Chapter 11.

Early, Embroidered Musical Instruments

Introduction to *Embroidered Musical Instruments*

The development of *Embroidered Musical Instruments* fulfilled my desire to create a multi-channel, pressure sensitive[1] skin that I could wrap around any sculptural object. In addition to my early work in the *Brain Opera*, I was inspired to create these instruments by Gili Weinberg, who was writing interactive music software for the *Squeezable Cluster*[2], an instrument made from soft foam balls glued around a central core of

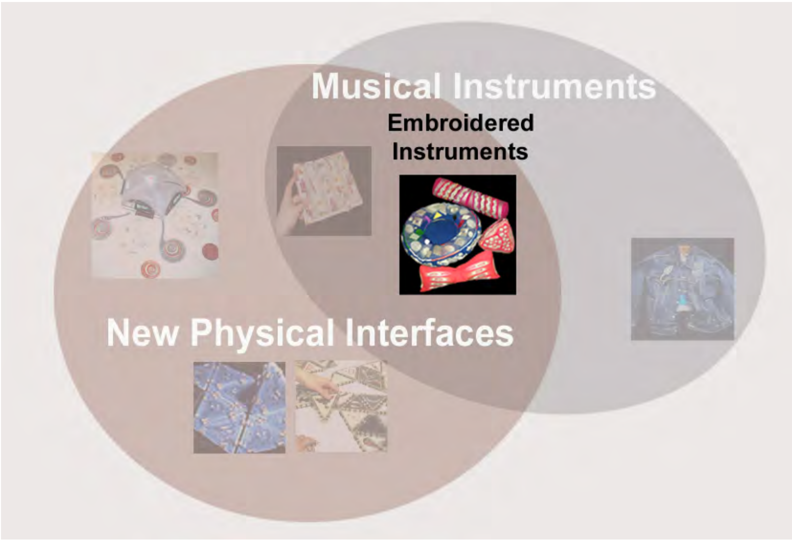

Figure 11.1 The *Embroidered Musical Instruments* within the Tree of Projects.

[1] See Chapter 13, Complex Impedance Sensing, for an explanation of what is actually being sensed in the balls.

2 Gan, Seum Lim, Sqeezables, Tactile and Expressive Interfaces for Children of All Ages, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, September, (1998).

electronics and commercial pressure sensors.[3] These sensors often failed and were bulky. I believed I could make a softer and more mechanically reliable version in textiles.

Physical Interdependency in the *Embroidered Musical Instruments*

Weinberg's first foam *Squeezable Cluster* was created to explore interdependency between sensors and its musical ramifications. Weinberg defines what he calls "internal interdependency"[4], or interdependency within a single instrument as using digital technology to map a single gesture or sensor input to various musical parameters.

"….players of most traditional instruments expect full control over precise musical parameters for every action they perform (from generating notes to articulation and expression marks). This autonomous control can be digitally enhanced by mapping one gesture to several, sometimes partly contradicting, musical parameters as well as by mapping different gestures to the same musical parameter. Individual interdependent musical connections allow gestures, which are being simultaneously controlled by other gestures or musical parameters, to control other musical parameters, or gestures."[5]

Figure 11.2 Gili Weinberg and Seum-lin Gan, *Squeezable Cluster*, 1998.

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[3] Descriptions from this chapter refer to:
Weinberg, G., Orth M., and Russo P., *The Embroidered Musical Ball: A Squeezable Instrument for Expressive Performance*, Proceedings of Conference on Human Factors in Computing Systems, (CHI 2000), The Hague, ACM Press, (2000).
[4] Weinberg, G., Expressive Digital Musical Instruments For Children, Thesis for the Degree of Masters of Science of Media Arts and Sciences at the Massachusetts Institute of Technology, Cambridge, MA, (1999).
[5] Ibid.

Weinberg also points out the difference between interdependency created in software and interdependency caused by hardware design. In the first foam *Squeezable Cluster*, the placement of sensors inside the ball meant that a player had to trigger more than one sensor simultaneously.

"Another factor that contributes to the complexity of the interdependent connection is the *Squeezable Cluster* hardware design. Since the instrument is held in both hands, it is relatively difficult to squeeze only one isolated sensor and to manipulate only one isolated arpeggio parameter. It is impossible to have a "non-squeezing" hand since each hand must provide contra force in order to allow for the other hand to squeeze in the desired axis. This contra force unavoidably exerts pressure on at least one additional sensor that manipulates at least one additional parameter. The placement of the sensors among the balls also contributes to the internal interdependency. The different angles at which the sensors are mounted make it difficult for the user not to trigger a cluster of neighboring sensors. Due to these factors, it is almost impossible to fully explore the *Arpeggiator's* parameters and to control them separately."

