.1.1

The input structure of a musical instrument determines the ways in which a musician physically controls and manipulates the instrument. Almost all instruments (acoustic and electronic) have multiple dimensions of control and will respond to a variety of physical actions or gestures for initiating and manipulating notes.

Some input structures are capable of accepting a wider variety of inputs than others. A drum is usually a very simple instrument; a membrane is stretched over a length of cylindrical tubing. In this case, the sound generator and control interface are one and the same. The drum head is a plane the musician can manipulate in different ways to obtain different sounds. The drum head can be struck with wooden sticks, mallets with wool-wrapped heads, or wire brushes. The player can stroke the head with their fingers, the palm or side of the hand. Where the drum head is struck affects timbre. Pressure on the drum head while a note is sounding changes pitch. The musician has many options available for controlling the sound of the drum.

A piano is a mechanically far more complex instrument than a drum, but its input structure accepts a narrower range of inputs. The piano keyboard offers control of pitch, loudness, and to an extent, timbre. Pitch is determined by selecting a key and loudness by the force used to depress the key. Timbre is a function of the loudness, unless unconventional playing techniques, such as playing 'inside' the piano to by-pass the key mechanism, are used. The pinao, of course, has the advantage of being polyphonic, and can sound all 88 notes at once.

Output Structures 4.1.2

The sound of a musical instrument is determined by its sound generating mechanism. For acoustic instruments this component is fixed, and consists of the vibrating and resonating elements of the instrument. Actions on the input structure are mapped to these elements to affect the sound produced. The output structures are such things as vibrating strings or reeds, resonating air columns or chambers (such as the body of a guitar or violin) or other elements.

There are many methods of electronically generating sound. Most methods are able to produce a very wide range of sounds, yet each has unique characteristics. The type of synthesis employed determines the range of sounds that can be produced and different types of synthesis are often more suitable for different families of sounds.

Each method of synthesis can be controlled in different ways. FM synthesis uses waveforms modulating other waveforms to produce sounds. The oscillators can be configured in different arrangements or 'algorithms' which also affects the sound produced. Timbre is changed by changing the frequency and depth of modulation of the various oscillators. Sample-playback synthesizers use digitally recorded waveforms as oscillators. These waveforms are run through time-varying filters and amplifiers to alter the sound. The timbre is changed by varying the cut-off frequency of the filters. The variable amplifier is used to alter the attack, decay, sustain and release characteristics of the sound.

Mapping 4.1.3

The mapping of the input structure to the sound generator determines how an action or gesture will affect the sound. In acoustic instruments, this mapping is fixed; a gesture always produces the same effect. A mapping can be quite complex; mappings are not limited to a one-to-one correspondence between a dimension of control input and a parameter of the sound produced. In many cases one input will control several sound parameters. Conversely, one parameter can be controlled by several inputs.

Figure 4.2 illustrates the mapping for a piano. Pitch is determined by which key is pressed. The velocity of the key determines the loudness of the note. The timbre of the note is a function of the loudness.

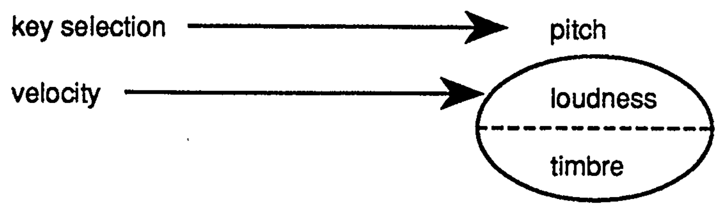


Figure 4.2
Input to output mapping of a piano.

Figure 4.3 illustrates part of the more complex mapping of a cello. The speed, pressure, the distance from the bridge at which the bow contacts the string (bow position) and even the part of the bow used (the tip or the frog) all affect loudness and timbre to varying degrees. As well, each of these variables can affect the others. For example, playing near the fingerboard limits the range of loudness available to the player and significantly affects the resulting timbre.

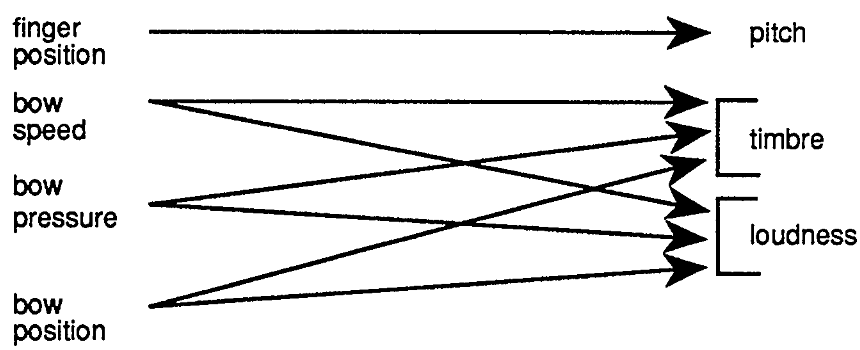


Figure 4.3
Partial diagram of the input-output mapping of a cello.

Electronic instruments are often distinguished from acoustic instruments by the variable nature of the mapping of input to output. In electronic instruments the same action or gesture can be mapped to affect one or many sound parameters or affect different parameters to varying degrees. Also, the various actions at the input can interact with each other in different ways.

Mapping Interactions 4.1.4

The expressive possibilities of musical instruments are determined by the input/output mapping of the instrument and by the number of control inputs available. Instrumets with similar control interfaces and sound generators can respond differently to the same input, indicating a difference in the mapping of input to output. The voice[2] of an acoustic instrument is embedded

[2] The voice or sound of an instrument is determined by the physical aspects of the sound generating mechanism such as how the sound is generated, the material from which the

in the sound generating mechanism and is sometimes difficult to distinguish as a separate component (as in the case of a drum, discussed earlier).

For example, a piano and a harpsichord have similar sound generators and control interfaces but their mappings between input structure and output structure are different. The control interface is a horizontal array of keys, each associated with a different pitch. The sound generating mechanism is a set of strings of graduated length coupled to a resonating soundboard. In the piano, depressing a key causes a hammer to strike the strings with greater or lesser force, depending on how hard the key is struck. In a harpsichord, the same action causes the strings to be plucked. The loudness of each note on a piano can be controlled, while loudness is constant for the harpsichord. The striking and plucking actions also impart different sound qualities to the instruments.

The trumpet and trombone operate on the same basic principles (a variable length of tubing through which a column of air is resonated by a lip reed), but have different control interfaces. On the trumpet, pitch is selected using a combination of depressing keys to alter the length of the column of air and the player's embouchure to cause the column of air to vibrate at a harmonic of its length. Pitch is a discrete variable on the trumpet. In contrast, the column of air in a trombone is infinitely variable within a range determined by the length of the trombone slide; pitch is a continuous variable. This characteristic gives the trombone different expressive capabilities from the trumpet.

Acoustic and electric guitars have the same control interface and mapping of input to output, but the electric guitar has a more elaborate sound generating mechanism that can be considered to include the pickups, amplifier, and different types of signal processing devices. Again, these instruments have different expressive abilities.

As with acoustic instruments, the sound generator and the voice or sound program of an electronic instrument are closely linked. However, the voice of an electronic instrument is variable, something not possible with an acoustic instrument.

INSTRUMENT ANALYSIS 4.2

The focus of this project is on designing an alternative controller or what can be considered a new sort of input structure. Examining the input structures of existing musical instruments and typical controllers will bring to light issues worthy of attention in the design process.

instrument is made and the size of the instrument. These things determine the basic character of the sound produced by an instrument.

Pressing (1988, 1990) undertakes such an examination, covering 10 issues he considers to be fundamental to the control interface. These issues are:

1. Physical variables used to carry information (as a function of time) from the musician's body to the instrument

These variables include finger position, force (or pressure), acceleration, velocity, area (shape), and others. Physical movements are used to select, initiate and modify a note or sound. In some instances an intermediary device such as a violin bow, guitar pick, drumstick, or mallet is used. These devices very often have a marked influence on the playing technique and the sound of the instrument. Musical instruments typically respond to a variety of physical inputs in different ways.

Acoustic instruments are based on (usually) easily understood concepts that do not change over the life of the instrument. Of course, easily understood concepts do not necessarily translate into instruments that are easy to play. Most acoustic instruments take many years of practice to master.

2. Dimensions of control

This is the number of dimensions of control, and whether those dimensions are weak or strong. Pressing examines musical instruments from a perceptual point of view. This implies three dimensions of control (the pitch, timbre and loudness of a sound). Different means of controlling the same aspect of a note or sound can have a different result and therefore can be considered different dimensions of control. For example, the speed a violin bow moves across a string changes the timbre of the sound. The distance between the bow and bridge also affects timbre but in a different way that can be easily heard. Each of these can be considered a different dimension of control.

The number of dimensions of control is subject to the law of diminishing returns, as too many dimensions will make the instrument difficult to learn and play. An instrument with too few dimensions of control will have limited usefulness. Pressing's investigation shows 4 dimensions of control to be a reasonable minimum for monophonic instruments.

3. Multiplicity of control

This is the number of parallel streams of independent information (e.g., musical lines) that can be sent simultaneously from a controller. The number of musical lines possible is limited by the physical nature of the instrument or by the physical and cognitive abilities of the player. A piano is polyphonic, capable of sounding 88 notes at once. Pressing estimates that an expert pianist can play only three musical lines simultaneously, even though the player has 10 fingers. He attributes this to cognitive loads, although physiological factors, such as independent movement of individual fingers, would also be a factor.

4. Control modality

The modes of information transfer can be discrete, continuous, or quantized continuous (the control interface is physically continuous but dispatches a limited set of discrete values), or some other form. Discrete and continuous control modalities can be considered the extremes of a continuum, with quantized continuous modes lying in between. Control modality for pitch is very often discrete, possibly because pitch is the dimension of sound to which our ear is most sensitive. For example, pitch selection is discrete on a piano, with 88 values (notes) available. Loudness is discrete/continuous; a piano's loudness is continuous within its range, but discrete in the sense that the loudness is pre-selected (determined by the velocity with which the key is struck) and cannot be varied once the note has been sounded. Pitch is discrete/continuous for the violin, and loudness is continuous. The pitch is continuous along the length of the fingerboard for each string, but each string has a different range of pitches (although the ranges overlap). Loudness is determined primarily by bow pressure, and is variable while sounding a note. The pitch of a guitar is a quantized continuous dimension. The finger can slide along the string with the frets of the fingerboard physically quantizing the pitch. As well, the pitch can be varied within a range at each fret by bending (stretching) the guitar string. The loudness of a guitar note is similar to the piano; it is determined by how hard a string is plucked, but cannot be varied while the note is sounding.

5. Control monitoring

Controls have different monitoring characteristics and can be one-shot or continuous, hold their last value or return to zero, skip out of the continuum possible or output continuous only values within the continuum, or act in other ways. This issue is generally confined to electronic instruments and the different types of controls (pitchbend wheels, sliders, breath controllers, etc.) used with these instruments. Pressing discusses the different types of controllers as separate elements of musical instruments. Polarity describes whether the controller adds or subtracts from a value. A pitchbend wheel normally has a centre détente (typically spring-loaded) and is used to adjust pitch up and down, so it is bi-polar. A breath controller responds only to increasing breath pressure, so it is uni-polar. A joystick can either return to its zero position or at its centre position, or stay at a selected value through friction. To change from one value to another with a joystick, pitchbend wheel, slider, or many other controls, you must pass through all the values in between (unless some special provision is made to allow one to do otherwise). Skipping directly from one value to another is not usually possible. Sensory reinforcement is aural and tactile and can also be visual. Independence refers to whether a controller interacts with another controller in some fixed way.

Table 2 shows the monitoring characteristics of the more common controllers of electronic instruments. Channel pressure and poly pressure (two important and commonly implemented MIDI messages) are realized by applying additional pressure on a key after it is depressed.

Physical Controller	Dimension	Polarity	Return/ Hold?	Skips Possible?	Sensory Reinforcement	Fully Independent
Modulation wheel	1	Uni	Hold	No	Good	Yes
Pitch bend wheel	1	Bi	Return	No	Good	Yes
Simple Joystick	2	Bi	Both	No	Good	Yes
Slider	1	Uni/bi	Hold	No	Very good	Yes
Ribbon/strip	1	Uni/bi	Both	Yes	Very good	Yes
Breath controller	1	Uni	Return	No	Good [1]	Yes
Foot controller	1	Uni	Hold	No	Fair	Yes
Channel pressure	1	Uni	Return	No	Good [1]	No [2]
Poly pressure	Multi [3]	Uni	Return	No	Good [1]	No [2]
Note selector (keyboard, etc.)	1 or Multi [4]	n/a	n/a	Yes	Variable	Yes

[1] Aural and tactile feedback only; no visual reinforcement
[2] These controllers cannot be accessed until a note is selected
[3] Poly pressure provides an independent dimension of control for each note depressed
[4] Keyboards can be mono- or polyphonic

Table 2.
Controller Characteristics (from Pressing, 1988, 1990)

6. Control distance function

This generally refers to pitch (but can refer to other variables as well), and instruments can be monotonic, non-monotonic, partially redundant, or uni/bipolar. Each string of a violin is a monotonic pitch controller (a string can only produce one pitch at a time). Pitch on a violin is partially redundant; a given pitch can be sounded on different strings at different finger positions. Uni/bipolar refers to the ability to 'bend' or adjust the pitch of a note. For a violin or acoustic guitar, the pitch can be adjusted upward by stretching the string with the finger. The pitch can only be adjusted downward by using the tuning pegs, and this is not normally done in performance. The mechanical vibrato mechanisms fitted to some electric guitars allow the pitch to be bent both upward and downward. In contrast, the pitches of the notes of a piano are completely fixed. Instruments can be monophonic or n-note polyphonic (a guitar is 6-note polyphonic, a piano 88-note polyphonic). As n increases, access to dimensions of control other than pitch selection decreases as a result of cognitive loads and physiological factors.

7. Literalness of control

Mapping of control variables can be one-to-one (Pressing calls this WYPIWYG - what you play is what you get), one-to-many, many-to-one, unpredictable (stochastic, chaotic), have a delayed response, be time dependent, or some other mapping. Control of acoustic instruments is usually literal in the sense that playing techniques can be communicated by demonstration and understood by observation. Pressing feels that, in a sense, literalness of control is an attitude toward music, not an absolute factor in musical design. He also points out that unpredictable effects can be achieved on all traditional orchestral instruments and electronic instruments can function the same way through overloading, feedback, or 'pathological' selection of parameter values.

8. Historical foundations

New instruments might use an existing performance technique, modify an existing technique, or require the creation of a new technique. Instruments such as the violin and trumpet have a long history of development and performance technique. Electronic instruments not based on existing acoustic instruments require the development of new performance techniques in addition to a repertoire. Pressing points out that real musical expression does not emerge until technique becomes sub- or unself-conscious.

9. Design appropriateness

This includes such factors as design efficiency, ergonomics, motor and cognitive loads, degree of sensory reinforcement and redundancy, and the appropriateness of gestures to expression. Appropriateness of design is frequently difficult to gauge. One might suspect there is a correspondence between 'design appropriateness' and the wide acceptance of an instrument. There is an element of truth here, but many well established instruments have serious design 'flaws' or deficiencies. The violin has become well established in western musical culture even though it is a very difficult instrument to master and is poorly considered with regard to ergonomics. Many violinists suffer neck problems because of the way in which the violin must be held. Others suffer hearing problems because one ear is always very near the origin of the instrument's sound. Other musicians also suffer injuries (repetitive strain injury, back injuries, carpal tunnel syndrome, etc.) as a result of the design of their instrument.

10. Psychological nature of control

This is the perceived naturalness of the link between action and sound response and also encompasses such things as whether the instrument is primarily used for exploratory or goal-oriented activities. A distinction should be made between physical relationships connecting action and sound and conventions established between music and instruments. Some physical relationships such as striking a drum with more force to make a louder sound, are 'natural' phenomena and governed by laws of physics. These relationships are usually easily perceived and intuitive in nature. Musical conventions, such as pitches on a keyboard ascending from left to right, are developed in a cultural context. Such conventions are widely accepted and some (although not many) exist in parallel in different musical cultures. However, conventions are not intuitive in the same sense as 'harder playing equals louder sounds'. Pressing points to the difficulty of playing drum-type sounds using a keyboard as a rather poor psychological match of gesture to sound.

4.2.1 Application to Musical Instruments

Pressing examines a number of instruments, including several electronic instruments, to illustrate how the issues discussed can be applied to musical instruments. The discussions are incomplete in that extended playing techniques used to increase the dimensions of control and the range of sounds produced by different instruments are not considered. Such techniques usually require considerable practice and are typically developed only after the conventional ways of playing have been mastered.

Pressing first examines the violin, played arco (bowed). The physical variables carrying the information are the downward bow pressure (controlling dynamics or volume), horizontal bow velocity (affecting timbre), distance from the bow to the bridge (also affecting timbre), and finger position on the fingerboard (controlling pitch). This gives 4 dimensions of control if bow velocity and bow to bridge distance are considered separately. The control multiplicity is two; a professional calibre player is capable of producing two independent musical lines. The spatial nature of the control or control modality is continuous; the fingerboard has no frets and a player is able to move the bow against the strings continuously. We are able to continually relate the actions of a player to the results so control monitoring is continuous. The control distance function is partially redundant. Each string is a monotonic pitch controller, but a given pitch may be played on more than one string. Control is very literal for the violin, given good technique.

The playing technique of the violin is based on techniques existing for previous instruments such as the viols. Pressing feels the violin has a high degree of design appropriateness for it is a very expressive instrument in the hands of a capable player. Visual feedback is adequate for skilled players, but less than the feedback available on fretted string instruments. The ergonomics of the violin are relatively poor and Pressing cites reports of stiff necks among violinists as evidence of this. The violin is well designed gesturally, and can be used for both exploratory (improvisation or composition) and goal-oriented (selecting a particular musical piece to play) performance.

Pressing chooses the trombone as a second example for analysis. A player must develop an embouchure to play the trombone, using shape, area and pressure variables generated by the mouth to affect pitch and articulation. The slide position affects pitch, and breath pressure affects dynamics (loudness). The trombone has 5 dimensions of control of which the player's embouchure is considered to provide 3 dimensions of control. The pitch control modality is continuous/discrete; the slide is continuous while the choice of overtone is discrete and depends on the effective length of the tubing and the embouchure. There is a fixed physical zero point with the slide fully retracted. The distance function is partially redundant and control multiplicity is normally 1, although this can be increased using special extended techniques. As with the violin, the control interface is highly literal. Pressing focuses on the first seven issues, believing the last three issues are quite similar for the common orchestral instruments although the specifics (ergonomics, feedback, broadness of gestures, etc.) are different for each instrument.

MIDI Keyboard Controllers 4.2.2

Pressing also examines the current generation of synthesizers and synthesizer controllers. Most synthesizers have a piano-type keyboard with two control dimensions: pitch and velocity (MIDI key number and key velocity). Many keyboards also sense pressure after the keys are depressed to produce an additional control dimension (MIDI aftertouch or channel pressure). Pressing feels that an expert performer can produce three completely independent musical lines, yielding 7 dimensions of control (2 hands x 3 control values (key number and velocity) + channel pressure). It should be noted that although more than three keys are depressed, the result is no more than three musical lines. Foot controllers and breath controllers are also available, increasing the dimensions of control to 10. Some keyboards offer polyphonic aftertouch (sensing the pressure on each key separately) and thus have correspondingly more dimensions of control.

Appendix B shows a table applying Pressing's means of analysis to a number of broad categories of instruments and an alternative MIDI controller. The categorization of the instruments is based on the manner in which sound is produced and similarities in the control surface (how the instrument is played).

Application To Electronic Instruments 4.2.3

The sound program of an electronic instrument must map the input structure to the sound generator in a way that passes control of the sound to the musician for the instrument to have a reasonable degree of expressivity. Different methods of sound synthesis could benefit from different maps. In analogue synthesis one way of controlling the timbre of a sound is to pass the selected waveform through a filter with a variable cut-off frequency. Timbre is a function of the frequency and amplitude of the waveforms used in FM synthesis. These means of controlling timbre are very different conceptually, and the same action or gesture might not be appropriate for both, depending on the sound being produced and the desires of the musician.

Programming the sound (the mapping of the control interface to the sound generator) of an electronic instrument is extremely important. The musician should be actively involved with this aspect of the instrument to fully understand both how it operates and how to get the most out of the instrument.

The elements of an electronic instrument must work in harmony to provide the greatest degree of expressivity to the performer. The design of the sound generating module must respond to sufficient degrees of control, while the design of the sound itself must exploit those means of control available from the physical interface. In turn, the physical interface must generate a sufficient number of control signals.

As an example of how these components are connected, consider a piano keyboard-type controller used to play a piano sound. On an acoustic piano, the velocity with which a key is struck determines the loudness of that note and also has a significant effect on the timbre and duration of the tone. One of the factors necessary for a realistic simulation of *playing* a piano is the generation of a value corresponding to the force used to strike a key. This is not, however, a requirement for an accurate simulation of a piano *sound*. Electronic keyboard instruments frequently generate a velocity value by measuring the time it takes for a key to move from its rest position to its fully depressed position. This velocity value is mapped by the sound program to the appropriate parameters of the sound generator. If the keyboard does not generate a velocity value (or some other value corresponding to the force used to strike the key), or if the sound generator has not been programmed to respond to such a value, the most significant dimension of control in emulating a piano is lost. The sound generator itself might have limited abilities for mapping a force or velocity value to the timbre or duration of the sound. If the control interface is not able to generate the necessary values, or the sound generator or sound program do not respond to values generated at the control interface, the resulting sound will certainly be less expressive than a 'real' piano. Such a sound would be a less valuable musical resource, and less satisfying for the performer because of the reduced responsiveness of the instrument.

The most significant difference between acoustic and electronic instruments is the variable nature of the electronic instruments. As the above discussion shows, electronic instruments are conceptually more complex than acoustic instruments. A musician must learn to deal with each of the three elements (input, mapping, and output) of an electronic instrument to make effective use of the instrument. Limiting the complexity and flexibility of these instruments limits their musical possibilities. Allowing users to have a hand in defining their musical instruments gives them greater opportunities for artistic expression.

One strategy developed from the preceding discussion for dealing with an electronic instrument is to address the following two points:

1.) Develop a fixed but easily understood general purpose control interface or input structure. The interface would allow the user to interact with the synthesis engine using a variety of actions and gestures. As well, the interface would allow the user to develop a set of skills for manipulating the elements of the interface; the user would be able to develop a vocabulary of repeatable physical gestures.

2.) Allow the user to develop their own mappings of the input structure to the output structure. Flexibility in mapping will increase the usefulness of such an instrument by allowing the vocabulary of gestures developed by the musician to be used in different ways. The ability to develop new mappings will allow users to personalize the control interface to meet their specific needs.

Musician-Instrument Interaction 5.0

... it became clear that the big problem was not how to make interesting sounds, but how to control them in interesting ways.
Tod Machover, composer[1]

GESTURE AND INTERFACE 5.1

Many electronic instruments do indeed meet the needs of many musicians, and some of these musicians are making exciting and innovative music using such instruments. However, as pointed out in the introduction, some musicians find existing electronic instruments limiting in some way. These individuals are demanding more from their electronic instruments and continue to seek new and better interfaces for their instruments.

Musician-Instrument Model 5.1.1

A model of the human-instrument interface will help elucidate the interaction between a musician and an instrument and aid in the design of an alternative controller. Pressing (1988a, 1990) developed such a model for his discussion of extended and intelligent instruments.

As discussed in Chapter 4, musical instruments can be divided into three parts: an input structure or physical interface, an output structure or sound generator, and the connections or map between input and output. The output structure is the means by which an instrument produces sound, and thus determines what parameters of the sound can be controlled. A sound generator typically consists of an oscillating element (a vibrating reed, string, stretched membrane, or other sound producer), a resonant element to which the vibrations are coupled (a tube, cone, plate or other resonant element, forming the body of the instrument), and the force that initiates and, in some cases, sustains the vibration. As an example, the strings of a violin are stroked with a bow, causing the strings to vibrate as long as the bow is in motion. The vibrations of the strings are coupled to the body of the violin, causing it to vibrate in resonance with the strings producing the violin's characteristic tone.

The input structure establishes the set of physical activities used to play an instrument. Baily (1985) states the activity of music making involves patterned movement in relationship to the active surface of the instrument, regardless of whether the instrument is blown, bowed, plucked, concussed, percussed, or made to sound in some other way. The movements used to play

[1] in "Tod Machover: Computer Music's Big Noise." by Tom Darter, in Keyboard, Vol. 17, No. 7, July, 1991.

an instrument can be broken down into two types of activities; activation gestures and the modulation gestures (Cadoz, et al., 1984). The release of a note, sometimes considered a separate gesture, can also be considered a part of the modulation of the note. Blowing, striking, plucking, bowing, and stroking are some of the activation gestures used to 'start' the sound generating mechanism of an acoustic instrument. Modulation gestures include striking with more or less force, rocking the finger stopping a string back and forth, blowing harder or softer, and other gestures that are used to modulate qualities of a note such as loudness, vibrato, and timbre.

The mapping between input and output structures defines the activities involved in playing the instrument. This mapping is usually quite direct for acoustic instruments. For example, pressing a key on a clarinet alters the length of the resonating tube, changing the pitch of the instrument, while blowing into the instrument with more or less force changes the loudness and timbre of the note.

Baily suggests that the physical interface (he calls this the 'active surface') of an instrument has a significant influence on the kind of music produced with that instrument. Clynes and Netthiem's (1982) evidence of a connection between touch expression (varying finger pressure) and musical expression (interpreted as an emotional response to a musical gesture) re-enforces Baily's contention.

Part of the difference in the nature of some instruments can be attributed to the close contact a player has with the sound generating mechanism of some instruments. A sax player has direct contact and control over the reed of the instrument. In contrast, there is an elaborate mechanism between a piano key and the hammer that strikes the piano's strings. Players of wind and brass instruments, stringed instruments (strings can be bowed, plucked, strummed, struck, or otherwise activated), and singers (the voice is certainly considered an instrument) have direct physical contact with their sound generation component of their instruments and there is a direct mapping of physical gesture to sound generation.

A physical interface should be mapped to the synthesis engine of an electronic instrument in such a way that a musician's physical gestures are translated into appropriate aural expression. The interface should also allow the musician to exploit the unique capabilities of the synthesis engine. Current interfaces offer some limited capacity for the translation of physical gesture into aural expression, but do little in the way of harnessing the unique capabilities of electronic sound synthesis. A new physical interface and flexible mappings will give musicians the ability to play an electronic instrument with some of the same expression found in acoustic instruments.

In most instances the interface of an electronic instrument is based on some existing acoustic instrument. Commercially available electronic instruments have interfaces based on organs, guitars, cellos, saxophones, trumpets, drums, marimbas, and other instruments. Aikin (1991) points out the problem with this approach: "Unfortunately, most of these controllers... suffer from the limitations imposed by their ancestry, even though these limitations are largely needless in an electronic instrument." Buchla points out that the traditional keyboard (the most common interface for electronic instruments) is a linear array of switches suitable for rapid access to a large number of sounds of fixed pitch, but much less useful for controlling other aspects of sound (in Aikin, 1984).

In virtually all instruments, the information transfer from human to instrument is a function of human movement. The parts of the instrument that are directly controlled or manipulated by the musician, and to which information in the form of physical movement is transferred, is called the control interface. Pressing calls the part of the instrument that produces the sound the effector mechanism (for the sake of consistency, this author will continue to refer to this as the sound generator). Between the control interface and sound generator is a processor of some kind that translates control information (resulting from physical actions) to a form the sound generator can understand. This processor is a discrete element in electronic instruments, and corresponds to the sound or voice program that maps the control information to the sound generator. In the case of acoustic instruments, the processor is bound to the physical aspects of the sound generator and is fixed for that instrument. Pressing applies his model to a piano for illustration: the keys and pedals are the control interface, the piano action is the processor, and the strings and sounding board are the effector or sound generator. Figure 5.1 illustrates this model.

Pressing points out that the information transfer between musician and instrument operates within complex traditions of culture, musical design and performance technique, and is shaped by human cognitive and motor capacities as well as personal experience. With traditional instruments, the response between the performer's actions and the result is nearly one-to-one. Interaction between the instrument and the musician takes place through the aural feedback loop as indicated.

HUMAN-MACHINE INTERACTION 5.2

Pressing's musician-instrument model is quite general and does not take into account the different kinds of interaction possible with instruments of lesser or greater complexity, or the special qualities of electronic instruments that set them apart from other instruments. Jens Rasmussen (1983, 1986) has developed a comprehensive model of human performance and information processing, and man-machine interaction that can be applied to the way musicians interact with musical instruments. This model can describe those elements common to all musical instruments and, because of the different types of interaction it describes, can be applied more effectively to instruments of varying complexity than Pressing's model.

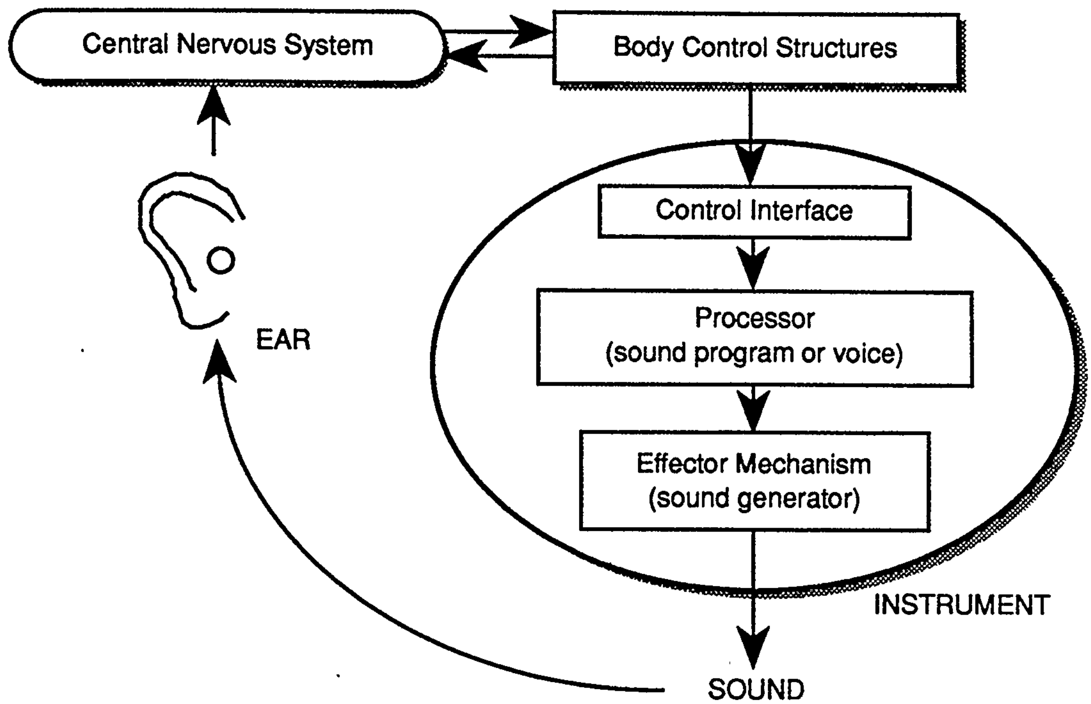


Figure 5.1
Musician-instrument model (after Pressing, 1988a, 1990).

Rasmussen's model divides activities into three levels of behaviour: skill-, rule- and knowledge-based behaviour. Associated with each level of behaviour is a different means of conveying information. Signs are associated with skill-based, signals with rule-based, and symbols with knowledge-based behaviour. The nature of the information varies with each level as well.

Figure 5.2 is a simplified illustration of the hierarchy of Rasmussen's model. In reality, interactions between the levels are much more complex than indicated. The arrows indicate flow, and not necessarily control. Goals or reasons activate behaviour from the top downward, while causes release actions from the bottom upward.

According to Rasmussen, the complexity of voluntary movement of the limbs indicates we rely on a dynamic internal map of our limbs and our environment. We use sensory input not to control movement directly but to update and align our internal map. As our dynamic internal map is modified by the information we receive, our mental model of the environment also changes.

The levels form a continuum of behaviours from skill-based to knowledge-based. Behaviour can migrate from one level to another, depending on such factors as repetition, familiarity and associated risk (Murphy and Mitchell, 1986). Figure 5.3 illustrates this concept.

