Methods for the In-House Development of Sensors for Musical Applications

Marcelo M. Wanderley and Rodolphe Koehly

Abstract— **This paper presents alternative ways to develop efficient force and position ("touch") sensors for new musical interfaces. We have studied three basic types of conductive materials – complex, composite, and porous – and evaluated the possibilities of using each to develop inexpensive and reliable touch sensors. We have built several sensor prototypes with varying electrical characteristics, shapes and sizes, and have evaluated them in terms of their response to applied forces and positions. Our goal is to provide digital musical instrument designers with straightfoward means to circumvent the limited offering of commercial sensors, which are restricted to a few technologies with predefined electrical characteristics, shapes and sizes.**

I. Introduction

The design of novel input devices used in digital musical instruments – instruments where an input device controls musical or synthesis processes produced by a synthesizer or computer – relies mostly on the use of electronic sensor technologies. Sensor technologies are varied and widely available. Indeed, commercial sensors exist for measuring virtually any body movement [1], with varying degrees of accuracy, precision, and cost [2].

Specifically, many technologies have been developed to realize force and position sensing devices. However, these devices have a common drawback - they only exist as products with predefined sizes, shapes and electrical characteristics. Musical instrument designers thus need to adapt the dimensions and characteristics of their interfaces to these existing sensors. In most cases this limited choice is not necessarily a drawback; many times the existing shapes and sizes of commercial sensors cannot adapted to the designer's needs.

The aim of this work is to study existing conductive material technologies and consider how to create "homemade" sensors – or, at least, "computer music laboratory-made" sensors – using these technologies. Our goal is not to compete with industrial sensors but rather to find inexpensive conductive materials sensitive to mechanical stress that can be molded into various shapes and sizes.

In this paper we present an evaluation of three conductive materials and report on prototypes of force (pressure) and position sensors which utilize them. These prototypes have been evaluated in terms of their electrical characteristics and compared to common commercially available sensors.

Input Devices and Music Interaction Laboratory/Sound Processing and Control Laboratory, Music Technology - McGill University, 555, Sherbrooke Street West, Montreal, Qc, Canada. Email: marcelo.wanderley@mcgill.ca

II. Examples of Existing Touch Sensors

Nowadays, many commercial sensors are inexpensive and readily available[1]. Furthermore it may be difficult to construct certain types of sensors without specialized knowledge and access to industrial facilities. The consequence is that the vast majority of sensors used in the design on digital musical instruments are commercial products [3].

Specifically, there is a varied offering of touch sensors, including Interlink's popular *Force Sensing Resistors (FSRs)*, also commercialized with various names by several musical interface sensor distributors, touch potentiometers (linear position sensing) such as models commercialized by Infusion Systems (*Slide* and *Slide Long*, with sizes of 14 cm to 39 cm, respectively), Eowave (*Position*, sold in three sizes: 10, 30 and 50 cm long), and LuSense's *Standard CPS 155 Linear Potentiometer*, able to simultaneously output both force and position values. Other related sensors that can be used in similar applications are strain gages (such as those manufactured and commercialized by Vishay Measurements Group) and bend sensors (such as those by Abrams/Gentile Entertainment or by Flexpoint).

A. Force Sensing Resistors

Force sensing resistors are thin isometric force sensors whose resistance decreases with the force applied in a nonlinear way. They are one of the most common sensors used in the design of new musical interfaces [3].

The Interlink FSR is comprised of 2 polymer films: one with a conductive surface and the other with printed (interdigitated) electrodes facing the first. Contact between the two surfaces causes the conductive layer to short circuit the printed electrodes, thereby reducing the electric resistance of the component. Typically, its resistance will drop from more than 100 kΩ to about 10 kΩ for an applied force of 10 to 10,000 g [4].

