Robust and Reliable Fabric, Piezoresistive Multitouch Sensing Surfaces for Musical Controllers

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ABSTRACT
The design space of fabric multitouch surface interaction is explored with emphasis on novel materials and construction techniques aimed towards reliable, repairable pressure sensing surfaces for musical applications.

Keywords
Multitouch, surface interaction, piezoresistive, fabric sensor, e-textiles, tangible computing, drum controller

1. INTRODUCTION
Multitouch array sensing with flexible substrates has been experimented with in the last three decades primarily for robotics and medical sensing applications [28]. Most of the research has been on core sensing and materials questions. The novel contributions reported here primarily involve the integration challenges of flexible surface sensing for musical controllers where reliability, repairability and robustness have to be addressed in addition to the sensing and materials challenges. These less glamorous issues have been mostly ignored in academic and hobbyist music controller designs that are rewarded more for apparent "novelty" and potential than long-term viability. We suggest that the "New" in NIME also refers to the experience for the performer that their controllers perform "like new" every time they play them–for decades to come.

We focus here on piezoresistive, multitouch sensing surfaces because the popular capacitive multitouch systems [15] do not provide sufficient taxel pressure resolution for musical applications. CNMAT's work for guitars [40] with Tactex Controls Inc. on the Kinotex [18] optical cavity sensing approach proved too difficult to scale to the high taxel counts required to capture nuanced musical gestures over large surfaces. FTIR optical surfaces have been developed with pressure sensitivity but they require bulky camera systems and have limited sensing bandwidth due to the slow frame rate of the cameras [32]. Systems fusing muscle sensing with surface sensing show some promise but the long reported latencies [2] (150ms) preclude them from most musical applications.

2. History of Piezoresistivity
Piezoresistivity, the modulation of electrical resistance according to stress, is observed in elemental materials, semiconductors and composites. This property has been exploited in sound and musical applications for well over a hundred years although it wasn't necessarily understood as such in earlier times [33].

A significant application of piezoresistivity in audio is Alexander Bell's microphone using carbon rods under strain. The subsequent commercial success of the telephone resulted in numerous refinements of carbon-based piezoresistive microphones from Edison, Berliner, Blake, Hughes, Hunnings and White and others. By the late 1800's piezoresistive microphones and liquid/conductor current modulation were broadly understood by engineers and were techniques used routinely in early electronic musical instruments.

Singer's 1893 patent [31] is important because its single claim is a carbon-based piezoresistive sensor for keyboard musical instruments. This patent signals the use of carbon granules in an elastomeric substrate (rubber in this case) a technique still widely-employed and for which patents are still regularly issued, e.g., US6820502 [34] (with no less than 80 claims).

The application Singer proposes is also congruent to established musical interaction design patterns [38], i.e. where sound dynamics are controlled by surface pressure gestures.

Piezoresistive pressure sensing techniques can be found in new electronic musical instruments and controllers throughout the twentieth century, and to the present day where they appear commercially at the rate of several products each year. There isn't enough space here to survey them all properly –a search in European patent listings resulted in over 50 entries for musical instruments employing resistive sensing. We should however mention that the expressiveness valued in the early instruments of the field, the Ondes Martenot [17], Heliphon [11] and Trautonium [35, 36] is attributable to their use of resistive pressure sensing to control sound dynamics.

In 1982 Franklin Eventoff introduced Force Sensing Resistors (FSR); printed piezoresistive sensor assemblies designed with musical applications in mind [7]. His firm developed low-cost, high volume manufacturing techniques for printing conductive ink and piezo-resistive polymer matrices onto plastic substrates. These devices are routinely used in NIME projects [16]. The advantage of using manufactured sensors is that they can be replaced from readily available spares instead of being repaired. This same may be said of steel and nylon guitar strings, for example.