These ideas led me to the believe that I could make a variety of instruments whose physical design had a direct affect on what happened in music software, and that explored interdependency by looking at how different physical designs, shapes, sizes and sensor arrangements might create different types of forced, *physical interdependency*. In this thesis, I will refer to interdependency between musical parameters caused by physical design as *physical interdependency*.

From the Generic to the Specific:

Timeline of the *Embroidered Musical Instruments*

My first of group of *Embroidered Musical Instruments* was a series of technical and design experiments, which led to both the stabilization of the electronic embroidery for use as continuous, fabric sensors, and to the development of the *Generic Musical Ball*, my first neutral, design, control object. This stable, design control object became the starting point for the specifically *Shaped Embroidered Instruments,* which were designed to *physically* create different musical and sensing effects in software. In this second series of instruments, different sensor designs and shapes were explored extensively, and a clear relationship between the physical design and the musical software it controlled was established.

My first *Embroidered Musical Ball*, *Squiggle Ball 1*, (1998) was an effort to jump right into an exploration of physical form and its relation to software. Consequently, I started with a ball whose organically shaped sensors were highly varied in size and shape. But this was simply too confusing, both because the sensing and fabric electrodes were not robust, and because the design was so amorphous that one could not understand what was happening in software. In order to simply verify that the sensing was working clearly, the balls had to use a more simply designed ring of sensors, as in the *Circle Balls* and the *Generic Ball*. But that simple design was so neutral that it was not musical. Because of the size of the sensors, and their layout, the *Generic Ball* was only was good for