The FlexiForce A201 force sensor from Tekscan is constructed of two layers of substrate (polyester/polyimide) film. On each layer, a conductive material (silver) is applied, followed by a layer of conductive ink. Adhesive is then used to laminate the two layers of substrate together to form the force sensor. The active sensing area is defined by the silver circle above the conductive ink. Silver extends from the sensing area to the connectors at the other end of the sensor, forming the conductive leads.

[1]Typical commercial sensor prices range from US$10 for position sensors (FSR) if purchased at the manufacturer – or up to US$45 if purchased at a musical interface sensor distributor – to US$50 for force and position sensors (LuSense).

B. Linear Position (Touch) Potentiometer

Potentiometers control an increase or decrease of current flow along a conductive material, thus increasing or decreasing the component's resistance.

Many companies such as Eowave or Infusion Systems commercialize such sensors. However, they have the same drawbacks as industrial sensors, because they are quite expensive (minimum US$40) and they are only sold in a few pre-defined formats. The LuSense CPS 155 simultaneously provides position and pressure measurement along one direction, but it is only available in two sizes.

Fig. 1. The *Moog Ribbon*, a touch position sensor, part of the Moog Modular Synthesizer.

Videotape-based Touch Potentiometers: Videotape is known as a material useful for making homemade linear potentiometers. In fact, it is just a thin inked polymer strip. The ink is conductive and uniformly printed onto the strip by a machine. Videotape has quite a high resistance in the hundreds of thousands of Ohms (conductivity of 10^{-5} S/cm) and the inking process provides uniform conductivity. But these properties can vary substantially between brands.

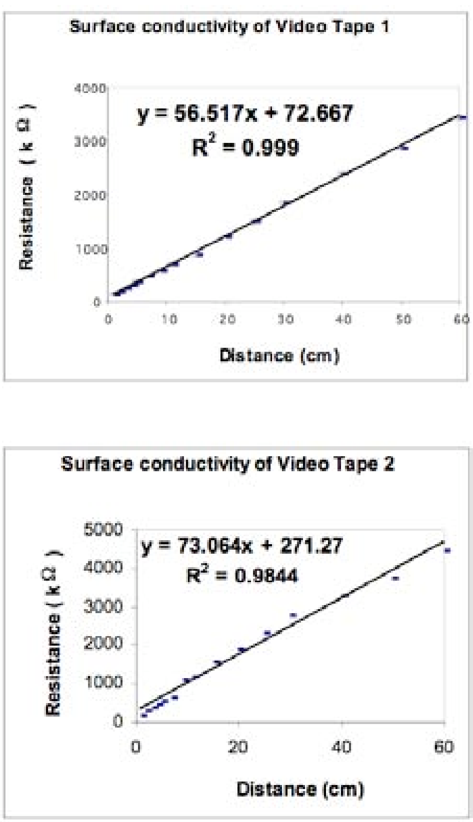

Fig. 2. Measurement of surface resistance for two samples of video tape.

We have measured surface the resistance of two samples of JVC videotape to evaluate its behavior with distance. Measurement along 60 cm was chosen as a compromise to account for the possibilities to control musical events along a linear potentiometer. Figure 2 shows the resulting relationship of the resistance to the tape length. Although the two video tapes are from the same brand it is clear that each video tape has its own unique characteristics, thus confirming the need to measure each sample used. Two related drawbacks of videotape are that it is very sensitive to scratches and that its resistance is highly susceptible to the effect of any defects along the conductive surface. Thus it has to be handled carefully and its electrical characteristics should be checked along its entire length before assembling the sensor.

C. Other Related Sensors

Strain gages are resistive elastic sensors whose resistivity is a function of applied strain due to mechanical stress (piezoresistive effect). Resistance decreases with compression and increases with tension.

Strain gages can be used for both tension and compression, but the drawback is their limited elastic range (less than 4% of the gage length) [5]. They cannot be used as direct contact sensors. Rather, they are bonded to a vibrating element and transmit signals corresponding to the material's deformation. Force is applied along the surface of the gage as opposed to perpendicularly to it as in the FSR, so care must be taken to bond the strain gage all along the surface of the support. Furthermore, the range of resistance is very different – several orders of magnitude for the FSR, but typically only a few Ohms for the strain gage.