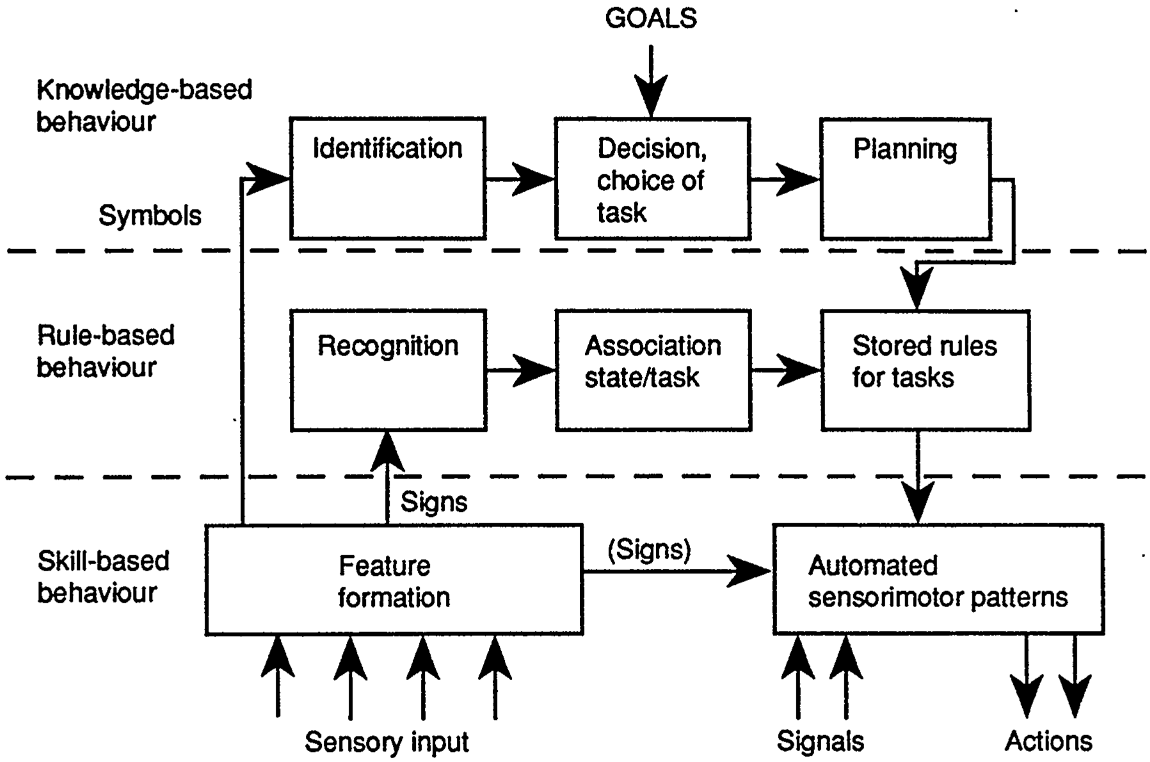


Figure 5.2
Skill-, rule-, and knowledge-based model (after Rasmussen, 1986).

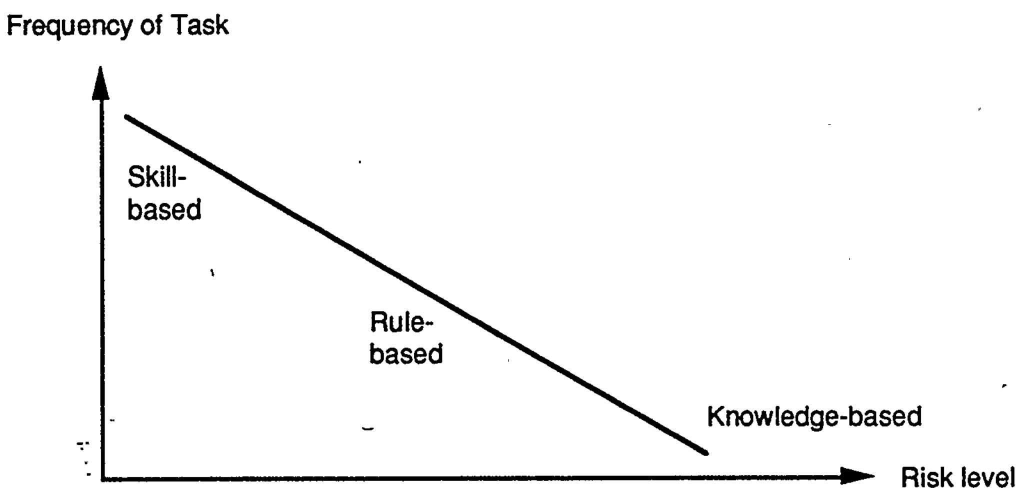


Figure 5.3
Behaviour continuum (after Murphy and Mitchell, 1986).

Rasmussen points out the boundary between skill- and rule-based behaviour is not distinct, and often depends on the level of training of the individual. Rule-based behaviour is the result of explicit know-how, and is characterized by the ability to report the rules being followed while performing an activity.

This concept is clearly applicable to musical instruments. Typically, we are given knowledge about music through instruction. This instruction often includes rules about playing music and how to play an instrument. We develop skills by following these rules and repeating patterns of movement. Eventually we may forget some of the rules and rely on skills for certain tasks. The hierarchy of behaviours can be seen in the activity of jazz improvisation. A musician will know a song (the chords, melody, etc.), use rules of music to derive musical phrases that will fit within the structure of the song, and then employ physical skills to play these phrases. Jazz performance also implies an element of risk in the improvisation.

In Rasmussen's model, skills are "sensory-motor performance during acts... [that] following a statement of intention, take place without conscious control as smooth, automated, and highly integrated patterns of behaviour." Skill-based behaviour relies on sensory feedback from the environment to guide the adjustment and eventual automation of skilled performance[2]. The rapid coordinated movements required for skilled behaviour (in this instance, expertly playing a musical instrument) indicate the possible presence of feedforward control in skilled behaviours. Pressing (1988b) feels both feedback and feedforward are extensive during musical improvisation.

Rasmussen defines rule-based behaviour as "a sequence of sub-routines... controlled by a stored rule or procedure which may have been derived empirically during previous occasions, communicated from other persons' know-how as instruction or a cookbook recipe, or it may be prepared on occasion by conscious problem solving and planning" (Rasmussen, 1983). Actions are based on internal rules triggered by external stimuli. In the case of playing a musical instrument, the stimulus could be a musical score, or the various types of feedback available from the instrument.

Knowledge-based behaviour takes place when no rules or skills are applicable to the situation. A goal is formulated through an analysis of the environment and the person's intentions. Rasmussen (1983) states "... a useful plan is developed - by selection - such that different plans are considered, and their effect tested against the goal, physically by trial and error, or conceptually by means of understanding the functional properties of the environment and prediction of the effects of the plan considered." Through this reiterative cycle of goal-setting and testing we develop a model of the environment in which we are working. If the means of achieving a goal are not immediately obvious (prompting rule–based behaviour), we try to use our knowledge of the system to develop and try different methods of achieving that goal. Each attempt adds to our knowledge of the system, and behaviour is then based on a mental model developed through this trial and error process. Knowledge is used to reason about the behaviour of the system as it responds to actions.

---

[2] In Rasmussen's model cognitive skills are part of knowledge-based behaviour.

Signals, signs and symbols are the forms of information we use to modify our internal map. According to Rasmussen, the distinction between these forms of information is primarily dependent on the context in which it is perceived. The same physical representation or manifestation of a given phenomena can be perceived as a signal, sign or symbol, depending on the action required.

Signals are related to skill-based behaviour in that they act as controls when physically manipulating objects in a space-time domain. The information is perceived as time-space signals or continuous indicators of what is happening in the environment. With regard to musical instruments, the primary signals are embodied in the sound produced by the instrument. Additional signals are available through visual, tactile and proprioceptive feedback from the instrument (Pressing, 1988b).

Signs are information that affect rule-based behaviour. Signs serve to activate or modify predetermined actions or manipulations, and cannot be used for reasoning or the formulation of new rules. In the area of music, signs are mostly independent of musical instruments. Signs could be the gestures of a conductor or musical notation in a score. Such signs serve to activate rules known to the musician. Acoustic instruments in themselves do not provide signs to the user although some signs may be specific to an instrument; a sign could indicate a special playing technique. The situation is somewhat different for electronic instruments. Controllers based on acoustic instruments usually do not provide signs for the user. However, electronic sound generators usually have some sort of alpha-numeric display and provide an important sign in the form of the voice or sound program name.

Symbols are internal conceptual representations of information, relationships and functional properties that can be processed formally and activate knowledge-based behaviour. As such, symbols are information used for reasoning in planning, problem-solving and predicting unfamiliar behaviour of the environment. Composers writing music, and musicians interpreting a score, use musical knowledge in this manner. Symbolic knowledge is used to develop an internal map of how electronic instruments work, and to some extent, how acoustic instruments work. A clear understanding of the operation of an electronic instrument is crucial to getting the most out of it.

Communication within musical activities uses all three forms of information. When dealing strictly with musician-instrument communication in the realm of acoustic instruments, communication is usually in the form of signals. In contrast, electronic instruments use all three forms of information. Signals are used when articulating individual notes or sounds. Signs are used to indicate a possible change in the meaning of signals; a certain physical action could have different effects, depending on the sound program or mapping selected. Symbols are primarily tied to the architecture of the sound generator and how sounds could possibly be modified.

Rasmussen uses his three part model of behaviour and information processing to develop a semiotic interpretation or model of human acts. Often these acts involve the use of tools or machines, and Rasmussen develops four separate models for tools and machines of various complexities. If musical instruments are considered tools for making and manipulating sounds, Rasmussen's models can be applied to musical instruments and each model is applicable to different instruments. In contrast, Pressing applies one model of interaction to all musical instruments. Pressing's musician-instrument model will be seen to be a form of Rasmussen's indirect manipulation.

Rasmussen discusses his interpretations in the same terms he uses for his models of behaviour and information processing. The transfer of information to a system will, in general, be in the form of physical actions on the system. In some cases, this action accomplishes the desired change, such as in assembly tasks. In other situations, the actions are indirectly involved through a tool or manipulator. In both cases, the movements are acting as continuous signals in a space-time information control loop involving the human body. Rasmussen's interpretations range from direct physical manipulation of an object without the aid of tools, to remote process control where the object being manipulated in the internal process of a complex machine.

Direct Manipulation

Direct manipulation of the physical environment takes place in manual tasks. Objects are perceived in terms of their functional implications. Intentions towards the objects in the environment are expressed as acts to perform or goals to reach, not generally as bodily movements. Statements of intention act as signs prompting actions or patterns of movement. Movements are controlled by sensing space-time signals affecting the alignment of the internal model or map. The spatial-temporal continuous signal loop through the sensorimotor functions is intact during highly skilled direct object manipulation. The loop is activated and the properties controlled by perception of cues as signs. Figure 5.4 illustrates this model of interaction.

Indirect Manipulation

Indirect manipulation involves the use of tools to manipulate or transform objects and is characterized by intention and attention being focused on the task at the interface between the tool and the environment. Figure 5.5 illustrates this model.

The tools or manipulators used can be perceived as extensions of the body; the sensory control loop remains intact. This implies that signals are

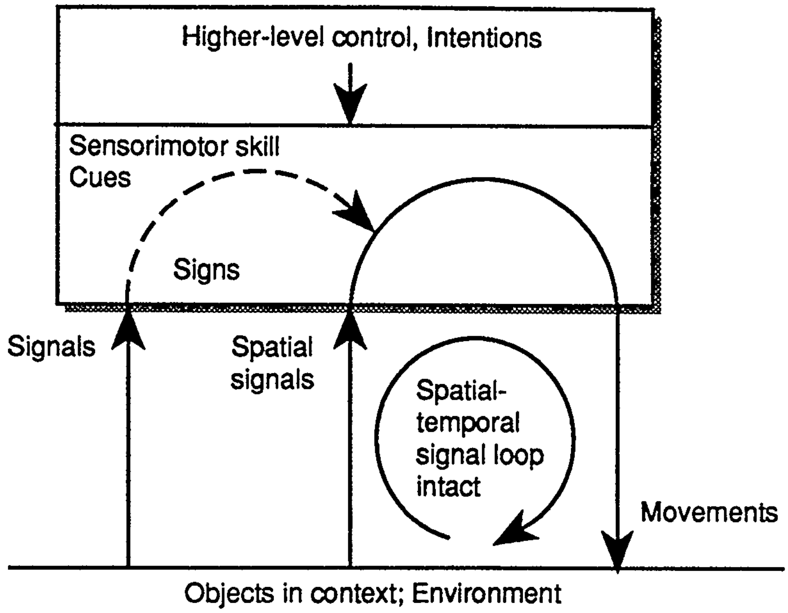


Figure 5.4
Direct manipulation of objects (after Rasmussen, 1986).

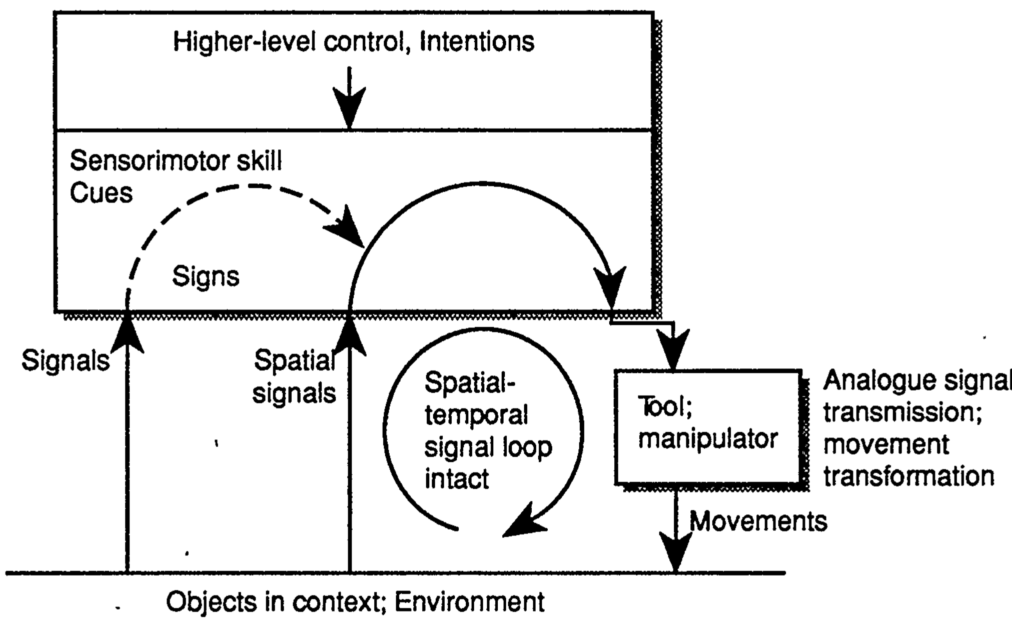


Figure 5.5
Indirect object manipulation (after Rasmussen, 1986).

transmitted from the point where the tool contacts the object to the point where the human contacts the tool. Movements of the body can then become dynamically integrated with movements of the tool. The focus of attention and intention becomes the task itself, not the operation of the tool. Higher-level control is activated by perception of properties and values, and of signs related to intentions. Skills are developed as the tool becomes an extension of the body.

Remote Manipulation

Remote manipulation introduces a channel for transmitting information from the location of the task to the human. This information channel becomes an extension of the human sensory system if the space-time signals necessary for control and the information required for higher-level formation of intentions are transmitted. Ideally the return information channel is transparent to the user for the information needed for the task. Attention and intentions are then focused on the interface at the remote location where the actual manipulation is taking place.

Remote Process Control

Rasmussen's fourth model is that of remote process control. Figure 5.6 illustrates this model. In this model the time-space signal loop may be broken in that the manipulation of controls may not transmit time-space signals but abstract coded orders. As well, the sensory channels might receive coded information rather than an analog representation of the effect of activities at the control interface. It should be noted that the abstract translator in the signal loop is not always present. Tasks characteristically do not relate to the concrete manipulation of an object, but to control of an invisible process. This is typically the case if the task is not related to the space-time manipulation of objects, but some physical process.

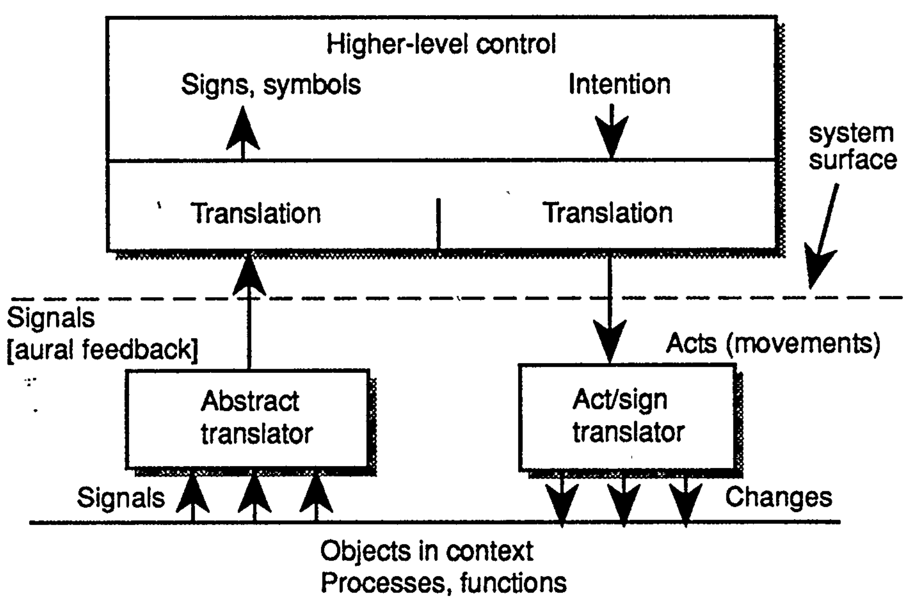


Figure 5.6
Remote process control (after Rasmussen, 1986).

If the time-space signal loop is broken by a mediator in both the act and signal channels, the attention and intentions are focused on the control interface during routine activities. In unfamiliar situations, skills are devoted to translation tasks unrelated to the higher-level tasks and are occupied by interface manipulation and sign recognition. Rasmussen feels interface systems should aim at eliminating the translation tasks. The interface should be designed to allow operation by direct manipulation of the representation of the remote process and information at the interface should relate directly to the internal functions being controlled. Ideally there will be a one-to-one mapping of the symbolic representation to the function to be controlled, so physical skills can be applied directly to the central task. Remote process control in effect becomes direct manipulation.

APPLICATION TO MUSICAL INSTRUMENTS 5.3

Rasmussen's models of human-machine interaction can be applied to musical instruments by taking into account the non-visual nature of working with sound as a material and the role the musician plays in the creation of the sound. All of the models deal with human actions causing a perceivable change in the environment. In three of his models, Rasmussen deals with the manipulation of physically existing objects that can be moved or assembled, or acted upon in a way that causes a such a change in the environment. The remote process model includes the manipulation of processes or functions that do not exist in the same sense as a physical object. Changes in the process or function initiated by a human operator must be perceptible or control of the process or function is not possible. Rasmussen emphasizes the visual perception of interaction; one sees the results of their actions[3]. Sound, while it cannot be seen or touched, is a physical phenomena and playing a musical instrument causes a perceptible change in the environment. Sound exists as something palpable and substituting the sense of hearing for vision does not alter the fundamental structure of Rasmussen's models.

The activity of playing a musical instrument can be categorized as direct manipulation, indirect manipulation, remote manipulation, or remote process control. For many acoustic instruments, the very direct physical connection between the instrument control interface and the sound generator places them in the direct manipulation category. This includes most wind and valve instruments, stringed instruments such as the harp and classical guitar, and any instrument where the body is in direct contact with the sound generator mechanism or actually forms the sound generating mechanism as is the case with the singing (vibrating vocal chords) or brass instruments (where the lips act as a vibrating reed). This direct contact constitutes a direct feedback path, and the spatial-temporal signal loop is intact.

[3] Visual feedback, while extremely useful when playing musical instruments, is not necessary for expert performance. Many blind persons have had, and continue to have, long and fruitful careers as professional musicians.

In many instances playing an instrument requires the use of some intermediary tool such as a plectrum (for guitars), bow (for violin, cello, etc.), stick or mallet (for percussion instruments). Playing such instruments is a form of indirect manipulation. The tools act as extensions to the body and return a degree of tactile feedback to the musician. In most instances the 'tool' is very simple and is used to impart additional energy to the sound generator, resulting in louder sounds. The bow allows sustained energy to flow to the sound generator as the player draws it back and forth across the strings. Because of the simplicity of the tools used, the feedback is very nearly direct. As well, in most cases the contact between the tool and the sound generator is visible to the user. In these instruments the signal loop remains intact and skills can be developed as the mechanisms involved become extensions of the body and are integrated with the musician's internal map. A skilled musician thinks of playing a note and a cellist does not usually break this activity down into the separate physical movements of placing the fingers in position, readying the bow, and then drawing the bow across the strings.

Playing instruments such as the piano and pipe organ are also instances of indirect manipulation. In these instruments, there is a more complex mechanical mapping of the actions of the musician to the sound generator. While the effect of the user's motions on the sound generator are not directly visible, the user's attention is still focused on the result of their actions (the sound produced), rather than the actions themselves.

Remote manipulation introduces an information channel that acts as an extension of the senses to the model. Instruments such as the electric guitar and electric violin fit this model. While the strings are acted upon in the same way as an acoustic instrument, the results of these actions are not intended to be heard directly. The vibrations resulting from the musician's actions are routed through an amplifier to make the vibrations of the strings audible. Rasmussen uses a microscope as an example of extending the senses, and an electronic amplifier functions in the same manner.

The electronic amplification of an instrument provides a signal path that can be exploited for additional processing of the sound signal. Many musicians consider the electronics to be an integral part of the instrument because of the significant ways in which the sound can be changed using signal processors in the signal path. The electronic component acts both to extend the senses, in that quiet sounds are amplified, and to extend the ability to modify a sound. The instruments that fall into this category are modeled on acoustic instruments with changes made to accommodate and compensate for the amplification of the instrument. Acoustic instruments are also sometimes "electrified" through the use of a microphone or pick-up, but this is not the primary way in which they are used.

Electronic musical instruments conform to Rasmussen's remote process control model. Physical movements are translated into data at the instrument's control interface (the system surface). This data is translated by the mapping process (the act/sign translator) into data the synthesis engine can understand. The synthesis engine (an invisible remote process) produces sound and also acts as the translator in the information channel. The information perceived is primarily the sound produced, although visual information is also available in some instances.

The correspondence of an electronic instrument to Rasmussen's model is clear when a separate controller and sound generator are connected using MIDI. The controller translates switch closures and the movement of knobs and other physical devices into MIDI data. The data is sent to the sound generator, where the sound program routes the data to the appropriate functions of the synthesis engine. As with any musical instrument, the most significant feedback from the instrument is the sound produced. Visual information is often provided in the form of an alphanumeric display indicating what sound program is in effect. Other information pertinent to the musician's performance (usually indicating the state of some function or process in the synthesis engine) is also sometimes available in the visual display. The feedback information (the sound produced and the visual information) is used by the musician to correct their performance and to determine what actions are available to them, and what effect those actions will have on the sound produced.

CONTROLLERS MODELLED ON ACOUSTIC INSTRUMENTS 5.5

A number of different controllers modeled on acoustic instruments are available, allowing skills developed on an acoustic instrument to be transferred to an electronic instrument. The controllers currently available are modeled on wind instruments (clarinet or saxophone), valve instruments (trumpet), stringed instruments (guitar, violin and cello), and percussion instruments (drums and vibraphone). As well, actual instruments such as the piano, violin, cello and guitar have been adapted to act as MIDI controllers.

The most common control interface is the organ keyboard[4]. These interfaces allow synthesizers to fit easily into conventional music structures and electronic instruments are often used to imitate existing acoustic instruments.

The designers of these controllers usually strive to maintain the physical model of the instrument on which they are based, with the performance gestures generally intact (harder playing results in louder sounds, shorter lengths give higher pitches, etc.). Rubine and McAvinney (1990) claim modelling a controller on an existing instrument will often result in similar music from the two instruments. Baily (1985) also suggests that the control

[4] An organ keyboard differs from a piano keyboard in that the keys of an organ simply act as on–off switches. A piano keyboard is a complex system of levers that cause a felt hammer to strike a set of strings. This system of levers imparts a distinct "feel" to the piano keyboard.

interface of an instrument is a determining factor in the kind of music produced with that instrument.

Modelling a controller on an existing instrument means that such a controller is best suited for use with sounds from the family of acoustic instruments on which the controller is modelled. Any controller can be used to play any sound the synthesizer it is connected to is capable of. As an example the Yamaha WX7 wind controller, which is based on a clarinet, could be used to play a bell-like sound. Those sound programs with a character similar to a clarinet or saxophone will best translate the performance gestures of such a controller into musically useful sounds. The wind controller is very responsive to breathe pressure during the sustaining portion of a sound. Percussive sounds (such as bells) may have a certain amount of sustain, but the tonal quality of such sounds is usually determined by the force used to initiate the sound. This is not to say that breathe pressure cannot be useful in such situations. this type of control could be used to modulate the pitch, timbre or loudness of the sound in a musically useful and interesting way.

Such use of breathe pressure points to an important concern regarding the physical interface of electronic instruments. Electronic instruments allow the design of sounds modeled on physically impossible instruments, such as a pitch-bendable bell, as well as new classes of sounds that spring from the imagination of the composer or performer. In many situations it is difficult, if not impossible, to derive an intuitive mapping of the effect of a performance gesture to the sound generating mechanism. As an illustration of this problem, consider a gesture appropriate for bending the pitch of a bell. Most bells do not allow the performer to adjust their pitch. Imagine that such an effect (perhaps sweeping the pitch of a bell up or down an octave) is found desirable by a composer. By long standing convention, pitches are arranged horizontally in ascending order from left to right or vertically from low to high. Physical movements along these axes could be effectively mapped to the pitch of the bell sound for a fairly intuitive performance gesture. Such a gesture relates to convention but not the physical properties of a real bell.

Now consider an appropriate gesture for changing the timbre of a bell. In the real world, the timbre of a bell is affected by how hard it is struck, the material from which the bell is made, the shape of the bell, the size of the bell, its acoustic environment, and many other factors. The gesture of striking a bell harder to effect a change is fairly intuitive, but this also affects the loudness of the sound. In some situations, one might wish to change the timbre of the sound without affecting the loudness. Gestures that can be directly associated with changing the material, shape or location of the bell do not exist in the real world, and some sort of analogous gesture must be used. Gestures might be found that are appropriate in this specific situation, but they may not transfer well to other sounds. As well, the gesture for changing the timbre of a bell might be more appropriate to a different parameter when used with another sound program.

Still another consideration is that in some situations non-intuitive gestures might be musically useful. Such a mapping could encourage a composer or performer to consider their gestures more carefully and deliberately, or provide a means of using known gestures to produce unusual and perhaps interesting results. Josef Zawinul, a highly regarded jazz keyboardist and composer, has used such a technique. Zawinul has, on occasion, "inverted" the keyboard of his synthesizer. That is, higher pitches are on the left and the pitches descend moving to the right. Mr. Zawinul has found this technique useful for stimulating new musical ideas.

SUMMARY 5.6

The preceding discussion makes it clear that a universal mapping of gesture to effect is not possible or even desirable. Introducing computers into the instrument system has given rise to a need for new gestures for making music. Rubine and McAvinney (1990) point out that a new instrument that responds to gestures in a fixed manner could result in new music, but originality could not be sustained. Zicarelli's concept (1991a) of flexible controllers coupled with software music environments (allowing the performance system to adapt to the musician's changing interests and needs) is an answer to this problem. User-defined mappings of gestures to a synthesis engine will result in a controller that is more useful than one with a single fixed mapping and sustains musical development and growth.

When playing electronic instruments is considered to be a case of Rasmussen's remote process control, a 'translator' exists between the system surface (the physical elements manipulated by the musician) and the synthesis process. The musician's skills are devoted to performing translation tasks to match their intentions to the synthesis process. Rasmussen feels system control interfaces should aim at eliminating translation tasks so skills may be applied directly to the main task. Even though in remote process control the user is manipulating a representation of a process, it should 'feel' like direct manipulation. To accomplish this, the translator between the system surface and the process must make visible the invisible process. The translators in a sense become transparent, allowing users to feel as though they are in direct contact with the process.

One way of achieving this is to provide a system surface that will respond to a variety of gestures, and give musicians control over the effect their gestures have on the sounds produced. Musicians then have the power to design their own 'translators' for performance gestures, thereby becoming more physically involved with the expressive resources possible in the electronic generation of sound.

Part 2

DESIGN

The stick of the blind man invents a new darkness.
Thomas McGrath

The following discussion outlines the design of an alternative MIDI controller based on the information presented in Part 1. Many of the ideas discussed in that section are not meant to be used to establish rigid requirements, but rather to be used as the seeds from which a design might grow.

PROJECT OBJECTIVES 6.1

The primary objective of this project was to design and build a proof-of-concept model of an alternative MIDI controller. This controller will form part of the system that makes up an electronic musical instrument. Figure 6.1 illustrates the design space of the project. The physical design focuses primarily on the control surfaces embodied in the controller, the computer software and, to a degree, the electronics of the controller. The computer software is a user interface for mapping the data generated by the controller to a MIDI synthesis engine.

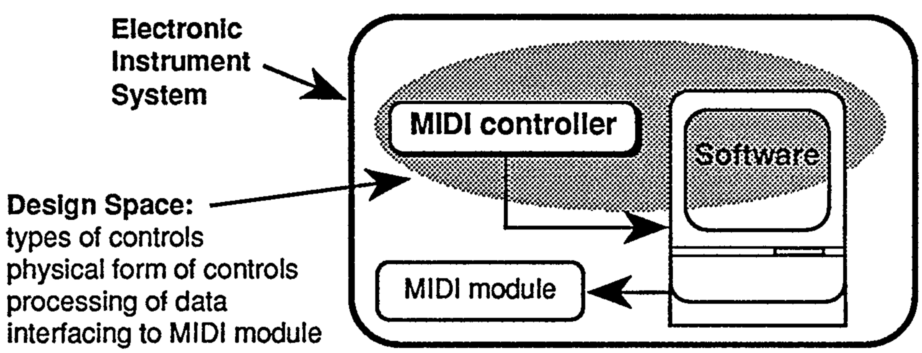


Figure 6.1
Design space of the project.

A secondary objective is to compile a body of knowledge that can be used as an aid in the design of input devices for computer-based products and, more specifically, alternative MIDI controllers.

The proof-of-concept model (built in the spirit of Hugh Le Caine's Electronic Sackbut) is used to determine if the design has a sound conceptual basis and sufficient merit to pursue further refinement. Building such a model is an important step in the cycle of product development.

As stated in the introduction, the main focus of this project is the human factors of interaction with an electronic musical instrument. Given this focus and the level to which the physical design has been pursued, discussion of aesthetic issues and issues related to production and manufacturing has been limited. This project is viewed as a significant step in the development of a product. Several cycles of testing and design refinement would be the appropriate next step before aesthetic and production issues could be fully resolved.

TARGET USER GROUP 6.2

The target user group of this alternative controller is made up of composers and/or performers looking for new ways of making and controlling sounds. These individuals will most likely perform their own compositions. The target group likely uses synthesizers and computers extensively. They also find existing controllers unsatisfactory or limiting. These individuals are probably engaged in composing and performing electronic or electroacoustic music, music that is often referred to as 'New-Age Music', alternative forms of rock music, or perhaps improvised music.

Someone who is strictly a performer of the classical repertoire is unlikely to find much use for an alternative controller; the repertoire for specialized electronic instruments is quite limited and this controller is not intended to be used to mimic existing instruments (as are most alternative controllers).

Musicians fitting the profile outlined above are usually quite familiar with MIDI. They typically use computers and a variety of software for sequencing, synthesizer programming, sound sample editing, music notation, algorithmic composition, direct to hard-disk recording or other tasks. A computer is frequently an integral part of their musical life.

DESIGN CRITERIA 6.3

The design criteria are as follows. Each criterion can be compromised in the interests of the overall 'goodness' of the design.

1.) The controller will provide a variety of control surfaces to accommodate different musical tasks.

2.) The controller will require both gross and fine physical movements.

3.) The gestures used to play the controller will be easy to comprehend. Most musical instruments are played using an easily understood set of gestures. This does not necessarily mean an instrument is easy to master and years of practice are often required to master the subtleties of those gestures. An instrument that requires little effort to master may, in the end, be treated more like a toy than a serious means of making music.

4.) An audience will be able to see the gestural activity of the performer. Cadoz points out that a listener tends to try to establish a connection between a sound and its cause (Cadoz, 1989). It is desirable to have an audience become aware of the relationships between a musician's gestures and the results of those gestures.

5.) The controller will be primarily monophonic to emphasize the 'inner life' of individual sounds (activity on Schloss's timbral level of control). Hugh Le Caine, designer of the Electronic Sackbut, believed monophonic instruments are the most important instruments and the starting point for all musical thinking because of their "... continuous and detailed control of the three musical parameters: pitch, loudness and timbre." (Young, 1990)

    Pressing, in speculating about the number of dimensions of control one could practically use, suspects that cognitive limits may impose more restrictions on the number of usable dimensions of control than motor control limits (Pressing, 1992). Monophonic instruments also typically provide more dimensions of control than polyphonic instruments. The piano has two strong dimensions and one weak dimension: pitch and loudness as strong dimensions of control, and limited control of the sustain of a note. The violin has several strong dimensions of control: pitch, loudness, and timbre are controlled by finger position, bow speed, bow pressure, bridge-to-bow distance, and other variables.

    Polyphony will be achieved in two ways with the controller: by causing consecutively played notes to sustain, or by having individual key presses cause more than one note to sound.

6.) The computer interface software will provide access to those parameters and values mostly likely to be of use to the musician and provide an initial default setting for those parameters and values.

DESIGN CONSTRAINTS 6.4

The constraints imposed on the design are as follows:

1.) The controller will use the MIDI specification (but not be limited to the specification).

2.) The controller will provide a minimum of 5 dimensions of control. Pressing's analysis (1991) of existing acoustic and electronic instruments shows almost all have less than 5 dimensions of control, and typically 3 or 4 dimensions of control.