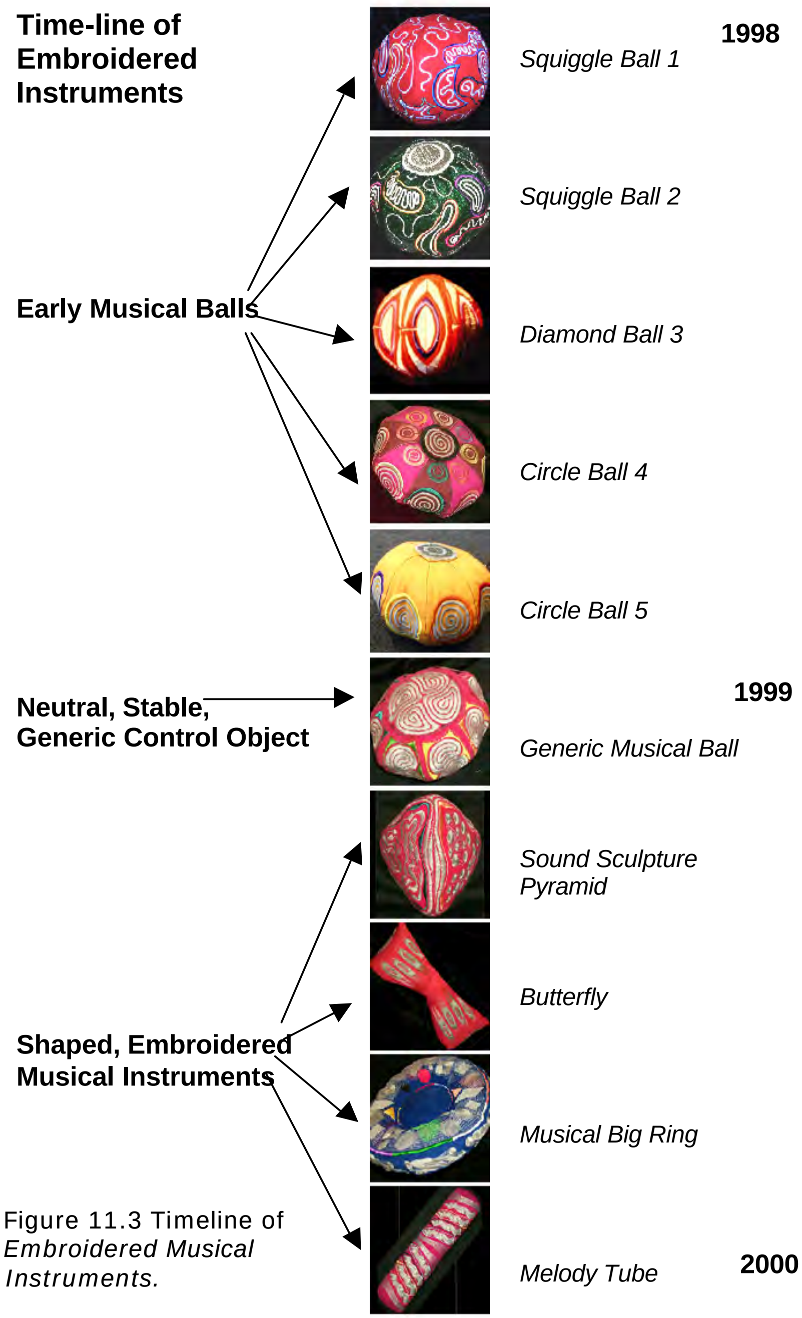

Figure 11.3 Timeline of *Embroidered Musical Instruments.*

trying each sensor individually. Its layout constrained players from using multiple sensors in different ways. However, it was stable and neutral enough that we could use it as a jumping off point for the *Shaped, Embroidered Musical Instruments*. Each of these instruments was *physically* designed to let players control its sensors in different ways. These differences in designs ultimately made each instruments more appropriate for a different type of musical software.

t is essential to emphasize that the design of the final *Shaped Embroidered Instruments* is not based on pre-planned ideas about how they would interact with specific software. During the design process there was lot of experimentation with different shapes and different software. In some cases, this led to a change in the instruments physical design, and in some cases it led to new ideas for software. This is not scenario driven design. With sculptable and direct materials we could sketch, experiment, find, and develop actual relationships between software and physical objects that were not merely imagined, and far richer than what could have been imagined without such an iterative and hands-on design process.

Embroidered Musical Instruments as a Smart Material System

Each *Embroidered Musical Instrument* contains eight embroidered pressure sensors, two ground electrodes, a central sensing circuit, (a PIC microprocessor and a few resistors on a circuit board), and a wired, serial connection to an off-board PC or Mac. Because the central processors, speakers, and synthesizers are

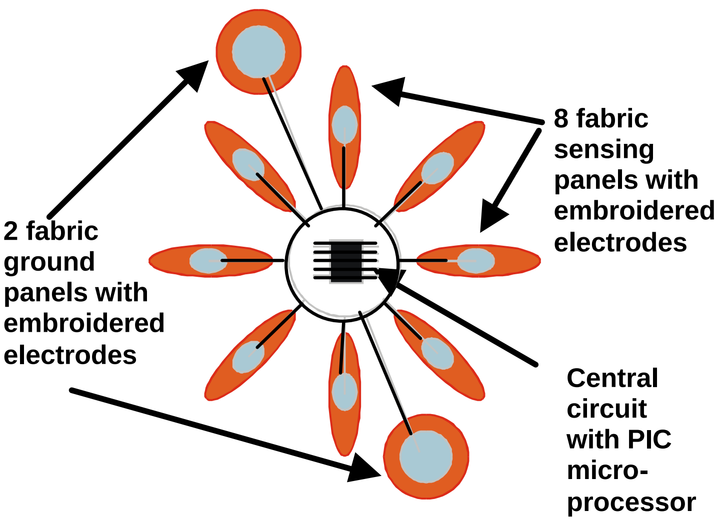

Figure 11.4 Diagram of a typical fabric pieces attached to central circuit.

located away from the fabric instruments, they remain very light, soft, and flexible. The textiles in the *Embroidered Instruments* were *smart or multifunctional* in that they were able to take over *most* of the remaining functionality required by the instrument. They function as pressure sensors, wires, connectors, and a soft, flexible, and durable physical housing. By connecting to entral circuitry and off-baosrd computers and audio gear, these smart textiles are part of a smart materials system.

The sensing in the *Embroidered Musical Instruments* is a significant advance over that done on the keypad in the *Jacket*. While the jacket could only sense on/off, these new *Embroidered Instruments* have continuous sensing, allowing players to experiment with a range of pressure, from soft to hard. Normally, continuous sensing in electronic instruments is accomplished with a number of bulky sliders, buttons, knobs, or bend sensors that are impossible to put into a single hand-held object. The fabric brought together all these bulky items, and their wire connectors into a single, integrated housing and sensing material.