When the Ondes Martenot touch key no longer performs as the player wishes they have to remix a new batch of a "magic" piezoresistive concoction (carbon and mica) that is placed in a leather sensing bag under the key [10]. This is an example of how the design of musical instruments assemblies involves deciding whether they are to be adjusted, repaired or replaced by the performer, a "technician", a luthier or at a factory. The concept of Mean Time To Repair (MTTR) is useful here. A common design pattern is to place the repair, tuning and replacement of the most fragile or stressed components in the hands of the performer. The oboe is an interesting case because of the high skill level required to construct a reed that is discarded–often after only a few hours of use. The Ondes Martenot touch key does not have to be replaced often but now there is such a small network of technicians that the replacement task defers to performers.

This paper will focus on design choices for piezoresistive multitouch surfaces driven by considerations of robustness and repairability and consistency of performance with the intention of guiding the development of instruments that can be played and maintained for the lifetime of the performer and beyond.

3. Materials

The core sensors we introduce are built from piezoresistive non-woven fabric from Eeonyx [8] and a new conductive, composite thread spun from silver-plated copper wire and polyester yarn [20-23].

3.1 Piezoresistive Substrate

Conductive-polymer-infused, non-woven fabrics have been refined by Eeonyx to minimize hysteresis and provide uniform resistivity with long-term stability. We rejected the option of conductor-loaded elastomeric materials (such as Zoflex [19]) because they exhibit higher hysteresis than fabric and paper and the conductor-loading considerably weakens the material–a concern in high impact situations such as drumming. Carbon-loaded paper has been proposed for these applications [14] with the idea that it so cheap that it can be simply discarded and replaced as needed. This may be true for a single point pressure sensor but it isn't for large-taxel-count multitouch where connection and integration costs far outweigh material costs.

Although there are indications that paper sensors give comparable performance to fabric, such experiments were done in laboratory conditions with fresh materials. An advantage of fabrics is that they can be engineered from a wide variety of base materials to last longer and be less susceptible to environmental and insect damage than paper.

Fabrics can be stretched and compressed making it possible to fit them to a broader class of surfaces [37] than paper which is limited to developable surfaces (Guassian curvature 0).

3.2 Robust, Solderable Conductive Thread

Piezoresistive materials may be sensed either by sandwiching them between two conductors or laying them onto a interdigitated grids of conductors. The designs proposed here use the former approach rather than the latter because it scales well to large taxel counts. This is because conductors can be simply arranged in parallel lines in orthogonal directions on each side of a piezoresistive patch of fabric.

Numerous choices for conductors in this application have been explored. We have chosen to use conductive embroidery thread because unlike printed silver inks, for example, threads can be easily repaired with readily-available tools and moderate skill level. With fabric and thread the core geometry of the instrument can be determined by the performer – just as the reed is customized by each oboe player.

This customizability is also valued in the wearable electronics field. Although suitable for quick exploratory prototypes, we have learned we cannot directly adopt the readily available materials and components from the hobbyist e-textile and wearables community such as the Arduino Lilypad or silver-plated nylon thread: the resulting assemblies are not robust enough for extended use and the gesture signal processing performance and transmission is not fast enough.

The spun-metal thread we are using has the advantage over silver-plated nylon thread of being less influenced by the effects of corrosion because of a higher overall metal content of the silver-plated copper wire. Another important advantage is that with an appropriate layout these threads may be soldered. This greatly eases the challenge of reliably connecting the sensor array with conventional electronic circuits. With plated threads we have observed an alarming increase over time of the electrical resistance of connections–something that does not occur with a spun metal thread.

4. Implementation Topography

We have explored four different ways of implementing the well-known design pattern for flexible-surface, resistive multitouch [5]. We have confirmed that the different implementations performed similarly as position and pressure sensing arrays. This is not surprising since the basic piezoresistive material, conductive threads and spacing were the same for all of them. However laboratory-condition sensor performance is just one of many important properties we need to evaluate for these implementations. We will discuss the build, repair and maintenance issues of each.

