Chapter 13.

Complex Impedance Sensing

Introduction to the Technical Story

The technical story of this thesis includes a timeline of developments in the sewing process, an index of electrically active textiles, a model of complex impedance sensing, and a definition and test for the sewabilty and flexibility of yarns with added conductive fibers. A summary of the technical contributions of this thesis includes various types of work, some of which is also explained in the project portfolio, rather than here in the technical story. These contributions include the first working prototype of a fabric keypad, a row and column switch matrix (with Emily Cooper), the first embroidered keypad, (with Rehmi Post). (I jointly hold a patent with Rehmi Post, Emily Copper and Josh

Smith on fabric circuit elements.[1]) After working to create the first high impedance embroidered keypad with Rehmi Post, (in the *Musical Jacket*), I further developed the embroidery and sewing process to create far more conductive and stable fabric electrodes, and sensors and circuit elements that were also soft, flexible and visually diverse. I directed and motivated the research that led to pressure sensing on fabric electrodes. I worked with Bekeart Corporation to create a new composite thread/braid that can easily tie an electrical/mechanical knot between a circuit and fabric electrode. (This yarn is now manufactured in small quantities by Beakart Co.) The machine embroidered electrodes and the knottable composite braid developed for this thesis both have been perfected to the point where the ultimate limitation on their conductivity is the fundamental conductivity of the cold-worked stainless steel. These two composite materials, (the machine stitched electrodes and the braid) combine high impedance textile materials with excellent mechanical properties, with low impedance materials that possess limited mechanical functionality. I created an index of electrically active textiles and described their mechanical and electrical properties. I also empirically developed an electronic model for understanding complex impedance sensing with fabric electrodes. This model provides support for the empirical observations made while designing the embroidered instruments and a guide for instrument design that enables better sensing. This model has

[1] Rehmi Post, Maggie Orth, Emily Copper, Joshua Smith, <u>Electrically active textiles and articles made therefrom</u>, US Patent# 6,210,771, (2001).

played an essential role in the design of my *Embroidered Musical Instruments*. I developed a definition and test for sewabilty and flexibility in conductive fibers. I co-invented and patented a new physical computing interface, the *Triangles*, and their new physical and electrical connector that allowed an immediate electrical and mechanical connection between two physical objects, specifically the *Triangles*.

Overview of the Sensing

This chapter presents a series of models, from simple to complex, of the sensing method used in both the embroidered keypads and *Embroidered Musical Instruments*. The sensing method used in all the *Embroidered Musical Instruments* is a measurement of the change in the RC time constant in an RC circuit. (Figure 13.2) The measurement is made in the time domain on a PIC microprocessor. The motivation behind creating these models was the empirical observations that I made while building the instruments. During this process, I noticed that measuring *pressure* required much more conductive electrodes, and a far more stable grounding of the player. It also required a *few black art* factors, like unwashed and warm hands, and lots of surface area and contact area. Understanding the role of these factors and the role of the human body in the sensing technique led me to look into a more precise model of the circuit and sensing method. My final model of the sensing circuit is based on a model of skin impedance from biomedical electrode technology. This model

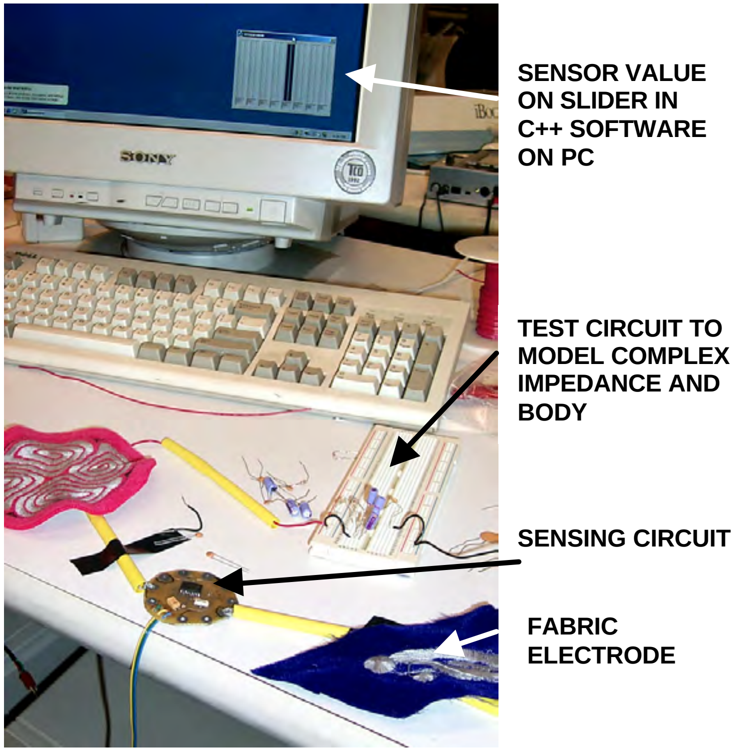

Figure 13.1 Mock-up of embroidered instrument and test circuit used to simulate the body, skin and electrode impedance.

demonstrates that the continuous measurement taken with the embroidered instruments is fundamentally a measurement of the change in skin impedance, and electrode to skin coupling. In the *Jacket*, this method is used to sense on/off. In the *Embroidered Instruments* it is used to sense a continuous measurement of *pressure*, or what I came to call *intimacy*. Empirically this appeared to be a combination of area of hand, area of electrode, pressure, temperature and conductivity of the skin and time.

