Ergonomic Design of A Portable Musical Instrument

Motohide Hatanaka
Center for Design Research, Department of Mechanical Engineering Design Division
Building 560, 424 Panama Mall, Stanford University
Stanford, California 94305, USA
+1-650-723-3286
motohat@cdr.stanford.edu

ABSTRACT
A handheld electronic musical instrument, named the Bento-Box, was developed. The motivation was to develop an instrument which one can easily carry around and play in moments of free time, for example when riding public transportation or during short breaks at work. The device was designed to enable quick learning by having various scales programmed for different styles of music, and also be expressive by having hand controlled timbral effects which can be manipulated while playing. Design analysis and iteration lead to a compact and ergonomic device. This paper focuses on the ergonomic design process of the hardware.

Keywords
MIDI controller, electronic musical instrument, musical instrument design, ergonomics, playability, human computer interface.

1. INTRODUCTION
The busy modern lifestyle provides few opportunities for music lovers to perform. However, people do have many short intervals of free time during which they can potentially play musical instruments. For example, many people spend time less actively when riding or waiting for public transportation for commuting. It would be a boon for busy music lovers if there were a musical instrument that they could easily carry around and play anytime anywhere without disturbing others, just like a portable audio device such as the Sony Walkman [10]. For instance, a harmonica is a very portable instrument but it can disturb others if played in public. On the other hand, an electronic keyboard can be played and heard through a headphone so as not to disturb people, but it is awkward to carry around and it may also irritate surrounding people because of its size. What would be ideal instead is a compact portable silent musical instrument with electric sound output (see Figure 1).

The Bento-Box was designed and built as a class project for a course on human computer interaction (HCI) theory and practice at Stanford University [11]. Basics of HCI theory as well as electronics and computer sound generation were taught, and students were given approximately a month to build musical instruments of their own interest in groups of two or three.

2. CONCEPT
2.1 Project Goal, Design Criteria, and Functional Requirements
The general goal of the project was to develop a device that contains maximum musical expressiveness in a limited size while assuring ease and comfort of performance. Some criteria were established to limit certain properties of the device for the user and the people around the performer. Functional requirements were also identified to assure satisfactory performance for the user.

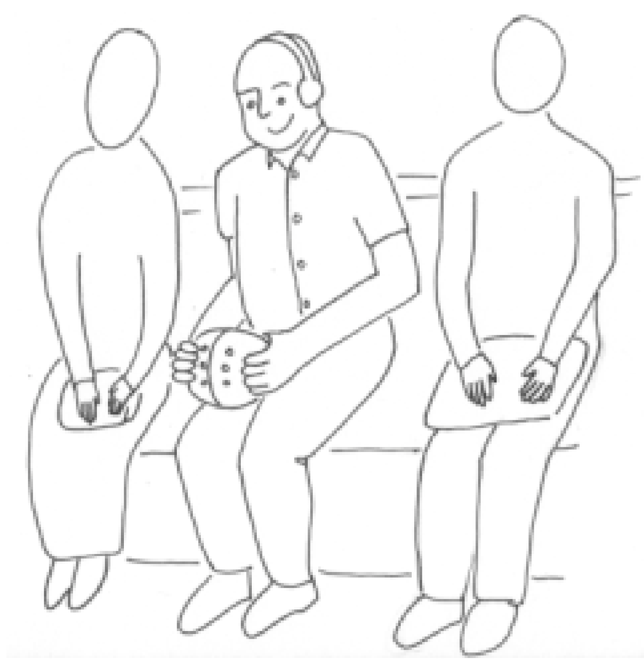

Figure 1. Compact quiet musical instrument for playing in public places

The device had to be portable both in terms of size and mass. The design team aimed for a size that can be held with two hands brought fairly close together and with a mass that can be supported comfortably for at least half an hour. The size constraints also result in a unit that the user can easily carry around, hence the name of the device Bento-Box (*bento* is a Japanese word for packed lunch). The performer's range of motion also had to be small enough not to disturb the surrounding people in crowded public transportation where people are seated shoulder to shoulder. So the device was designed to be played without having to move shoulders but only hands, wrists, and forearms. Furthermore, the instrument also had to be quiet during performance. Hence, quiet input devices, such as buttons without clicking noise, were selected to minimize noise generation.