4.1 Sandwich

In this implementation the piezoresistive fabric is sandwiched between two non-conductive pieces of fabric each of which has parallel lines of conductive thread sewn into them. The three component fabrics are held together with a sparse array of light tension stitches. The outside fabric pieces are of course arranged so the threads on top and bottom are orthogonal to each other.

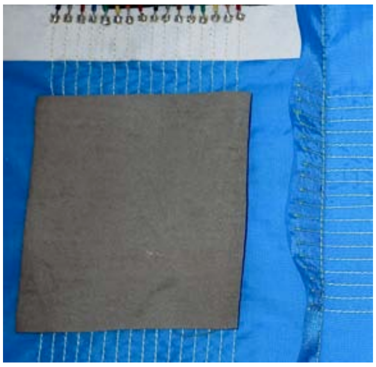

Figure 1: Sandwich

4.2 Machine Sewn

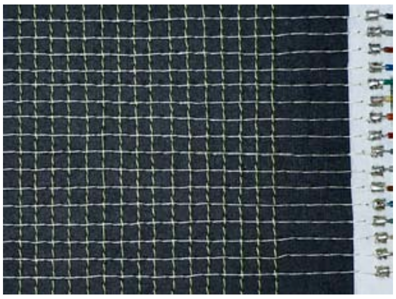

Figure 2: Machine Sewn

An ordinary sewing machine is set up with a conductive bottom thread and insulating top thread. As parallel lines are sewn into the piezoresistive fabric thread tensions are carefully adjusted (or "misadjusted" according to conventional sewing norms) to minimize the possibility of conductive thread being pulled on to the wrong side of the fabric. After one side is complete the fabric is turned over and an orthogonal array of lines is sewn in.

Shorts between the layers can be avoided by careful positioning of the stitches on the second side.

4.3 Trapped Conductor

An ordinary sewing machine is used to lay in narrow rows and columns of insulating zig-zag couching stitches on respective sides of the piezoresistive fabric. Conductive threads are then interlaced through the couching stiches by hand. Note that a variety of couching stitch styles could be employed including straight stitches or wide patterns. We favor the zig-zag stitch because interlacing the conductive threads is facilitated by the straight line path through them.

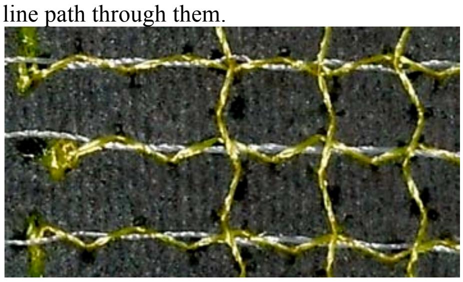

Figure 3: Trapped Conductor

4.4 Woven

The woven implementation [29, 30] is the only one where the conductive threads periodically alternate sides of the piezoresistive fabric. The periods of these running stitches are synchronized so that orthogonal runs are always on opposite sides of the fabric.

These runs are created by hand, a process that can be sped up somewhat by punching or cutting an array of holes in the substrate fabric.

Figure 4: Woven

4.5 Discussion and Comparison of Construction Methods

The sandwich construction offers advantages for large production volumes because the outer layers can be cut from long, wide rolls of pre-manufactured fabric.

Figure 5: Strain-relieved cabling and solder pad

We illustrate this in Figure 5 using a woven fabric that integrates stripes of conductive yarn made by Eleksen.

Note the use of spun-metal thread to transition between the conductive yarn and soldered connections to a flat cable. The sandwich construction also allows a worn or damaged piezoresistive patch to be easily replaced independently of the conductive components.

The machine-sewn construction is accessible to hobbyists on introductory-model sewing machines and results in a thin, one-piece assembly. Repairs to broken or frayed threads may be done by hand with the appropriate equipment.

The trapped conductor approach is the fastest to repair because only a needle and thread are required to replace an entire row or column.