All the *Embroidered Musical Instruments* use a similar central sensing circuit, which measures the change in the RC time constant and communicates that change serially to a PC. The PC maps the serial data to sliders and music software. The central circuit is tied to the embroidered electrodes with a low impedance stainless steel braid. All the models presented in this chapter were confirmed or discovered experimentally with the use of this same circuit. A mock-up embroidered instrument was built and connected to the C++ program, which mapped the sensor data to sliders. (Figure 13.1) The models of the body and skin were constructed in a test circuit and their effect on the sensing circuit was observed using the C++ software.

A Simple Capacitive Model

Simple Model 1 diagrams the player's hand in relation to the circuit elements. In this model, the internal body is modeled as a simple capacitor, which holds the charge in place, changing the RC time constant. The microprocessor measures change in the RC time constant by charging its pins to the upper TTL level

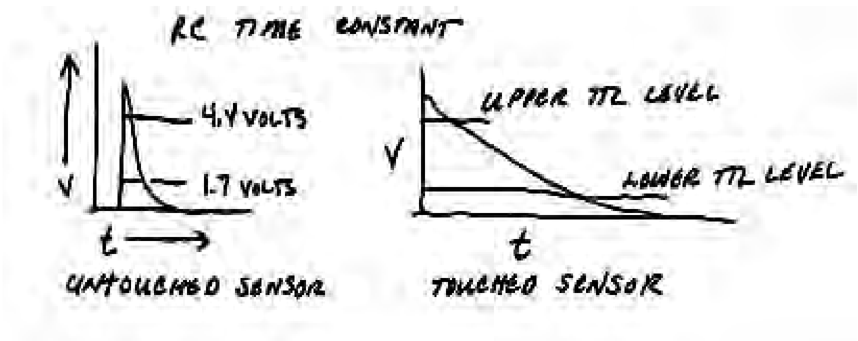

Figure 13.2 Change in RC time constant on touched electrode.

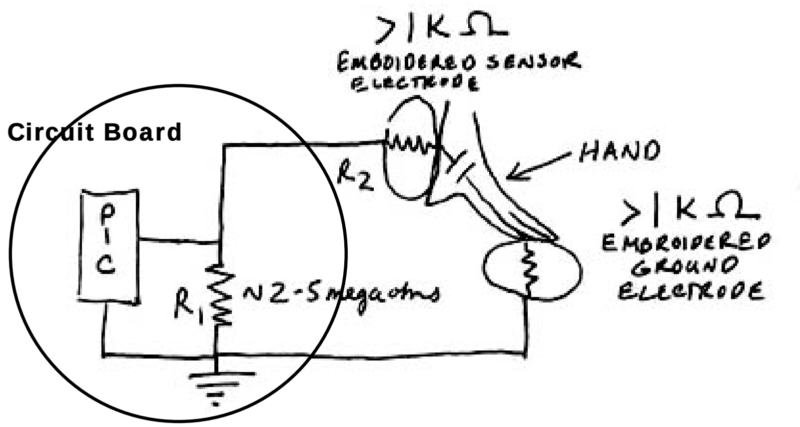

Figure 13.3 **Simple Model 1**, the body as capacitor.

and then watching until the charge or voltage level decays to the lower TTL level. (Figure 13.2) When the electrodes are touched the charge is held in place and the time constant increases. (Figure 13.2) If the time exceeds the normal time constant, it is assumed that the electrode has been touched and either an on/off switch is triggered, or measurement of the change in time is made.

When modeling the sensing method in the *Musical Jacket* it is possible to use **Simple Model 1** and imagine the body or hand as a capacitor. This is because ANY change in the RC time constant is valid to measure on/off and no continuous information is needed. Almost no environmental factors affect this sensing. Consequently, embroidered electrode resistances can vary up to 10K ohms.

Grounding Issues

On/off sensing in the *Musical Jacket* was functional when the player was AC coupled to ground. In the fully functional *Jackets*, (with MIDI synthesizer and speakers), this AC grounding between the sensing circuitry and the player was created by the fabric bus that distributed ground, serial, audio and power across the back of the jacket. In the *Buzzy Jackets*, (*Jackets* that had only audio buzzers directly attached to the sensing circuit), a fabric ground plane had to be ironed onto the back of the *Jacket* to establish a relative grounding between the players body and the sensing circuit. This is very different from continuous sensing, which requires direct DC coupling of the player's hand to the ground electrode to be effective.

What is Pressure in the *Embroidered Instruments*?

The *Embroidered Musical Instruments* measure pressure or continuous information by measuring the length of the RC time constant on the embroidered electrodes. This is not a forgiving process. Empirically, I observed a number of factors that directly influenced both the stability and the sensitivity of the sensing. (The stability refers to how *smooth* and continuous the measurement was, and the *sensitivity* refers to how quickly and easily the sensors reacted to the players squeezing.)