3.) The controller will afford the user means of controlling pitch, timbre and loudness in the time domain. It should be noted that this and the preceding constraint are also very much dependent on the synthesis engine connected to the controller and the way that synthesis engine is programmed. For example, if the controller sends velocity data about how hard a key is struck, the receiving module must be programmed to respond to that data, otherwise the data will have no effect. In some circumstances the controller may be connected to MIDI modules that are not necessarily sound generators.

4.) The controller (in combination with a computer) will be programmable, allowing the user to map gestures to desired functions and 'transmogrify' the data as desired.

5.) The controller should limit or minimize any physical discomfort for physically normal adults. Anthropometric and ergonomic data will be used when appropriate.

6.) A proof-of-concept model will be built using off-the-shelf components wherever possible.

DESIGN SOLUTION 6.5

The controller can be divided into two parts: the physical control surface that the musician will 'play', and a software component the musician will use to customize the controller for their own purposes and needs. This chapter describes the control surface and mentions those software aspects of the control surfaces that can be customized by the user. The electronic hardware and software are described in more detail in the next chapter.

The physical part has three control surfaces, roughly corresponding to Schloss's levels of control. The levels of controls are strictly defined, and there is some crossover between the levels. Each hand is engaged with a different control surface and deals with different tasks. The control surfaces are:

1.) At the timbral level, an enhanced joystick providing 4 dimensions of control and 4 programmable switches;

2.) At the note level, a velocity sensitive chord-type keyboard[1] with 2 additional dimensions of control;

3.) At the musical process level, an array of programmable switches, divided into one group of 4 and one group of 8 switches.

[1] A chord keyboard is an array of switches that are pressed individually or in combinations, producing a single output for each key or key combination.

The left hand controls the joystick, the right hand the chord keyboard, and the switch array is located for easy access with either hand.

The following description is primarily based on the proof of concept model. Some minor differences exist between this model and the design due to the pragmatism necessary in building this model. Readily available resources were used wherever possible and some compromises have been made in realizing the model. It is the author's belief that the model accurately represents the design in that all significant aspects of the design are functional.

Dimensioned drawings of the components are collected in Appendix C.

Chord Keyboard 6.5.1

Chord keyboards do not produce musical chords (that is, multiple notes simultaneously), although the name is derived from the similarity to playing chords on a piano keyboard. The keys are depressed in different combinations, giving 31 ($2^5 - 1$) possible combinations for a five-key keyboard. Each key combination produces a different note. Chord keyboards are typically used for one-handed data entry tasks such as mail-sorting (Greenstein and Muto, 1988).

A chord-type keyboard was chosen because it is unique in this application and because chord keyboards are inherently monophonic in nature.[2] An informal survey conducted by the author shows no other controllers are available with velocity sensitive chord keyboards. Also, one of the established design criterion is that the controller be monophonic.

Velocity sensitive keys arranged in different configurations were considered, but rejected for the following reason. Providing an individual velocity sensitive key for each possible pitch is neither economical nor efficient for a monophonic instrument. The chord keyboard has a significantly lower parts count than a keyboard that uses a one key = one pitch mapping.

One advantage of chord keyboards is that finger travel is minimized because the fingers remain on the same keys. Chord keyboards are also compact, allowing them to be positioned so that unnatural keying postures of the hand sometimes associated with conventional keyboards may be avoided. (This comment was made by Cushman and Rosenberg [1991] in reference to QWERTY keyboards, but is equally applicable to piano keyboards.) Available studies indicate that learning times and data entry rates are similar to QWERTY keyboards (Greenstein and Muto, 1988, and Eilam, 1989).

A precedent for the use of a chord keyboard can be found in the similarities with the wind and brass families of instruments. The fingering patterns of

---

[2] Each key or key combination produces a single, unique 'signal'.

these instruments are similar in nature to those of a chord keyboard; one or more keys are pressed simultaneously to play a single note. (Wind instruments typically also sound a note when no keys are depressed.) The keys of the wind and brass instruments are not, however, velocity sensitive.

The spacing of the keys is derived from Eilam (1989). Eilam measured the forearm-hand length, hand length, hand breadth at the thumb and hand breadth at the metacarpal of his test subjects, but failed to find any significant correlation between these variables and the layout of the keys. He states this lack of correlation may be explained by the fact that the fingers are flexed when using a chord keyboard and the variance of finger length will shrink if the flexure of the long and short fingers is not the same within and between subjects.

Figure 6.2 illustrates Eilam's key layout for the right-hand for the 50th percentile of his sample group. The figures within the rectangles indicate the centre point of that rectangle. The thumb is located at 0, 0. This data was used as the basis for the keyboard design. Eilam declines to provide 5th and 95th percentile layouts on the grounds of limitations imposed by his sample size. (His sample group consisted of 40 male college students.) Coincidentally, it was found that the average horizontal distance between key centres of Eilam's layout and the key centres of the white keys on a typical piano keyboard are very nearly identical (2.4cm and 2.3cm, respectively). The spacing of the piano keys has been arrived at through several hundred years of craft design refinement. The convergence of this data would seem to recommend the use of Eilam's layout.

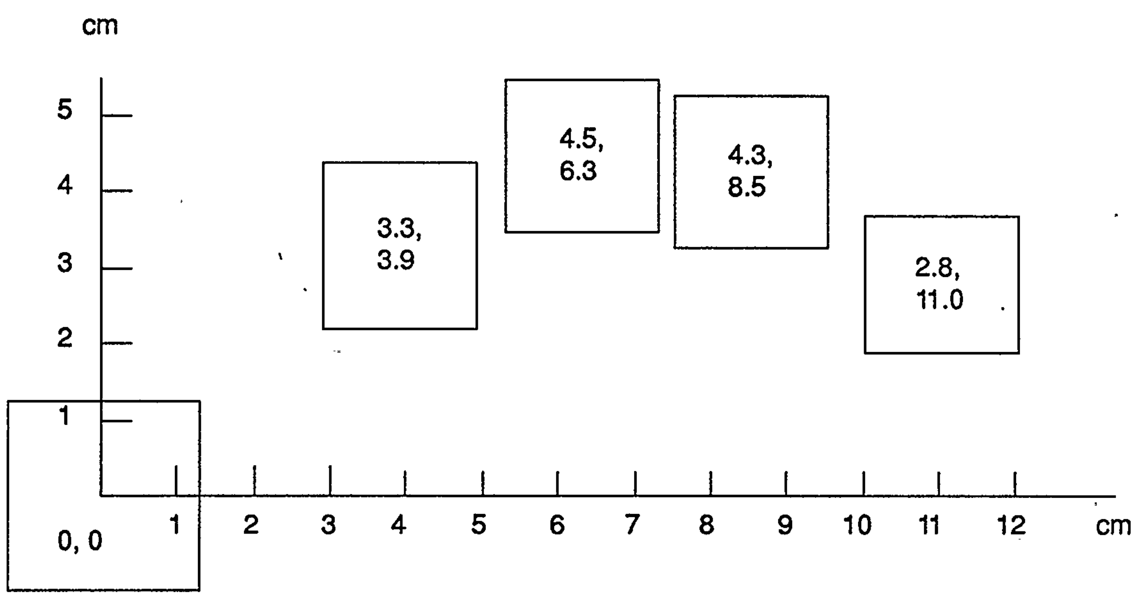


Figure 6.2
Key layout. (from Eilam, 1989)

The keyboard echoes the shape and motion of the hand. The keys of the chord keyboard are tapered to accommodate different hand sizes. The spacing of the key centres becomes narrower closer to the line formed by the knuckles and wider at the other extreme. This tapering assumes hands with shorter fingers will be narrower and hands with longer fingers will be wider. This is, of course, not always the case. The user has some freedom in where the hand is placed, and most users should be able to find a comfortable hand position. The layout of the keyboard discourages ulnar deviation of the wrist and abduction of the little finger away from the hand. These conditions cause difficulties with the ulnar and median nerves (Hargreaves, et al., 1992). The key layout was compromised slightly to produce the tapering of the keys; the middle- and index-fingers are spread slightly more than desirable. The dashed circles indicate the ideal spacing recommended by Eilam. Figure 6.3 illustrates the key layout.

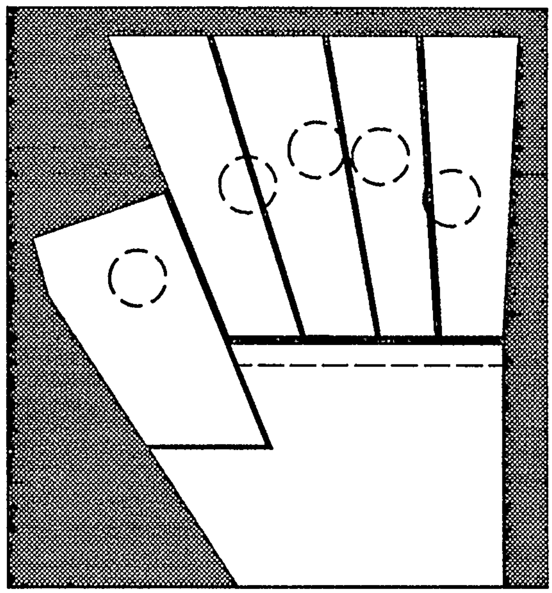


Figure 6.3
Keyboard layout.

The palm rest is curved to provide a relaxed hand position and is also cut away to allow free movement of the thumb. The thumb key is normally parallel to the ground and shaped to allow for different thumb sizes and positions. Figure 6.4 is a three-quarter view of the keyboard.

The four finger keys are hinged in a line perpendicular to the thumb and slope downward, allowing the fingers to arch over the keys. This provides a comfortable hand position and allows the keys to be struck with varying amounts of force (a requirement for the velocity sensing, discussed below). Maximum key travel is 7mm, about half the key travel on a typical synthesizer keyboard. The shorter travel partially compensates for the shorter distance from the pivot point to the point of finger contact compared to a typical keyboard. This amount of travel also distinguishes the keyboard from a standard synthesizer keyboard. A rubber elastomer spring is used under each key to return the key to its off position. This spring also provides some cushioning at the bottom of the key travel.

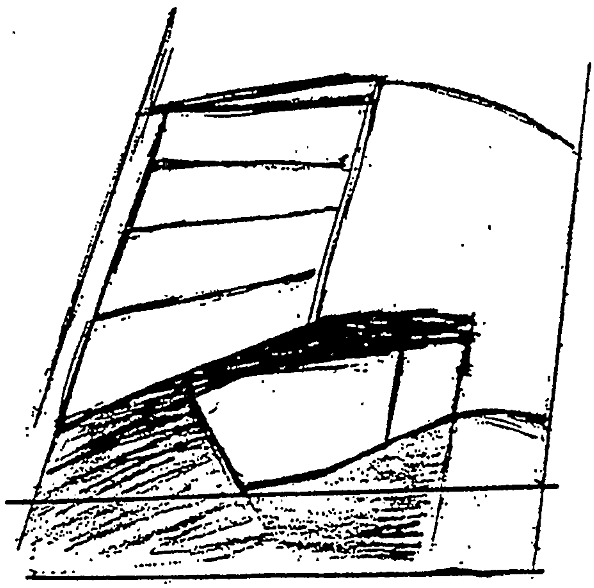


Figure 6.4
Sketch of the chord keyboard.

Each finger key is 105mm measured from the tip of the key to the hinge point. The length from the hinge point to the rubber spring of the little-finger key makes this key somewhat harder to depress than desirable. Each key was made the same length to accommodate the switch assembly used and to facilitate building the model. Figure 6.5 illustrates a key layout that conforms more closely to Eilam's recommended spacing and takes into account the different finger lengths. A disadvantage of this layout is that each key has less variation in width than the previously described layout.

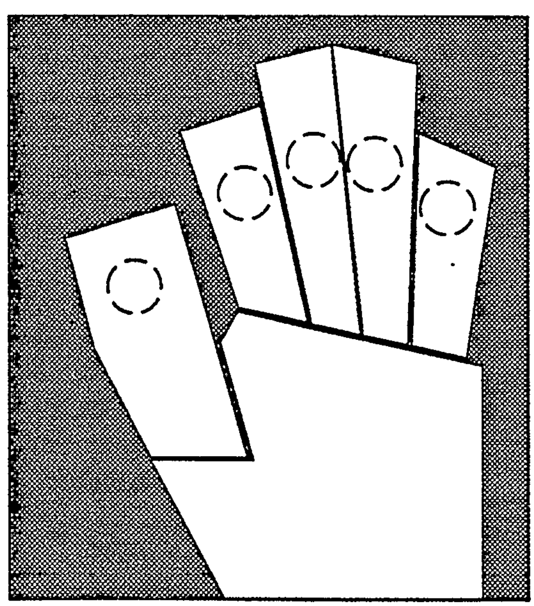


Figure 6.5
Possible key layout.

The palm rest supports the hand and the weight of the arm, allowing the arm to be maintained in a comfortable posture. The shoulder and upper arm are relaxed, typically with the upper arm perpendicular to the ground and the forearm parallel to the ground. The overall height of the instrument is adjustable so that a comfortable posture can be achieved. These issues are discussed further in the section describing the overall form of the controller.

Fingering Possibilities

As mentioned, 31 keying combinations are possible for a five key keyboard. Some combinations, however, should be avoided; in particular those requiring independent motion of the ring finger and little finger. These combinations are difficult for many people and can result in high error rates. Markison, in discussing keyboard designs for typing tasks, states that 35% of hands have a congenital linkage of the ring and little finger flexor tendons (Hargreaves, Rempel, et al., 1992). Greenstein and Muto (1988) point out the most difficult fingerings tend to require one or two fingers to be held up while the neighbouring fingers on each side depress keys.

The more difficult combinations can be avoided or reserved for special functions by using the easier fingerings for a single octave of pitches combined with additional switches for octave transpositions. Twelve fingerings (one octave) combined with the 4 transposition keys would give a range of 5 octaves. The transposition switches are used to transpose the 'home' octave by +1, +2, -1 and -2 octaves. The 5 octave range is adequate for most applications, and the vast majority of commercially available synthesizers are equipped with 5 octave keyboards. The transposition switches are located on the joystick controller, under the thumb of the left hand.

The use of additional fingerings gives a corresponding increase in the range of available pitches. Twenty-four fingerings combined with ±1 and ±2 octave transpositions gives a range of 84 pitches, very close to the 88 pitches of a piano. This configuration also makes each pitch available in two fingering positions. For example, a note in the second, un-transposed octave (fingerings 13 to 24) is also present in the first upwardly transposed octave (fingerings 1 to 12, plus one octave). Twenty-four fingerings combined with ±2 and ±4 octave transpositions gives 10 octaves of pitches (120 notes), very near the complete 128 pitches available in the MIDI specification.

It should be noted here that few acoustic instruments have a range of more than 3 to 4 octaves (the piano being the notable exception). A number of technical factors (sampling rates, aliasing distortion, and others) limit the useful range of many electronically produced sounds to less than 5 octaves.

The programmable nature of the instrument makes it feasible to provide the user with a selection of possible fingerings. Initially the 12 basic fingerings (one octave), along with the transposition keys, could be used exclusively.

Once these have been learned, the next 12 fingerings (a second octave) could be introduced. This scheme breaks the learning experience into more manageable chunks. Alternatively, the second 12 fingerings could be used for quartertones, where an octave is divided into 24 tones. Other tuning systems that divide the octave into more or less than 12 notes could also be accommodated.

The default fingering follows a simple binary pattern. The thumb is the first binary digit and the little finger the fifth digit, with each finger changing the corresponding digit to a 1 when the key is depressed. The pattern starts at note C -1 (MIDI note #48). Although this pattern does require the use of the more difficult fingerings, it is easy to learn, musically useful and unique. The intervals form whole tone and chromatic scales and symmetrical scale patterns appropriate for many 20th century musical idioms are easily formed. The thumb and index finger raise the note formed with the other three fingers by a semi-tone and whole tone respectively, making it easy to play trills (Eagle, 1993).

The concept of using a Hamming distance of 1 was used as a starting point for the development of a second fingering pattern. Gerald Beauregard (1991) developed an alternative fingering system for wind controllers based on a modified Gray code with a Hamming distance (a concept used in information theory to distinguish one piece of information from another) between adjacent notes and adjacent octaves of 1. This means only one finger needs to be moved to reach an adjacent note or transpose to an adjacent octave. Beauregard describes his controller as "eminently playable", and finds "the fingering is fantastic for chromatic scales, but it also works very well for diatonic and whole tone scales, and arpeggios, in any key." The pattern developed here is limited to a single octave to avoid awkward transitions from one pattern to another.

A third possible fingering pattern is loosely based on a 'Casio'-type fingering. The Casio company manufactured an inexpensive MIDI wind controller for several years. The fingering of this controller is optimized for easy playing of a whole-note scale; the note a tone above or below any sounded note can be reached by lifting or depressing a single key. Three keys under the fingers of the right hand are used to play seven of the wholetones of an octave (C, D, E, F, G, A and B). Two additional keys cause the note played to become sharp or flat by a semi-tone, and two more keys are used in combination to transpose an octave down and either one or two octaves up. These four keys are under the fingers of the left hand. The advantage of this fingering system is that the little finger of the right hand is not used at all, and most keys have at least one alternative fingering that allows the use of the little finger of the left hand to be avoided. The Casio fingering gives a 4 octave range using only 6 keys (use of the 7th key provided can be avoided entirely). The pattern developed here also has a Hamming distance of 1, and is also limited to one octave.

A fourth pattern is an attempt to develop a logical progression that would be easy to remember and prove musically useful. The usefulness of any particular fingering pattern cannot be determined without testing, and this was not possible for the project.

The four fingering patterns described here are illustrated in Appendix D.

Velocity Sensing

The keyboard is velocity sensitive, giving MIDI velocity values from 1 to 127. A single-pole double-throw switch is located beneath each key. At rest, the common pole is in contact with the top switch contact. The velocity value is derived from the time it takes the common contact to move from the top contact to the bottom contact when a key is depressed. Striking the keys with greater force causes the time the switch is open (the common pole is not making contact with either the top or bottom contact) to decrease, giving higher velocity values. This means of deriving velocity is quite common in keyboard MIDI controllers.

A velocity map determines the relationship between played velocity and the MIDI velocity data and can be linear, exponential, logarithmic, or some other shape (see Figure 6.6). Most higher quality keyboards offer a choice of velocity maps, allowing users to customize the feel of their instruments. Velocity maps for the chord keyboard are provided in the *MAX* programming environment.

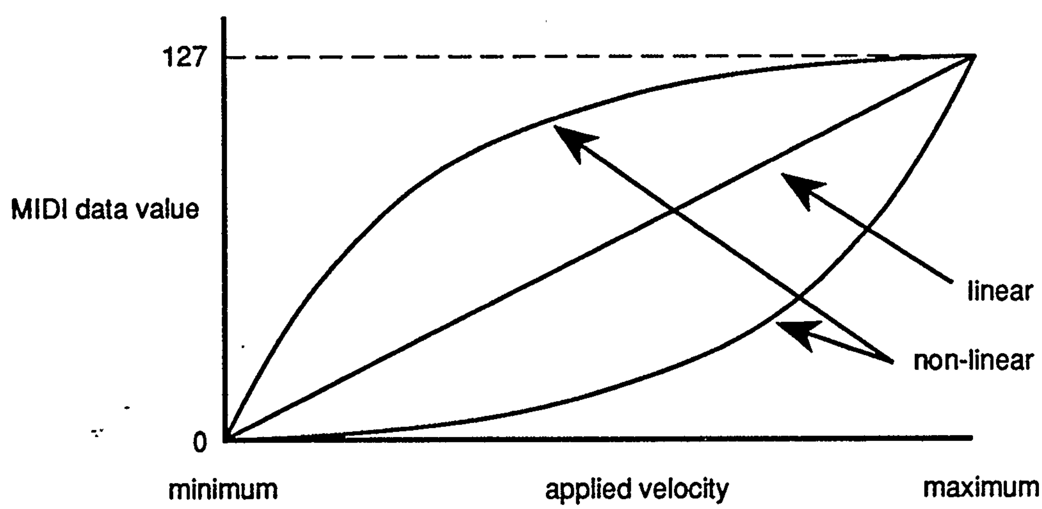


Figure 6.6
Velocity maps.

The actual operation of the chord keyboard is dependent on the operating mode of the sound engine. Most synthesizers and sound modules have three or four modes of operations. Although manufacturers give these modes different names, all have modes that work in a similar fashion.

The most common mode of operation is polyphonic. When a note-on message is received, an amplitude envelope is triggered to sound the note. The amplitude of the note is maintained at the sustain level of the amplitude envelope until a corresponding note-off message is received. The envelope then moves on to the release segment. This is illustrated in Figure 6.7. The overall amplitude is determined by the velocity value generated when the key is struck, if the sounding voice is programmed to be velocity sensitive. Consecutive note-on messages (without corresponding note-off messages) cause additional notes to sound with the same velocity-dependent amplitude envelope.

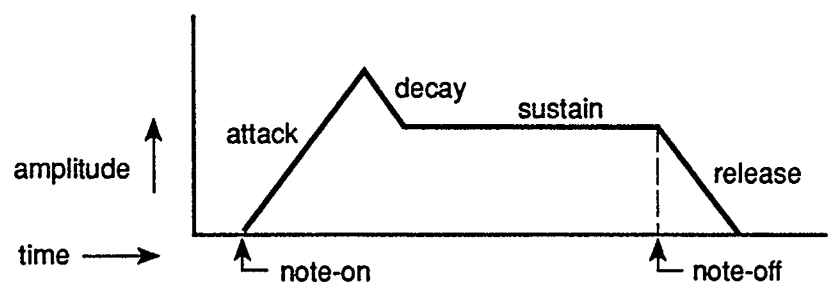


Figure 6.7
Polyphonic mode amplitude envelope.

Two monophonic modes of operation are also common. One is frequently called monophonic-retrigger mode. In this mode, only one note at a time sounds, with overlapping key depressions causing a new envelope to be triggered for each key depression. New sustain levels are also generated if the voice is velocity sensitive. Figure 6.8a illustrates this. The second mode is frequently called monophonic-legato mode. In this mode of operation overlapping key depressions cause the attack portion of the newly triggered envelopes to be skipped, going directly to the sustain part of the envelope. New attacks are triggered only after all the keys have been released. This is illustrated in Figure 6.8b.

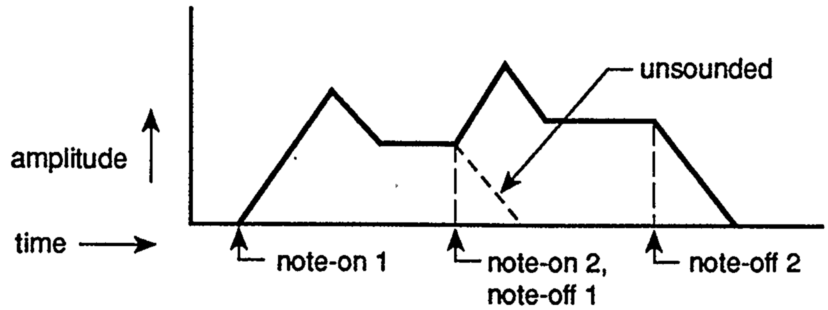


Figure 6.8a
Typical monophonic-retrigger mode amplitude envelope.

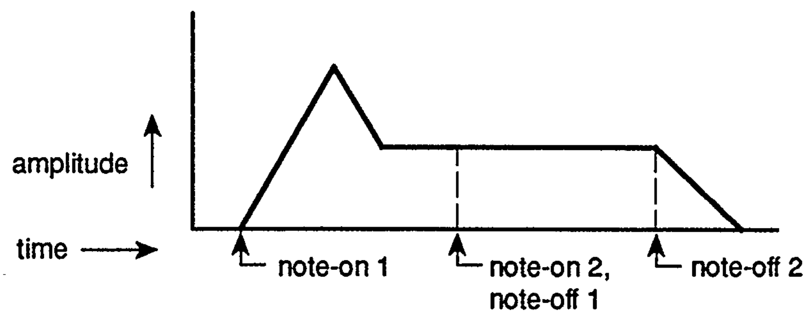


Figure 6.8b
Typical monophonic-legato mode amplitude envelope.

Channel and Key Pressure (Aftertouch)

MIDI Pressure messages are generated by applying increasing pressure on the keys of a keyboard after the keys are depressed. There are two kinds of pressure in the MIDI specification. Polyphonic Key Pressure is defined as continuously varying values for each key to which pressure is applied. Channel Pressure is defined as a single varying value corresponding to the pressure applied to all of the keys depressed. These MIDI messages are also called Channel and Poly Aftertouch messages, and this is recognized in the MIDI specification. Aftertouch is the term that will be used here. Most commercially available keyboard synthesizers generate Channel Aftertouch, and a few generate Poly Aftertouch messages. Many of the synthesis engines used in synthesizers and sound modules, however, respond to both Channel and Poly Aftertouch messages.

Increasing pressure on the keys of the chord keyboard compresses a foam rubber strip and causes a plastic disc to come in contact with a force-sensing resistor. Applying more force to the resistor causes its resistance to drop. This is converted into Channel or Poly Aftertouch messages. These messages are continuous, start at 0 (no pressure applied) and range up to 127 (maximum pressure).

Pitch Bend

The chord keyboard also generates Pitch Bend Change messages. A force-sensing resistor is located on either side of the keyboard body in line with the palm rest. As pressure is applied to the left, the pitch bends downward and as pressure is applied to the right, pitch increases.

Pitch Bend Change messages can use one data byte or two bytes for high-resolution pitch bending. The working model uses one data byte. Pitch Bend Change messages are typically continuous and bi-polar, increasing and decreasing from a mid-point value. A value of 64 (or 8192 when using two byte messages) specifies no pitch bend. The more the value differs from 64 (or 8192) the greater the pitch bend (see Figure 6.9). The total amount of pitch bend is usually an adjustable parameter in the synthesis engine.

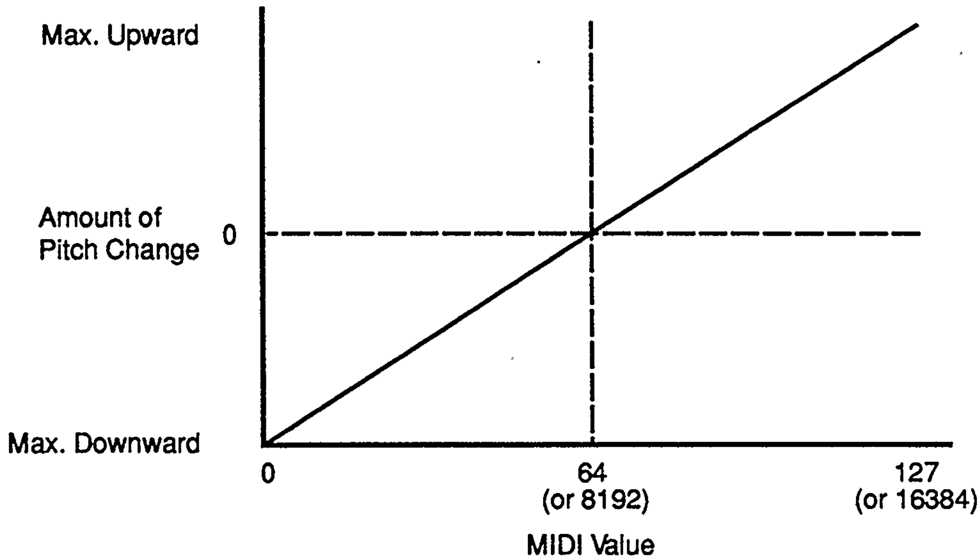


Figure 6.9
Pitchbend amount vs. MIDI Value

Key Simultaneity

A velocity sensitive chord keyboard has an inherent characteristic that may present a problem in its use. Keys must be depressed simultaneously to sound some notes. Given the small variations in the distances the contacts of the key-switches travel and the physical capabilities of human performance, it is highly unlikely that the key-switches will be closed absolutely simultaneously; some time will elapse between the closure of the first key-switch and the last key-switch of a key combination.

The electronics of the keyboard must somehow be able to make a distinction between keys depressed in combination and consecutive key depressions. This has been done by introducing a small delay factor; if more than one key depression occurs within a window of time, the depressions are treated as occurring simultaneously. The event window introduces a delay between the last key depression and the sounding of a corresponding note. For example, consider that a single key has been depressed. The keyboard electronics 'knows' this key is down, but waits for a certain amount of time to see if any more keys are pressed. If another key is depressed within the specified time, the keys are treated as having been depressed simultaneously and only one note-on message is generated. Otherwise, two separate note-on messages are produced. The result of the introduction of this event window is that the chord keyboard must be played with a more precise technique than a standard organ-type keyboard to avoid sounding unintentional and unwanted notes.

The event window is adjustable from roughly 250ms down to 5 ms. A novice player with poor technique can set a longer window time, thereby introducing a longer delay. As the player's technique improves and keys are depressed with greater simultaneity the window can be shortened along with the inherent delay. In the author's experience, a window of approximately 30ms is not unreasonable to start with, but does require concentration to play the keyboard without mistakes. The shortest practical event window has not yet been determined.

The time delay between key depressions and the sounding of a note may prove to be unacceptable in some situations. Guitar controllers that rely on pitch detection to generate corresponding MIDI note-on messages are often criticized for having a slow response. A good pitch detector requires at least 2 cycles to determine the pitch of a waveform. It takes 8ms to read the lowest note of a guitar (160 Hz), and a delay of this magnitude is perceptible to many guitar players. (In this situation there is a great deal of transfer of expectations, as a guitar controller would be expected to behave exactly as a guitar.) As well, sounds with percussive attacks can have initial decay times of less than 10ms. The delays inherent in the way the chord keyboard has been implemented may present problems for some musicians.

Several possibilities exist for reducing or eliminating the delay. It may be possible to develop a faster algorithm by using information derived from the top, normally closed key switch contacts. A second possibility is that the top surfaces of the keys may be made sensitive to the area (mm^2) of a finger contacting a key. This information could be used to determine what note is to be played before the keys are actually depressed. This technique has been used successfully by Kramer and Moog (1989).

A third possibility is to use a neural network. This proposed use of neural networks is based on an assumption that there will be a certain consistency in the timing of moving from one fingering position to another, at least within individuals. Neural networks have been successfully used to map performance gestures to control parameters for sound synthesis and algorithmic composition (Lee and Wessel, 1992 and Lee, Freed and Wessel, 1991). Neural networks are 'taught' using pairs of input data and corresponding desired output data. This process establishes the behaviour of the network, and the network can then calculate an output for any input. A neural network could be taught to recognize the different key combinations along with any characteristic deviations from simultaneity on a person-by-person basis. Lee, et al., (1991) foresee neural networks being used for self-adjusting controllers that would adapt to different playing styles automatically, as a means of compensating for physical disabilities, or to create more ergonomic instruments.

Joystick 6.5.2

A joystick was chosen for the timbral level for several reasons: joysticks are easy to use, their basic operation is easy to understand, and they have a minimum of two dimensions of control that can be navigated simultaneously. These dimensions can also be independent of each other. An important consideration is that a joystick can be designed to allow the fingers to be used for additional dimensions of control (assuming the arm is used for movements in the X and Y dimensions). Cushman and Rosenberg (1991) suggest a joystick "is generally the preferred control for... complex perceptual/motor tasks... ."

Woodson (1981) recommends that no more than six functions be incorporated in a joystick because users sometimes activate the wrong control either through confusing functions or through inadvertent motion inputs if more functions are available. Woodson's recommendations concern a pistol-grip type joystick designed for use in military aircraft where confusion or inadvertent motions could be disastrous and may even result in the loss of life.

Musical applications are, of course, less critical. There is also a general consensus that the small, uncontrolled or uncontrollable motions of a person playing a musical instrument that can cause random variations in the generation of a sound contribute a desirable element of 'liveness' to the sound and performance. Most synthesis engines include modulation sources employing random noise in an attempt to emulate this 'liveness'. Sequencing software often includes functions that allow the introduction of random variations in timing, loudness, and other parameters. The generation of small, unintentional control value changes may not be completely undesirable and might be viewed as making a positive contribution to the 'liveness' of the controller.

Initially an upright 'ski-pole' joystick with a projecting 'paddle' was considered (see Figure 6.10). A third dimension of control (in addition to the X and Y dimensions) is provided by sensing pressure parallel to the cross-section of the joystick shaft. As well, a pressure-sensitive strip along the edge of the 'paddle' gives a fourth dimension of control. This design has one significant problem; in order to be moved, the joystick must be gripped firmly and constantly between the thumb and the palm of the hand in a pinch grip, causing the hand to tire quickly. This problem was remedied by rotating the 'paddle' to form a palm rest on the top of the joystick shaft (see Figure 6.11). The functions of the joystick are basically unchanged.

The palm of the user's hand rests on the palm rest and the fingers are slightly arched. Four switches are provided under the fingertips. A touch-sensitive strip is located just behind two of the switches for easy activation using the middle- and fore-fingers.

The palm rest is cut away to allow free vertical movement of the thumb. The thumb switches and the break that follows the line formed by the knuckles serve to locate the hand on the palm rest. The initial design was based on the span of the hand at the metacarpal and the angle of the grip line (8.9cm for the 95th percentile male and 12 degrees; both figures from Diffrient, 1988).