The design team decided that they wanted an instrument that can play melody with at least two octaves of tone range for sufficient musical expression. They also agreed on having at least two timbral effects to control. Other functions were added to the device as required or desired as the design evolved.

2.2 Design Strategy
The design takes full advantage of the fact that this is an electronic instrument. An acoustic musical instrument may

have structural design constraints that may result in poor ergonomics. In contrast, electronic instruments have much more freedom in structural design since the sound usually does not depend on the physical properties of the device. Hence, here, the instrument was designed prioritizing ergonomics, while also assuring high expressiveness. Such a design can be done through a combined analysis of the tasks, hardware characteristics of input devices, and human ergonomics (see Figure 2).

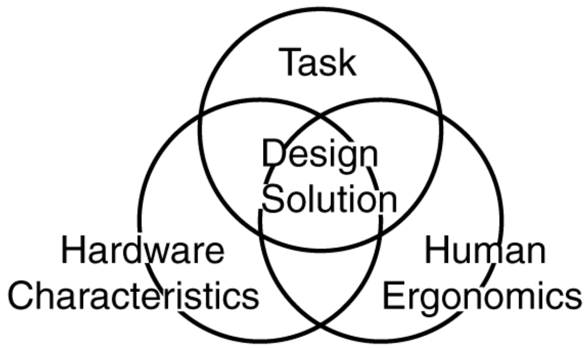

Figure 2. Design approach involves the analyses of task, hardware characteristics, and human ergonomics

Many compact handheld and hand-worn musical devices take advantage of being free from physical constraints seen in acoustic instruments. The hardware designs often differ greatly from one to another because of the intended application. The Hands used by Waisvisz is a pair of rather sophisticated hand-worn MIDI-controllers with numerous sensors that allows expressive performance [12]. A family of hand-held instruments developed recently by Weinberg and collaborators generally have simple hardware that are easy to operate and comfortable to hold, probably considering use by children, and their applications have broad goals such as enabling collaboration among performers [13-15]. Since we were developing an instrument for an entirely new setting, design inspiration were sought not only from such existing musical devices but also other electronic devices used in similar settings such as mobile phones and portable video games like the Nintendo Gameboy [7]. However, the greatest source of ideas were various types of brainstorming exercises highlighted by building quick mockups and playing with them, acting out as if they were real instruments.

2.3 Initial Design

The initial concept was to have a spherical device that had touch sensors, such as buttons or force sensitive resistor (FSR) pads, on the surface for basic melody and chord performance. There were also to be several effects controlled by twisting and squeezing the device (see Figure 3).

In order to maximize the playability and sound range of the instrument on the limited space of the instrument, a scale (style) selection slider was to be installed. Notes in the selected scale and key are assigned to the melody performing sensors (see Figure 4). This assumes that the performer only needs to play notes that are in the scale. Hence, having a sensor (or a part of a sensor) assigned to an off-scale note would be a waste of space. This has an advantage, especially for beginner musicians trying to improvise, in that the performer will not produce a note that is terribly dissonant.

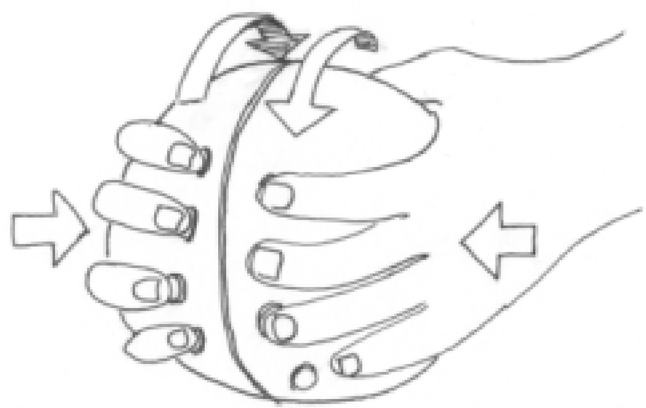

Figure 3. Controlling effect parameters by twisting and squeezing the instrument was one of the earliest ideas.