Black Art Sensing Factors

The *black art* factors that affected the continuous sensing in the embroidered instruments included:

- The contact surface of the electrode, or how much conductor the skin could contact easily due to the area and loft or fuzziness of the electrode.
- The area of the electrode.
- The conductivity of the electrode.
- The temperature of the player's skin.
- How recently the player had washed his or her hands.
- The part of the hand used to touch.
- The individual player.
- The quality of the grounding to the player.
- The time that the player was in contact with the electrodes.

Creating a more stable and reactive sensing process involved manipulating all these factors. It is worth noting that predictably, the sensitivity of the circuit increased when the pull down resistor increased in size from 2 to 5 mega ohms. However, the instability or noise in the circuit increased also. Using a larger pull down resistor is an important design strategy when designing electrodes with smaller areas.

While building the *Embroidered Musical Instruments*, I noticed that decreasing electrode resistance and increasing area improved the sensitivity or the reactiveness of the sensor. Over time I began to wonder why. If the rate of decay is *related* to RC directly, then why does the RC time constant increase when the resistance of the electrodes (R2 in **Simple Model 2)** decreases? I also wondered why decreasing the resistance on the electrodes increased the stability of the sensing technique. **Simple Model 2** takes into account the resistance of the embroidered electrodes in the circuit. From this model I began to wonder where the continuous measurement came from. Certainly when a player squeezed the ball the RC time constant increased, but what did that mean? If the internal capacitance of a person's body is fixed, what was changing the RC constant when the ball was squeezed? Observation led me to believe that this measurement was a matter of contact. The better a person was in contact with the sensor, the longer the RC time constant and the more "pressure" was read. I defined contact as the area of the hand on the electrode, the time it was on the electrode and the quality of contact, i.e. the temperature of the hand, sweatiness and saltiness.

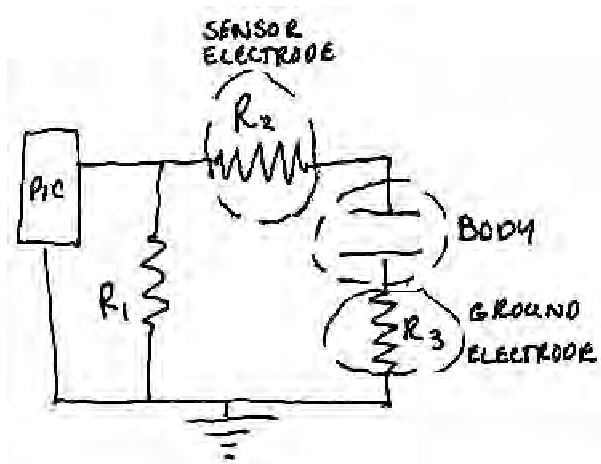

Figure 13.4 **Simple Model 2**, electrodes in series, body as capacitor.

Test Circuits

The following test circuits were built to model the body and skin and placed in the ball circuit to observe their results. The first test circuit that I placed in the *Embroidered Instrument* circuit was designed to understand the capacitance and/or complex impedance of the body. I started with a test circuits of the internal capacitance of the body. On the LCR meter the Cs and Rs (series resistance and capacitance) measured .5 pico farads and 10-100 kilo ohms respectively. According the Joshua Smith, the internal resistance of the body (beyond the skin) as practically zero and the internal capacitance of the foot as large as hundreds of pico farads.[2] In **Test Circuit 1**, with a capacitor in series, a minimum capacitance of 360 picofarads was required to change the RC time constant. The sensors reached their maximum range at 1200 picofarads. Varying the size of the capacitor varied the RC time constant. It is highly significant that NO sensing was accomplished when the body was modeled with ANY parallel resistance, (see **Test Circuit 2**).

Test Circuit 3 involved modeling the skin impedance, skin to electrode contact impedance, and electrode resistance as a simple resistor and varying that resistance. This model confirmed my observation that decreasing the resistance on the electrodes increased the sensitivity or change in the RC time constant. The lower the resistance of R1 and R2, the more sensitive

[2] Smith, J., Electric Field Imaging, Thesis for the Degree of Doctor of Philosophy, at the Massachusetts Institute of Technology, Cambridge, MA, (February, 1999).

C > 360 pico farads
C < 1200 pico farads

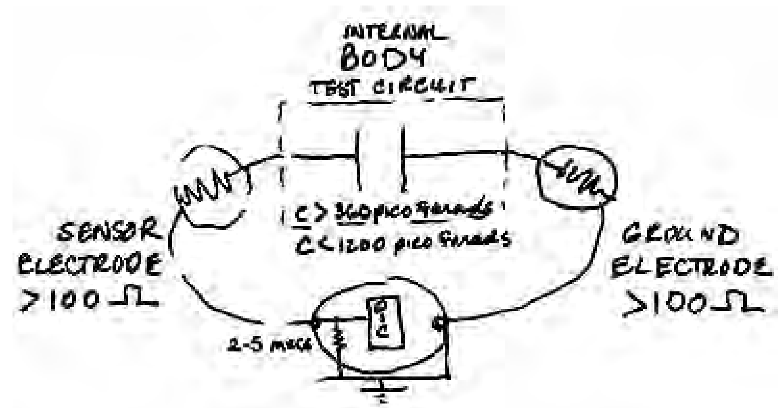

Figure 13.5 **Test Circuit 1**, the body as capacitor.