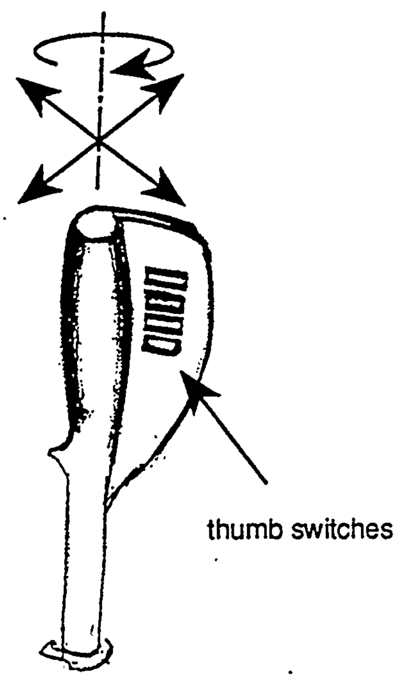


Figure 6.10
'Ski-pole' joystick concept.

Comments made in informal situations with a number of potential users of the controller indicated that differences in finger length between individuals should be taken into consideration. The touch-strip and switches are therfore housed in a separate assembly. The distance between the line formed by the knuckles and this assembly is adjustable to compensate for differing finger lengths.

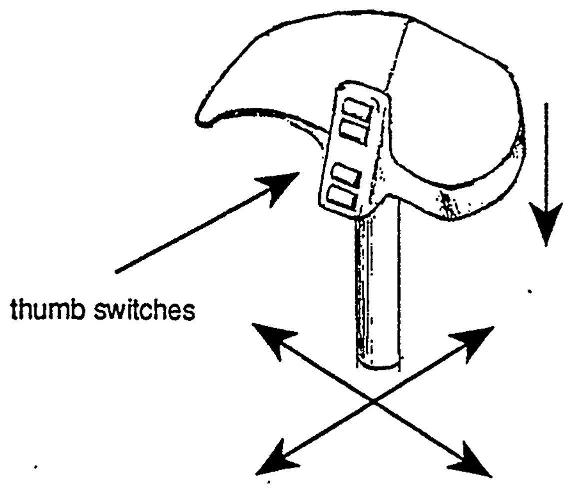


Figure 6.11
Palm rest joystick.

The X and Y dimensions of control are activated by moving the palm rest. The area described by the motion of the palm rest is a portion of the surface of an imaginary sphere. The size of this area is determined by the length of the joystick shaft and the amount of deviation from a vertical position. The shaft of the joystick deviates ±20 degrees from vertical in both X and Y dimensions. This falls within the ±6 degrees and ±30 degrees of typical joystick movement (Doran, 1988). The length of the shaft from the pivot point to the top of the palm rest is 21cm. The X and Y dimensions of control are continuous and generate all intervening values when moving from one position to another.

One design goal is to keep occurrences of unnatural and awkward postures of the wrists to a minimum in the hope that this will reduce incidence of repetitive strain injuries. The location of the joystick in relation to the body causes the muscles of the forearm to be used for movement in the X and Y dimensions. The relatively small deviation from vertical of the joystick helps to minimize abduction and adduction as well as ulnar and radial deviation of the wrist. There is some pronation of the forearm at the extremes of the range of movement. A shorter shaft for the joystick would help to reduce this.

The deviation and the shaft length partially determine the physical resolution (number of values generated as a function of distance moved) of the X and Y control dimensions. Reducing either deviation or shaft length reduces the area described by the palm rest, thus reducing resolution. The resolution is also dependent on the transducer that converts the movement of the joystick into electrical signals, and a reduction in resolution caused by decreased movement can be compensated for relatively easily. A point where the shaft would pass through the top surface of the palm rest moves through a distance (in one dimension) of approximately 17cm at maximum deviation (see Figure 6.12). This gives a resolution of 7.5 values per 1cm of movement

(128÷17=7.53). Just over 1mm of linear movement will cause a change from one value to the next.

The X and Y dimensions of control are assigned MIDI Control Change numbers 16 and 17. Several manufacturers using X-Y joysticks in their products have adopted this convention, although these Control Change numbers are described as 'general-purpose controllers 1 and 2' in the MIDI specification.

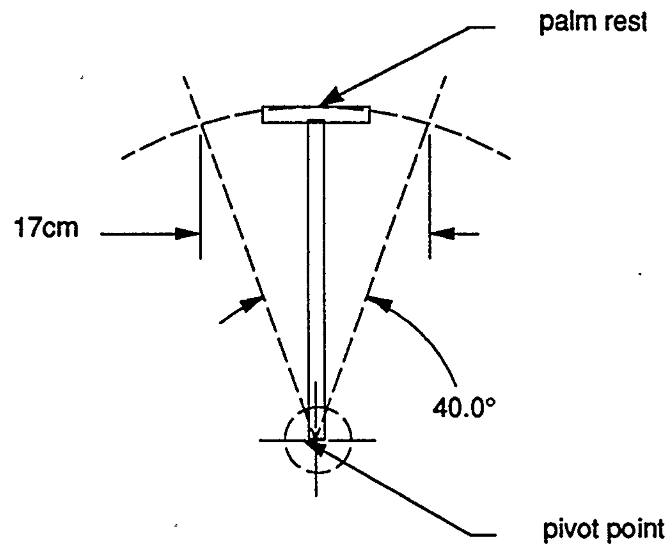


Figure 6.12
Range of movement of palm rest (not to scale).

Pressure Sensing (Z dimension of control)

The pressure sensor under the palm rest produces uni-directional continuous values in a third or Z dimension. The palm rest pivots about a point below the knuckle line. Rotation is constrained to approximately 5 degrees in a clockwise direction (viewing the joystick from the side with the front edge to the right). Increasing pressure on the front of the switch array compresses a silicon rubber disc against a pressure sensor to give increasing values in much the same manner as the aftertouch sensing incorporated in the keyboard. Raised bumpers are provided immediately in front of the switches so that pressure can be applied without activating the switches. The rubber disc is surrounded by a foam rubber pad that acts as a spring and returns the palm rest to its rest position (returning the value to zero).

The default assigned for this dimension of control is MIDI Control Change number 1, defined as modulation wheel or lever. Other Control Change numbers can be assigned by the user. The modulation wheels or levers of most commercially available synthesizers do not return to a zero value when released. To accommodate this difference in behaviours, one of the palm rest switches can be programmed to turn the control change messages on and off. New values are transmitted to the sound module only when the switch is simultaneously depressed. The inverse of this function might also be useful; values are sent as long as the switch is not depressed.

Finger Touch-strip

The touch-strip on the top of the palm rest is similar to a slide control. The active part of the strip is 14mm wide and 57mm long, roughly parallel to the index and middle finger switches so these fingers can be used to activate the strip. The surface of the strip is smooth and a finger will slide easily on this surface, and only a very light touch is required. The touch-strip is slightly recessed into the surface of the joystick. This provides a guide for the fingers and helps to prevent accidental activation.

A distinctive characteristic of the touch-strip is that it is a continuous/discrete controller; new values can be generated continuously by sliding a finger along the strip, or discretely (jumping directly from one value to another) by simply touching a different point on the strip. The strip is touch sensitive in that values other than zero are generated only when something is in contact with its surface (typically a finger). The value returns to zero when nothing is in contact with the strip. The default setting of the finger strip is MIDI Control Change number 18 (general purpose controller #3).

Joystick Switches

Switches are located under the tips of the middle, index, ring and small fingers of the left hand. As mentioned above, a raised bumper is located at the front edge of each switch. Initially the location of the switches was determined using a mirror image of the data for the right hand developed by Eilam. This assumes there is a symmetry between the shape and size of the left and right hands of an individual. Spacing was adjusted because the fingers are not required to curve as much as when using a chord keyboard. As a result, the fingers are not drawn together as much and the distance between switch centres is correspondingly greater. Informal polling of a small number of individuals chosen for their variety of hand sizes indicated no significant problems with the switch spacing at this time.

The switches used in the model were chosen for their size, tactile qualities, and quietness of operation. Similar switches would be used in a production model. The area of the switches engaged by the finger is rectangular and 13mm wide and 10mm long. Cushman and Rosenberg (1991) recommend finger activated push button switches have a diameter (or length for rectangular switches) of 13mm. Although the switches used are slightly smaller than recommended, no problems are anticipated as the fingers are always positioned immediately in front of the switches. The switches are not acting as targets where the hand is required to move a considerable distance to reach them.

The switches have just over 2mm of travel, within the 1 to 6mm recommended by Diffrient (1974). The switches are silent in operation and have a 'springy' feel that gives no tactile feedback indicating a switch closure. Initially switches with less travel but an audible and tactile 'snap-action' were tried. These switches proved unsuitable because it was difficult to activate more than one switch simultaneously and the noise produced (a sharp 'click') was unacceptable in a quiet environment.

The switches can operate as either momentary or push-on/push-off switches. When operating as a momentary switch, an 'On' message (MIDI value 127) is sent when a switch is depressed and an 'Off' message (MIDI value 0) when the switch is released. In push-on/push-off operation, depressing a switch sends an 'On' message and releasing the switch does nothing. Pressing the switch again causes a corresponding 'Off' message to be sent.

The default assignment of the index finger switch is damper pedal or Sustain (MIDI Control Change number 64), Portamento (Control Change number 65) for the middle finger switch, Sostenuto (Control Change number 66) for the ring finger, and Soft Pedal (Control Change number 67) for the little finger. Unfortunately, not all synthesizers or sound modules on the market respond to all of these Control Change messages. The switches can, therefore, be programmed for different functions as described above (turning the Z dimension of control off and on).

Thumb Switches

Four switches are located in a line roughly perpendicular to the top surface of the joystick. The switches fall under the thumb of the left hand and, because of their fixed position, serve to locate the hand on the joystick. The array of switches is angled slightly outward at the bottom so the user is required only to move the thuumb up and down. These thumb switches work in conjunction with the chord keyboard to provide a means of transposing the selected note up or down by one or two octaves.

The switches take the form of small cylindrical rollers. The rolling action encourages users to slide their thumb over the switches (see Figure 6.13). Roller keys are commonly used on wind instruments to activate key combinations by sliding a finger.

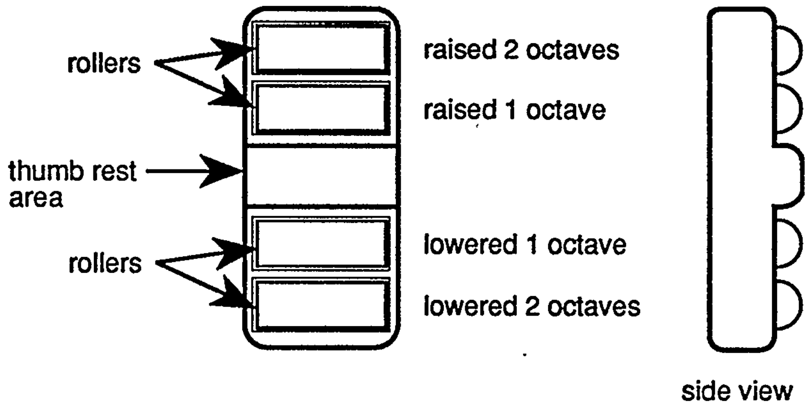


Figure 6.13
Thumb roller switches.

The switches are divided into two groups of two, with a 'dead space' between. This dead space is a place for the thumb to rest when no transposition is desired. The two switches above the rest position give, respectively, one and two octaves of transposition upward. The two below the rest position transpose downward in a similar manner.

The electronics associated with the switches are designed so the switch giving greater transposition takes precedence if two switches are depressed. That is, if the 2 octave transposition switch is depressed while the 1 octave transposition switch is also depressed, notes will be transposed by 2 octaves. If the 1 octave transposition switch is depressed when the 2 octave switch is already depressed, only the 2 octave transposition will be given. The physical layout of the switches make it extremely awkward, if not impossible, to depress an upward and downward transposition switch at the same time.

Simple push button switches were used on the model, and only 1 octave of transposition upward or downward is possible on the model at this time. The arrangement and operation of the switches is intended to encourage users to slide the ball of their thumb over the surface of the switches. Informal observation of persons using the switches showed almost all used a pressing action, lifting the thumb from the rest position and pressing the desired switch. The resulting action is somewhat awkward and slower than a sliding motion. The discrepancy between the intended action and the action actually used may be a result of the incongruity of mapping a continuous action (sliding the thumb) to a discrete function (transposition by octaves).

Switch Array 6.5.3

The switch array is made up of general-purpose switches that can be 'user-defined' for such things as control at the musical process level. Schloss (1991) calls this level macroscopic, but only obliquely defines what a musical process might be. He refers to Chabade's concepts of interactive composition, where one controls some aspect of a computerized musical composition algorithm in real-time and also to Tod Machover's *Hyperinstruments* as operating on the musical process level (Chabade, 1984 and Machover, 1989). Both references involve complex processes that would most likely be employed only by advanced users.

The array has 12 momentary contact switches divided into a group of four and a group of group of eight. This division serves two purposes. The number of switches in each group does not exceed the 7 plus or minus two recommended by Miller for easy retention (Miller, 1956). Also, by having one group affect the operation of the other, the number of functions addressed can be greatly increased. The 'patch-select' function (described more thoroughly in the next chapter) is an example. Three of the group of 4 switches select a bank of patches. The other group is used to select 1 of 8 patches within the selected bank. The user has access to 3 x 8 = 36 patches using this method. Other types of functions could be similarly addressed.

The switches are arranged in a linear array and located for easy access using either hand. Each switch is 25mm long and 35mm wide with 26mm between centres, exceeding the recommended minimum 13mm length for push buttons. Travel is slightly over the recommended minimum 1mm. The switches are slightly peaked to provide an actuation surface for fingers of each hand (see Figure 6.14). The amount of slope is small enough and the ridge formed by the sloping surfaces is slightly rounded so that the whole switch surface can be used with either hand.

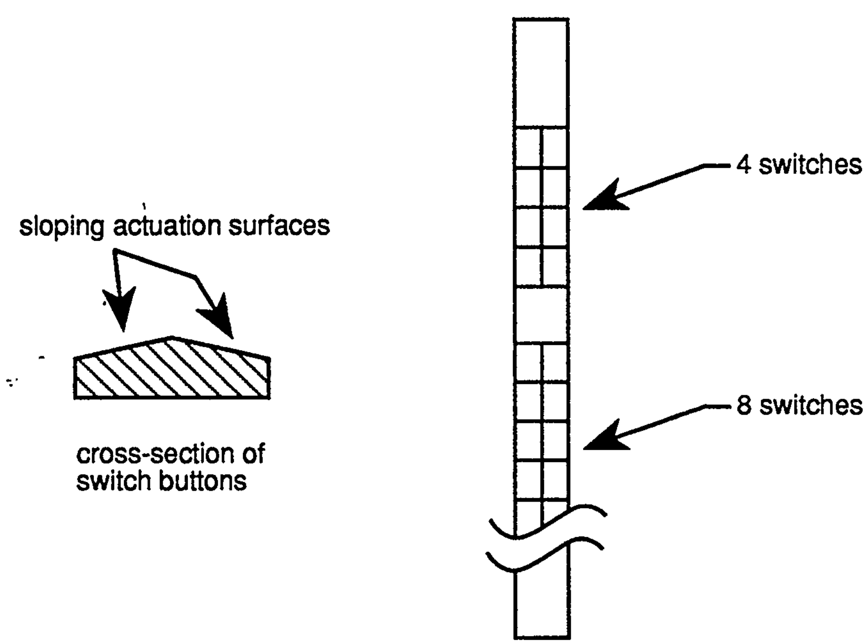


Figure 6.14
Switch array layout.

Some of the functions of the software have been alluded to in this section; the software and programmable aspects of the controller will be described in more detail in the next chapter.

ADDITIONAL CONSIDERATIONS 6.3

An important aspect of any musical instrument is how it 'feels' to the player. The tactile qualities of an instrument are often hard to describe and in many cases different for individual musicians. The issues of 'feel' were not addressed explicitly in the model or the design. However, it is worthwhile to mention some of the factors that might influence the tactile qualities of this controller.

Cushman and Rosenberg (1991) discuss four characteristics of controls that can be influenced by control resistance. These characteristics are:

1.) the speed and precision of control manipulation,

2.) the 'feel' of the control,

3.) the smoothness of the movement of the control, and

4.) the suseptibility of the control to accidental movement or activation.

Cushman and Rosenberg also discuss four types of resistance (friction, elastic resistance, viscous damping, and inertia) that influence the characteristics listed. Two types of friction (static and sliding) can influence control movement. Static friction is the initial resistance of a control to movement. This kind of friction holds a control in place and helps prevent accidental activation. Sliding friction is the continuous resistance of a control to movement that is not affected by either velocity or acceleration. Generally, both types of friction are undesirable as they tend to degrade performance. Elastic resistance increases with the displacement of a control; spring-loaded controls that return to a null or zero position are typical examples. Viscous damping is dependent on the velocity of a control; the faster a control moves, the greater the resistance. Viscous damping can be beneficial for making precise settings and small changes in control position, and can aid in smoothing control movement, especially where a constant rate of movement is required. Inertial resistance is caused by the mass of the control and varies in relation to acceleration. Inertia causes a control to resist sudden changes in velocity. It can also aid in smooth control movements, but also increases the difficulty of making precise adjustments because controls with high inertia are susceptable to overshoot.

Control resistance should be carefully balanced, or be made adjustable where possible. A static friction mechanism is required to hold the joystick in place when the user removes their hand from the palm rest. The resistance should become as small as possible once movement is initiated. The mechanism should also be self-adjusting so that the static friction remains constant despite any wear that may occur in the mechanism. Sliding resistance should be made as small as possible. Some viscous damping would make for smoother control movement, and this should be adjustable according to the user's preference. A small amount of interial resistance may be desirable to aid in smooth control movement, but not so much as to cause any significant overshoot. Some elastic resistance (perhaps in the form of a soft bumper) should be provided at the extremes of the range of motion of the joystick so a user knows when he or she is approaching the limits of travel. It may be disconcerting to encounter the physical limits of travel without warning.

The joystick should move smoothly, freely and silently in the X, Y and Z dimensions simultaneously. The joystick mechanism should be mechanically stiff (that is, the parts of the mechanism should fit precisely and not bend or flex) and have as little backlash as possible to insure control changes are precise and accurate. Mechanical deadspace (where control movement results in no response) should be minimized as any desired deadspace can be introduced electronically.

Synthesizers are sometimes equipped with a 'weighted' keyboard action that simulates the feel of a piano keyboard. A weighted action provides tactile feedback that makes it easier for the player to modulate the velocity of key depressions and releases. On the other hand, in some situations (such as those where velocity does not affect any parameters of a note) a quick and light action may be more appropriate. The ideal solution would be to have an adjustable keyboard action, although this would be very difficult to accomplish.

The means of generating Pitch-bend messages (sensing pressure as the palm rest is moved to the left or right) cannot be used to impart a pleasing vibrato to a note. The range of movement and the effort required are not conducive to producing an oscillating motion in the roughly 4 to 6Hz range necessary for vibrato. It appears desirable to somehow sense side to side finger motions on the depressed keys and derive pitch bend data from those motions.

The switches of the switch array should offer sufficient tactile feedback that the user can tell when a switch is closed without relying on other forms of feedback. The action of the switches should not be so light that they can be activated accidentally.

This chapter briefly describes the electronics of the proof-of-concept model and presents a possible implementation for a production model.

PROOF-OF-CONCEPT MODEL 7.1

The model uses two Intel 8031 8-bit microprocessors. One processor handles the analogue-to-MIDI conversion of the continuously variable signals. These include joystick movement, pressure sensing for the aftertouch and pitch bend, and the touch-strip. The other processor is dedicated to the chord keyboard and the various switches.

The assembly handling the analogue-to-digital conversion and MIDI output is commercially available in kit form (Clark, 1991). A small amount of additional circuitry is necessary for interfacing the force-sensing resistors used for aftertouch and pitchbend to the a-to-d converter. This board includes a MIDI signal merging input that is used in this instance to combine the MIDI data of the two processors into a single data stream.

The second microprocessor board was custom built and programmed for this project by Grant Beattie of Music Technologies Group in Edmonton, Alberta. This assembly handles all of the switches on the controller (the chord keyboard, transposition switches and the switch array) and is described in detail in Appendix E. Figure 7.1 is a block diagram of the electronics of the constructed model.

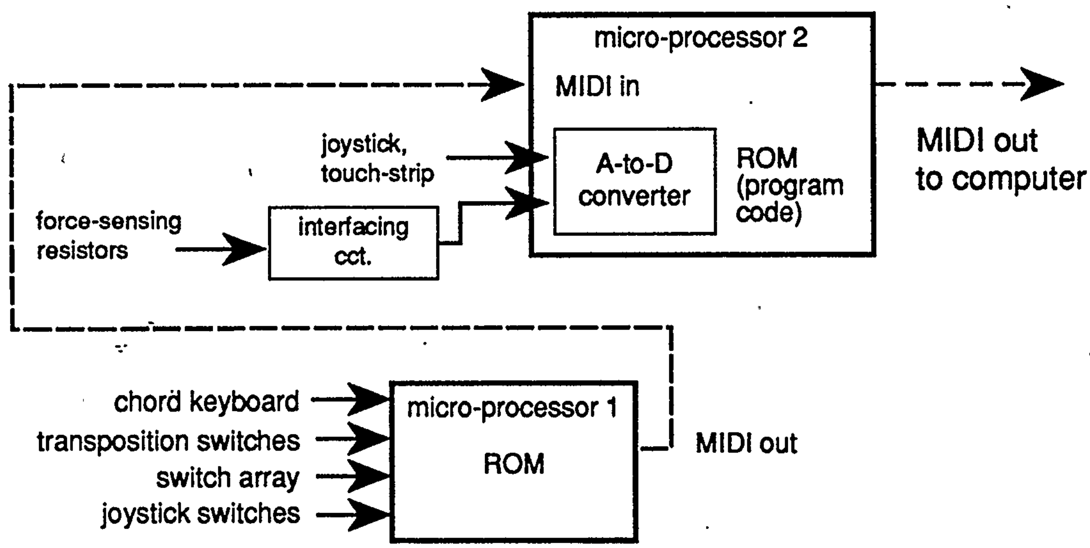


Figure 7.1
Block diagram of model electronics.

This arrangement was intended only to work well enough to test the conceptual basis of the controller. The most notable drawback is the significant amount of redundancy. Two microprocessors are used, each with their own firmware in ROM (**R**ead **O**nly **M**emory) and associated support circuitry (address decoders, voltage regulators, etc.). The electronics could be consolidated by using a single 16-bit microprocessor (for example a member of the Motorola 680x0 or the Intel 80x86 family) that would be able to handle the necessary tasks easily and provide additional advantages discussed below.

DESIGN ELECTRONICS 7.2

Advances in electronics are being made at such a rapid rate that nearly any proposed design feature can be realized, if not today (given a sufficient budget), in the very near future. The intent of this project was to describe a controller that does not rely on exotic or expensive technology that will be available in several years time. Keeping the electronics as simple as need be allows a greater portion of the available resources to be devoted to the physical aspects of the controller (primarily the joystick and chord keyboard mechanisms).

The controller electronics are divided into two parts. The controller body houses the microprocessor board that converts the analogue inputs to MIDI data. A separate rack-mount box houses the various connectors required, the power supply, a MIDI-to-serial interface to the computer, and a 10 to 20 watt stereo audio amplifier to drive the speakers in the controller body. The weight of the power supply and the audio amplifier, the heat generated by these components, and the connections that must be made to other pieces of equipment make a fully integrated controller housing all of these elements impractical. A block diagram of the system is illustrated in Figure 7.2. The computer part of the system greatly increases the available computing power for data processing and manipulation and also handles visual display and data storage tasks.

Housing the microprocessor circuitry within the body of the controller offers two advantages. The number of conductors required between the controller body and the rack-mount electronics is greatly reduced and the possibility of electrical interference is also reduced. Housing the microprocessor circuitry in the rack-mount box would require that wires be run from all the switches, sensors and the joystick to the circuitry. A cable containing this number of conductors would be bulky and subject to electrical interference (a voltage change of less than .05 VDC causes a change from one MIDI value to another). The proposed arrangement requires a nine conductor cable for the following: positive and negative voltages and ground for power, three conductors for the MIDI signal loop, left and right audio signals, and a high speed serial signal line (discussed below).

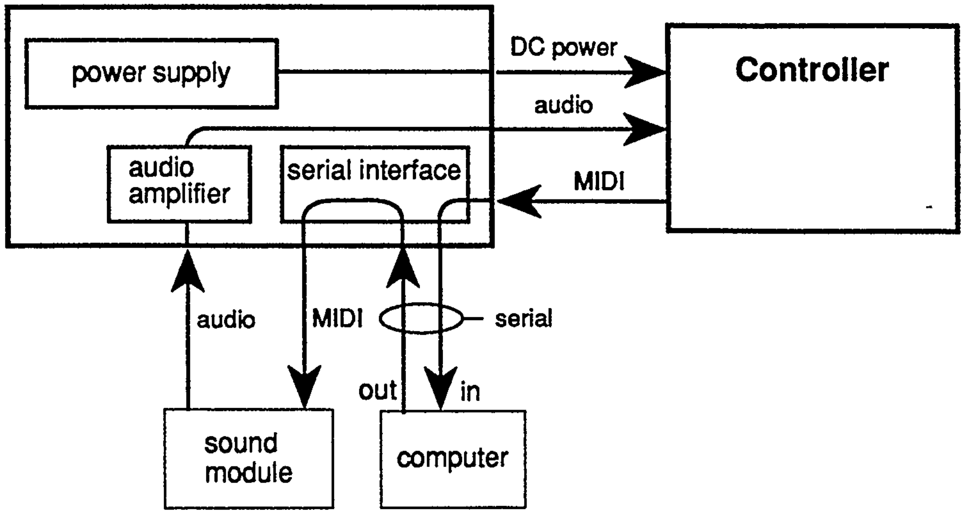


Figure 7.2
Block diagram of system electronics.

Figures 7.3a and 7.3b show the front and rear of the power supply and interface electronics box. This box (48cm x 4.5cm x 29.5cm) is of a standard width and height suitable for rack-mounting. The front panel shows an ON/OFF switch and indicator, a connector for the controller and an 'activity' indicator LED. This LED flashes when data from the controller is received, showing the user the connections to the controller are intact and the electronics of the controller are operating. The rear panel shows the serial connector for making connection to the computer, a MIDI input connector, two MIDI output connectors, audio jacks for input of left and right signals, and an AC power cord. The MIDI input jack is provided as a convenience for users, allowing other devices to be connected to the computer without needing a separate MIDI interface.

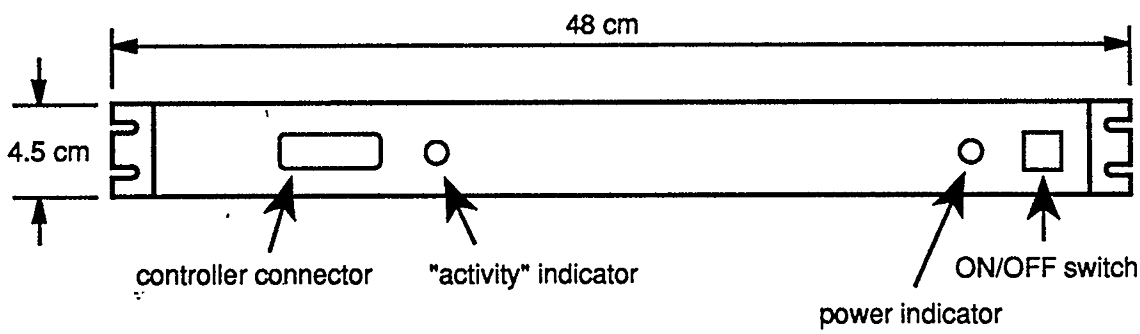


Figure 7.3a
Front panel of rack-mounted unit.

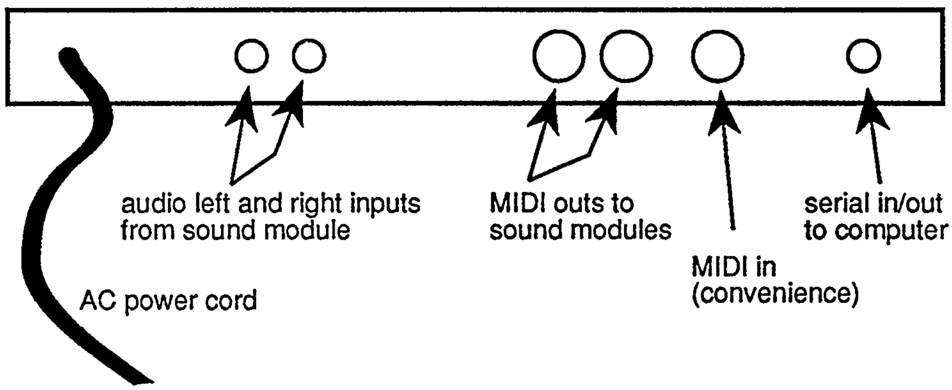


Figure 7.3b
Rear panel of rack-mounted unit.

Using a more powerful microprocessor in the controller would have several benefits. One benefit is that the resolution of the analogue-to-digital conversion can be increased. The 256 possible values from an 8-bit converter are sufficient for most purposes as the MIDI specification uses only 7 bits (128 values) for most types of signals. The MIDI specification, however, provides for both 7-bit and 14-bit MIDI control change messages and pitch bend messages. The 14-bit messages have 16,384 possible values. This increased resolution gives much smoother parameter changes than 7-bit messages, eliminating the stepping from one value to the next sometimes heard when 7-bit messages are used. This stepping, when audible, is called 'zippering'.

Another benefit of using a more powerful microprocessor is that electro-optical sensors (reflective object or slotted optical sensors) similar to those used in computer mice could be used for the X and Y axes of the joystick. Such sensors are typically used to generate pulses by sensing light reflected from a patterned surface (reflective sensors) or by sensing interruptions of a light beam (slotted sensors). Different types of information can be derived from the number and speed of the pulses generated. Additional signals (besides the X and Y position) indicating the direction, speed and velocity of the joystick's movement could be derived easily. Optical sensors are highly reliable and, because there is no direct physical contact with the sensor, not subject to wear and the associated problems common to standard resistive potentiometers. The absence of physical contact also means that these kinds of sensors do not add any friction (either static or sliding) to the control mechanism.

Optical or hall-effect (magnetic) sensors would also be used for the switches of the chord keyboard to avoid the problem of dirty contacts giving unreliable operation. An additional advantage of hall-effect sensors is that they can give a continuously variable output. This capacity may useful in dealing with the problem of simultaneity discussed in Chapter 6.

A high speed serial port would operate in parallel with the MIDI port. MIDI is sufficiently fast for most musical applications although some individuals have argued that it is not fast enough to accurately capture the subtleties of musical gestures (Moore, 1988). As well, it is often pointed out that MIDI was developed specifically for keyboard instruments and music, and therefore has a bias in this direction (e.g., the comments of Rhea in Vail, 1993). Converting the player's actions into MIDI data before the computer inserts a potential bottle-neck into the data path; the computer can process the data generated by the controller only as fast as it is received. This can introduce delays when complex processing of the MIDI data is required. The MIDI specification has a maximum transmission rate of approximately 1,000 messages per second. This is clearly less than the rate at which a computer can receive and process data.

A high-speed data pathway from the controller to the computer can be used to impement Zicarelli's concept of 'meaningless numbers', discussed in the introduction. A number of alternative controllers, notably Buchla's Thunder and Lightning controllers, offer high speed ports specifically for communicating with computers. Objects have been created for the *MAX* programming environment for the Lightning controller and the Mathews/Boie Radio Drum controller. An arrangement using a high speed serial data path is illustrated in Figure 7.4.

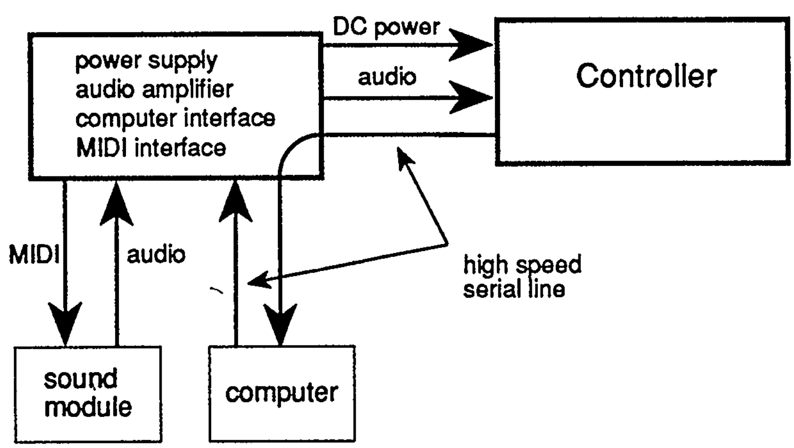


Figure 7.4
High speed serial data path.

A small amount of battery powered RAM (random-access memory) would retain a number of 'programs' for the controller. This would allow the controller to be used without a computer although this would reduce functionality; the controller would not be able to perform the more complex tasks (such as difficult data transformations or algorithmic composition) handled by the computer. Such an arrangement is already used in several electronic music products.