Bend sensors[2] operate on the same principle as the strain gage, as flexion of the material is equivalent to tension along one side of the bending radius (the other side being in compression).

Manufactured bend sensors consist of a strip of plastic with conductive ink. Bending causes its resistance to increase, typically from 6 kΩ (flat position) to 500 kΩ (bent at 180 degrees) [6]. It is interesting to note that the inked side has to be on the convex side of the bent surface. Otherwise, flexion would compress the ink layer instead of stretch it.

Typical sizes of commercial bend sensors range between 3.7 and 8.3 cm. But what if one needs a sensor of a different size? In principle, the input device would need to be adapted to the existing sizes. A solution to this very common problem is to develop one's own sensors. This can be done by using conductive pigments and supports in various development strategies.

D. Non-Commercial Touch Sensors

Among the very few examples of alternative sensors that have been reported in the literature, there are two main groups:

[2] We make a distintion between strain gages and bend sensors because in the former the variation of resistance with strain is small, while in the latter it can be susbtantial.

- *linear position sensing devices* such as Robert Moog's *Ribbon Controller* and examples of linear position sensors using videotape[3] or conductive fabric [2]
- *force sensing surfaces* using conductive fibers and pigments suspended in an elastic material such as rubber.

Two examples of force sensing materials used in musical interfaces have been reported. Lippold Haken and colleagues developed a force and position sensing device using composite materials and used it in one of the incarnations of the *Continuum Music Keyboard* [7]. Carbon fibers were inserted into rubber 1.25 cm thick and oriented in one direction (along its height). Coupled with a position matrix, they comprised an efficient sensing surface measuring both pressure and position in two dimensions. By applying pressure at a given point, the impedance was reduced locally, proportionally increasing the current passing through the rubber. Because the rubber had high impedance horizontally, the effect was localized. Difficulties with this design included problems making the electronic connections to the rubber (high-quality conductive glue was used) and the lack of robustness (after using it for some time, the authors reported that the fibers would break down and the rubber would became equally conductive in all directions).

More recently, Mikael Fernström [8] developed a composite material made of silicon and carbon pigments that he called *Plubber*. This material enabled a pressure sensing surface, the *Z-tile*, used in the construction of a sensing floor. Although responsive to pressure, the Plubber was later replaced by Interlink's FSR's due to the increasing unreliability of the sensor's response.

In the following sections we will analyze the possibilities of producing such sensors using various technologies and show measurement results using prototypes built in our laboratory. Technical details about the implementations as well as results from other electrical and mechanical tests to characterize the sensors are available from [9] and [10].

III. Types of Conductive Materials

We have classified conductive materials into three main categories. All three categories make use of metallic or other conductive pigments, usually in the form of conductive inks or glues, the difference being how they are mixed and the method of application.

- *Complex materials*. A non-conductive material covered with a conductive ink layer enables surface conductivity, or uniform conductive junction between two conductive materials (with the use of glue). This type of material is very interesting as the ink layer thickness influences the conductivity and – depending on the process – one can imagine interfaces with any distribution of conductive and non-conductive areas. The conductivity is mainly a result of metallic pigments (typically carbon or silver) suspended in the ink or in the adhesive. Conductive polymers can also be used[4]. One drawback to this technology is that it is quite recent and is only adapted to industrial inking processes. Several sensors are made with conductive ink, for example Interlink's or Tekscan's force sensing resistors and LuSense's force/position sensor. There are also materials providing a conductive printed surface on an insulating base, such as videotape, conductive fabrics, or *Mylar*, an aluminum-coated polymer.
- *Composite materials*. In this case, a polymer is used as an elastic matrix and uniformly distribute conductive pigments *inside* it[5]. Depending on the choice of polymer and on the concentration and type of pigment used, one can control both the material's conductivity and its elasticity. This category includes both the conductive rubber by Haken and colleagues and Fernström's Plubber.
- *Porous materials*. This category includes conductive foam, "electret" polymers and paper[6]. The air inside the material decreases its conductivity. Compressing such a material decreases the air volume inside it, increasing its conductance. However, these materials are not quite as elastic as some of the previous ones. Foam is commonly found in electronic circuit packaging as a static electricity dissipator. Electret polymers are synthesized polymers, more complex and expensive than foam. One example is *Emfit*, an elastic, permanently charged electret film that converts mechanical stress into proportional electrical energy. Conversely, it mechanically expands when voltages are applied to it, a principle similar to the physical behavior of piezo crystals.