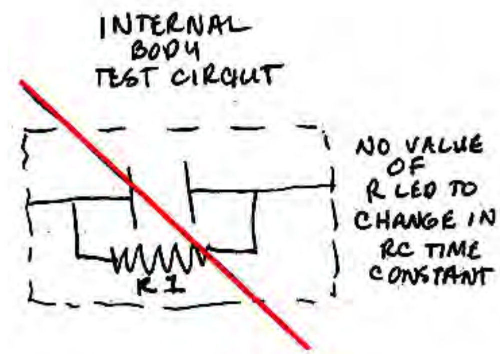

Figure 13.6 **Test Circuit 2**, the body as complex impedance.

the circuit was to lower capacitances in series. Larger body capacitances, (modeled with a real capacitor), were required to activate the sensor if large resistances were in place. Given a constant body capacitance of less than 1200 pico farads, (required for the maximum sensor value), the resistor values that affected the circuit behavior ranged from 1 K on both the ground and sensor electrode, for a minimal decrease in the RC time constant, to 13 k for the maximum.

This circuit also showed that the two embroidered electrodes (ground and sensor), could be modeled as a single resistor in series with the capacitor (the body), (**Test Circuit 4**). It is significant that a full range of sensing values could not be achieved with this sensing method without a DC connection to ground. An AC coupling to ground of the player only allowed for a small variance of the RC time constant. This circuit also demonstrated that as the resistance of the electrodes increased, the instability, i.e., jumpiness of the measurement also increased.

While modeling "what was going on between the skin and the electrode" as a resistor initially worked, further consideration led to thinking about it as a complex impedance. I also began to wonder which of the two were varying, the body capacitance or the series impedance? At this point I was excited to discover that models of skin impedance and skin to electrode impedance created for the biomedical industry supported much of my empirical findings. Figure 13.9 shows Swanson and Webster's Model for Skin

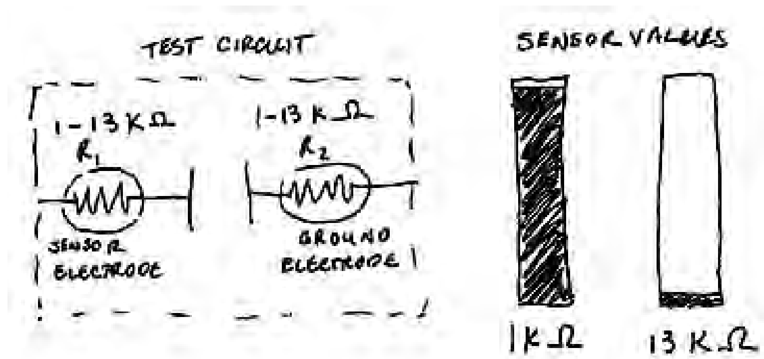

Figure 13.7 **Test Circuit 3**, skin to electrode as simple resistor. The greater the resistance, the less sensitive the sensing.

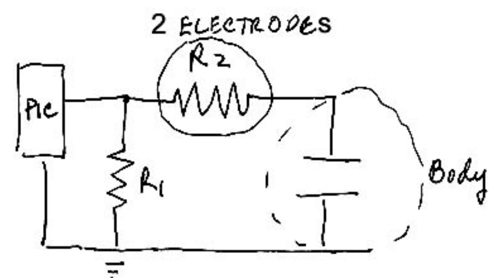

Figure 13.8 **Test Circuit 4**, the two electrode impedances are modeled as one.

Impedance[3] designed for biomedical electrode technology. This model shows a complex impedance between the skin and the electrode and in the skin itself.

Swanson and Webster also list the factors affecting skin impedance as: “electrode paste concentration, emotional state of the subject, current amplitude, skin abrasion, electrode area and sweat.”[4] These factors align extremely well with the empirical observations that I have made about improving the sensing technique. Moreover, they point out that most of the impedance takes place in the epidermis, and that it can vary widely depending on the thickness of skin. Their model discounts the impedance of electrode to skin because of use of a highly conductive paste. My model has no paste, and this impedance must play a more substantial role.