The electronics of the controller are kept relatively simple by using an existing computer platform for the tasks requiring greater computing power. These tasks include maintaining a graphical interface, complex data processing, and data storage. Housing the heavier and heat-generating components separately from the MIDI electronics reduces the weight of the controller and eliminates the problem of heat dissipation in close vicinity to the player's body. In the future this unit could also house the digital signal processing electronics required to realize Wessel's idea of controlling the loudspeaker radiation pattern of an electronic instrument. The inclusion of a high speed serial data path has the advantage of increasing the speed of communication between the controller and the computer. This can also help to reduce or eliminate the keyboard bias of the MIDI specification.

Software 8.0

This chapter describes the software that runs on the computer to which the controller is connected. The software associated with the controller provides a graphical interface for users, enabling them to program the controller to suit their own purposes. Users can adapt the controller to the way they want to work and are not forced to adapt to the way the controller works.

THE *MAX* PROGRAMMING LANGUAGE 8.1

The software has been written using the *MAX* interactive graphical programming environment (Puckette and Zicarelli, 1990). The *MAX* environment was initially developed at IRCAM (Institut de Recherche et Coördination Acoustique/Musique) in Paris, France in 1986 and later commercialized by Opcode Systems, Incorporated, of Menlo Park, California, for the Macintosh computer platform.

The *MAX* environment is an interpreted language, and applications written in *MAX* must run under the *MAX* application itself. A run-time version of *MAX*, called *MAX*play, allows persons to run *MAX* applications without access to the programming aspects of *MAX*.

MAX was specifically developed for the purpose of controlling MIDI equipment. It has since grown to encompass non-MIDI equipment such as CD-ROM players, video-disk players, serial data communications devices, and other types of equipment. A number of manufacturers of electronic musical equipment currently make available interfaces for their equipment written in the *MAX* language.

An application has been written using *MAX* to process MIDI data from the controller and provide a graphical interface for control of this processing. *MAX* also serves a secondary purpose here as a proto-typing tool. Some of the functions that would be better dealt with by the controller's own micro-processor (such as velocity curves) are handled by the *MAX* program.

GRAPHICAL INTERFACE 8.2

The software is divided into nine parts, each displayed in a separate window. The parts are:

1.) the 'aXiØ'[1] window giving the user access to the other windows;

[1] The controller has been named the aXiØ for alternative, X-pressive, input Object.

2.) a Transmogrifier window that gives the user access to 8 'transmogrifications' they have defined;

3.) a Joystick window dedicated to control of the functions of the joystick;

4.) a Joystick Switches window dedicated to control of the joystick switches;

5.) a Keyboard window dedicated to control of the chord keyboard;

6.) a Switch Array window dedicated to the switch array;

7.) a User Patcher window for the user to add their own *MAX* programs (called 'patchers' in *MAX*);

8.) a Monitor window dedicated to providing visual feedback of the data generated by the controller;

9.) a Tools window that provides the user with some utilities;

10.) a Preferences window for setting preferred operating characteristics; and

11.) a Help window offering assistance to the user.

The interface allows users to determine how the controller 'talks' to the synthesizer or sound module to which it is connected. The user is able to design their own 'transmogrifications' or translators between the system surface (the physical part of the controller) and the remote process (the synthesis engine) as described in Chapter 6.

aXiØ Window 8.2.1

The main navigation window (Figure 8.1) is called the 'aXiØ' window. The function of this window is to open and bring to the front the different programming windows by clicking on a button labeled with the corresponding window name. Windows currently open (other than the aXiØ window) are closed when a new window is opened, with the exception of 'sub-windows' as used in the joystick window (described below). This reduces screen clutter on small screen Macintosh computers and also reduces the potential for confusion on the part of the user by presenting only one facet of the program at a time. This function can be switched off for larger screen Macintoshes, or simply if the user so desires. The various programming windows can also be selected using pull-down menus.

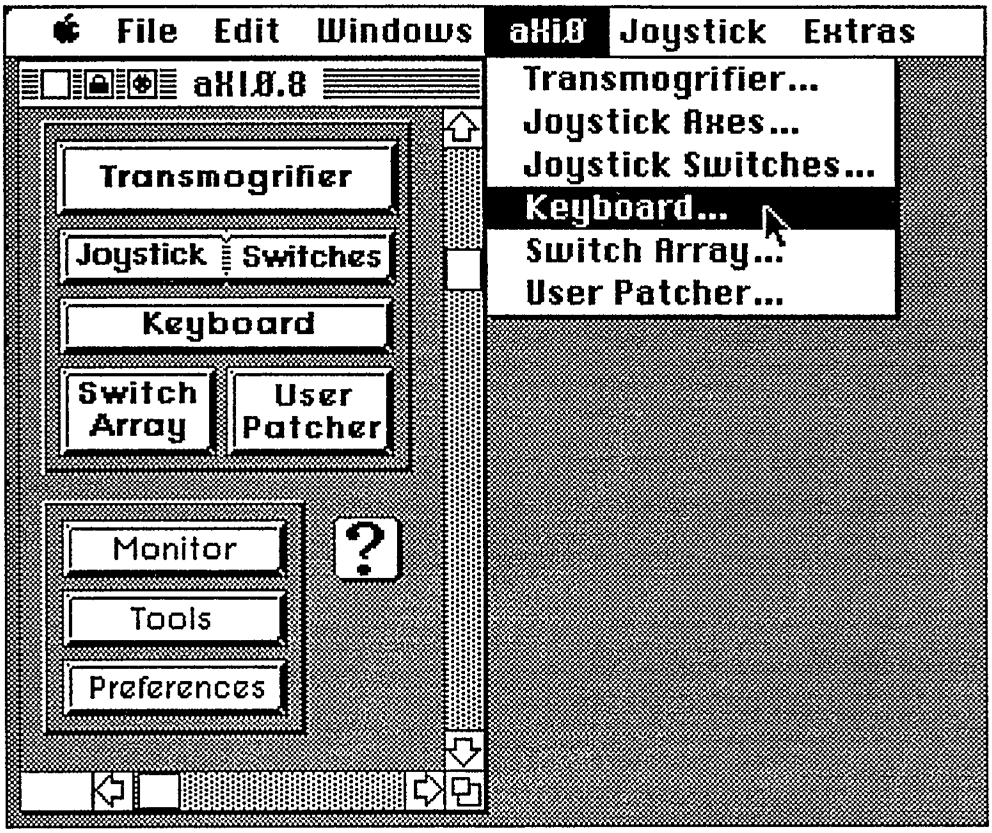


Figure 8.1
aXiØ window and menu bar.

Transmogrifier Window 8.2.2

The Transmogrifier Window (illustrated in Figure 8.2) allows the user to select 1 of 8 'Transmogrifications'. A Transmogrification is the way in which the output data from the controller is mapped to the MIDI input of the connected device. The 8 Transmogrifications correspond to the 8 presets available in the programming windows; selecting Transmogrification #1 selects all #1 presets, Transmogrification #2 selects all #2 presets, and so on. The user is also able to name the different Transmogrifications by clicking on the button next to the name to be changed and entering text in a dialog box that then appears. New sets of Transmogrifications can be saved by saving the aXiØ program with a new name.

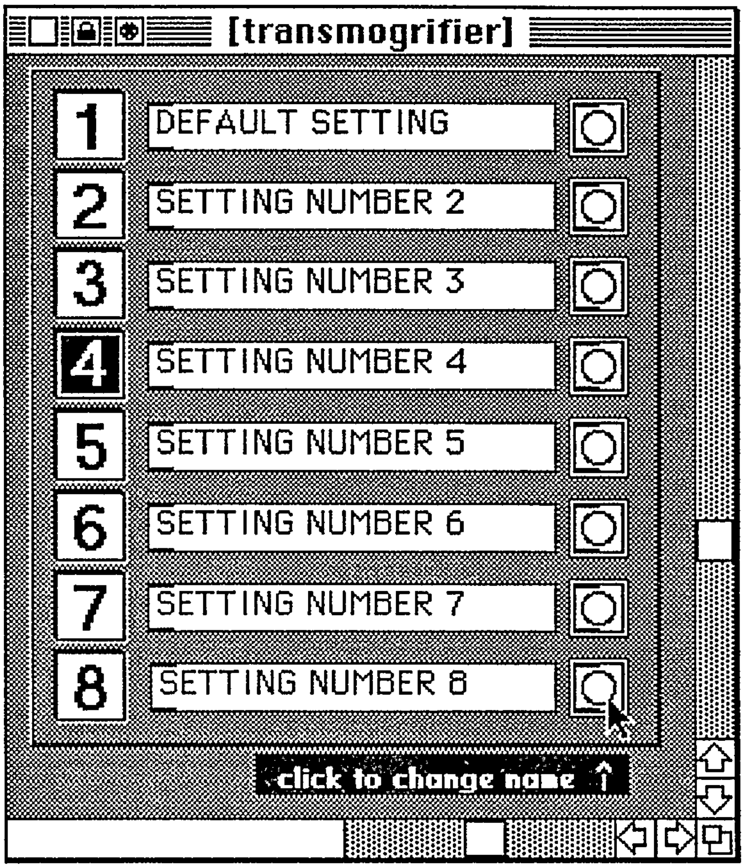


Figure 8.2
Transmogrification window.

Joystick Window 8.2.3

This window (illustrated in Figure 8.3) allows the user to define certain aspects of the operation of the X, Y and Z dimensions of the joystick along with the operation of the touch-strip on the top surface of the joystick.

Each dimension of control can be assigned a different controller number and channel number in the main joystick window. Sub-windows for the X, Y, Z and S (for touch-Strip) dimensions give the user control over the minimum and maximum values, a 'Dead Zone'(for the X and Y dimensions), a transfer function, and a patcher window. Eight presets are available in both the joystick window and the sub-windows.

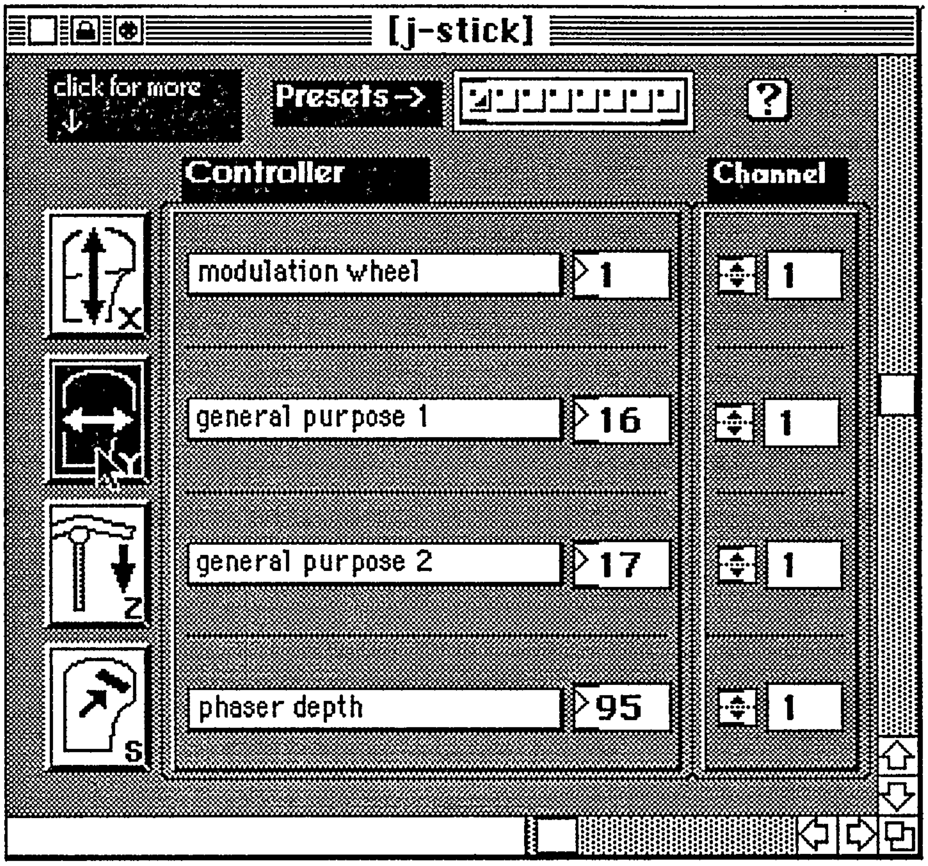


Figure 8.3
Joystick window.

The controller number is set using a pop-up menu and a number box. This was done because there are 120 (1 through 121) possible controllers from which to select and many of the controllers are referred to by number only (they remain undefined in the MIDI specification). The menu selection is reflected in the number box.

Individual undefined controllers are selected using a number box. Changes in the number box are reflected in the menu if the controller chosen has a corresponding name.

The channel on which the controller messages are sent is selected using an 'Inc/Dec' object. Clicking on the arrow in the upper half of the box increments the value by 1; clicking in the bottom half decrements by 1. Holding the mouse button down causes continuous changes that gradually increase in rate.

Figure 8.4 illustrates one of the sub-windows accessed by clicking on the buttons on the right side of the joystick control window. The window pictured is for the X axis of the joystick; this is movement in the forward direction from the body. The slider controls immediately above the 'Dead Zone' label set the range of the associated control variable. This range is automatically scaled over the full range of movement in that dimension. For example, if the value nearest the preset control is set to 90 and the other value is set to 30, moving the joystick fully forward produces a value of 90, the mid-position gives a value of 60, and the other extreme of the range of movement (nearest the body) gives a value of 30. These sliders are also used to invert the control function. If the top value is set to a value lower than the bottom value (for example, settings of 20 and 110, respectively) the input to output mapping is reversed; smaller values are in the forward direction and larger values closer to the body.

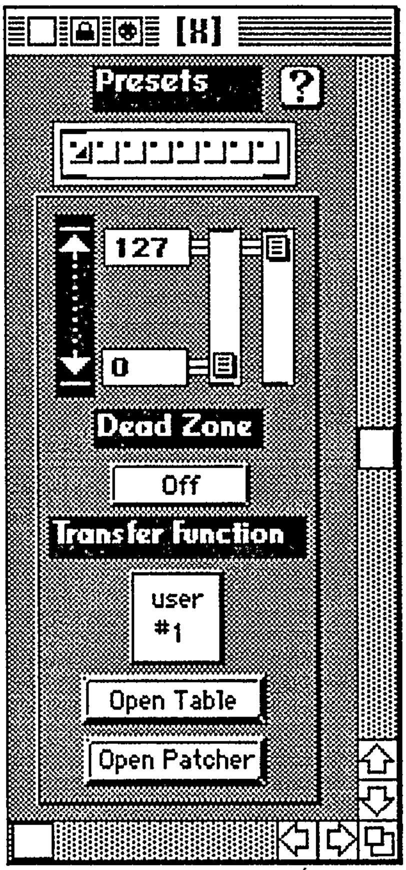


Figure 8.4
Joystick X-axis sub-window.

A 'Dead Zone' for the X and Y dimensions established a zone at the middle of the travel where joystick movement does not produce a change in output. The Dead Zone is always at the middle of the physical movement, regardless of the settings of the control values. The Dead Zone is selected by mouse-clicking on a soft button that indicates the current state of the function. This toggles between the on and off switch states.

The transfer function maps the control variable to a curve, similar to the velocity mappings discussed in the previous chapter. Seven mappings are possible, and the desired mapping is selected using a button. Repeated mouse-clicks on this button cause it to cycle through the seven possible selections. A graphical indication is given to indicate which transfer function has been selected. The first mapping is linear; the output is the same as the input. The next two mappings are exponential and logarithmic. The remaining transfer functions are user defined by drawing a desired curve in a graphics window. It should be noted that the transfer functions are arbitrary in that there does not have to be a mathematical basis for the curve drawn. A soft button is used to open the selected table for editing. The label of this button remains blank for the fixed functions. The button reads 'Open Table' for the editable functions. Figure 8.5 shows an open table that causes movement in the X-axis to generate values that swing from 0 to 127 three times between the extremes of the joystick movement.

The last item available in these sub-windows is a button that opens a patcher window where users can program their own function for that dimension of control.

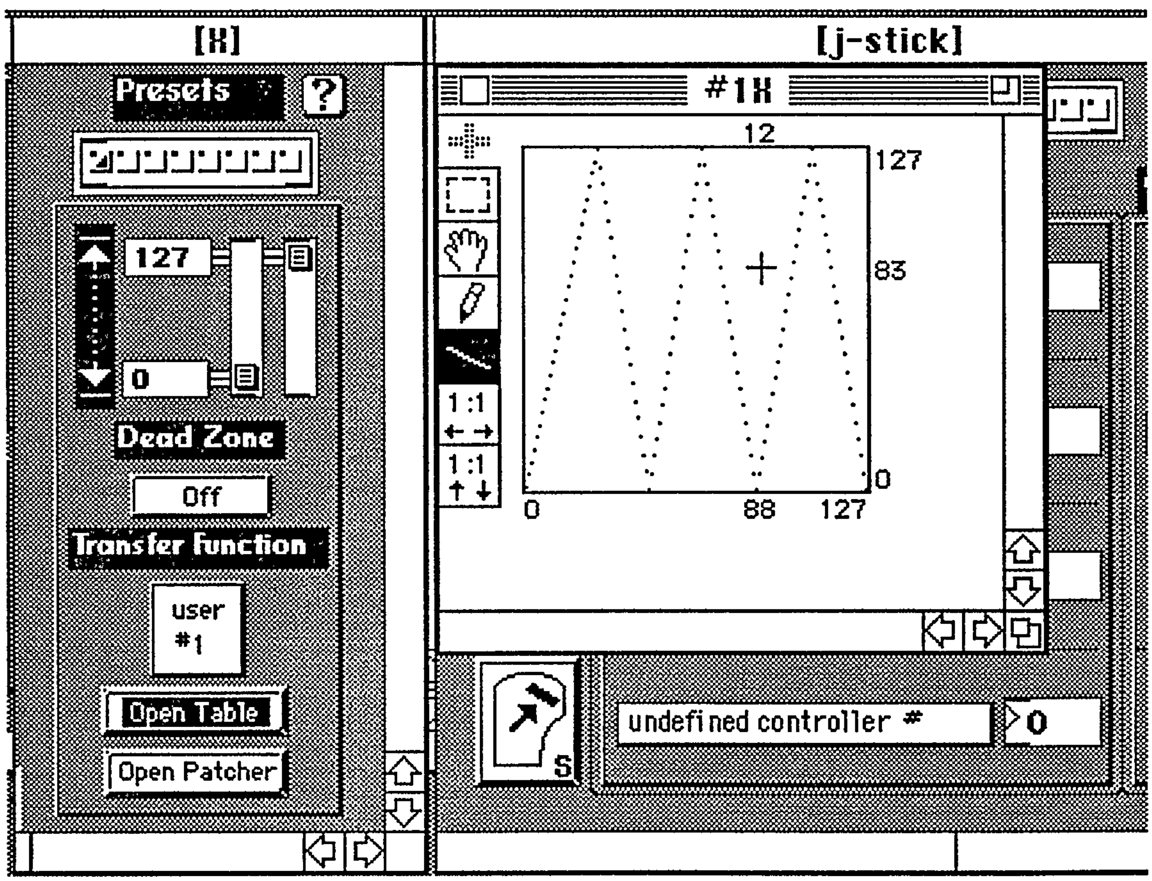


Figure 8.5
User table #1X open.

Another window is dedicated to controlling the functions of the four finger switches on the joystick. These switches can be programmed in three ways: the user selects the mode of the switch, the controller number of the switch, and the channel on which the controller message is sent. The channel number is selected in the same manner as the joystick functions described above. A set of 8 presets is available for the user.

Each switch can be set to act as a momentary switch or a push-on/push-off switch by clicking on the appropriate button. A checkmark appears in a box adjacent to the bottonindicating which mode is selected. This window is shown in Figure 8.6.

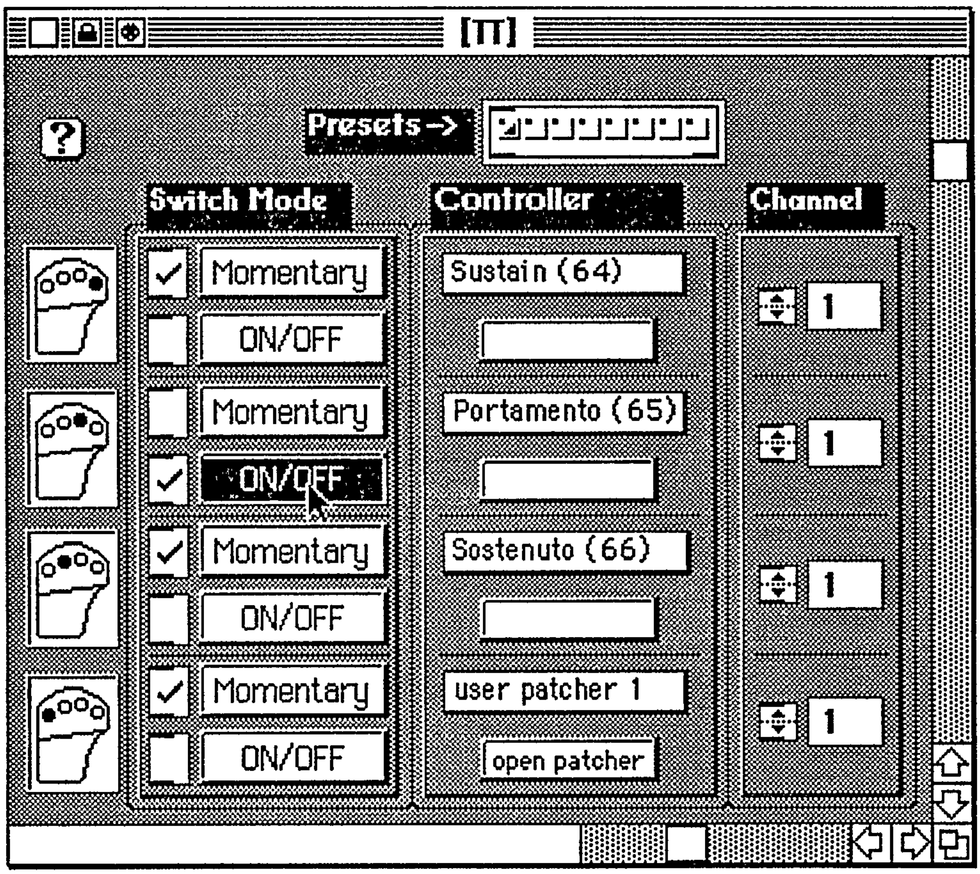


Figure 8.6
Joystick switch window.

The switches send a value of 127 as 'on' and 0 as 'off'. In the momentary mode of operation pressing a switch sends 127 and releasing it sends a 0. In the push on/off mode pressing a switch sends a 127 and releasing it sends no message. Pressing the switch a second time sends a 0 and the release sends no message. The push on/off mode of operation is useful for initiating a sustaining function or activity.

MIDI controller numbers 64, 65, 66 and 67 (Sustain, Portamento, Sostenuto and Soft Pedal), or one of 4 user defined functions can be selected from a menu. The four defined controller numbers are the ones most commonly implemented on synthesizers and sound modules. A soft button indicates when one of the four user defined functions is selected. Clicking on the button then opens a corresponding patcher window. The patcher window has an input for the switch values and outputs for the controller values and the controller number.

Keyboard Window 8.2.5

The Keyboard window (Figure 8.7) provides control of the MIDI data generated by the chord keyboard. The user can select the default fingering pattern, the binary fingering pattern (both described in the keyboard hardware design section), or one of four user-definable patterns. The note velocity and aftertouch data can be manipulated in the same ways as the data generated in the joystick Z dimension, so the description of these controls will not be repeated here. Presets and a 'user patcher' are available in this window. A button opens a sub-window for controlling pitchbend.

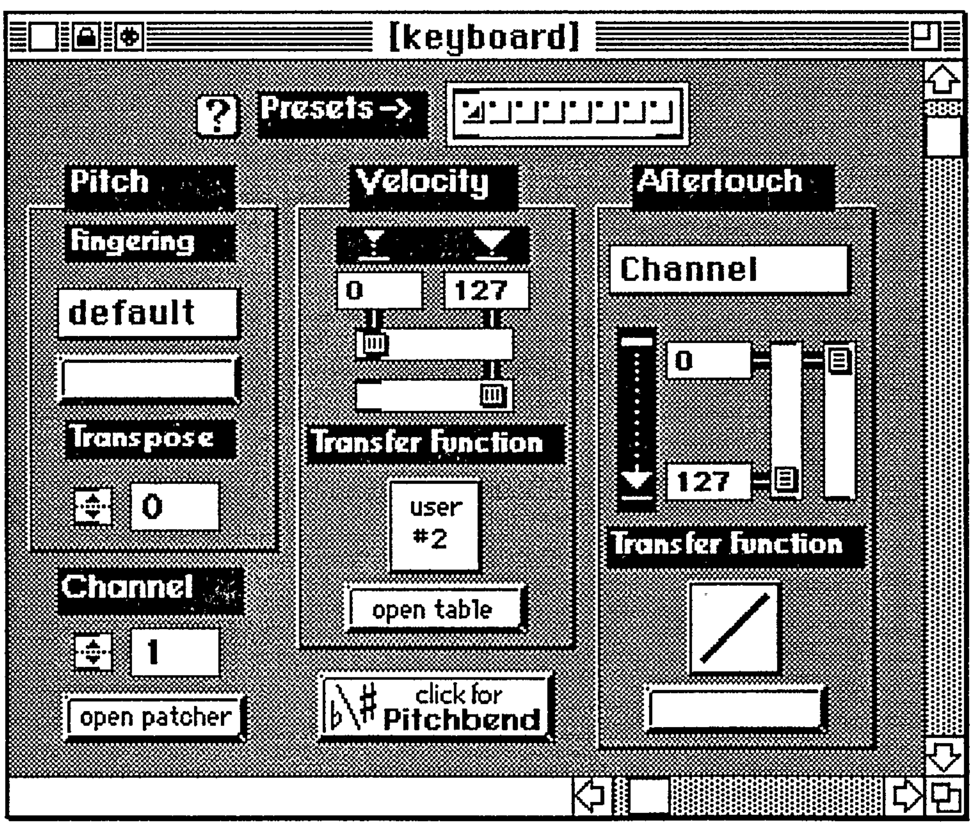


Figure 8.7
Keyboard window.

The Pitchbend window is illustrated in Figure 8.8. Pitchbend data is bi-polar in nature, increasing and decreasing from an fixed value. This is the reason for the negative Minimum value. The range of the Minimum and Maximum value sliders is from -64 to +64. The actual range of the pitchbend heard is determined by the programming of the sound engine. The controls in the pitchbend window work within the range for which the synthesis engine is programmed. For example, if the synthesis engine is set to give a maximum pitchbend of a wholetone, and the Minimum value in the Pitchbend window is set to -32, the maximum downward pitchbend that will be heard is a semitone, one-half of the possible range. The Transfer Function operates in the same way as the other windows.

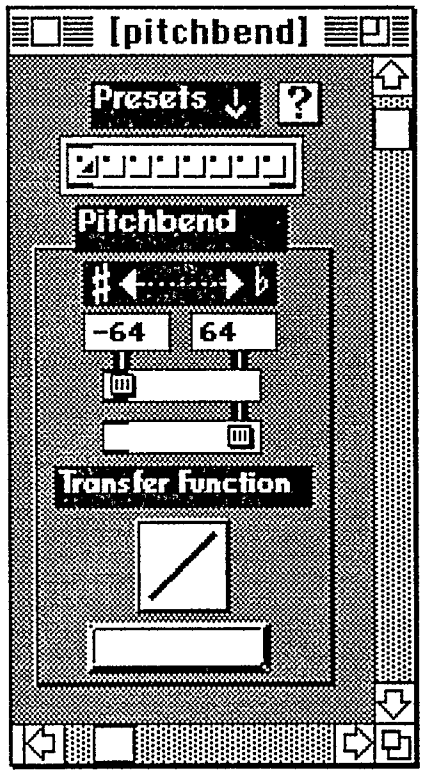


Figure 8.8
Pitchbend window.

Switch Array Window 8.2.6

It is expected that the switch array will be dedicated to higher level functions determined by the user. The following is an illustration of how these switches might be used to select different voices on a synthesizer or sound module.

The window illustrated in Figure 8:9 allows the user to select one of 24 voices programmed on the connected sound engine. These are arranged in 3 banks of 8. Pressing one of the group of 8 buttons of the switch array on the controller highlights the associated number in the display. Three of the group of 4 buttons are used to select one of the banks. The selected bank is indicated in the corresponding window. Clicking on the button so labeled allows the user to enter the names of the voices desired. This example shows how dividing the buttons into two groups increases the number of available selections without unduly increasing the user memory load.

Figure 8.9
Switch array window programmed to show voice names.

This is only one example of how these buttons might be used. The buttons might be programmed to trigger pre-recorded sequences of notes, trigger algorithmic composition processes, control a CD-ROM player, video-disk player or some other piece of equipment, or functions as yet unanticipated.

User Patcher Window 8.2.7

The user has access to a window specifically for the purpose of developing their own programs. This window is opened by clicking on the 'user Patcher' button in the main navigation window.

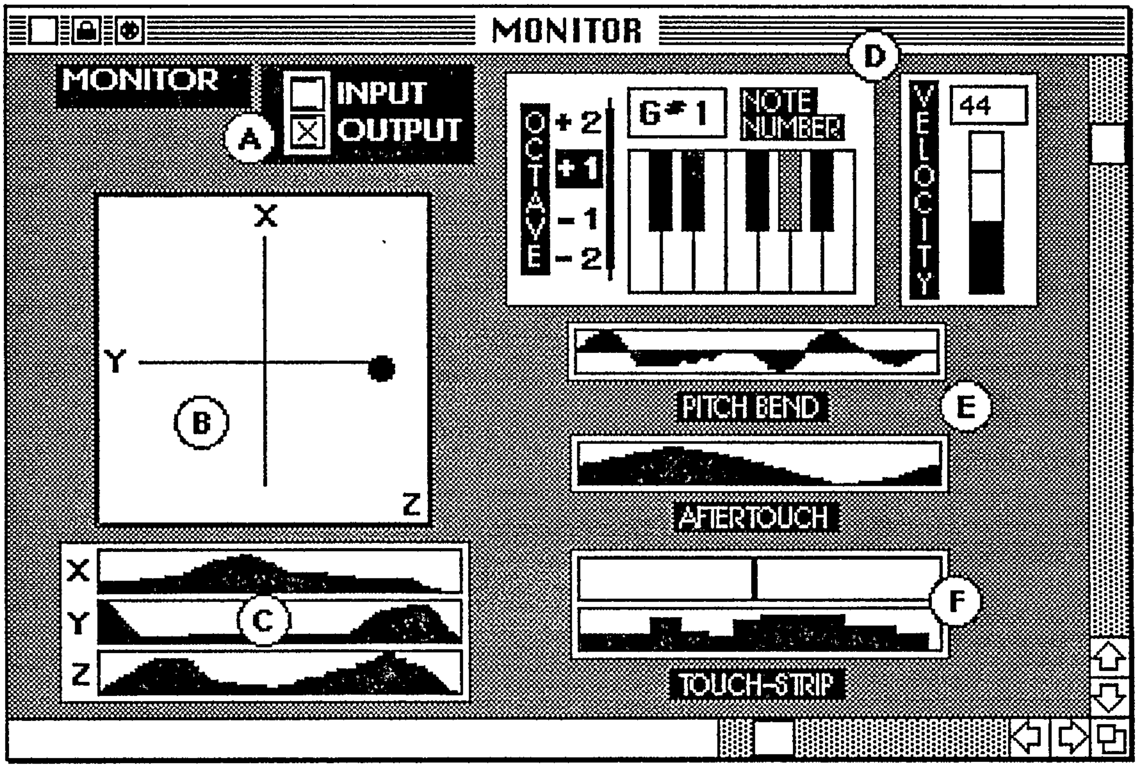


Figure 8.10
Monitor window display.

The Monitor window provides visual feedback for the user and is shown in Figure 8.10. This window has 6 distinct elements. Element **A** allows the user to choose between monitoring the output of the controller itself and the MIDI data directed to the synthesizer or sound module. Element **B** gives an instantaneous indication of values of the X, Y and Z axes of the joystick. The Z value is indicated by the size of the black dot, getting larger as the value increases. Element **C** shows the Z, Y and Z values over a short period of time. The display scrolls to the right whenever a new value is received, so the time period displayed varies with the speed of the data input; data input at a faster rate displays a shorter time period. Element **D** shows the note being played, the MIDI note number, which octave switch is depressed, if any and the velocity value of the note. The velocity is displayed as a numerical value and as a single element bar graph. The bar graph has a peak-hold function that displays the highest velocity recently detected. Element **E** displays pitch bend values and aftertouch values in the same manner as element **C**. Element **F** shows the present value and recent values generated by the touch-strip of the joystick.

Tools Window 8.2.9

The Tools window provides the user with several utilities for doing such things as generating curves for tables (values can be cut and pasted between tables), generating envelopes, setting up new fingering patterns and processing control data in different ways.

Preferences Window 8.2.10

The Preferences window allows the user to control several aspects of the graphical user interface operation. Currently two functions are provided. The user can select between having previously opened windows close automatically when a new window is opened and having all windows remain open until closed using the window's close box. The user can also toggle the aXiØ menus on and off. The regular *MAX* menus may sometimes be required when programming new patches.