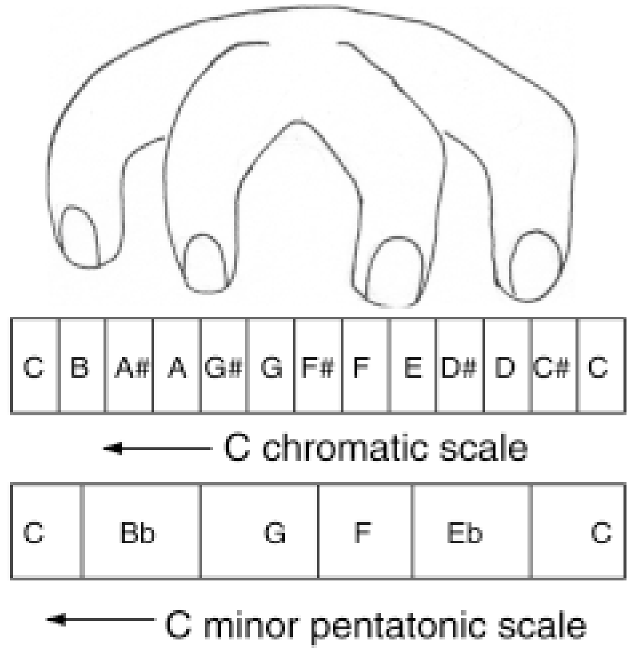

Figure 4. By changing scale settings, the instrument limits itself to produce only the notes that are in the specified scale.

3. HARDWARE DESIGN

3.1 Shape Determination

The hardware design went through ergonomics analysis and testing using mockups to maximize playability and expressiveness. The usefulness of prototyping in early stages is discussed in a book on product design by Kelley [5]. Three mockups were built using rigid urethane foam. One was cylindrical, with tapered ends, 90mm diameter and 115mm length, and the other two were rectangular, one being narrow (80mmx150mm x55mm thick) and the other being almost square in its front profile (150mmx150mmx55mm) (see Figure 5).

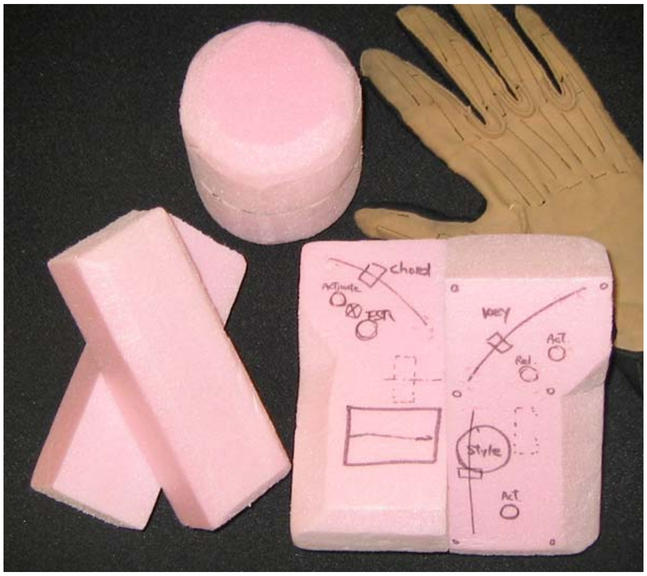

Figure 5. Foam mockups for initial instrument design. The glove is placed for size reference.

For the cylindrical shape, it was discovered that the hands conform too nicely to wrap around it such that it left the fingers with little freedom to move (see Figure 6).

Figure 6. Having no free space between the instrument and the fingers limits the freedom of finger motion.

The narrow rectangle relied on the fingers and thumb for supporting the instrument. As a consequence, both of the thumbs as well as two fingers from each hand had to stay on the instrument for stable support. This greatly inhibited their freedom for performance (see Figure 7).