Figure 13.12 shows the role of the body and skin impedance in the embroidered musical instrument circuit. Figure 13.10 reduces the electrode, electrode to skin impedance and skin impedance to a single impedance Z. This reduced model demonstrates the 2 possible variables in the circuit, the complex impedance Z and the internal capacitance of the body. The fact that body size and proximately to the sensors are constant as well as my own empirical observations

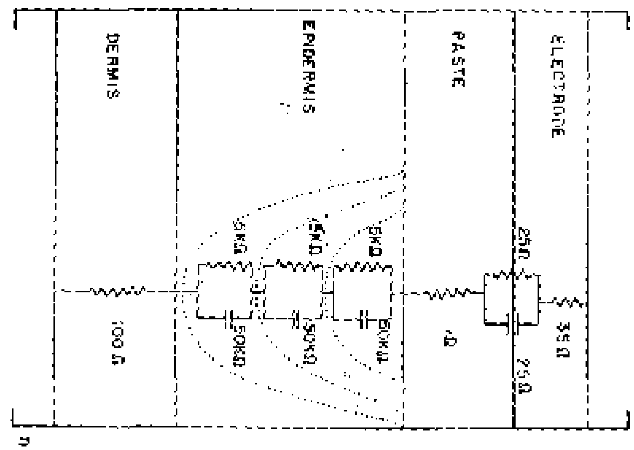

Figure 13.9 Swanson and Webster’s Model for Skin Impedance.

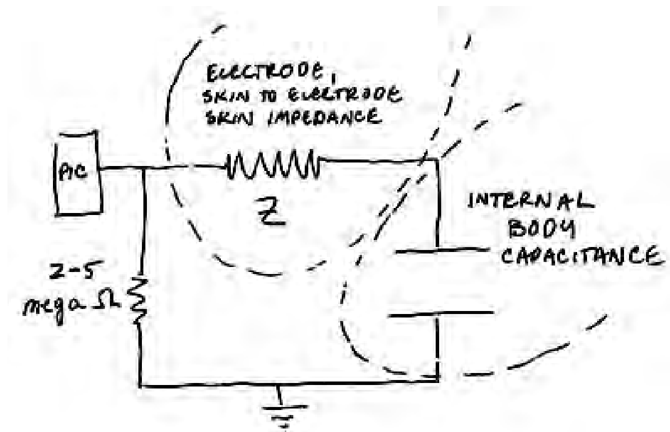

Figure 13.10 Complex Impedance of skin, skin to electrode, and electrode reduced to single impedance Z.

[3] Swanson, D.K. and Webster, J.G., *A Model for Skin-Electrode Impedance*, in Miller, H.A. and Harrison, D.C. (eds.), Biomedical Electrode Technology: Theory and Practice, New York: Academic Press, (1974).
[4] Ibid.

leads me to conclude that Z is the fundamental variable in this circuit. The reduced model is useful for understanding why decreasing the electrode resistance increased the RC time constant. If we model Z as R2 we find that a simple voltage divider has occurred. (Figure 13.11)

$$VR1 = \frac{R1 * vo\ e^{-t/rc}}{R2}$$

This equation points out the inverse relationship of R1 and R2 to t, supporting my observation that R2 must be reduced.

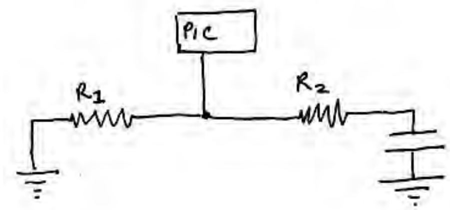

Figure 13.11 Circuit as voltage divider.

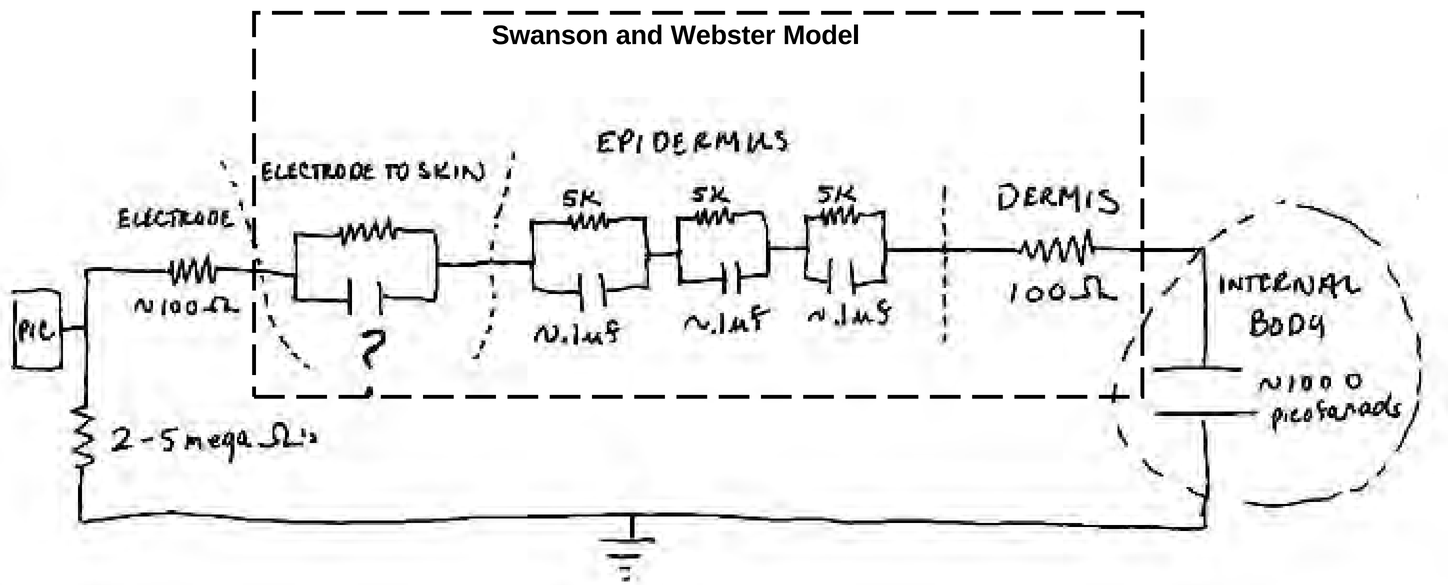

Figure 13.12 Final model of sensing circuit with skin and body.