IV. Complex Materials

The idea behind complex materials is to bond conductive materials to a flexible insulating surface. Such conductive materials could be powders such as copper (or other metal) powder, graphite or organic components.

One way to create a complex material using conductive powder is to stick the powder onto an adhesive tape. Although this simple method works, it is quite a messy process as powder is highly volatile, making a uniform distribution on the tape a challenge. A better solution is to formulate a conductive ink with these powders.

Conductive Inks

Inks consist of a mixture of pigments and a medium. A specific amount of a pigment is needed to produce a desired color, just as enough medium is required to obtain an optimal ink consistency and viscosity. Our work is based on the same principle, except that we focus on the conductivity of the ink, instead of its color. We will therefore be interested in finding the limit load of conductive pigments: the ink must be conductive and at the same time fluid enough to enable

[3] See the following websites for instructions on how to build linear position sensors using videotape:
http://www.electronicpeasant.com/projects/ribbon/controller.html
http://www.geocities.com/tpe123/folkurban/synthstick/synthstick.html
http://www.angelfire.com/music2/theanalogcottage/ribcont.htm

[4] Silver conductivity is around 104 S/cm while polymer conductivity varies between 1 and 100 S/cm

[5] Although conductive inks are also used in composites, we prefer to classify them separately since our aim is to apply the ink to a support, thus creating a material composed of various layers.

[6] Foams and electret polymers are porous due to special airflow processes used in their manufacture.

uniform printing, thus enabling constant surface conductivity in the printed material.

A. Specifications

Pigments should have particles with small sizes (smaller than 1 μm), while the medium must not insulate pigments and must remain fluid. The ink must dry well and avoid cracking, which would create flaws on the conductive surface. This depends much on the medium, the pigments load, the layer thickness, and the drying conditions. Once dried without cracks, ink is usually quite resistant to mechanical stress. Such an ink would enable the production of linear potentiometers, bend sensors, strain gages, or even FSRs with an industrial printing process.

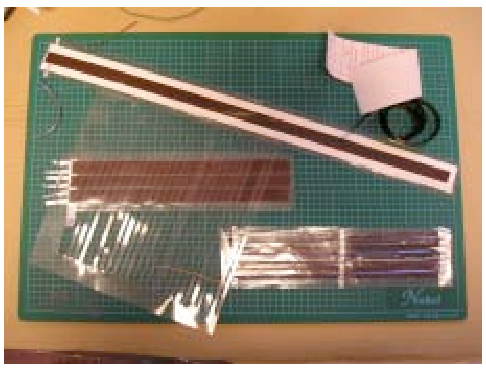

Fig. 3. Examples of position sensors using complex materials.

Without access to industrial printing processes, it is difficult to produce strain gages or printed FSRs. Nevertheless, using painting rollers, a blade system, or ink pulverization, it is possible to develop linear potentiometers with similar characteristics as industrial ones.

B. Experimental Results

Various pigments, mediums and supports were investigated. Pigments used were Graphite (GRA1) and two Carbon Black options (CBA1 and SR511). Mediums were PolyVynilAcetate (PVA) and Vernish (VER). Pigments were also mixed into China ink and ink-jet black ink. Supports included porous paper and cardboard.