The woven approach lends itself to rapid hand repair but the regular switching from one side of the substrate fabric to the other is not easy to automate. This means this approach will be rather labor intensive for high taxel counts. However it is worth considering when an application demands hand construction for other reasons–for example, when an array is required to match a non-rectangular and non-convex shape with cutouts such as the top plate of a guitar. Hand construction allows the density of sensory node points to be modulated throughout the surface and the integration of insulating patches to route conductors around holes and concavities.

5. Sensor Data Acquisition and Gesture Analysis

An important axis in the design space of touch sensing devices represents a trade-off between complexity of the sensing surface and complexity in the data acquisition hardware and software systems. Capacitive multitouch [39] is popular in high volume consumer products because the complexity of the sensing challenge can be concentrated in a single integrated circuit that performs analog and digital signal processing, calibration, gesture interpretation, data formatting and transmission. Capacitive sensor arrays are built at low cost per taxel by etching or printing processes that are already well-established for multiplexed, flat displays. The difficulty of this particular point in the design space for musical instrument applications is that only standardized sizes and shapes are available and pressure sensing performance is still poor or completely unavailable.

The 4-wire XYZ pad [13, 26, 42] shows that good pressure and position performance can be achieved at a range of sizes using fabric. These can be assembled in ten minutes with ordinary tools and skill. The basic data acquisition algorithms required are also accessible to hobbyists. However the spatial precision of this device depends on the uniformity of the piezoresistive fabric and uncoupling of the interaction between pressure and position. This can be achieved using algorithms less accessible to hobbyists [27]. The touch surfaces explored in this paper address these difficulties by moving some of the complexity into the construction, increasing the number of conductors across the surface so that the spatial resolution is mostly determined by the positioning accuracy of the conductive threads–not the uniformity of the piezoresistive substrate.

If gestures are assumed to be constrained to single touches in predetermined regions the gesture interpretation software is of moderate complexity and accessible to non-specialists. The full potential of high density arrays of pressure sensors is realized when force profiles of large numbers of objects placed anywhere on the surface can be analyzed and for which sophisticated machine vision algorithms are usually employed. This complexity can be managed by partitioning the design so that the electronics and software integrated into the touch surface delivers an uninterpreted taxel image that can be processed by a target computer system to the desired level of detail.

5.1 Multiplexed scanning of the surface

Multiplexing is the approach available for moderate-to-large taxel counts. The cost of connections is too high in these applications for each pressure sensing point in the array to be separately wired to a data acquisition channel. The main technical challenge with multiplexing resistive arrays is to isolate the resistance change at a particular node in the array from neighboring resistance changes. Many approaches to this are known [12] and some have been evaluated in terms of acquisition performance and implementation complexity [6]. These older complexity measures (that count discrete components such as op-amps, drivers, analog switches etc.) are not very useful in current designs because these components are now integrated into embedded microcontrollers. Also component costs have dropped to a point where integration and connection costs now dominate designs. For this reason there is a renewed interest in data acquisition techniques that involve wiring the sensing array directly to the microcontroller with a minimum number of external components.

By writing software that dynamically changes the function of microcontroller pins from outputs to A/D conversion inputs we have implemented data acquisition without any other external components for both XYZ pads and multitouch arrays. However in the multitouch case it is difficult to eliminate lateral current flows across the piezoresistive fabric without additional electronics to avoid cross-talk contaminating the taxel pressure estimates.

Developers of the “UnMousePad” [24] introduced anisotropicity in the conductivity of the piezoresistive materia (by adding conductors) to reduce crosstalk [25]. Their demonstrations were built with established conductive ink printing processes where these additional conductors add no cost. Since our sensors are embroidered their approach would result in an increase cost in time and materials on the surface. We have found that a careful, efficient implementation of current nulling approaches [9] addresses crosstalk without substantially increasing systems costs. A single op-amp and resistor are required for each of either the row or column conductors. An important advantage of the current nulling approach is that an entire row or column of taxels can be measured concurrently–an essential requirement to achieve a high taxel frame rate (8kHz) for large arrays.