For the fabric to sense continuous information (or what at this time was described as pressure) with embroidered electrodes, both the sensing and sewing technique had to be perfected. Accurate complex impedance pressure sensing on embroidered pressure sensors was achieved with new and improved circuitry, better microprocessor software, and the use of better conductive threads and sewing methods that made the sensing electrodes far more conductive, durable and consistent. These new sewing methods allowed for a

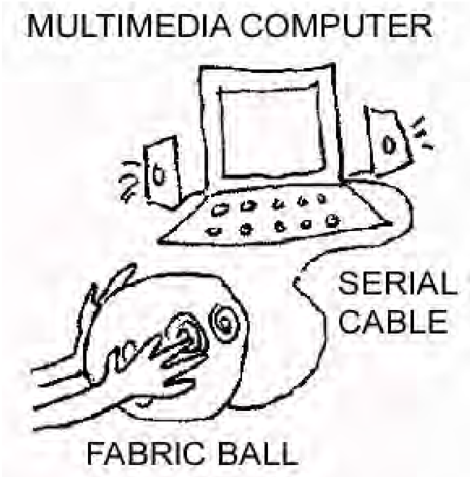

Figure 11.5 *Embroidered Musical Ball* attached to multi-media computer.

more direct relationship between the visual and tactile design of the sensors and their electrical properties.

The later *Embroidered Musical Instruments* also used a new, mechanically knottable and highly conductive braid to literally tie the electrodes electrically and mechanically to the sensing circuitry. This is a significant advance over the keypad in the *Musical Jacket* and *Tablecloth*, which were directly connected to the sensing circuit board, leaving only the top part of the keypad truly flexible. Moreover, this thread allowed a means for a quick and reliable mechanical and electrical connection between the fabric and circuit. This material was essential for easy iteration and experimentation on different musical instruments.

Early *Embroidered Instruments*

This chapter presents five early *Embroidered Instruments* (1998-1999) that lead up to the sixth and final instrument presented in this chapter, the neutral, *Generic Musical Ball*. These instruments represent a design journey from the chaotic and amorphous *Squiggle Balls,* to the regulated and cognitively clear, *Generic Musical Ball*. That journey was necessary for two reasons. Without clear sensor design it was not possible to test and stabilize the continuous sensing technique and electrode design. A clear design was also necessary to understand how the sensor design behaved in musical software.

Through direct observation, I learned that to improve the continuous sensing in the *Embroidered Musical*

Figure 11.6a, b Back of *Musical Jacket* keypad with circuit board directly connected to the fabric, by a mechanical/electrical connection made by a knotted yarn.

Instruments, far more conductive electrodes had to be sewn than of the *Electronic Tablecloth or Musical Jacket*. Finding a highly conductive, machine sewable thread was difficult. Gimped, or foil wrapped threads, stripped in the sewing machine. Threads with higher percentages of stainless steel jammed the machine. Eventually, highly conductive threads were tried the bobbin. This was significant because the bobbin puts far less mechanical stress on threads, allowing us to sew far less flexible threads.

The *Embroidered Instruments* in this chapter represent simultaneous experiments in electrode design, bobbin threads, panel design, and overall shape and form. At this point the design of the ground electrode also began to play a significant role. In the *Musical Jacket*, the player was grounded relative to the circuit through either the fabric bus, which ran across the back of the J*acket,* or a ground plane ironed into the back of the jacket. In the *Embroidered Musical Instruments*, the player's hands has to be directly in contact with a ground electrode as well as the sensing electrode. Consequently, strategies for properly placing the ground electrode and avoiding a short circuit with the sensing electrode became very important when designing the *Embroidered Musical Instruments* with continuous sensing.

Squiggle Ball 1*[*] with Composite Thread

This was the first fabric instrument that used embroidered pressure sensors. These sensors were

[*] In collaboration with Peter Russo.

high impedance electrodes (in the kilo-ohms), embroidered from composite stainless steel and polyester thread that was run through both the bobbin and needle of a commercial embroidery machine. The organic electrodes were shaped in an intertwining pattern in an attempt to create forced, *physical interdependency*. Their size was varied to explore how making one sensor bigger, and therefore more likely to be touched, would affect the music. The randomness of the pattern was an attempt to physically create a more intuitive and less one-to-one experience for the player, and *physical interdependency* between the sensors. The goal was to not to allow the player to immediately realize which sensor he or she was controlling, but instead to give him/her an immersive musical experience *immediately*. The design was also meant to allow an investigation of what happened when sensors were different sizes and shapes and had different physical relations to one another. Some sensors were closer together and even wrapped around each other.