The square shape was selected at the end as its wide shape allowed for the user's palms to support the instrument without hindering the dexterity of thumbs and fingers (see Figure 8). The result of the experiment shows that round shape does not necessarily make a device ergonomic. Various ways of grasping are listed and described in books by Cutkosky [3] and MacKenzie and Iberall [6].

3.2 Sensor Selection and Layout

Controlling a timbral effect parameter by twisting the instrument was one of the featured ideas of the design. Twisting and bending are motions that could be easily applied by the performer's wrists. Therefore, making use of that motion was perfectly suited to represent our ergonomics consideration approach for expressiveness maximization. The positioning of the twisting pivot was also experimented and determined using the foam mockups. The pivot was first positioned at the center of the device, which worked fine for the cylindrical shape. However, having the pivot at the center of the rectangular mockups required large motions of the forearms, which could lead to elbow motions that disturb surrounding people. The problem was solved by shifting the pivot toward the wrists.

Figure 7. In a grip using fingertips, thumbs and some fingers must always remain on the instrument to support it.

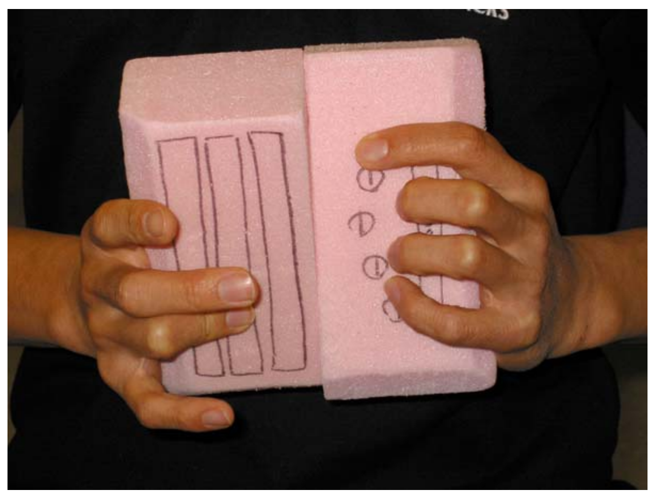

Figure 8. Palms are used to support the instrument, leaving the thumbs and fingers free to move.

Another expression parameter was to be controlled with the squeezing force between the two halves of the instrument. The twist and squeeze sensors were integrated in one unit. The rotary potentiometer for sensing the twist was suspended on a linear slider that allows it to translate in the direction parallel to its rotating axis. An FSR was installed behind the potentiometer via a rubber cushion to sense the squeeze.

Design of other input devices was done by analyses and matching of the task, device characteristics, and human ergonomics all together. Predicted interaction frequency as well as the required signal output (continuous or discrete) were listed out for various control parameters (see Table). For example, melody pitch changes are required much more frequently than scale change. Properties of various input devices such as the output signal types and the time required to manipulate them were also listed. The list was used to identify the potential couplings of control parameters and sensors.

Table 1. Body parts, control parameters, and sensors were matched by analyzing their characteristics.

	parameter	No.	control frequency	signal	sensor
fingers (R)	pitch	2	high	continuous	flex pot
	volume	2	high	continuous	flex FSR
Thumb (R)	scale release	1	medium	discrete	button
	style	1	low	continuous	pot
	style activate	1	low	discrete	button
Wrist	octave shift	1	high	continuous	pot
	compress	1	high	continuous	FSR
Thumb (L)	key	1	low	continuous	slider pot
	chord	1	medium	continuous	slider pot
	key activate	1	low	discrete	button
	chord activate	1	low	discrete	button
fingers (L)	sustain	1	medium	continuous	slider pot
	reverb	1	medium	continuous	slider pot
	vibrato	1	medium	continuous	FSR
	harmonics	1	medium	continuous	slider pot