6. Integration Design and Implementation

It is a formidible challenge to reliably connect the conductors from a flexible sensing surface that is subject to high continuous and impulsive stress and strain to the relatively rigid and unyielding circuit boards holding the sensor acquisition electronics. Promising techniques are being developed for intrinsic fabric electronics and flexible circuit constructions for extrinsic electronics for textile applications. A recent adaptation of chip-on-board techniques to a fabric substrate is attractive [41]. However low-volume or hobbyist application of these approaches is unlikely in the near future especially when high connection counts are required.

We summarize here a series of exploratory experiments that have yielded viable solutions to the connection problem for low production and hobbyist applications.

The following table quantifies the problem. It describes variations in electrical contact resistance of various approaches to connecting conductive spun-wire thread to circuit boards including wrapping, gluing with conductive epoxy and soldering.

Further work is needed in this area to develop stronger data with analysis of long-term failure processes with accelerated life testing etc. but we have enough data to conclude that the particular contact method matters.

Table 1 Connection resistance

	Before Mechanical Stress		*After Mechanical Stress*	
Connection	avg resistance (ohms)	std dev	Avg. resistance (ohms)	std dev
10x wrap	.43	.16	.25	.034
5x wrap	.202	.053	.271	0.04
5x wrap + CircuitWork conductive epoxy	.255	.036	fail	n/a
5x wrap + MG chemicals conductive epoxy	.189	.015	.149	.023
5x wrap + solder on same hole	.142	.0144	.17	.024
0x wrap with stress relief on adjacent hole	.263	0.05	fail	n/a

We found that the fastest method for hand construction with readily-available tools is soldering. In automated production conductive glues are attractive because they can be printed, and achieve higher densities than soldering because they don’t require special structures to dissipate heat. We focus now on soldering because construction is rapid, repair is much faster than conductive glues. Solder also has a longer shelf-life and easier accessibility than conductive glues.

7. Soldered textile connections

7.1 Strain relief wrapping

Since a soldered joint holds the thin wires of the spun-metal thread to a large rigid surface the wires can quickly suffer metal fatigue and breakage unless strain relief is provided. One solution illustrated here is to lace the thread into a pair of holes and then solder the metal plies to a third contact point on the board. We prefer this approach to the scheme on the Arduino Lilypad [3, 4] of wrapping the thread between a hole and the sharp edge of a fiber-glass circuit board. The edge of these boards is much more abrasive than a plated hole. In any case it is essential that the circuit board be well anchored to the substrate fabric with other threads specifically optimized for this purpose so that the stress of snags and pulls of the board are absorbed by them instead of the conductive threads. To better control these two different roles of threads it is advantageous to provide a zig zag and loose path for the conductive threads.

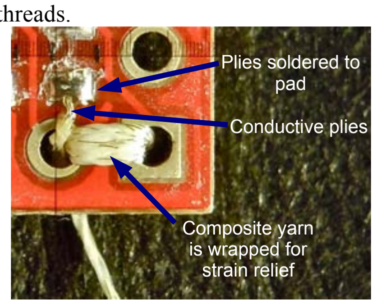

Figure 6: strain relief and soldered thread

Another alternative for circuit board connections is to use existing multiwire cabling assemblies such as ribbon cables and solder these to specially constructed fabric solder pads as shown in Figure 5 and described more fully in the next section. Notice that the flat cable is anchored to the substrate fabric with insulated-thread stitches in the interstices of the conductors.

Figure 7 shows the compatibility of the spun-metal thread with flexible circuit board materials, another approach to strain relief:

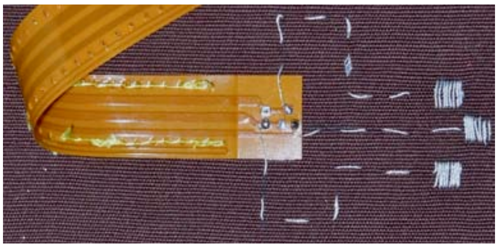

Figure 7: Sewing to flat cable

7.2 Embroidered Soldering Pad and Via

Solder melting points are higher than the melting and combustion temperatures of many fabric materials. Our solution with spun-metal embroidary thread is to sew pads on cotton tape that serves to insulate the polyester piezorestive fabric and to provide a large enough pad area for the heat to be rapidly dissipated across its surface.