The sensing in this instrument failed because of high electrode impedance. We knew that the high impedance electrodes were causing the problem because when Peter Russo and I originally tested the sensing microprocessor code and circuitry, we did so with perfectly conductive copper electrodes. As soon as we attached the circuitry to embroidered electrodes, we had numerous problems. The highly resistive sewn electrodes did not provide as consistent sensing results as the highly conductive copper ones. This led me to attempt to increase the conductivity of the embroidered electrodes to improve the sensing.

Figure 11.7 *Squiggle Ball 1.*

materials notes: BK(50/2).

Squiggle Ball 2 * with 100% Non-Continuous Stainless Steel Thread in Bobbin

The new sewing technique used in this instrument represented a major breakthrough in creating conductive electrodes. Until now, experiments in making highly conductive electrodes had focused on getting thread with higher conductivity through the needle. This was because the complex impedance sensing technique required players to come into DC contact with, (physically touch), the conductive surface of the embroidered electrodes. All of the highly conductive threads that we experimented with simply could *not* be sewn through needle of a sewing machine. They bunched, or their conductive wrapping stripped. During the development of the *Musical Jacket* we learned that using a conductive bobbin in conjunction with a conductive top thread led to far more conductive electrodes. Until now, we had used a highly resistive composite thread in both the bobbin and needle. But by placing a 100%, non-continuous, stainless steel thread in the *bobbin* we were able to mechanically sew a highly conductive thread and create an extremely conductive and stable electrode.

Unfortunately, the non-continuous, 100% stainless steel threads used in the bobbin also presented many problems. Because these non-continuous threads are made from very small pieces of ultra-fine stainless

Figure 11.8 *Squiggle Ball 2.*

* In collaboration with Peter Russo.

steel fibers, they were very fuzzy and had a lot of stray fibers. The stray fibers caused skin irritation for the person sewing the ball, and short circuits between the sensing and ground electrodes. On *Squiggle Ball 2*, the squiggly ground electrode, (which must be touched at the same time as sensing electrode), was shorted to the sensing electrodes by the stray fibers. To test the ball we disconnected the ground electrodes and grounded the player with a wrist strap. We could then see that the more highly conductive electrodes were far more responsive and consistent, than their restive counterparts. Eventually, two highly conductive metallic organza electrodes were sewn onto the top and bottom of the ball for grounding. These electrodes were created with an appliqué technique. While they were highly conductive they were also stiff, so I did not see this as a long-term solution to creating more conductive electrodes.

Even after the removal of the ground electrodes, stray fibers still created electrical cross talk between the sensing electrodes. This made it difficult to really see how the physical design and pattern of the sensors was affecting software. In addition, the electrodes on this ball spanned multiple panels, and there was no good way to electrically connect them. Between the inconsistent electrodes, the cross talk, and the amorphous design it was almost impossible to understand what was going on, either in the sensor design or the music.

materials notes: see BK(50/2) and 100 % non-continuous stainless steel.

Diamond Ball 3[*] with 100% Non-Continuous Stainless Steel Thread in Bobbin

This ball represents my first attempt to create a cognitively clear sensor pattern, and to integrate the ground electrode around the sensing electrode so that the two could be simultaneously touched with ease. Each embroidered internal diamond was a sensor electrode. The diamond-like pattern surrounding it was the ground electrode. All the electrodes were the same size, so that it was easy to observe if the sensing was consistent. The electrodes were also arranged evenly around the ball. Each sensing electrode and the surrounding ground electrode were sewn on a single panel. This helped reduce the possibility of cross talk between electrodes and also reduced the need to electrically connect parts of electrodes sewn on different panels.

I had hoped that by sewing a non-conductive satin stitch between the ground and sensing electrode, I could eliminate short circuits. Unfortunately, this did not work. While I was anxious to design a ground electrode that was more integrated into the final instruments, I realized that as long as I used this hairy thread, every electrode would have to be sewn on a separate panel, with lots of space in between, and lined. This was because a lot of stray fibers were released during the sewing process, so electrodes on the same panel tended to get shorted out.

materials notes: BK(50/2) and 100 % non-continuous stainless steel.

[*] In collaboration with Peter Russo.