Ten different inks were formulated with various concentrations of GRA1 or SR511 and either PVA, VER or China Ink. Around 20 samples were painted, each time with 6 g ink on the roller and 20 coats of ink.

Figure 4 shows the results of measurements of surface resistance for 6 samples of complex materials developed in our laboratory, with the indication of the types and percentages of materials used.

One can notice that resistance ranges are comparable, all in the range of a few to a hundred thousand Ohms, showing that these samples have a higher conductivity than typical values for videotape (c.f. Figure 2). The best result is terms of resistance range was a mixture of 10% graphite in a medium of china ink using porous paper as a support, with 10 times variation in 60 cm. The lowest range was obtained using 10% SR511 in a medium of oil vernish on cardboard, still giving a resistance range of 4 times in 60 cm. The linearity for all results is very high, showing that it is possible to develop these materials in a computer music laboratory.

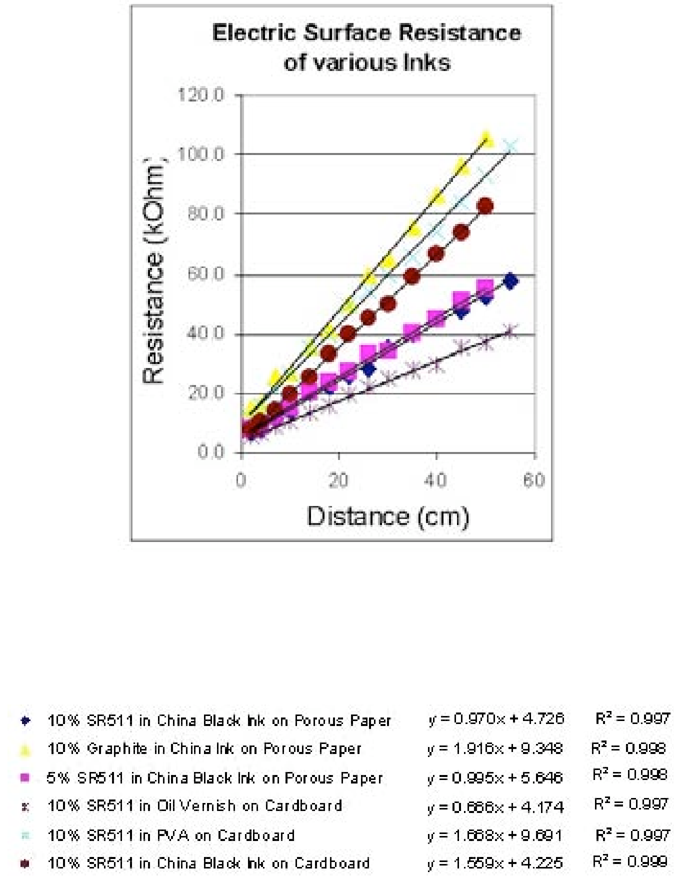

Fig. 4. Various samples made of varying pigments and supports. Note the variation in resistance obtained from the different samples.

V. Conductive Elastomers and Composite Materials

As mentioned before, composite materials will typically consists of conductive pigments or inks mixed with other materials such as latex or rubber. Not all combinations of pigments and materials will be conductive and conductance will also be dependent on the percentages of materials in the mix.

A. Specifications

In developing composites, experiments were first carried out with graphite powder and latex. Latex was highly insulating and graphite rapidly increased the viscosity of the mix. We reached a paste state for 3 parts latex in volume with 9 parts graphite, and only at this point did the material become conductive. Although it is not trivial to produce such a uniform material without industrial tools, we could make a resonably sensitive pressure sensor from this paste.

B. Experimental results

Measurements were made with an electronic weighing machine (2 g resolution and 5 kg max load) and a multimeter.