Figure 8 Soldered thread

Note that by embroidering the pads with conductive thread on both sides a via is formed allowing for all the soldered connections for the array to be implemented on one side of the fabric.

The space is left in the layout design for sewing a new pad to connect to in the case of failures. This is more reliable ultimately than reusing the original pad.

In the example of Figure 5 various circuit paths are explored. Alternating access to each side of a run increases the density of the pads. Connecting both sides of a run provides a redundant path that allows a run to still function correctly with a single breakage anywhere along it.

8. Software considerations

Before driving current into the array a special sequential scan is done to identify shorted and broken conductors. Shorts across the two layers require immediate repair. Broken connections and shorts between adjacent conductors can be compensated for in the software.

During regular use any unusual pressure data triggers the same power-on evaluation sequence. The idea is to provide enough resiliance so that a performer need not abort a performance when a single wire breaks or shorts.

To minimize performance bottlenecks from USB we encode an array scan as compact OSC blobs with one byte per taxel.

9. Performance and Spatial Density

Readily available 8-bit microcontrollers with integrated USB can scan a 12x12 taxel array at around 200Hz. The limiting factor in these chips is the A/D conversion speed. 32-bit microconrollers with 16 channels of A/D conversion are available with higher A/D conversion rates and can scan a 16x16 taxel array at 500Hz. At this point the USB implementations become the limiting factor. This can be addressed by tiling 4 multitouch arrays and microcontrollers and aggregating the four streams with a USB 2.0 hub. For arrays larger than 32x32 custom hardware using FPGA's is a better way of managing the necessary parallelism to achieve high sample rates and host computer communication rates [38]. This is the scale where hobbyist fabric multitouch becomes challenging. The impact of these constraints is application dependent because conductor and spatial sampling density are still free variables of the design. We have chosen to explore 2.5mm and 5mm spacing. We believe the former may provide sufficient spatial resolution to estimate both finger position and orientation on the surface. The latter is sufficient to estimate finger position with sufficient resolution to capture vibrato-like gestures quite well. In this recording below the vertical axis represents displacements in mm of the second nuckle of the performers index finger. This measuring point is 5.4cm from the tip of the finger at the sensing surface.

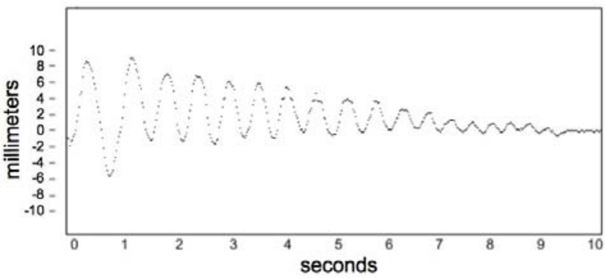

Figure 9. Vibrato Gesture pressure sensing

10. Conclusion and Future Work

We have achieved 7-bit dynamic range of pressure sensing at each taxel of our piezoresistive multitouch arrays. The piezoresistive fabric we are using was designed for foot pressure measurements so we have excellent sensitivity for ballistic interactions and high pressures. We will refine the materials to improve this sensitivity for light, stroking gestures.

As we gain more experience with our smaller arrays we will scale up and move away from USB 2.0 to USB 3.0 or Gibabit Ethernet to approach our goal of an 8kHz taxel frame rate. At these rates multicore parallel computation will be required to execute the machine vision algorithms for effective taxel scene analysis [1].

We have demonstrated new design techniques to create robust, reliable and repairable multitouch. We continue to explore faster and easier methods of construction both for small scale manufacturing and individual hobbyists.

11. Acknowledgements

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