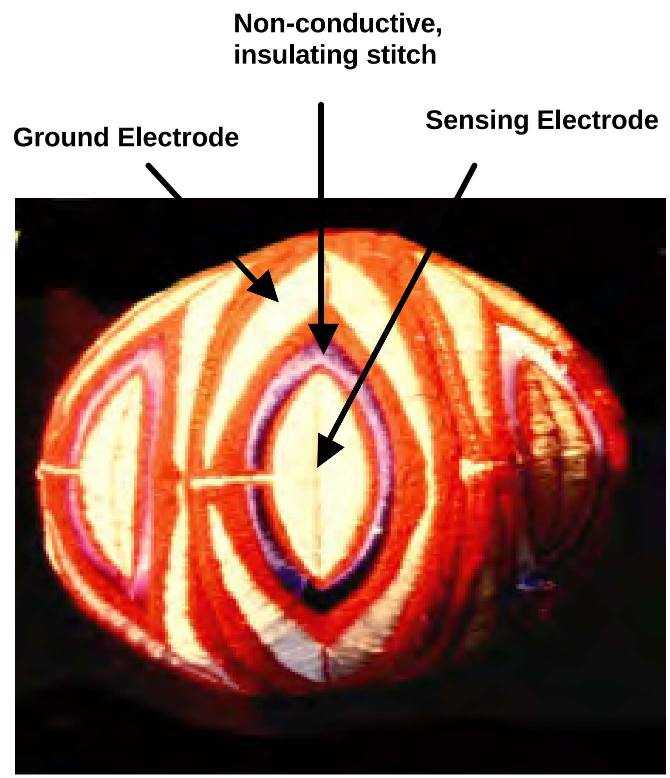

Figure 11.9 *Diamond Ball 3*.

Circle Ball 4 * with 100% Non-Continuous Stainless Steel Thread in Bobbin

The goal of this ball was to create stable electrodes for sensing on a single panel, and a clear, legible design to enable an understanding of their musical function and playablity. To solve the problem of short circuits between electrodes sewn with 100% non-continuous stainless steel, two steps were taken. Each sensing and ground electrode was sewn on a separate panel, so that any stray fibers that occurred during sewing could not spread between two electrodes. Each panel was also lined with cotton, to prevent stray fibers from *reaching out* and connecting to the fibers on other panels, after the instrument was assembled. To create a cognitively clear design for easy playability, eight identical sensors were evenly arranged in a ring around the outside of the ball.

This ball was technically very successful, but a few drawbacks remained. The hairy thread was difficult to work with because it was painstaking to prevent short circuits by lining, and the fibers still caused skin irritation for the machine operator. At this point, it also became clear that this sensing method required the player be very WELL grounded. This meant that the ground electrode needed to be very conductive, and carefully placed so that the player's hands were always in contact with it. Because the electrodes needed to be sewn on separate panels, it was difficult to place the ground in an easy-to-reach spot. To avoid possible short circuits, every electrode had to be on a separate

[*] In collaboration with Peter Russo.

GROUND ELECTRODE APPLIQUÉD FROM METALLIC ORGANZA FOR EXTRA CONDUCTIVITY

Figure 11.10 *Circle Ball 4*.

panel and evenly spaced, so I had little freedom to experiment with shape, size, placement or physical relationship of the sensors. I felt highly constrained as a designer.

materials notes: BK(50/2) and 100 % non-continuous stainless steel.

Circle Ball 5[*] with Wrapped Thread

This ball used the same electrode design as the previous ball, but replaced the hairy stainless steel bobbin thread with a very neat and highly conductive thread made from nylon wrapped with three strands of continuous stainless steel. While the conductors in this thread stripped and bunched when passed through a needle, they remained intact in the bobbin. The electrodes it created were very conductive and tidy.

Surprisingly, *Circle Ball 5* did not work as consistently as the *Circle Ball 4* with 100% non-continuous stainless in the bobbin. After experiments, it became clear that this was now a reflection of the area of the electrode. The hairy bobbin thread was fat and provided the electrode with a lot of conductive area. The player coupled to that area through the high impedance composite thread on the top of the fabric. While the thin continuous stainless steel fibers in the new nylon thread were highly conductive, they did not provide enough electrode area to couple to. This was particularly significant for the ground electrode, which was replaced by an appliquéd piece of metallic organza.

[*] In collaboration with Peter Russo, software by Gili Weinberg.