Final selection and physical layout of these input devices on the instrument were done through an experiment to move thumbs and fingers in every possible way on the foam mockup. The objective was to discover how to extract maximum expressiveness out of the hands. The range and speed of motion as well as force and control involved were analysed. Level of comfort was another factor that was tested. The layout determination also considered maintaining enough comfortable room for the thumbs and fingers to rest. It is worth keeping in mind that fingers are good at flexing and extending but they are not so finely controllable nor forceful at abduction or adduction, especially when they are bent. There are also slight but noteworthy differences in the dexterity among the four fingers. The index finger, for example, has much more independence in motion compared to the other three fingers. Meanwhile, a thumb can exhibit a variety of complex motions unrivaled by fingers. Such facts about hands can also be obtained from literature by, for example, Kaplan [4] and Wilson [16], but the effectiveness of mockup experimentation cannot be completely replaced by reading only. However, while experiments can reveal what one can do, literature on ergonomics such as [1] by Cacha can provide more information about what is good or bad for the hands in long term ergonomics so that injuries can be prevented.

Here are some examples from the resulting design. There are two sliders positioned diagonally on the thumb side of the device. They are assigned for key and chord selection. Another slider is placed lower on the device for style change, where it is not as accessible, since it will not be used as frequently as the two others (see Figure 9). The chord/key/style settings change only when an activation button is pressed. This allows the user to control the sliders during performance in preparation for a future change without interfering the ongoing performance.

The right fingers do the melodic performance by pressing buttons (see Figure 10). Fingers are good for selecting and pressing buttons. They are also quite capable of varying pressure on each finger if needed. Fingers on the left hand were used to trigger effects-selection toggle switches.

4. SYSTEM CONFIGURATION

Sensor information from the Bento-Box was collected by an Atmel ATMega 163 microcontroller and was sent to a desktop computer as MIDI data. Pd [8] was employed to process the data and generate sound with plugins created from Synthesis ToolKit (STK) physical models [2]. C++ plugins were also employed to ease signal processing (see Figure 11).

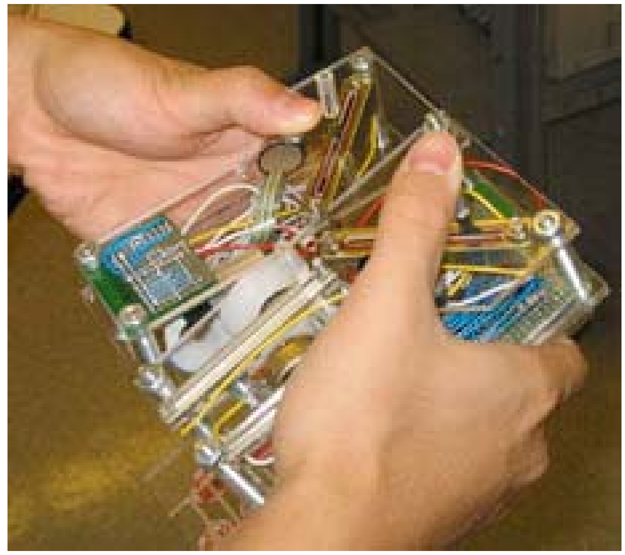

Figure 9. The Bento-Box (150mmx150mmx45mm, 526g) Frequently used controllers are ergonomically placed.

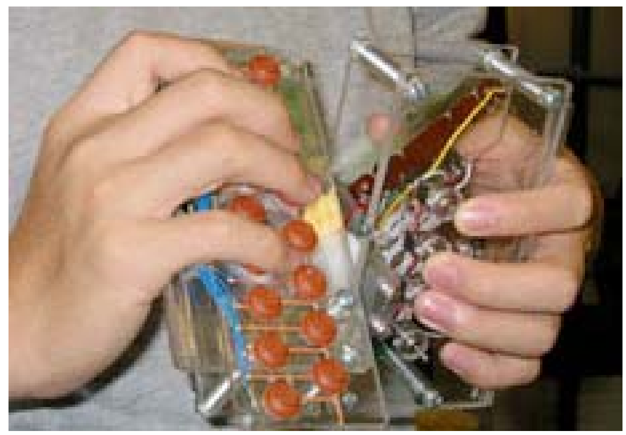

Figure 10. Noiseless buttons for playing melody.