Help Window 8.2.11

The Help window (Figure 8.12) gives the user access to a number of help screens by clicking on the appropriate name. The screens describe the functions of the different controls and how they operate. Because the user may want access to a help screen while using the controls described therein, the help screens do not cause already open windows to close (as opening other windows does). A help screen will remain open until closed by the user.

SUMMARY 8.3

The software described provides users with significant control of the data generated by the controller. This allows users to invent their own 'Transmogrifications' (or mappings) between the controller and the synthesis engine or other equipment to which the controller is connected. The software is deliberately open-ended so that users are free to add or subtract from the interface and personalize the program as they see fit.

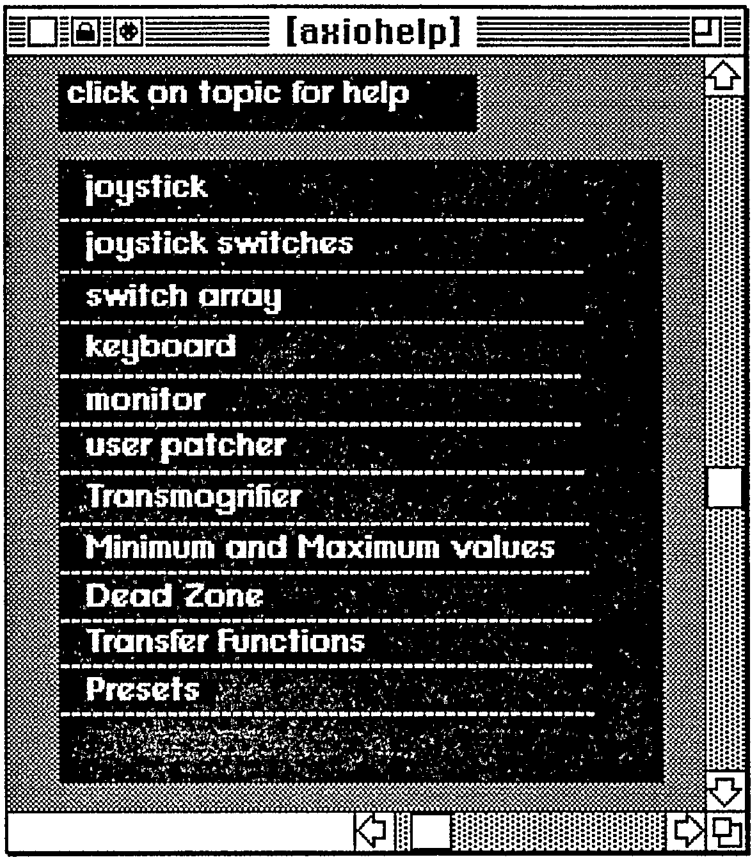


Figure 8.12
Help window.

One should note that as new technical developments alter the object and make it "intelligent", they also set the object on a plane with no prior cultural references. This demolishes all critical instruments based on traditional aesthetics (based on physical forms), because the physical aspects of the components that confer upon the object its new qualification of "intelligent" occupy dimensions that escape our perception.

Thus all references to form disappear, as it becomes a marginal question: what we consider as being the form of a personal computer with a sophisticated interface, is more a system of relations than the quality of its body.

In these new objects ... their true form, that is the image that they impress in our minds, does not correspond to their actual physical form, but rather to the form of the system of relations which they imply. ... we must conclude that... a new domain of systems of relations — of forms which vary in time — now exists and needs studying.

Ezio Manzini[1]

Manzini brings to our attention that the forms of "intelligent" products are not just visual or physical experiences. The perception of such products lies as much in how they are used as in how they look. Electronic products can, in many cases, assume whatever form the designer chooses and aesthetic criteria become the primary criteria to be satisfied. The form of acoustic musical instruments is largely determined by the mechanics of how the instrument produces sound, and aesthetics are, in general, related to the craftsmanship of building the instrument. Electronic musical instruments are a new order of things, and at this stage in their development, the forms used should be primarily determined by issues of 'use-ability'.

The overall form of the controller is principally a response to design criteria concerned with human factors issues. Aesthetic issues are considerably less influential at this stage of the product development. Further refinement of the hardware, software and mechanical aspects of the controller are required before aesthetic issues can be fully resolved. The aesthetic aspects of the controller presented here are therefore conceptual and speculative in nature. This is one of many ways the controller could possibly look.

---

[1] in The Material of Invention, pp. 26.

Human Factors Issues 9.1.1

The human factors issues relative to the overall form of the controller are anthropometric in nature. These factors are:

1.) the controller does not cause the user physical discomfort or injury, and

2.) the controller will be used by typical North Americans (2.5 percentile women to 97.5 percentile men).

These issues are addressed by fixing the relationship between the primary control surfaces (the chord keyboard and the joystick) and by making other aspects of the controller adjustable.

The chord keyboard and the joystick are aligned so the hands are in the same plane. This is illustrated in Figure 9.1. The height of this plane is adjustable using the T-shaped leg of the controller. The T-shape of the leg provides stability and prevents the user from leaning the controller to the left or right. It is intended that the users' forearms will be parallel to the ground plane when using the controller, with the palms of the hands in the same plane as the elbows or slightly below the elbows. The palm rests of the keyboard and joystick help to maintain a comfortable and relaxed posture by supporting the weight of the arms. Assuming an erect posture is used, the maximum elbow height is 115cm for the 97.5 percentile man (Diffrient, et al., 1974). The range of adjustment is sufficient to allow the controller to be used in a sitting as well as standing position. The 2.5 percentile woman is accommodated in this range.

The switch array is located for easy access with either hand. It is expected that, given the nature of its functions, the switch array will be used less frequently than the keyboard or joystick. The switch array is mounted on an arm that pivots to rest on the user's left shoulder, as illustrated in Figure 9.2. This adjustment allows the controller to be placed at a comfortable distance from the body when a comfortable hand plane height is found.

It is intended that the body of the controller be perpendicular to the ground so the user's wrists are straight. The weight of the controller is concentrated behind the plane of the support leg. This prevents the controller from tipping forward, away from the user.

The switch array arm is angled 9 degrees from the vertical. The switch array arm intersects the shoulder approximately midway between the neck and outside of the shoulder when the controller is positioned directly on the axis in front of the user's body. The arm is padded in the area where it rests on the shoulder.

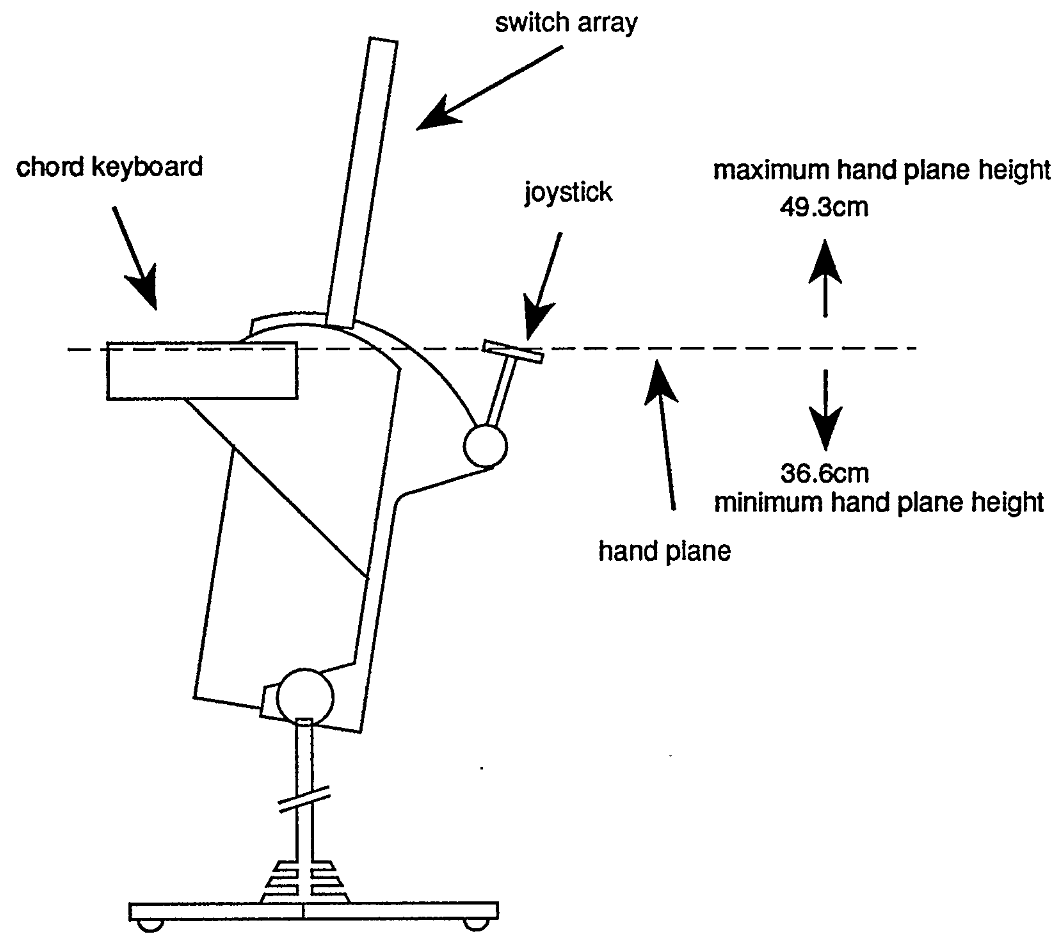


Figure 9.1
General layout of controller (front view).

The distance between the mid-point of the chord keyboard palm rest and the mid-point of the joystick palm rest (in its vertical position) is fixed at 45cm. Diffrient, et al., (1974) recommends the optimal work width be equal to the user's shoulder width. This dimension ranges from 36.6cm (2.5 percentile woman) to 49.3cm (97.5 percentile man). Diffrient specifies a greater dimension for touch system keyboards, giving a figure of 38.1cm for 2.5 percentile women, slightly more than their shoulder-width. The 45cm distance falls within the optimal work area for both the 2.5 percentile woman and the 97.5 percentile man (see Figure 9.3). User-testing may show it desirable to make this dimension adjustable. Coincidentally, 45cm is the shoulder width of the 50 percentile man and the 97.5 percentile woman, indicating smaller women may experience difficulty with this dimension.

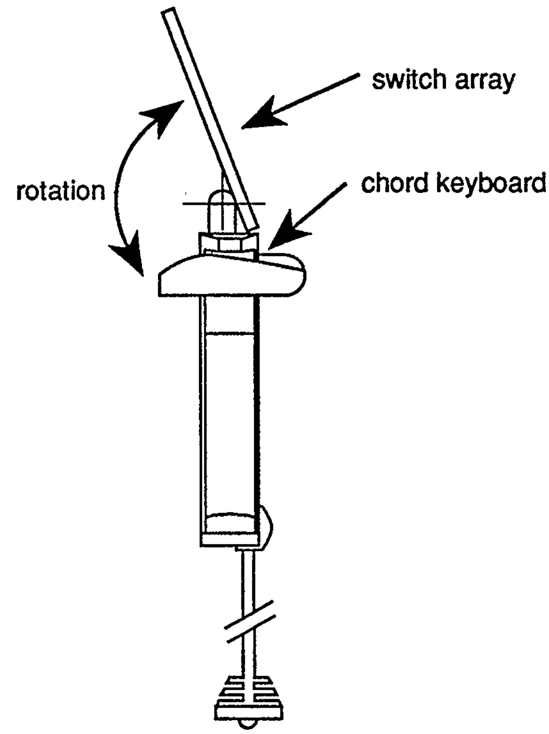


Figure 9.2
Rotation of switch array arm (side view).

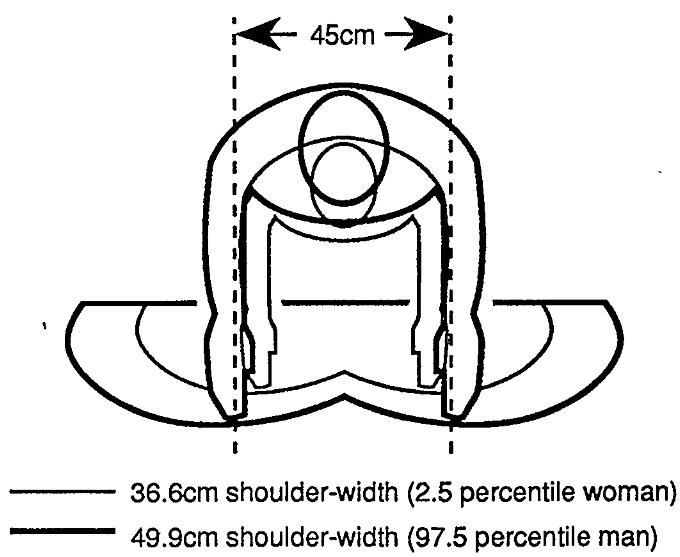


Figure 9.3
Optimal work area overlap (after Diffrient, et al., 1974).

As mentioned, the controller can be used in both a seated and standing positions. Users may prefer the seated position for extended periods of practice or rehearsal. This is illustrated in Figure 9.4.

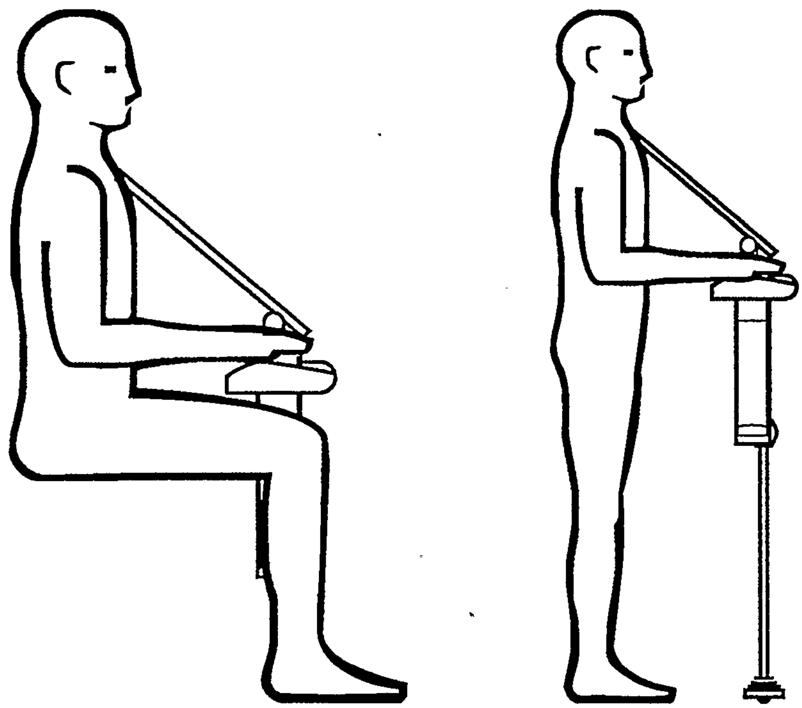


Figure 9.4
Sitting and standing playing positions (after Diffrient, et al., 1974).

Human factors issues specific to the chord keyboard, joystick and switch array have been discussed in chapter 6 in the sections devoted to their design.

Aesthetic Issues 9.1.2

At the outset of this chapter, it was stated that the aesthetic issues of this project were subservient to human factors issues. The body of the controller has three purposes: to fix the spatial relationship of the chord keyboard, joystick and switch array, to house the necessary electronic and mechanical components, and to unite the elements of the controller in a single unit.

The form reflects the 'high-tech' nature of the controller. At the same time, references to existing musical instruments or controllers are consciously avoided. Such references, while possibly alluding to the purpose and function of the controller, can promote false assumptions on the part of the user.

An arc across the top of the form visually links the chord keyboard, joystick and switch array. This gives the form visual unity by leading the eye from the chord keyboard to the switch array and on to the pivot point of the joystick. The switch array forms a tangent to the this, but does not disrupt the visual flow. As mentioned, the switch array is angled at 9 degrees from the vertical. The body of the controller echoes this angle, adding visual interest by being canted from a vertical position. The support leg is visually connected to the body with a round knob that echoes the shape indicating the joystick pivot point. Figure 9.5 illustrates the underlying geometry developed to visually unite the form.

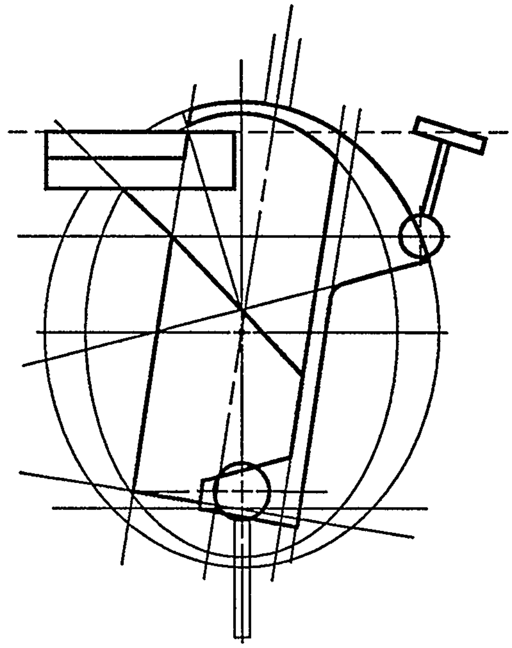


Figure 9.5
Visual geometry of the controller form.

The body is divided into three primary elements. One houses the electronics, another the loudspeakers, and the third acts as a 'spine' to which the other elements are attached. The third element also forms the arc that visually unites the elements. Variations in texture and colour further define the elements of the form.

A combination of flat planes and curved surfaces in three dimensions give the form a sculptural quality and serve to further unite the overall shape of the body. Figures 9.6 a through 9.6i are frames from a computer generated animation of the controller. This shows the controller as the support leg is extended and the switch array is rotated into the playing position.

Variations in the size and form of the different elements add visual interest and make the overall form dynamic and interesting from different points of view.

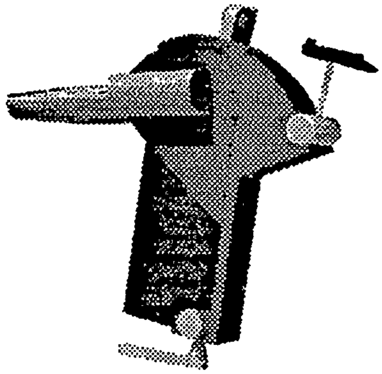


Figure 9a.

Figure 9b.

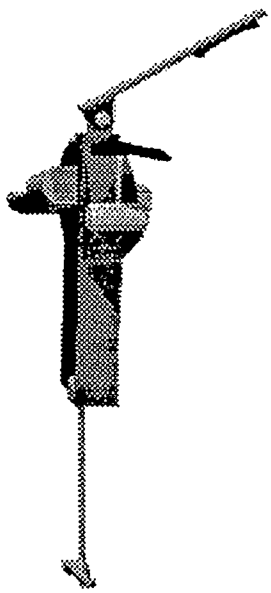


Figure 9c.

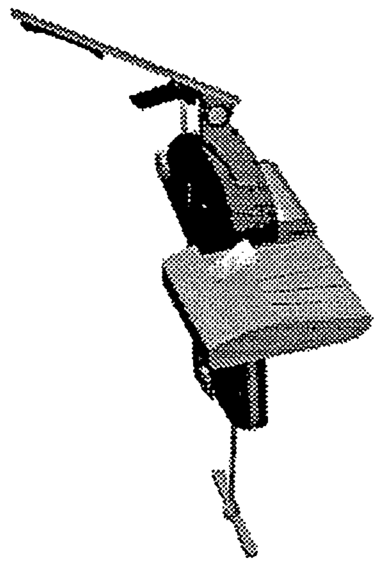


Figure 9d.

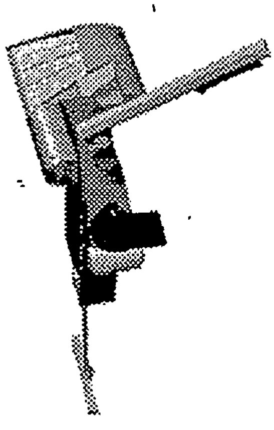


Figure 9e.

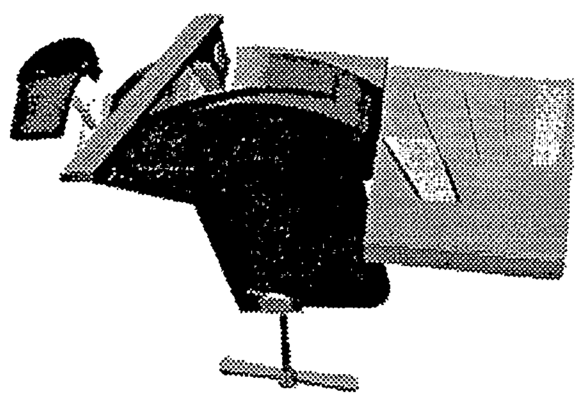


Figure 9f.

Computer generated views of the controller.

The form of the controller presents a "high-tech" image to the user and to the audience. Musicians typically using such a controller are accustomed to equipment that projects an image of advanced technology and would expect a controller to fit into this hierarchy of form. Electronic musical equipment typically has smooth, minimally articulated forms and the controller adopts such an aesthetic. The simple geometric shapes making up the form of the controller help in achieving this. In contrast, the built model reveals the technology (to a degree) by showing some of the electrical wires, sensors, and switches.

Drawing on the forms of acoustic instruments would offer a false and misleading image. An audience should not expect to hear imitations of trumpets or violins or other familiar instruments but rather expect something new and different. An audience's perception of the controller is dependent not only on the appearance of the controller, but on the situation in which the controller is used. Concerts taking place in a concert hall produce expectations different from music preformed in a 'club' atmosphere. The elegance of the form would not look out of place on a concert hall stage, in a music gallery performance space, or on the stage of a trendy nightclub.

The controller might also be perceived as having a somewhat anthropometric form: a body stands on a single leg, arms extend on either side, and the neck extends upward from the body. When using the controller, the musician might think of the controller as a partner, and they work together to make music.

The materials used for the skin of the controller lend themselves to a variety of surface treatments that the musician can use to personalize its appearance. A musician that does not wish the controller to attract attention might use a neutral palette of matte grays. Another musician, perhaps one that plays avant-garde, experimental music, might prefer a more active appearance and use contrasting colours for each of the forms of the controller.

The appearance of an instrument or controller is of secondary importance to the majority of musicians. While an attractive appearance is desirable and sought by many musicians, the primary criteria on which an instrument is judged is its functionality. If an instrument or controller does not perform to the level required, it does not matter what it looks like. Many musicians cherish older instruments that have scratches or nicks or have some of the silver-plating worn off because these instruments sound good and are 'playable' in the sense that the instrument does what they want it to, and does it easily.

The demand for alternative controllers is quite small in comparison to conventional synthesizers equipped with clavier keyboards. An initial production run of approximately seventy-five units would be appropriate. The initial production run of the Buchla Thunder controller, a product developed by a well established presence in this field, was one hundred units.

The small number of units makes mass-production manufacturing techniques requiring high initial tooling investments unfeasible. This eliminates processes such as injection-molding and die-casting, and the materials that require such processes. Alternatives are less expensive mass production techniques such as extrusions, castings, vacuum forming or pressure molding plastic parts, and CNC fabrication of parts and labour intensive fabrication techniques such as welding, machining and some types of casting.

Electronics 9.2.1

The electronics of the controller are easily accommodated on a 12cm x 12cm single-sided circuit board. The circuit board could be much smaller using techniques such as a multi-layer circuit board, but at a certain point decreases in size increase costs and can make servicing difficult or impractical in the case of an electronic failure. High density multi-layer circuit boards usually require special tools for repair, or frequently a board-swapping repair strategy is employed. A performing musician cannot afford to lose the use of their instrument (or controller in this case) for extended periods of time. Easy serviceability would therefore be one of the goals in the design of the electronics. This can be achieved through the use of commonly available parts and reasonable circuit board layout.

The controller body also houses two 10cm co-axial loudspeakers. Most synthesizers and sound modules available have stereo outputs. Each loudspeaker reproduces one audio channel, although the very short distance separating the speakers will not allow much of the stereo effect to be heard. Placing the 'sound producing' elements in close proximity to the user rather than in separate enclosures may promote a closer connection between the user and the controller by providing more 'intimate' feedback.

In a discussion of possible directions for electronic instruments in the future, Wessel (1991) argues for a loudspeaker system that consists of loudspeakers in a single location with a programmable radiation pattern. Wessel finds mixing electro-acoustic and traditional acoustic instruments in performance situations a frustrating experience because of the speaker systems used with the electro-acoustic instruments. The result is that the electronic and acoustical instruments sound as if they are in different acoustical spaces. Wessel's proposed system could be used to produce acoustic radiation patterns that are more sonically compatible with acoustic instruments than conventional stereo or quadraphonic speaker systems. Figure 9.7 illustrates the basic layout of the electronics and loudspeakers.

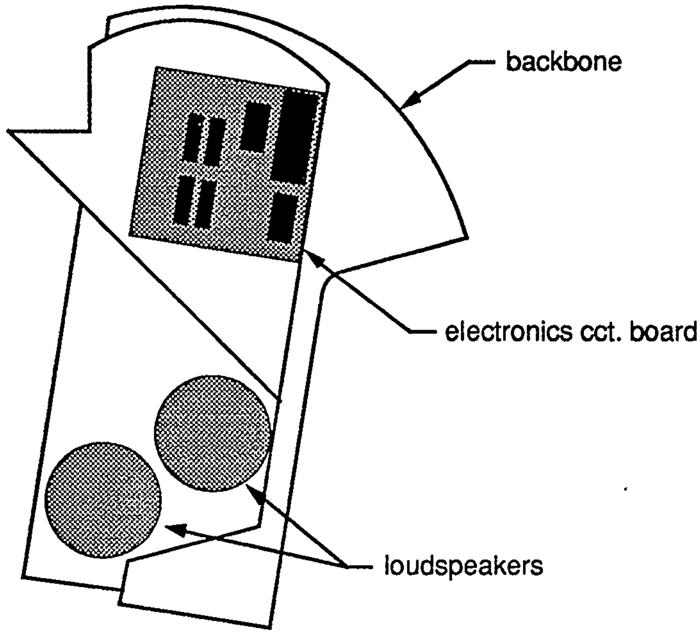


Figure 9.7
Internal electronics and loudspeakers.

Chord Keyboard 9.2.2

The chord keyboard requires a number of small mechanical parts. Many of these fittings are available as off-the-shelf components, but some components, such as the keys themselves, must be custom fabricated. The framework holding the key-switches, key return springs and hinge mechanism is CNC fabricated and bent from light gauge sheet metal. This provides the necessary long-term dimensional accuracy for proper alignment of the various keyboard parts. The framework and internal components are covered with a fiberglass housing. The area of the palm rest is structurally re-enforced and covered with a material that provides a pleasing tactile quality, such as a thin sheet of neoprene or silicone rubber.

The construction of the keys of the keyboard is similar to that of the keys of a piano. The key is fabricated of wood, preferably seasoned plywood for its strength, dimensional stability and light weight. A thin plastic covering is then bonded to the surface of the key. A plastic material called Heavy VALOX resin is used for piano keys. This material is a 65% mineral filled crystalline PBT (polybutylene terephalate) thermoplastic that can mimic the tactile qualities of glass, ceramics, metal and ivory. PBTs can be extruded in profile, sheet or film form and can be machined in a variety of ways (Brozenick, 1986). VALOX can have a glossy, high luster finish that eliminates the need for finishing operations such as painting. Because each key is flat and only the top surface needs to be covered, sheet material can be used and trimmed to the shape of the key. Injection molds of the individual keys are not required, reducing construction costs.

Joystick 9.2.3

The joystick mechanism is assembled using CNC fabricated aluminum and nylon parts where off-the-shelf components are unavailable. The shaft of the joystick is of 20mm diameter 6061 thin wall aluminum tubing selected for its stiffness and light weight. The joystick palm rest is cast from acrylic plastic over a CNC fabricated reinforcing framework. The housing for the finger switches and touch strip is also cast from acrylic plastic (Jans, 1986). The pivot and pressure-sensing mechanisms of the joystick palm rest are covered using vacuum-formed polystyrene housings.

Switch Array 9.2.4

The switch array arm is fabricated as an aluminum extrusion. Aluminum extrusions are light weight and inexpensive, and can be designed to be very strong. The extrusion has a centre channel to hold the switches and wiring. The padded shoulder rest also fastens to the extrusion.

The coverings for the switches are a coextruded plastic with hinges molded directly into the extrusion. An extrusion can be cut into appropriate lengths for the individual switches. A material such as VLDPE (Very Low Density PolyEthylene) (Rundlof, 1986) for the switch hinges can be combined with a HMW (High Molecular Weight) high density polyethylene (Dix, 1986).

The pivot for the switch array arm is fabricated from CNC machined aluminum and nylon parts. The assembly will have an accurate fit and be durable enough to last the life of the controller.

The shoulder rest is cast using a self-skinning multicomponent liquid foam polyurethane. Molds for small production runs (up to 100 pieces) can be made from room-temperature vulcanized silicone rubber. Such molds can have deep undercuts if necessary. (Hayes, 1986)

Support Leg 9.2.5

The support leg needs to be especially stiff so it does not flex from side to side when forces are applied to the chord keyboard. A 30mm diameter 6061 anodized aluminum tubing is suitable for this application.

The 'feet' are sand-cast and machine-finished aluminum. The necessary bearing surfaces are machined nylon. A spring and ball-bearing detent holds the feet in their open position.

Spine 9.2.6

The various elements of the controller (the switch array, chord keyboard, joystick, and internal elements) are attached to a "spine". This part must be very strong, stiff and light weight. For these reasons it is fabricated as two mirror-image sand-cast aluminum pieces. The castings are machine finished where necessary and then welded together to make a single unit.

Body Coverings 9.3.7

The coverings that enclose the electronics and loudspeakers are made of woven glass fiber cloth using a hand layup molding process. Fiberglas is strong, light in weight and relatively impact-resistant. A high quality finish can be achieved through the use of a gel coat applied to the mold before layup begins. Alternatively, the surface takes paint well and can be finished to meet customer requests. (Moore, 1986)

Rack-mounted Unit 9.3.8

The power supply, audio amplifier and serial interface are contained within a pre-fabricated rack-mount housing of appropriate dimensions. The sizes of these housings have been standardized, and such housings are readily available from different sources. The boxes are painted and labelled as required.

SUMMARY 9.3

The underlying human factors that influenced the overall form of the controller have been outlined. A pleasing form has been developed within those human factors constraints. Appropriate production techniques have been outlined for the forms and materials chosen.

An in-depth investigation of materials and production techniques has not been undertaken; no one could take the information presented here and build one of these controllers. Many issues remain to be resolved before material choices and means of production can be finalized.

Conclusion 10.0

The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man.
George Bernard Shaw

The objectives of this project were to design an alternative MIDI controller and to compile a body of knowledge that can be applied to future design endeavors in this field. This thesis documents both objectives. Concepts from the field of human-machine interaction have been applied successfully to the design of the controller. A working, proof-of-concept model including the computer software has been built and demonstrated.

A paper describing the controller and the basic concepts behind its design has been published (Cariou, 1992). As well, the controller was presented by the author at the 1992 International Computer Music Conference in San Jose, California. A review of conference presentations in Array, a publication of the International Computer Music Association, described the controller as "odd-but-sexy" (Cook, 1992).

Reactions to the controller have been positive and encouraging, and interest has been expressed by individuals working in electronic music. The controller is unique, powerful and flexible in its applications.

Controller Analysis 10.1

Examining the controller using the criteria put forth by Pressing (see chapter 4) will show that the controller is indeed a useful interface for electronic music-making.

1. Physical variables

The controller uses finger and arm position (the touch-strip and joystick), pressure (joystick and keyboard [aftertouch and pitchbend]), and velocity (keyboard). The direction and speed of the joystick movement can also be used.

2. Dimensions of control

The controller produces 6 continuously variable dimensions of control (joystick X, Y and Z, touch-strip, aftertouch and pitchbend) and 3 distinct discrete dimensions (pitch [keyboard], joystick switches and switch array).

3. Multiplicity of control

The controller is purposely designed to be monophonic, generating a single stream of musical information. Polyphony can be achieved in limited ways.

4. Control modality

The controller inherently provides discrete, continuous and discrete/continuous modalities (the switch array and keyboard, joystick and keyboard aftertouch and pitchbend, and touch-strip respectively). Each continuously variable dimension of control can also be programmed to operate in the quantitized continuous or discrete modes.

5. Control monitoring

Both uni- and bi-polar controls are provided. The touch-strip inherently allows skips to be made, and the other controls can be programmed to allow skipping from one value to another. The joystick X and Y dimensions inherently hold control values, while the other continuous dimensions all return to 0 (or mid-point for pitchbend). Dimensions of control are independent, expect for aftertouch.

6. Control distance function

The pitch control distance function is inherently monotonic and not recursive. Users can program their own fingerings to introduce recursiveness if desired. Other dimensions of control are also monotonic and not recursive, but can be programmed as desired.

7. Literalness of control

The literalness of control is dependent on the programmed mapping of the controller. The controller is designed to be programmed by the user, and the degree of literalness is therefore very much the user's choice.

8. Historical foundations

Imitation of existing instruments and controllers was consciously avoided, although precedents were not excluded. Historical foundations for the philosophy behind the controller and the functions it incorporates can be found in Le Caine's Electronic Sackbut (Young, 1989), Mathews and Moore's Groove system (Mathews and Moore, 1969), and the recent writings by Zicarelli (1991a, 1991b) and others.