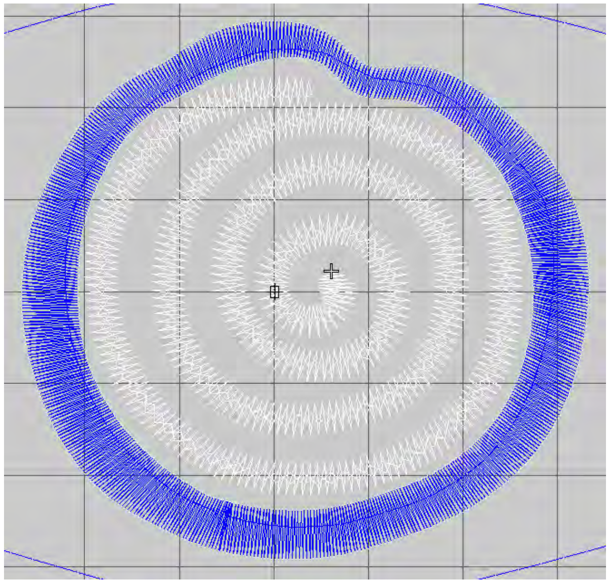

Figure 11.11 Embroidery CAD File of circle sensor.

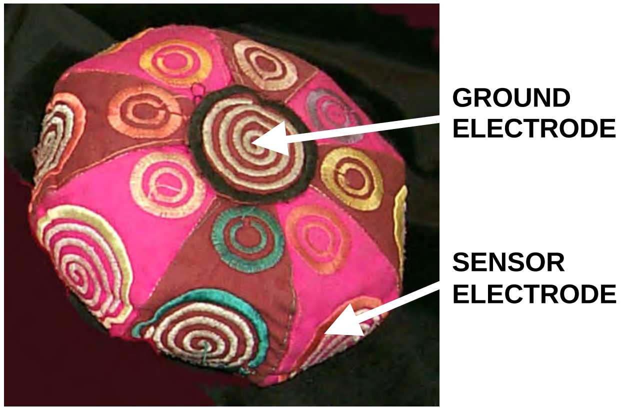

Figure 11.12 *Circle Ball 5.*

materials notes: BK(50/2) and nylon wrapped with continuous stainless steel.

***Generic Ball 6*✱: A Design Control Object**

This instrument is the final and stable *Generic Ball* from which later experimentation with physical form and software began. The clarity of the *Generic Ball's* physical design and sensor layout, and the technical success of its sensing, presented a clear jumping-off point for later instruments. The electrode design was both conductive enough, and had ample area to allow consistent sensing. The bugs in sensing circuitry had been perfected. The *Generic Ball's* clear layout of eight sensors around a large top and bottom electrode made it possible to think about the form of the ball in relationship to its musical applications. The sensors and ground electrodes were very large, guaranteeing that the player's hand could easily contact the two simultaneously. Each electrode had a different colored border, by which the player could identify it. Each sensor and ground electrode was sewn on a separate lined panel to prevent short circuits. To increase the area and stability of the conductor in the electrode, the electrodes were sewn in a very dense satin stitch, and as one continuous trace, in layers that build up over one another.

While the physical design of the ball enabled stable sensing through electrode layout and size, it also limited the expressivity and experimentation of the player. Because the sensing technique demands an

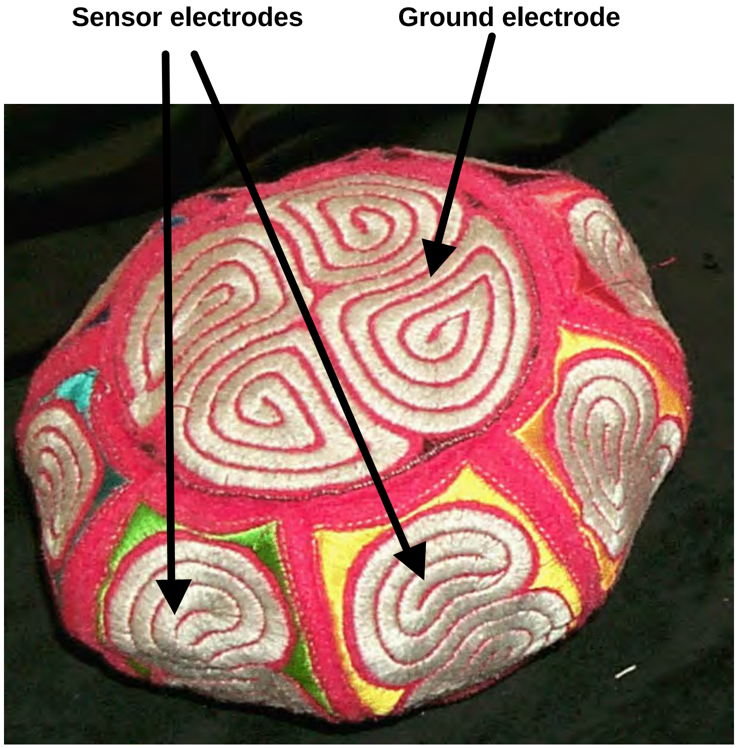

Figure 11.13 *Generic Ball 6.*

✱ In collaboration with Peter Russo, software by Gili Weinberg.