Design Implications of Sensing Model

The consequences of using the skin impedance model for this type of sensing are significant to both the physical design and software of embroidered instruments. Clearly, electrodes must have a large area and lots of conductive material to touch. An excellent DC coupling of the player to ground must also occur when the ball is first touched. The ground must therefore, be touched immediately by the player when he or she grasps the instrument. Given the SIGNIFICANT role that skin impedance and skin to electrode impedance plays in this model, it is important that the design of such instruments does NOT constrain the placement of players' hands, nor require specific parts of the players hands, like fingertips to play specific sensors. Due to calluses, each player may have different areas of skin on his or her hands that are more conductive. He or she must be able to experiment with hand placement to see what type of squeezing works best. Usually, the whole palm and multiple fingers work far better than single fingertips. Thus, it is important to make instruments that use a *natural squeezing style* for playing, rather than finger-by-finger control.

The requirements of reducing skin impedance result in two classes of instruments with different physical designs, and different music software styles. These two instrument styles are clearly represented in the final *Embroidered Instruments* designed for this thesis. They include large sensors for precise, single parameter control, and smaller sensors that explore physical interdependency.

Large Sensors for the Precise Control of a Limited Number of Musical Parameters

Large sensors enable the precise control of one or two parameters at a time. Because large sensors reduce skin impedance, they provide stable sensing and more precise control. Consequently, they are better for direct one to one mapping to a musical parameter, like volume. Large sensors also require a smaller pull down resistor, which introduces less noise into the sensing process. Because the sensors are large, they do not let players trigger more than one or two at a time. As a result, they are not good for exploring the interdependency of many musical parameters. (The *Big Ring* is this type of instrument.)

Small Sensors for Intuitive Exploration of Numerous Interdependent Musical Parameters

The second instrument style has small sensors that explore interdependency. Small sensors are less stable because they require a larger resistor to ground to increase sensitivity. But small sensors let players trigger many sensors at a time. By using the less stable sensors to explore interdependency, some of the sensing instability is masked. (Both the *Melody Tube* and the *Sound Sculpture Pyramid* are this type of instrument.)

Software Filtering*

The artifacts created by both the skin impedance and electrode to skin impedance can be relatively easily filtered in software, using a variety of methods. The method that is currently used is a weighted average. The last ten sensor values are stored in a buffer. They are averaged. They are then added to the latest value in the buffer and averaged again.

N= array of values in buffer
X = New data
Nav = average of values N

Filtered value = (Nav + x)/2

This method smoothes the sensing noise and provides a limited lag in the filtered values over the raw values.

Given the fact that some players are not as reactive as others (either a function of their skin impedance or their body's capacitance), a calibration technique in higher-level software has been designed. This technique changes the maximum value of the sensor form 128 to a lower number, such as 40. While some resolution is lost with this technique, it is very helpful when working with children, who have small hands and bodies.

Beyond The Resistive Element

The artifacts produced by measuring skin impedance in the *Embroidered Musical Instruments* led to the

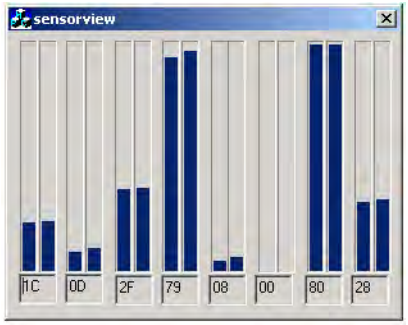

Fig. 13.13 Filtered sensor data on left next to raw data on right.

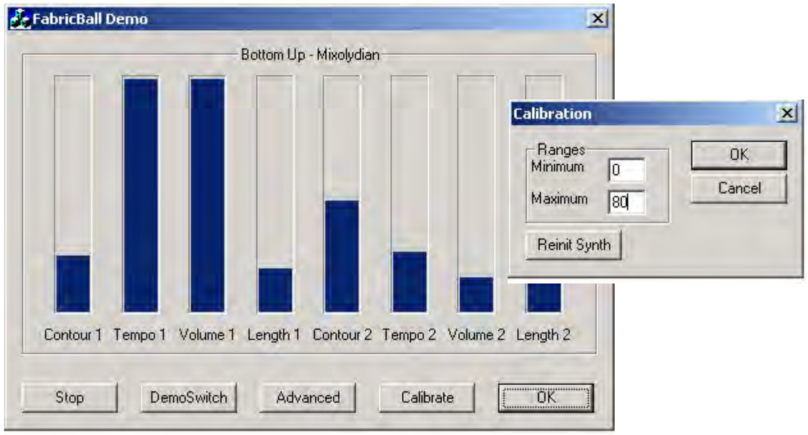

Fig. 13.14 Eight sliders of data and C++ calibration software that lets the player choose the maximum value best for him or her.