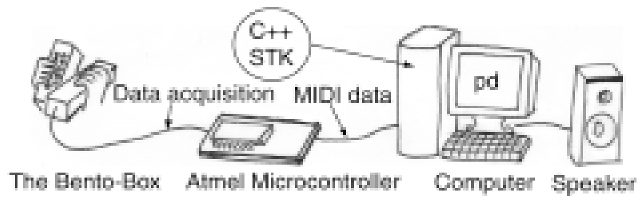

Figure 11. System configuration

5. SETUP ALTERATION

Once the entire setup was built according to the initial design, some alterations were made in the assignment of sensors to effect parameters after some experimentation. Certain sensors turned out to be ergonomically difficult to use. Some modes of control were avoided because they were confusing for the user. Furthermore, less-used functions were replaced by more desired functions for a richer musical experience.

5.1 Initial Setup

The initial setup was as follows (please refer to Figures 12 and 13). There were two rows of eight buttons each for the right fingers, each assigned to individual notes. The note assigned to these buttons changed depending on the style and key setups, which were selected by sliders operated by the right thumb. The style slider was located lower than the key slider, which was positioned diagonally at the top of the back right side (Back refers to the thumb side of the instrument, which faces toward the user). There is a chord selection slider, which was planned to automatically accompany the melody performed, on the left back side symmetrical to the key selection slider. The style, key, and chord changes are only to occur when one of the two small red activation buttons, installed on both right and left just below the two symmetrical sliders, are pressed. A large black button next to the activation button for the right thumb was to be a scale-reset button which enables the user to instantly change the note designation for the right finger buttons to a chromatic scale. Symmetrically on the left is an FSR for a volume effect. It was to decrease volume as it was pressed.

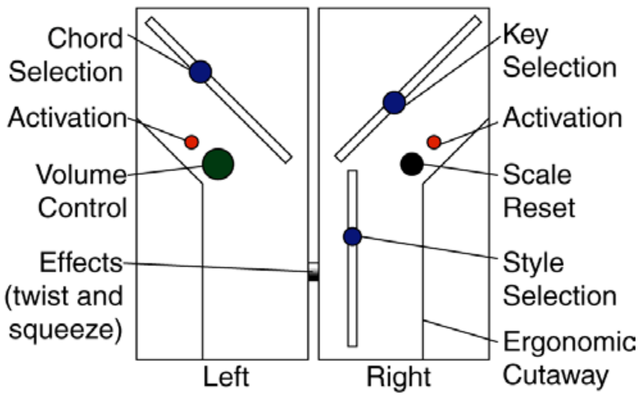

Figure 12. Thumb (back) side schematic of the initial setup

On the front side, there are four three-way momentary toggle switches for the left fingers. Each of these were to be assigned a sound effect, and used to select a sensor for controlling the effect; either the twist or the squeeze sensors at the center of the device.

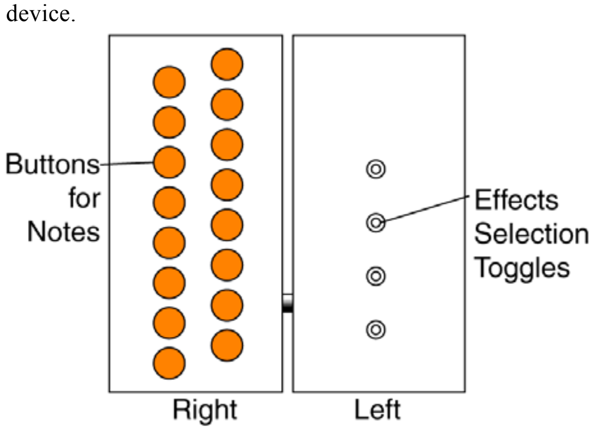

Figure 13. Finger (front) side schematic of the initial setup

5.2 Altered Setup

These four toggle switches turned out to be difficult to operate with fingers. They had to be pulled toward or pushed away from the palm, and the latter was especially difficult. The switches were also rather stiff. These switches were not employed in the final setup since it was found to be very confusing for the performer to alter the effects assigned to various sensors. Avoiding modes like this is recommended in HCI design in general [9]. The left fingers can instead be used to play notes like the right fingers by installing more buttons.