excellent connection to ground, the placement of the ground electrodes on any ball is essential to how it is played. While the size of the sensor and ground provided a good area for coupling, it also made it difficult to grasp a number of sensors simultaneously. With the *Generic Ball*, players could precisely control only two to four sensors at a time, with each hand touching ground and one or two sensing electrodes, simultaneously. With great effort, a player could play all the sensors on the ball and stay well grounded, but have little control over which one, he or she played, when. New players had to be taught how hold the ball to properly to get a contact with ground and the sensing electrode, simultaneously. In this way, the ball did not allow for as much immediacy and exploration of physical interdependency as had been hoped for. And while this new electrode design was very sensitive, they were also unfortunately stiff and dense.

Experimentation with the *Generic Ball* led to the desire to create specific balls for specific musical applications. The application that this ball played was a multi-track piece of pre-composed music by Gili Weinberg. Different sensors controlled the volume and timbre parameters of each track or voice. The ball allowed users to experiment with the mixing of the tracks, for instance bringing in violins, pianos or flutes, each playing different music. The physical form of the *Generic Ball* let players bring in and out one to four of these tracks with ease and control. It also let players bring in many tracks simultaneously with less control. As different applications were experimented with, it became apparent that the generic shape of this instrument, while good for experimentation, was not

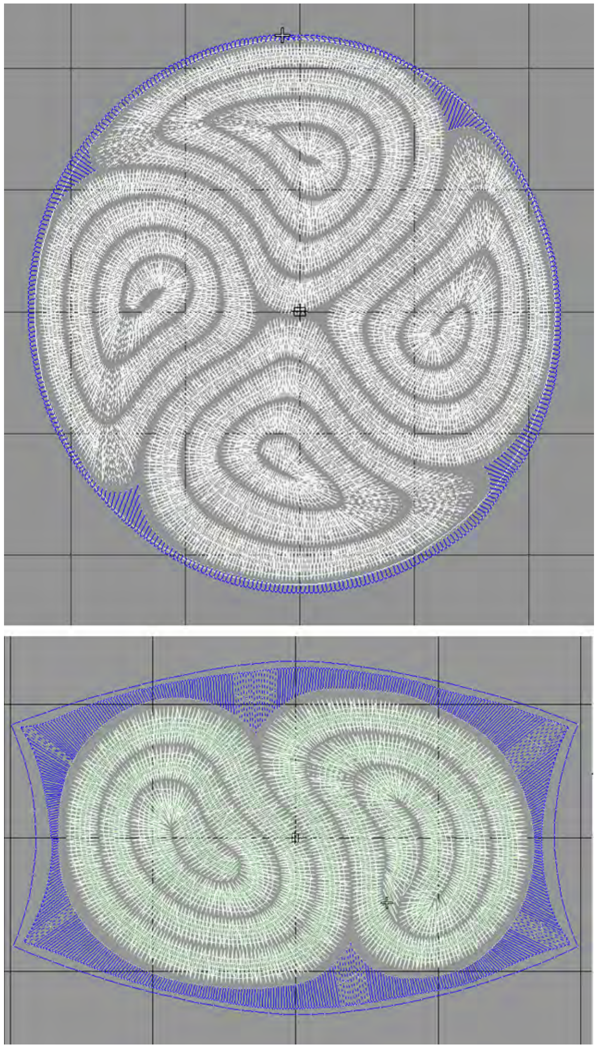

Figure 11.14 CAD file electrode design from *Generic Ball*. Ground Electrode is above and sensor electrode below.

suited well to any specific musical application. Exploring the relationship of the parameters mapped to the sensors was difficult. Because its form was symmetrical, players could not use shape to orient themselves while playing. The texture and shape of the sensors also did not inform the players in any way.

materials notes: BK(50/2) and nylon wrapped with continuous stainless steel.

Figure 11.15 Embroidered ground electrode from the *Generic Ball*.