* In collaboration with Alejandro Sedeno.

question of whether it would be possible to make a continuous, pressure or contact based measurement on the fabric electrodes that produced fewer artifacts as result of skin impedance. There is a broad history at the lab of continuous measurement in the capacitive realm for non-contact based measurement, using a variety of “Fish” sensors.[5] To better understand this problem, a network analyzer was used to look at the frequency response of the fabric instruments when the hand is in contact with the two electrodes. This analysis was meant to look at whether it would be possible to reduce the skin impedance noise in the circuit by sensing at a higher frequency, and whether continuous sensing of contact or pressure, vs. non-contactor gestures, could occur at a higher frequency. The following images and diagrams are a result of an analysis of frequency response using the geometry shown in Figure 13.15.

Frequency Response Across Skin and Fabric Electrodes

The network analyzer was used to look at the frequency response of the real and imaginary impedance and the log magnitude and phase in the fabric instrument circuit. The following images are from a frequency sweep from 50 Khz to 10 Mhz. (Figure 13.16) A strong circuit resonance appeared at approximately 6Mhz. This resonance is related to the electrode geometry and changes with different

[5] Smith, J., Electric Field Imaging, Thesis for the Degree of Doctor of Philosophy, at the Massachusetts Institute of Technology, Cambridge, MA, (February, 1999).

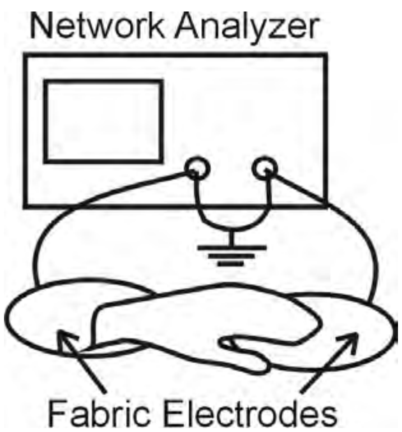

Figure 13.15 Geometry of the sensing circuit used to analyze frequency response.

electrodes and different relationships between the electrodes.

Three basic hand-to-electrode configurations were tried. The first was with no body or hand in the circuit, the second was with the hand just above the surface of the electrodes, and the third was with the hand on the electrodes. Significantly, there was little imaginary impedance response in the non-contact sensing regime (square 1, Figure 13.16), for frequencies below the circuit resonance, or less than 4 Mhz. There was however, a significant imaginary impedance response when the electrode was touched (Square 2, Figure 13.16). This implies that it might be possible to measure pressure on the fabric electrodes by designing a circuit that would look only at the imaginary component of the complex impedance of the skin. The advantage of looking at only the imaginary component of the complex skin impedance would be that it might eliminate the resistive artifacts of the skin impedance.

In retrospect, this makes sense. I have spent a lot of time trying to remove the resistive component of the RC time constant by reducing the resistance in the fabric electrodes. It would make more sense to simply ignore this component and measure only the imaginary impedance in a new circuit. Such a circuit would have to take into account the geometry of each instrument to avoid the unique resonant “bump” that each electrode design creates.