9. Design appropriateness

The interest expressed by potential users leads the author to believe that the controller is designed appropriately for the task described. User testing and time will tell how appropriate the design is.

10. Psychological nature of control

The links or mappings between the user's actions and the sound response are programmable in nature. The mappings can be as 'natural' as the user desires and changed as the current application of the controller dictates.

The controller provides many different dimensions of control, control modalities and means of control monitoring. The programmable nature of the controller makes it very flexible in use and adds a great deal to its value. The usefulness of the controller is increased significantly in that the controller can be adapted to many different applications and situations.

Future Considerations 10.2

Two important topics have not been addressed within the scope of this project and deserve attention. The current generation of electronic instruments rely on some form of visual display and the sound produced to provide feedback to the user. Force-feedback has the potential to give the user important additional information. The actual validity of the design cannot be properly assessed without user testing. Such testing can only improve the product.

User Testing

At the time of writing no user testing has been undertaken, although informally gathered feedback has influenced the design. The lack of ergonomic information about velocity sensitive chord keyboards and joysticks with additional dimensions of control is a concern.

Testing could reveal problems regarding such things as the appropriateness and durability of individual components (switches, etc.) and construction and the appropriateness of the functions designed into the software and the software interface itself. Testing could also uncover desirable functions not yet implemented. Several cycles of testing and prototype construction are required before production of a product of this nature would begin.

Force-feedback

An area worthy of investigation is that of force-feedback. Most musical instruments provide the user with some form of active tactile feedback. Gillespie (1992) points out that the haptic senses play an important role in playing an instrument. These senses provide a bi-directional information flow to and from the instrument. Information about the instrument's behavior is derived from the reaction forces and responses generated by the instrument. These forces act as information in the form of signals (see the discussion of signals, signs and symbols in Chapter 5) and play an important role in the development of sensorimotor skills.

Research in the area of force-feedback by Minsky, et al., (1990) and Cadoz, et al., (1990) point to some possibilities. Minsky, et al., have used a force-feedback joystick to successfully simulate the feel of different textures. Users can 'feel' these textures as they move the joystick. They have also simulated such things as variable viscosity soups, springs and yo-yos. Cadoz, et al., have described a kind of electrical motor developed for the purpose of providing sensory feedback. They found that the introduction of force-feedback to manual tasks has increased accuracy and control, and "opened up a genuine new dimension in the [hu]Man/Machine relation" in some applications.

Summary 10.3

Synthesizers and sound modules are shedding their skins and becoming plug-in boards that turn a computer into a machine for making music. The accumulation of equipment now often necessary for a electronic music performance is being distilled into a system comprising a controller and a computer. Aside from the increased power, ease of use and overall reduction in hardware, this approach has a significant economic advantage; a plug-in circuit board is considerably less expensive to produce than a module that includes an LCD screen, switches and other controls, a power supply, and a metal or plastic casing.

The *MAX* environment is already being used to control DSP (*D*igital *S*ignal *P*rocessing) plug-in boards directly for the processing and synthesis of sounds. (Bate, 1992, and Sosnin, et al., 1992) A DSP board can be programmed for a wide range of signal processing and sound synthesis techniques including some not commonly available in commercial products. Some of these developments are still in experimental stages. As computing power becomes less expensive and development continues, these tools will become available to more musicians.

The availability of more powerful general-purpose DSP boards will bring with it a closer union between controllers and the synthesis engines to which they are connected. Controllers will be able to address directly the desired synthesis parameters with the resolution and speed required for the most complex musical gestures. Additionally, the rapid increase in multimedia presentations and performances calls for a controller with the capacity to drive devices such as CD-ROM and video disc players.

A general-purpose controller that can respond to complex gestures and be adapted to the needs of the musician will hold an important position in the scenario described above. It is hoped the controller presented here will fill that position.

Appendix A

THE MIDI SPECIFICATION

MIDI is an acronym for Musical Instrument Digital Interface. The MIDI specification was established in 1983 by American and Japanese musical instrument manufacturers. It is a combination of hardware and software that allows easy and inexpensive communication between computers and computer-controlled devices such as synthesizers and drum machines. The standard is commonly referred to as simply 'MIDI'.

The following is a very brief and therefore incomplete description of the MIDI 1.0 Specification. This abbreviated description shouldprovide a basic understanding of the MIDI specification.

MIDI is a serial form of communication operating at 31.25 (± 1%) Kbaud, asynchronous, with a start bit, 8 data bits (D0 to D7) and a stop bit. This is 10 bits for a period of 320 microseconds per byte.

MIDI communication uses multi-byte messages, consisting of one Status byte, followed by one or two Data bytes, with the exception of Real-Time and Exclusive types of messages.

There are two main categories of MIDI messages; Channel and System. Channel messages contain a four-bit number in the Status byte that addresses the message to one of sixteen channels. System messages do not have channel numbers and are thus intended for all units in a system.

Special messages called System Exclusive messages include a Manufacturer's Identification code and can have any number of bytes. These messages are recognized only by a specific piece of equipment identified by the Identification code. A unit that does not recognize the Identification code will ignore the System Exclusive message.

MIDI employs two Data Types. Status bytes are eight-bit numbers with the Most Significant Bit (MSB) set (binary 1). Status bytes identify the message type (the purpose of the data bytes immediately following). New Status bytes always command to receiving unit to adopt their status. Status bytes are followed by one or two Data bytes. Data bytes are eight-bit numbers with the MSB at binary 0. A Status byte must be followed by the required number of Data bytes.

Most MIDI messages take three bytes, giving a message transmission rate of just over 1,000 MIDI messages per second (31,250 bits per second transmission rate ÷ 30 bits per message).

The following table shows the format for a number of MIDI messages. The table is not complete, but serves to illustrate the relationship between Status and Data bytes.

Status Bytes	Data Bytes	Description
1000nnnn	0kkkkkkk	Note Off [1], [2]
	0vvvvvvv	vvvvvvv: note off velocity
1001nnnn	0kkkkkkk	Note On [3]
	0vvvvvvv	vvvvvvv: note on velocity
		vvvvvvv = 0: equivalent to note off message
1011nnnn	0ccccccc	Control Change [4]
	0vvvvvvv	ccccccc: controller # (0-121)
		vvvvvvv: control value
		ccccccc = 122 thru 127: reserved
1100nnnn	0ppppppp	Program Change
		ppppppp: program number (0-127)
1101nnnn	0vvvvvvv	Channel Pressure (After-Touch)
		vvvvvvv: pressure value

[1] nnnn: Voice Channel Number (1-16)
[2] kkkkkkk: note number (0-127)
[3] A note on message must have a corresponding note off message or the equivalent note on with a velocity of 0, otherwise the system will have 'stuck' notes.
[4] Controllers 0 thru 63 are defined as continuous controllers, with values from 0 to 127. Controllers 64 thru 95 are defined as switches, with value 0 as off and 127 as on. Controllers 122 thru 127 are reserved for Channel Mode messages.

Table 1.
MIDI Messages.

Additional messages are available for pitchbend, polyphonic key pressure, system timing, mode messages, and other functions. It is worth noting that the MIDI specification does not include information about the length of a note. A MIDI note-on message must be followed by a note-off message at the appropriate time to turn the sounded note off. This gives rise to the 'stuck note' phenomena; appropriate note-off messages get lost (due to a hardware or software failure of some kind) and notes continue to sound until the piece of equipment is reset, usually by turning it off then back on.

The complete specification is available from:

MIDI Manufacturers Association
5316 West 57th Street
Los Angeles, CA 90056

Appendix B

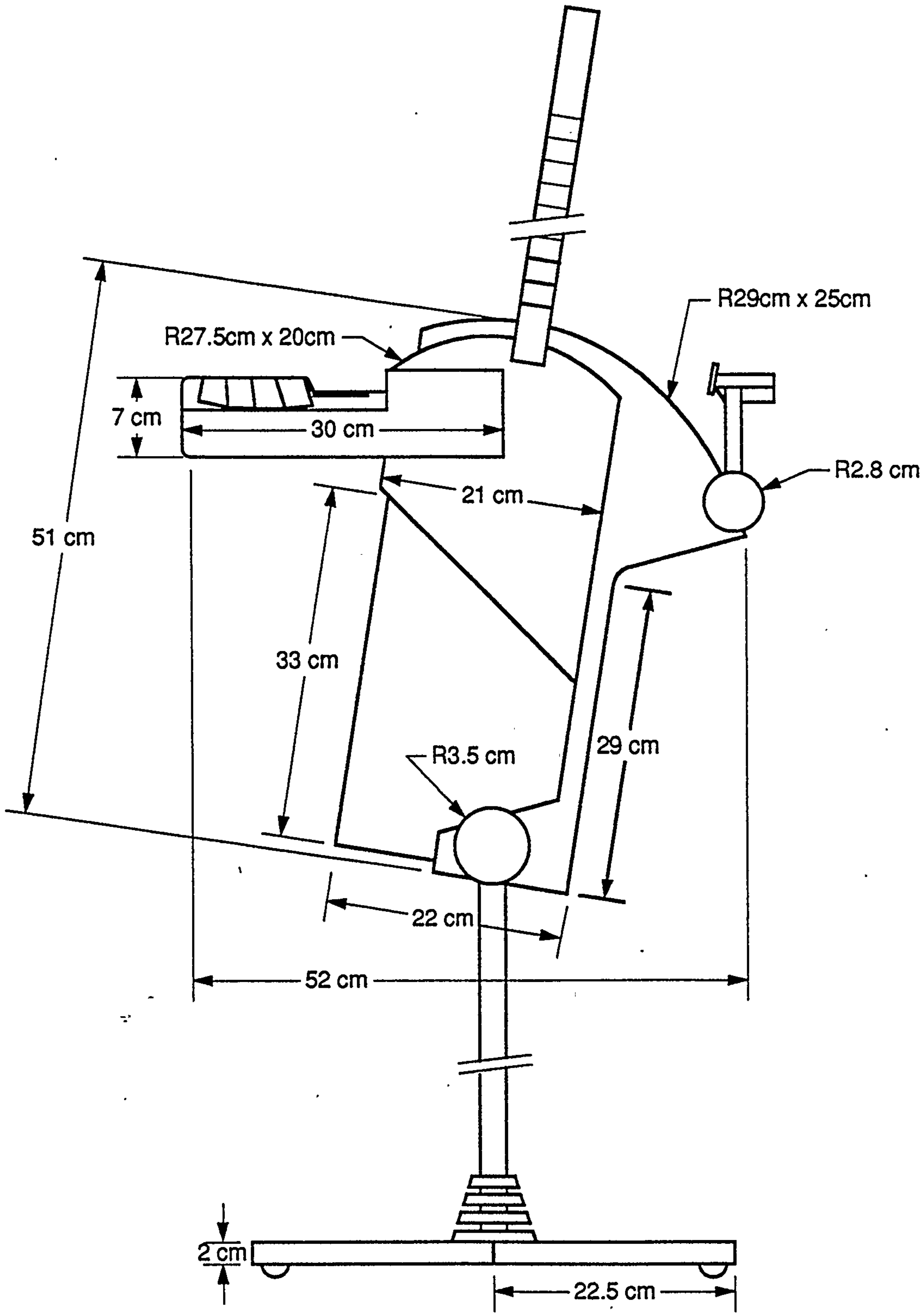
INSTRUMENT ANALYSIS

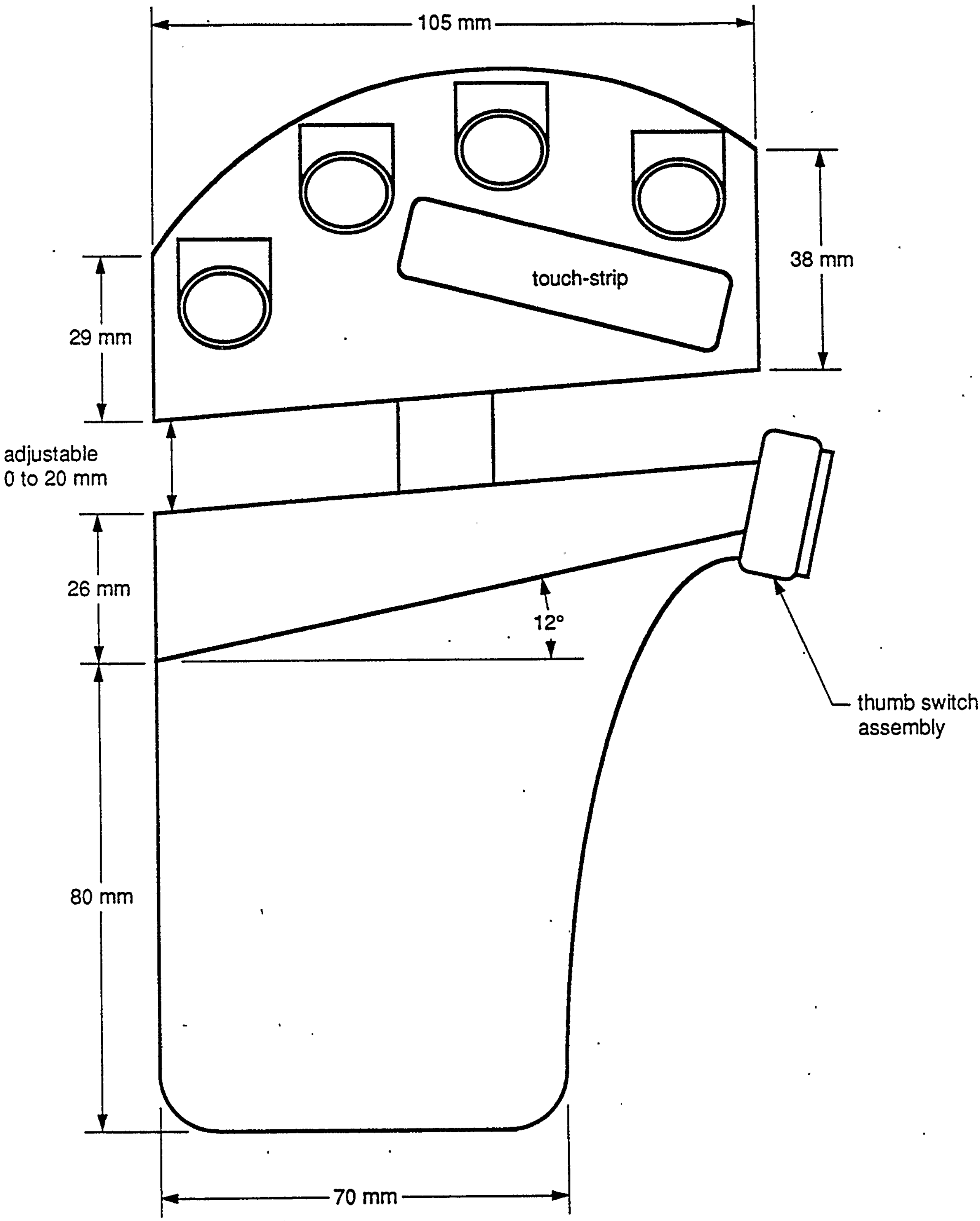
	String Instruments (violin, cello, etc)	String Instruments (fretted - guitar, banjo, etc)	Woodwind Instruments (saxophone, clarinet, etc)	Brass Instruments (trumpet, cornet, etc)
Physical Variables (as a function of time)	bow position, pressure, velocity (loudness and timbre) finger position (pitch)	pick position, force, (loudness and timbre) finger postion (pitch)	wind velocity (loudness, timbre, pitch) embouchure (shape, area, pressure) finger position (pitch)	wind velocity embouchure (loudness, timbre, pitch) fingering (pitch)
Dimensionality of Control	4 dimensions	4 dimensions	4 dimensions	4 dimensions
Multiplicity of Control	2	3	1	1
Control Modality	continuous	discrete/continuous (fretted, string bending)	discrete (pitch) continuous (loudness and timbre)	discrete/continuous (pitch) continuous (loudness)
Control Monitoring	continuous	continuous	continuous	continuous
Control Distance Function	polyphonic (2 notes) partially recursive unipolar	polyphonic (up to 6 notes) partially recursive unipolar	monotonic (partially recursive) unipolar	monotonic (partially recursive)
Literalness of Control	WYPIWYG	WYPIWYG	WYPIWYG	WYPIWYG
Design Appropriateness	excellent (expressive) ergonomics questionable visual feedback questionable	excellent (solo lines) v. good (polyphonic) ergomonics OK, visual feedback good	excellent (expressive) ergonomics questionable poor visual feedback	good ergonomics questionable poor visual feedback
Psychological Nature of Control	good	good	good	good
Historical Foundations	several	many		many instruments

	Pitched Percussion Instruments (vibraphone, marimba, etc.)	Keyboard Instruments (piano)	Typical Keyboard Synthesizer	Radio Drum (electronic controller)
Physical Variables (as a function of time)	stroke velocity (loudness) position (pitch)	velocity (loudness) position (pitch)	velocity (loudness, timbre) position (pitch) pressure (loudness, timbre, pitch) pitch and modulation wheels [1]	velocity (loudness, timbre) position (X, Y, Z)
Dimensionality of Control	2 dimensions	2 dimensions	[2]	4 dimensions
Multiplicity of Control	2	6 (2 dimensions x 3 lines)	7 (2 dim. x 3 lines + 1dim.) [3]	8 ((X, Y, Z + velocity) x 2) [4]
Control Modality	discrete (pitch) continuous (loudness)	discrete (pitch) discrete (loudness)	discrete/continuous (pitch) discrete/continuous (loudness) discrete/continuous (timbre)	discrete/continuous (velocity) Discrete/continuous X, Y, Z
Control Monitoring	continuous	countinuous	continuous	continuous
Control Distance Function	polyphonic (typically 2 or 4 notes) non-recursive	polyphonic (up to 88 notes) non-recursive	polyphonic (up to 16 notes) non-recursive	polyphonic (2 notes) user definable
Literalness of Control	WYPIWYG	WYPIWYG	mostly WYPIWYG	depends on programming
Design Appropriateness	good good visual feedback	good good visual feedback good tactile feedback	good good visual feedback fair tactile feedback	good fair visual feedback fair tactile feedback
Psychological Nature of Control	good	good	variable	variable
Historical Foundations	numerous	numerous	primarily piano	remotely modelled on drum

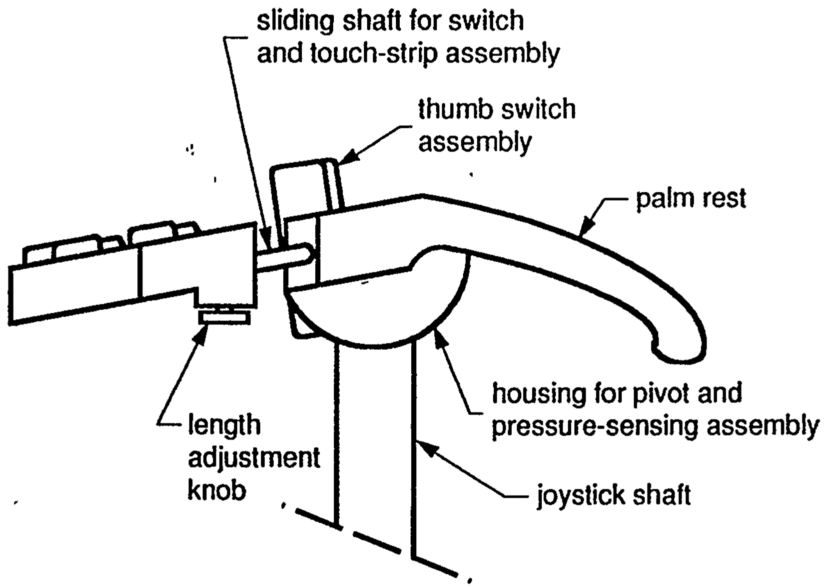
[1] Modulation wheel can be routed to different parameters.
[2] Loudness, pitch, timbre, pitch bend and modulation.
[3] Velocity and pitch x 3 lines +1 aftertouch.
[4] X, Y, and Z can be mapped to different variables. Striking force (velocity) can be independent from Z dimension.

DIMENSIONED DRAWINGS

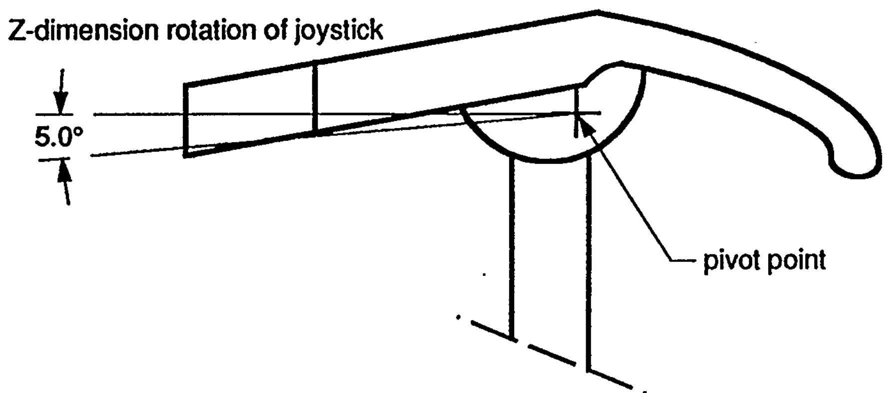




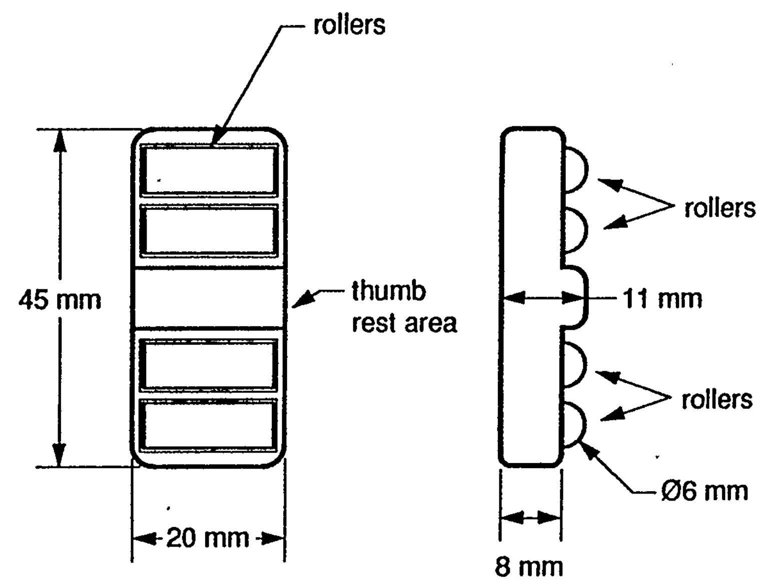
joystick top view (actual size)



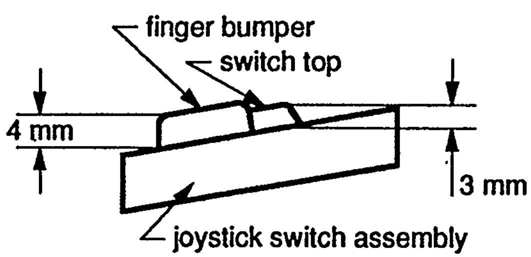
Joystick side view



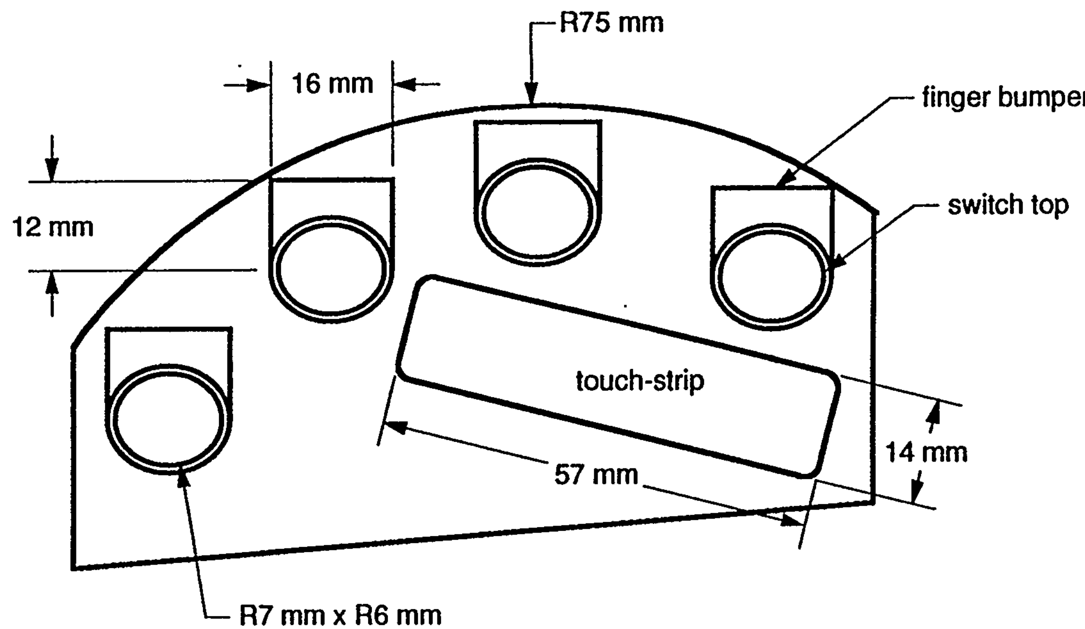
Joystick Z-dimension movement

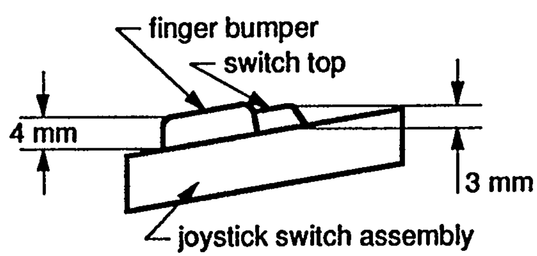


Thumb switch assembly

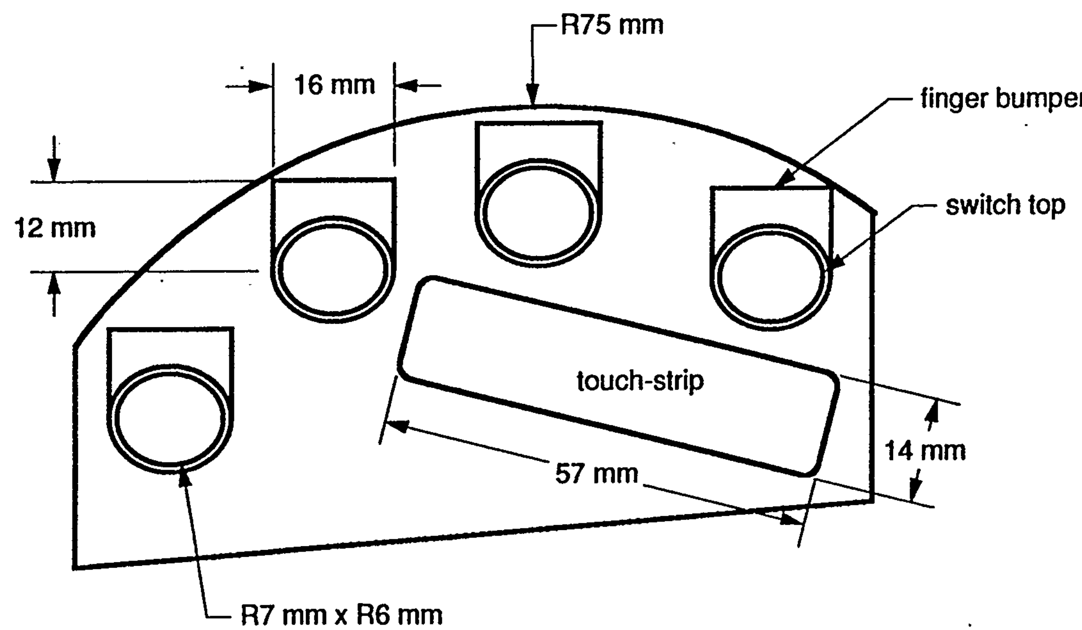


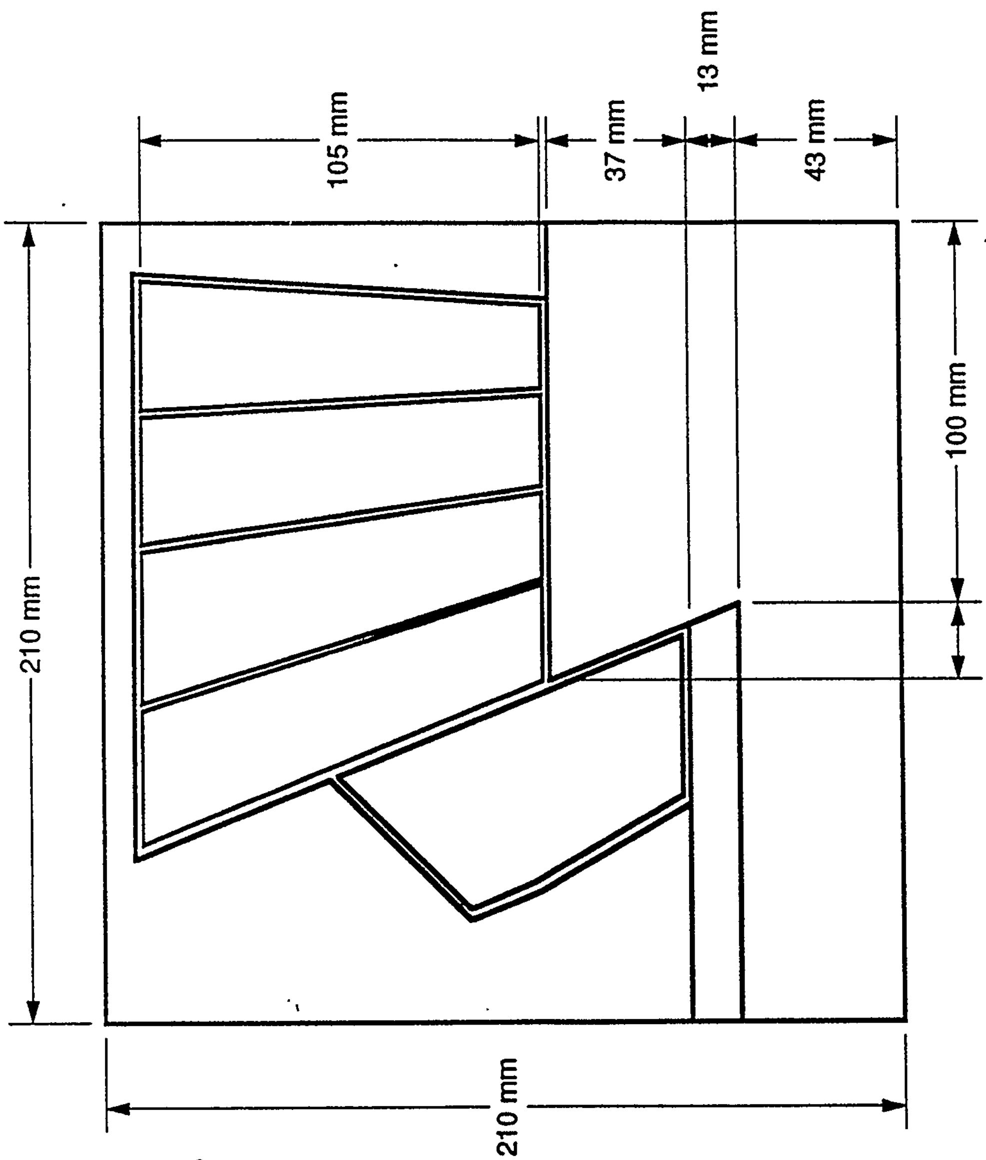
switch detail, side view (2x actual size)