The key and chord selectors were not used during test trials. The key selector was left unused as no key change took place during performance. The chord selector was not needed since the melody buttons, controlled by the right fingers, could play chords. Instead of the initially intended applications, these two sliders were assigned to control more effect parameters.

As the result of the above changes, the two activation buttons were no longer necessary. Furthermore, the scale-reset button and the volume effect controller were never used. These input devices were not used in the final setup.

6. FINDINGS AND FUTURE IMPROVEMENTS

Future improvements are suggested from the experience of playing with the finalized setup. The musical setup, employing the style selection slider and numerous effect controls, was quite a success. Generally, more feedback is ideal in both physical and visual forms. Some mechanical improvement is also required for comfort and robustness. In addition, device-specific functional consideration would improve the quality of performing experience. Furthermore, there is the engineering task to make it a real portable device.

6.1 Feedback

Visual information feedback is necessary to show the style and key setup as well as any other parameters that may need indication. (Although the key control was eliminated in the final setup, it would still be a necessary function.) This would simply require a small LCD on the backside of the instrument.

Force feedback would be useful in some of the continuous effect controls. Passive feedback by springs might be sufficient for the application. Such a system can also help bring the effect control back to the neutral position.

The importance of tactile feedback was confirmed when operating the note buttons on the blind side of the instrument. For example, it would be very difficult to locate buttons if they were all flat. Alternatively, hand location with respect to the instrument may be realized by placing an indexing feature where the palm touches the instrument.

6.2 Mechanical improvement

The twisting pivot, which connected the right and left halves of the instrument, had a robustness concern. It was a rotary potentiometer and was not necessarily designed to bear load. A load isolation mechanism must be introduced to improve the structural reliability of the instrument.

The square Plexiglas construction is uncomfortable to hold. The material and the fabrication method constrained the instrument surfaces to be designed flat. Three-dimensional freeform manufacturing capability would greatly increase design freedom and the resulting ergonomics.

Sliders also had some usability problems. There was frictional resistance making the operation difficult when fast control was desired. The linear motion was also not very ergonomic for the thumbs. Instead, a curved pressure-sensitive touch-pad would be a nice replacement as there would be virtually no frictional resistance upon operation. It can also make better use of the dexterity of thumbs by added sensing dimensions: two- dimensional coordinates and vertical pressure.

6.3 Device-Specific Development

Currently, the various sound effects are arbitrarily assigned to the sensors on the instrument. As a result, the physical motion of the performer does not correlate with the resulting effects in any intuitive way. Hence, custom developed effects that relate intuitively to the physical actions are desired. For example, sound may be ”twisted” or “squeezed” by skillful multi-speaker output system.

6.4 Stand-alone

Here, the system required three separate components; the Bento-Box as the controller, a micro controller for data acquisition, and a desktop computer for sound generation. It would be desirable to integrate all of it so that everything will be enclosed in a Bento-Box size package for true portability.

7. CONCLUSION

A prototype for a portable handheld electronic musical instrument was successfully built. Its unique style selection capability allows the user to easily perform a variety of styles of music, which would otherwise have been difficult to learn. The initial motivation was to create a personal instrument to be heard only by the performer. However, the resulting instrument, with a rich capability to control various interesting sound effects, is fit for performing out loud along with other musicians. The design was done with mockup iterations and functional and ergonomic analyses, and has led to many interesting findings. The experimentation with the completed setup has inspired further improvements.

8. ACKNOWLEDGMENTS

I would like to thank my project teammates Seth Nickell and Katia Zarrillo for the collaboration, the class teaching team (Professors Bill Verplank and Max Mathews, TA’s Michael Gurevich and Wendy Ju) for giving me the opportunity, and Professor Mark Cutkosky and Weston Griffin for support in writing.

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