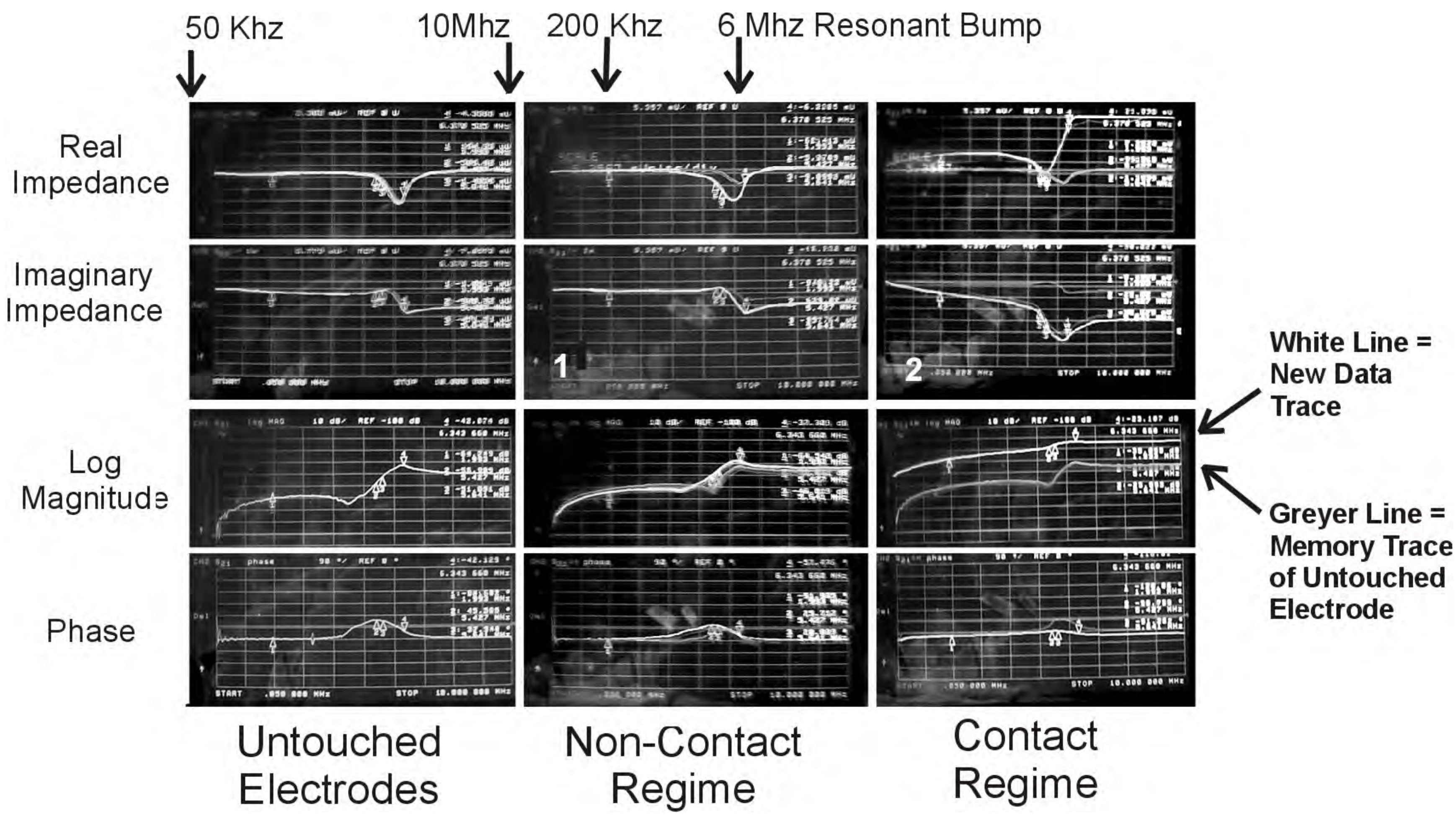

Fig. 13.16 Frequency response in *Embroidered Musical Instruments.*

Conclusions

The assertion that the *Embroidered Musical Instruments* are fundamentally measuring complex skin impedance strongly supports my empirical observations that the current sensing method primarily senses skin contact, or *intimacy* with the sensors. It supports my observations that decreasing electrode resistance, increasing electrode area, and increasing the surface area for contact (the amount of fuzzy conductive thread on the surface of the electrode), all improve the reactivity and stability of the sensors. It also supports my observation that if player's hands are cold, the instrument was less reactive. (Cold is sited as reducing skin impedance.[6]) Slightly more mysterious was the fact that recently washed hands worked badly. But rubbing players hands with salt created more sensitivity in the circuit. It can therefore be assumed that washing the player's decreases salt and increases skin impedance. This model also supports the mysterious observation that SWEATY hands work poorly. According to Webster, sweat decreases skin impedance. Therefore sweaty hands should make the embroidered instruments more sensitive. However, the circuit model demonstrates that sweat on the hands may cause a resistance parallel to the capacitance of the body. The absorption of sweat by the fabric actual creates a resistance parallel to the body's capacitance to ground. (Figure 12.) It has been demonstrated

[6] Swanson, D.K. and Webster, J.G., *A Model for Skin-Electrode Impedance*, in Miller, H.A. and Harrison, D.C. (eds.), Biomedical Electrode Technology: Theory and Practice, New York: Academic Press, (1974).

earlier in this chapter that such a parallel resistance prevents the sensing technique for operating.

This model does not explain the artifact of time in the sensors. When a player touches the sensors, even if he or she squeezes no more tightly, the sensor value will rise steadily. I have attributed this to a charge build up on the electrode, based on the fact that it does not return to ground, but only the lower TTL level.

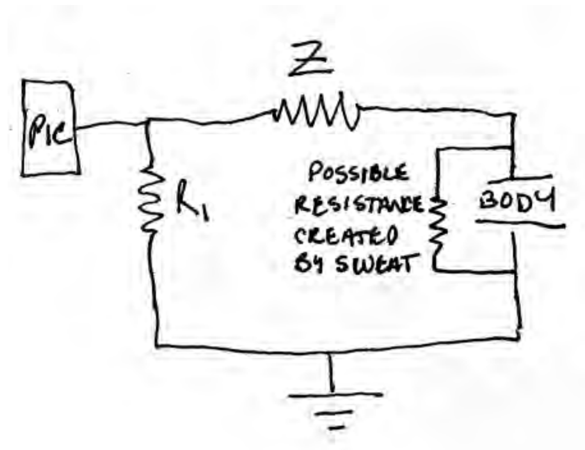

Fig. 13.17 Parallel resistance caused by sweat, which interferes with the sensing process.