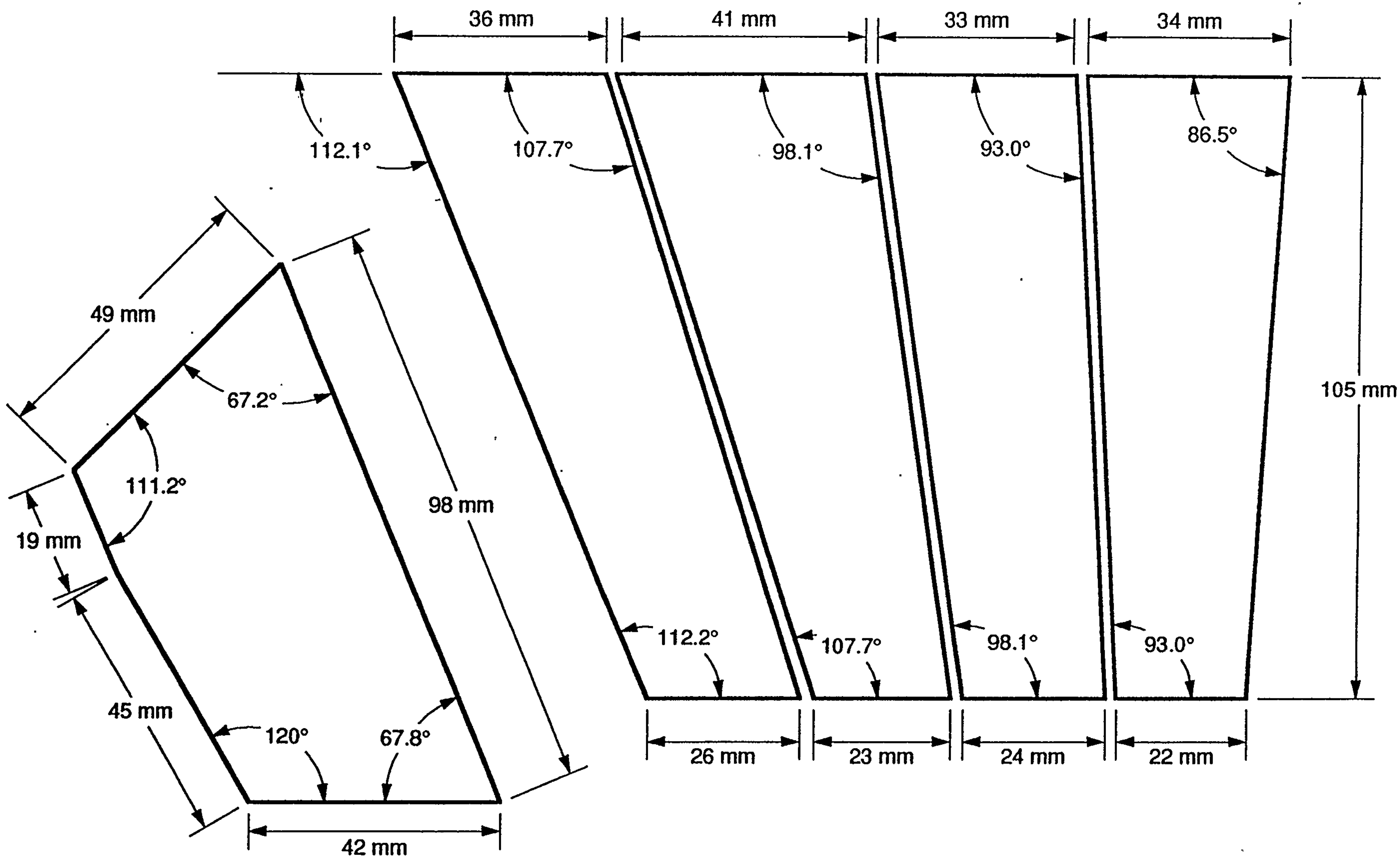


switch detail, side view (2x actual size)

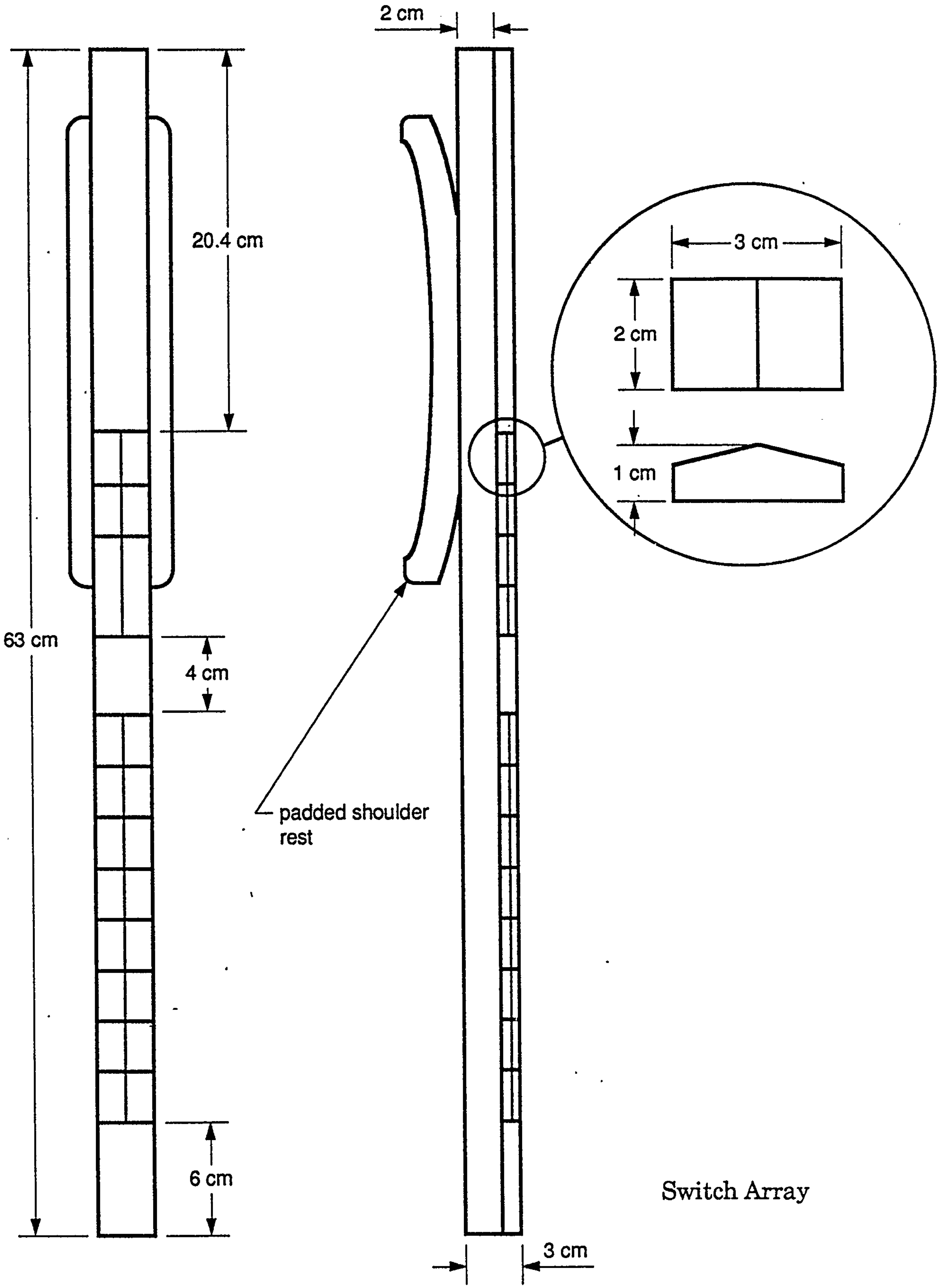




Keyboard dimensions



Chord keyboard key dimensions



Switch Array

Appendix D

FINGERING CHARTS

	1	2	3	4	5
C	X				
C#		X			
D	X	X			
D#			X		
E	X		X		
F		X	X		
F#	X	X	X		
G				X	
G#	X			X	
A		X		X	
A#	X	X		X	
B			X	X	
C1	X		X	X	
C#1		X	X	X	
D1	X	X	X	X	
D#1					X
E1	X				X
F1		X			X
F#1	X	X			X
G1			X		X
G#1	X		X		X
A1		X	X		X
A#1	X	X	X		X
B1				X	X
B#1	X			X	X
C2		X		X	X
C#2	X	X		X	X
D2			X	X	X
D#2	X		X	X	X
E2		X	X	X	X
F2	X	X	X	X	X

Chart 1.
Binary code fingering.

For all charts:

1 - Thumb
2 - Index Finger
3 - Middle Finger
4 - Ring Finger
5 - Little Finger

	1	2	3	4	5
C	X				
C#	X	X			
D	X	X	X		
D#		X	X		
E		X	X	X	
F			X	X	
F#			X	X	X
G				X	X
G#		X		X	X
A	X	X		X	X
A#	X			X	X
B	X		X	X	X
C1	X	X	X	X	X

Chart 2.
Fingering with a Hamming distance of 1.

	1	2	3	4	5
C		X			
D		X	X		
E		X	X	X	
F		X	X	X	X
G			X	X	X
A				X	X
B		X		X	X
C2	X	X		X	X
C#	X	X			
D#	X	X	X		
F#	X	X	X	X	
G#	X		X	X	X
A#	X			X	X

Chart 3.
Wholetone ('Casio'-type) fingering with Hamming distance of 1.

	1	2	3	4	5
C		X			
C#	X	X			
D			X		
D#	X		X		
E				X	
F	X			X	
F#			X	X	
G	X		X	X	
G#		X		X	
A	X	X		X	
A#		X	X		
B	X	X	X		
C1		X	X	X	
C#1	X	X	X	X	
c		X			X
c#	X	X			X
d			X		X
d#	X		X		X
e				X	X
f	X			X	X
f#			X	X	X
g	X		X	X	X
g#		X		X	X
a	X	X		X	X
a#		X	X		X
b	X	X	X		X
c1		X	X	X	X
c#1	X	X	X	X	X
extras					
					X
	X				X

Chart 4.
Non-Hamming fingering.
Little finger is not used for primary octave and thumb is not used alone.

Appendix E

KEYBOARD ELECTRONICS

The following is a copy of the documentation provided by Grant Beattie of Music Technologies Group accompanying the electronics he developed for this project.

MultiMax

Single Board Computer for
Alternative Midi Controllers

INTRODUCTION

The MultiMax Single Board Computer (SBC) is the electronic component of the alternative midi controller. Since the intended destination for its midi information is the Opcode MAX programming environment on the Apple Macintosh computer, the name MultiMax was chosen.

The original and desired operating mode was that of a keyboard which generates monophonic note information based on a particular keyboard chord or combination. That incarnation was called MonoMax. During the development of this device a five note polyphonic version was tested and it was named PolyMax. Since this final version contains both programs it is called MultiMax.

INFORMATION

- 12 MHz Intel 8031 microcontroller
- Powered by +5 volt regulated or +7.5 to +10 volt (regulated or unregulated) d.c. power
- Five note velocity sensitive keyboard
- Four octave transpose switches
- Sixteen controller switches
- Mode select and Reset switches

GETTING STARTED

For instant gratification, the MultiMax SBC and accompanying demo switch board can be hooked up for testing purposes:

1) **Note that this is a static sensitive electronic device. Use normal CMOS handling precautions when connecting and using this equipment.**

2) Connect the two circuit boards. Using the 14 pin flat cable provided connect the two boards at their 14 pin DIP sockets. Each board has a red line above the socket which corresponds with the red line on the cable provided. (This will ensure that pin 1 on the CPU board

connects to pin 1 on the demo switch board, etc.) Normally, the CPU board sits to the LEFT of the demo switch board and all of the writing on the switches can be easily read.

3) Connect the power. Regulated +5 volt power supplies should be connected to the board using the RED terminal (+5v) and BLACK terminal (gnd). Supplies in the range of approximately +7.5 volts to +10 volts should be connected to the VIOLET terminal (positive voltage) and BLACK terminal (gnd).

4) Connect the MIDI OUT from the CPU board to the MIDI IN of the destination sound module (or whatever).

5) Turn on the MultiMax SBC and then the destination module. Select Midi channel 1 on the destination module. Make wonderful music.

POWER-UP DEFAULTS

When the unit is initially powered-up the unit will default to a certain mode ASSUMING THAT NO KEYS OR SWITCHES ARE PRESSED.

- The unit defaults to midi channel 1 and this currently NOT adjustable.

- The unit also defaults to Uni-Retrigger (monophonic) mode.

- The default event window size is .080 seconds. See below on choosing other event window times.

SELECTING MONOPHONIC MODES

There are two monophonic modes: Uni-Retrigger (the default) and Uni-Legato. At any time pressing the MODE button will toggle from one mode to the other. No other settings will be altered by a mode change (ie. event window size). The mode switch may be pressed quickly or held for an indefinite amount of time - the result in either case will be a single mode toggle.

Although there is no visual indication of the operating mode, a test point (TP1) has been provided which indicates the operating mode. On the enclosed schematics, TP1 is located on pin 10 of the CPU. Using a logic probe or voltmeter, this point will change logic levels as the mode is altered.

If you wish to connect an LED to this point you MUST ALSO include either a driver transistor or logic IC.

SELECTING POLYPHONIC MODE

There are two ways of selecting the polyphonic mode in which the keyboard performs as a five note polyphonic keyboard.

1) Power-up selection. Press and hold one or more of the keyboard keys at the bottom of its travel while the unit is being powered-up.

2) Reset selection. First of all, the reset switch must be made available to the operator on the outside of the machine in the same manner as the mode and controller switches. Press and hold reset - press and hold one or more of the keys - release reset.

The unit can be restored to its PREVIOUS monophonic mode by pressing the reset switch alone. You must, however, re-enter your event window size at this time (unless you are using the default).

KEYBOARD NOTE ASSIGNMENTS

1) Monophonic (both modes)

FINGER	thumb	index finger	finger finger	ring finger	little finger
NOTE WEIGHT	16	1	2	4	8
NOTE SOUNDED IF PLAYED ALONE	3Fh 63d	30h 48d	31h 49d	33h 51h	37h 55h

2) Polyphonic

FINGER	thumb	index finger	finger finger	ring finger	little finger
NOTE WEIGHT	1	1	1	1	1
NOTE SOUNDED IF PLAYED ALONE	30h 48d	31h 49d	32h 50d	33h 51h	34h 52h

TRANSPOSE

The four transpose buttons function differently depending on the chosen operating mode:

1) Monophonic. If any transpose button is pressed while a note is sounding the current note is turned off and a new note-on is issued according to the chosen octave.

2) Polyphonic. Transpose only affects NEW note-on's. Held or released notes are not affected. Any note-on issued while a transpose button is selected will be issued in the selected octave.

CHOOSING AN EVENT WINDOW SIZE (Monophonic Modes Only)

In order for the device to correctly interpret keyboard activity and translate this into meaningful midi note information, a timed "event window" system has been employed. The desired outcome of such a scheme is so that the device can discern between several "quick intended notes" and one very poorly played "chord".

On a normal piano (or any polyphonic keyboard implementation) playing a three note chord in a very sloppy fashion (that is, the three notes do not occur perfectly in time) has no penalty. The result is that the three notes all sound eventually and the final chord is correctly built. On a monophonic keyboard such as the MultiMax, a single note is determined by a unique COMBINATION of keys playing at any instance. Therefore, if the same three note chord is played, MultiMax must somehow determine if the intended performance is one event (the result of the chord combination) or three quick events (perhaps an arpeggiation).

To resolve this problem, a "timed event window" is employed. That is, any series of discrete key events occurring within the window is treated as a single midi event. Any key events occurring outside the event window maintain their discrete midi status.

On the MultiMax, the power-up default window size is .080 seconds. For instance, suppose you wish to play a two-key combination which results in one single midi note-on. From the time the first key is established, there is a "window of opportunity" of 0.080 seconds in which the second key must be established. If it does fall within that window the correct single note-on is sent. If the second key is not established until some time later, then two different note-on's are sent, neither of which was the intended one!

One of sixteen different settings can be selected using the following methods:

1) Power-up selection. By holding down one of the controller switches (1-16) during power-up the window corresponding to that switch is selected (see the table below).

2) Reset selection. Press and hold reset - press and hold one of the controller switches - release reset. Again the window size follows this table:

EVENT WINDOW (switch no.)	WIDTH (seconds)
1	.015
2	.031
3	.047
4	.064
5	.079
6	.095
7	.112
8	.127
9	.143
10	.159
11	.175
12	.191
13	.207
14	.223
15	.239
16	.255

NOTE: As a result of this window technique, there will always be a midi delay equal to the window size (this is not true in polyphonic mode). Therefore, as the individual becomes more skillful, reduce the window size accordingly.

MIDI CONTROLLER SWITCHES

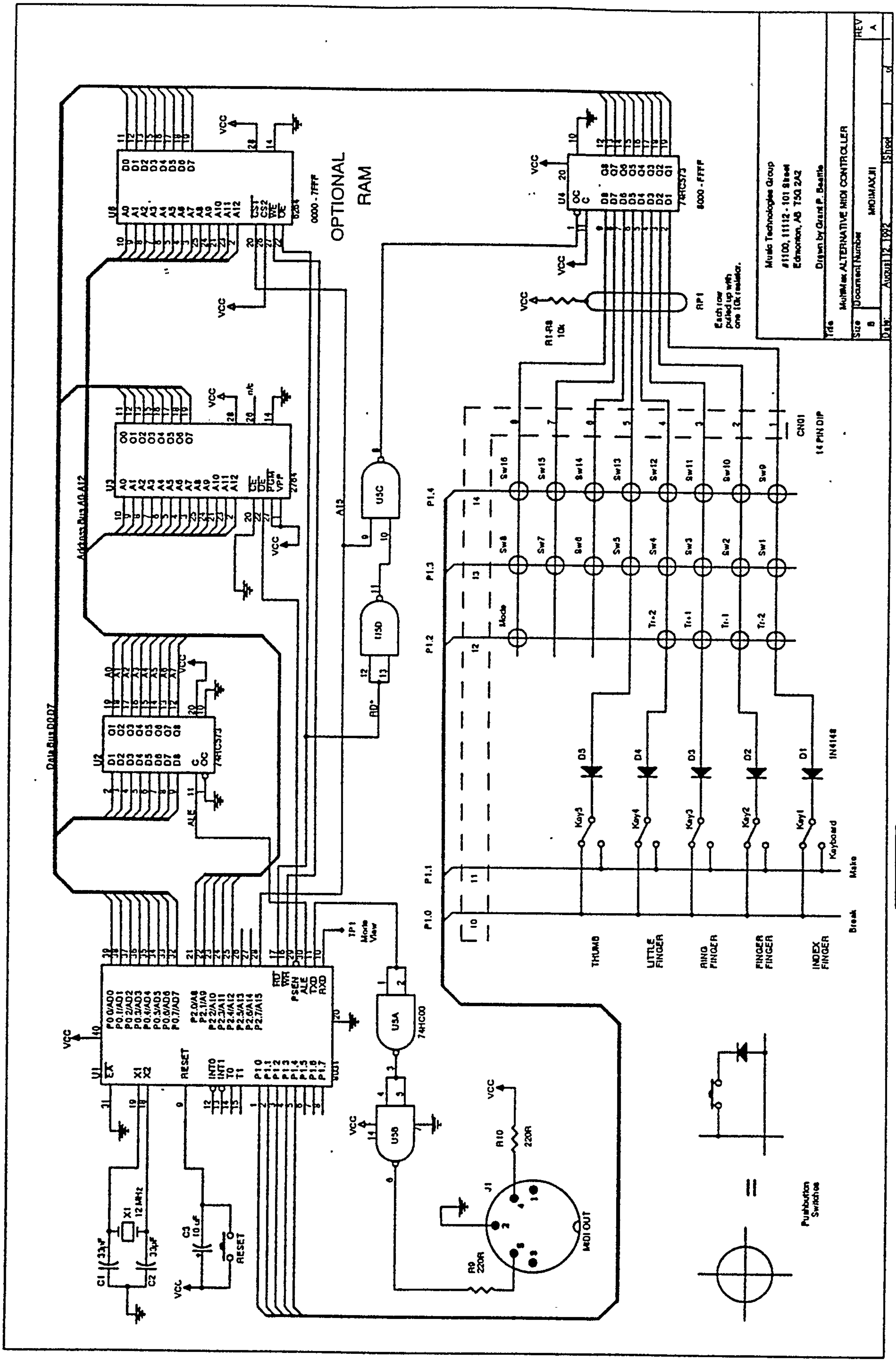
The switches numbered 1 to 16 correspond to midi controllers 40 - 4F hex (64 - 79 decimal). As each switch is depressed a controller message is sent with value 127 (B0 - 40 - 7F for switch 1 which is sustain). As the switch is released the message is sent with a value 0 (B0 - 40 - 00).

HAVING TROUBLE?

The only weird anomaly I've noticed is that on two occasions, my DX7 (with E!) locked up when it was powered up before the MultiMax SBC. This never occurred with the MEP-4, nor is any midi information displayed on the midi monitor. My fix has been to turn the MultiMax on before the DX7. I have not been able to establish if there is some spurious information sent from the MultiMax SBC at power-on or there is some weirdness with my DX7 or E! (this wouldn't be the first time). If you have any trouble with this please let me know.

On the following pages are two copies of the schematic (one wallet-size and one poster size), the complete source code listing and some additional notes and flowcharts regarding various algorithms used internally be the device.

Grant P. Beattie
Music Technologies Group
#1100, 11112 - 101 Street
Edmonton, AB
T5G 2A2
(403)474-5460


Music Technologies Group
#1100, 11112 - 101 Street
Edmonton, AB T5G 2A2
Drawn by Grant P. Beattie
Title
MultiMax ALTERNATIVE MIDI CONTROLLER
Size
B
Document Number
MIDIMAX.III
REV
A
Date:
August 12, 1992
Sheet
OPTIONAL RAM
Address Bus A0-A12
Data Bus D0-D7
74HC00
MIDI OUT
Each row pulled up with one 10k resistor.
14 PIN DIP
THUMB
LITTLE FINGER
RING FINGER
FINGER FINGER
INDEX FINGER
Break
Make
Keyboard
Pushbutton Switches
RESET
12 MHz

MIDI IMPLEMENTATION CHART

Function		Transmitted (1)	Transmitted (2)	Recognized	Remarks
Basic	Default	1	1 – 16		
Channel	Changed				
Mode	Default	3	3		
	Messages	X	X		
	Altered	***	X		
Note Number	true voice	24 – 103 ***	0 - 127 ***		
Velocity	Note ON	O (9n, v=1 – 127)	O (9n, v= 1–127)		
	Note Off	X (9n, v=0)	X (9n, v=0)		
After	Key's	X	O (selectable)*		key and/or channel aftertouch selectable
Touch	Channel's	O	O (selectable)*		
PitchBend		O	O		
Control Change		1, 2, 4, 5, 6 0 to 127 64 to 79 0 or 127	controllers 1 to 121 n = 0 to 127, or n = 0 or 127		5 continuous and16 switch controllers available
Program Change		X	O*		
System Exclusive					
System Common					
	Song Position	X	**		
	Song Selection	X	**		
	Tune	X	**		
System Real Time					
	Clock	X	**		
	Commands	X	**		
Aux Messages					
	Local ON/OFF	X	**		
	All notes OFF	X	O		
	Active Sense	X	**		
	Reset	X	**		

* programmed using aXiØ software

** can be implemented by user if required

*** not applicable

(1) transmitted directly from controller

(2) transmitted from computer

Aikin, Jim. "Interview with Don Buchla." in The Art of Electronic Music. comp. T. Darter. New York, NY: William Morris and Company, 1984.

Aikin, Jim. "The Light Touch: Remote Gesture Sensing Powers the MIDI Controllers of the Future." in Keyboard, Vol. 16, No. 6, 1990.

Aikin, Jim. "Banging vs. Scraping." in Keyboard, Vol. 17, No. 4, 1991.

Baily, John. "Music Structure and Human Movement." in Musical Structure and Cognition. ed. P. Howell, Ian Cross, and R. West. Toronto: Academic Press, 1985.

Bate, John. "MAX+UniSon – Interactive control of a digital signal multi-processor." in the Proceedings of the International Computer Music Conference at San Jose, California, October 14 - 18, 1992.

Beauregard, Gerald T. Rethinking the Design of Wind Controllers. Ms. Thesis, Dartmouth College, Hanover, New Hampshire, 1991

Brozenick, N. J. "Polybutylene terephthalate: PBT." in Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Cadoz, C., A. Luciani and J. Florens. "Responsive Input Devices and Sound Synthesis by Simulation of Instrumental Mechanisms: The Cordis System." in Computer Music Journal, Vol. 8, No. 3, pp. 60 - 73, 1984.

Cadoz, Claude. "Instrumental Gesture and Musical Composition." in the Proceedings of the International Computer Music Conference at Cologne, Germany, September 20 - 25, 1988.

Cariou, Brad "Design of an alternative controller from an industrial design perspective." in the Proceedings of the International Computer Music Conference at San Jose, California, October 14 - 18, 1992.

Chabade, Joel. "Interactive Composing: An Overview." in Computer Music Journal, Vol. 8, No. 1, pp. 22 - 28, 1984.

Chabot, Xavier. "Gesture Interfaces and a Software Toolkit for Performance With Electronics." in Computer Music Journal, Vol. 14, No. 2, pp. 15 - 27, 1990.

Chen, Michael and Frank Leahy. "A Design for Supporting New Input Devices." in The Art of Human-Computer Interface Design. ed. Brenda Laurel. Reading, MA: Addison-Wesley Publishing Company, Inc., 1990.

Clarke, Eric F. "Generative Principles in Music Performance." in Generative Processes in Music. ed. J. Sloboda. Oxford, England: Oxford University Press, 1988.

Clark, Kent. "Creative Control With the EM MIDI Fader." Electronic Musician, Vol. 7, No. 2, February, 1991.

Clynes, Manfred and Nigel Nettheim. "The Living Quality of Music: Neuro-biological Basis of Communicating Feeling." in Music, Mind, and Brain. ed. M. Clynes. New York, NY: Plenum Press, 1982.

Collins, Nicolas. "Low Brass: The Evolution of Trombone-Propelled Electronics." Leonardo Music Journal, Vol. 1, No. 1, pp. 41 - 44, 1991.

Cook, Perry R. "Observations and Comments on Technical Sessions." Array, Communications of the ICMA, Vol. 12, No. 4., Fall, 1992.

Copland, Aaron. What to Listen for in Music. New York, NY: McGraw-Hill Book Company, Inc., 1957.

Cushman, William H. and Daniel J. Rosenberg. Human Factors in Product Design. New York, NY: Elsevier Science Publishing Company Inc., 1991.

Darter, Tom. "Tod Machover: Computer Music's Big Noise." Keyboard, Vol. 17, No. 7, July, 1991.

Diffrient, Niels, et al. Humanscale 1/2/3. Cambridge, MA: The MIT Press, 1974.

Diliberto, John K. "An Interview with Donald Buchla." Polyphony, Vol. 8, No. 5, 1983.

Dix, J. S. "HMW high density polyethylene." Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Doran, David. "Trackballs and Joysticks." in Input Devices. ed. Sol Sherr. San Diego, CA: Academic Press, Inc., 1988.

Eagle, David. private communication, 1993.

Eilam, Z. "Human engineering the one-handed keyboard." Applied Ergonomics, Vol. 20, No. 3, pp. 225 - 229, September, 1989.

Emmerson, Simon. "Computers and Live Electronic Music: Some Solutions, Many Problems." in the Proceedings of the International Computer Music Conference at Montreal, Quebec, October 16 - 20, 1991.

Foley, James D., V. L. Wallace and P. Chan "The Human Factors of Computer Graphics Interaction Techniques." IEEE Computer Graphics and Applications, pp. 13 - 48, November 1984.

Hargreaves, William, David Rempel, et al. "Toward a More Human Keyboard." in Human Factors in Computing Systems, CHI '92 Conference Proceedings, Reading, New York, N.Y: ACM Press, 1992.

Harris, Craig. "Looking Ahead: Visions for the 1990s." Electronic Musician, Vol. 6, No. 1, January 1990.

Hayes, R. G. "Multicomponent liquid foam processing." Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Holmes, Thomas B. Electronic and Experimental Music. New York, NY: Charles Scribner's Sons, 1985.

Jans, R. W. "Casting of acrylic." Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Krefeld, Volker. "The Hand in The Web: An Interview with Michel Waisvisz." Computer Music Journal, Vol. 14, No. 2, pp. 28 - 33, 1990.

Kramer, Gregory and Robert Moog. "The Hybrid: A Music Performance System." in the Proceedings of the International Computer Music Conference at Columbus, Ohio, November 2 - 5, 1989.

Kurkela, Kari. "Score, vision, action." Contemporary Music Review, Vol. 4, pp. 417 - 435, 1989.

Lee, Michael and David Wessel. "Connectionist Models for Real-Time Control of Synthesis and Compositional Algorithms." in the Proceedings of the International Computer Music Conference at San Jose, California, October 14 - 18, 1992.

Lee, Michael, Adrian Freed and David Wessel. "Real-Time Neural Network Processing of Gestural and Acoustic Signals." in the Proceedings of the International Computer Music Conference at Montreal, Quebec, October 16 - 20, 1991.

Machover, Tod and Joe Chung. "Hyperinstruments: Musically Intelligent and Interactive Performance and Creativity Systems." in the Proceedings of the International Computer Music Conference at Columbus, Ohio, November 2 - 5, 1989.

Manning, Peter. Electronic and Computer Music. New York, NY: Oxford University Press, 1985.

Mathews, Max V. and F. R. Moore. "GROOVE — A Program to Compose, Store and Edit Functions of Time." Communications of the Asssociation For Computing Machinery, Vol. 13, No. 12, pp. 715 - 721, 1969.

Miller, G. A. "The magical number seven, plus or minus two: Some limits on our capacity for processing information." Psychological Review, No. 63, 1956.

Minsky, Margaret, Ming Ouh-young, et al. "Feeling and Seeing: Issues in Force Display." Computer Graphics, Vol. 24, No. 2, pp. 235 - 243, 1990.

Moog, Robert. "Shape Them Notes!" Electronic Musician, Vol. 7, No. 6, 1991.

Moore, F. Richard. "The Dysfunctions of MIDI." Computer Music Journal, Vol. 12, No. 1, pp. 19 - 28, 1988.

Moore, P. F. "Glass." Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Morthenson, Jan W. "Aesthetic Dilemmas in Electronic Music." in On the Wires of Our Nerves: The Art of Electroacoustic Music. ed. R. J. Heifetz. Toronto: Associated University Presses, Inc., 1989.

Nishijima, Masako and Kazuyuki Watanabe. "Interactive Music Composer Based on Neural Networks." in the Proceedings of the International Computer Music Conference Proceedings at San Jose, California, October 14 - 18, 1992.

Pressing, Jeff. "Cognitive Processes in Improvisation." in Cognitive Processes in the Perception of Art. ed. W. R. Crozier and A. J. Chapman. Amsterdam: North Holland, pp. 345 - 363, 1984.

Pressing, Jeff. "The Cybernetics of Extended and Intelligent Instruments." in the Proceedings of the 8th Symposium on Small Computers in the Arts, Philadelphia, SCAN Network, pp. 32 - 55, 1988a.

Pressing, Jeff. "Improvisation: Methods and Models." in Generative Processes in Music. ed. J. Sloboda. Oxford: Clarendon Press, pp. 129 - 78, 1988b.

Pressing, Jeff. "Cybernetic Issues in Interactive Performance Systems." Computer Music Journal, Vol. 14, No. 1, pp. 12-25, Spring, 1990.

Pressing, Jeff. Synthesizer Performance and Real-Time Techniques. Madison, Wisconsin: A–R Editions, Inc., 1992.

Puckette, Miller and David Zicarelli. *MAX*, Opcode Systems, Inc., Menlo Park, California, 1990.

Rasmussen, Jens. "Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and other Distinctions in Human Performance Models." IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-13, No. 3, pp. 257 - 266, 1983.

Rasmussen, Jens. Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering. New York, NY: North-Holland, 1986.

Rothstein, Joseph and Michael Metlay. "Products of Interest: The Musician-Machine Interface to MIDI." Computer Music Journal, Vol. 14, No. 2, pp. 26 - 41, 1990.

Rubine, Dean and Paul McAvinney. "The VideoHarp." in the Proceedings of the International Computer Music Conference at Cologne, Germany, September 20 - 25, 1988.

Rubine, Dean and Paul McAvinney. "Programmable Finger-tracking Instrument Controllers." Computer Music Journal, Vol. 14, No. 1, pp. 26 - 41, 1990.

Rundolf, L. C. "Very low density polyethylene." Modern Plastics Encycolpedia. Vol. 63, no. 10a, October, 1986.

Rowell, Lewis. Thinking About Music. Amherst, MA: The University of Massachusetts Press, 1983.

Schloss, W. Andrew. "Recent Advances in the Coupling of the Language MAX with the Mathews/Boie Radio Drum." in the Proceedings of the International Computer Music Conference at Glasgow, Scotland, September 10 - 15, 1990.

Schloss, W. Andrew. "Intelligent Musical Instruments: The Future of Musical Performance or the Demise of Virtuosity in Music?" in the Proceedings of the International Workshop on Machine-Machine Interaction in Live Performance, Computer Music Department of CNUCE/CNR, Pisa, Italy, June 7 - 8, 1991.

Schwartz, Elliott. Electronic Music: A Listener's Guide. New York, NY: Da Capo Press, 1989.

Sosnin, Jim, David Hirst and Graeme Gerrard. "Patching and control of multi-processes in a real-time DSP environment." in the Proceedings of the International Computer Music Conference at San Jose, California, October 14 - 18, 1992.

Vail, Mark. "Happy Birthday, MIDI! (MIDI is Ten Years Old)." Keyboard, Vol. 19, No. 2, February, 1993.

Waisvisz, Michel. "The Hands: a set of remote MIDI controllers." in the Proceedings of the International Computer Music Conference at Burnaby, British Columbia, 1985.

Wessel, David L. "Instruments That Learn, Refined Controllers, and Source Model Loudspeakers." Computer Music Journal, Vol. 15, No. 4, pp. 82 - 86, 1991.

Woodson, Wesley E. Human Factors Design Handbook. New York, NY: McGraw-Hill Book Company, 1981.

Young, Gayle. The Sackbut Blues: Hugh Le Caine, Pioneer in Electronic Music. National Museum of Science and Technology (Canada), 1989.

Zicarelli, David. "Music for Mind and Body." Electronic Musician, Vol. 7, No. 2, 1991a.

Zicarelli, David. "Communicating with Meaningless Numbers." Computer Music Journal, Vol. 15, No. 4, Winter 1991b.