Fig. 5. Various samples made of composite materials.

Resistance was measured at 20 loads when the displayed load was steady. The sample used was 5 mm thick and highly elastic, so there was a time delay between the time we set the load and the time the weighing machine displayed a steady value.

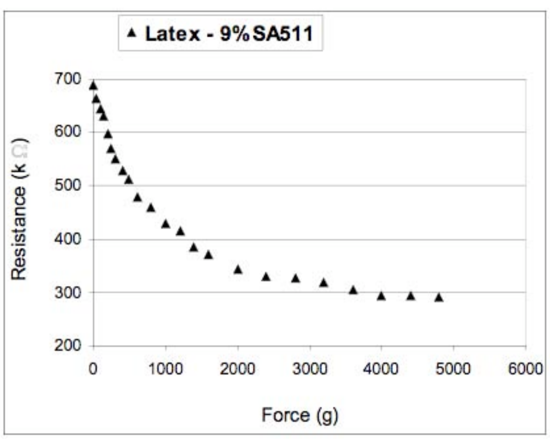

Fig. 6. Measurement of variation of resistance with force for one composite material.

The results show that a pressure sensitive material made of polymers and conductive pigments is feasible. When using these sensors with corresponding conditioning circuits (voltage dividers), a sensor-to-MIDI interface, and Max/MSP, we could not notice a difference between an Interlink FSR and the homemade latex sensor, except for the tactile sensation of the sensor surface.

Another development possibility is to insert pigments between two thin latex membranes and bond the whole together so as to make a conductive elastic membrane. This worked well, as we could easily construct a highly sensitive strain gage with a range of nearly 50% stretch. The drawback of this new sensor is the time-response: it took around 10 seconds for the resistance to come back to its original value under no strain. Therefore it cannot be used for absolute (quantitative) stretch measurements, but may be useful in applications where a qualitative measurement is needed.

Fig. 7. An example of a sensitive membrane made of an elastomer.

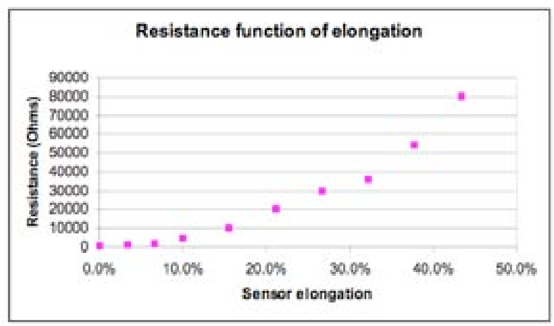

Fig. 8. Measurement of variation of resistance of the latex membrane from Figure 7.

VI. Conductive Porous Materials

The third type of conductive material investigated was porous material. Specifically, we focused on the possibilities of using paper to develop force sensitive resistors.

A. Specifications

Cellulose is not inherently conductive but can be made so if coated with conductive pigments such as graphite or black carbon. This is the case in some stained papers, where these materials are used for providing a specific color. By using conductive pigments and cellulose we were able to develop a very interesting material with the following properties:

- Conductivity along its surface and along its thickness
- Pressure sensitivity as a porous material. Compression decreases the volume of insulating air inside it thereby increasing its conductivity.

One drawback of such a material is that it is not homogeneous, which can prevent it from having linear electric properties. Moreover it is a destructible type of material, so that a usable time needs to be specified.

B. Experimental results

Measurements were made for surface conductivity, with both faces of the paper analyzed. Indeed, paper is a very heterogeneous material – it is made from pulp (individualized fibers in water), and poured onto a moving table so as to form a sheet of paper. The difference with basic pulp is that in the case of stained papers cellulose is pre-tinted with black carbon and retention polymers. Carbon particles tend to go through the paper and remain between the fabric and one face of the paper where they bond as they dry, called the *wire side* of the paper. We should expect to have a higher conductivity along this side of the paper.

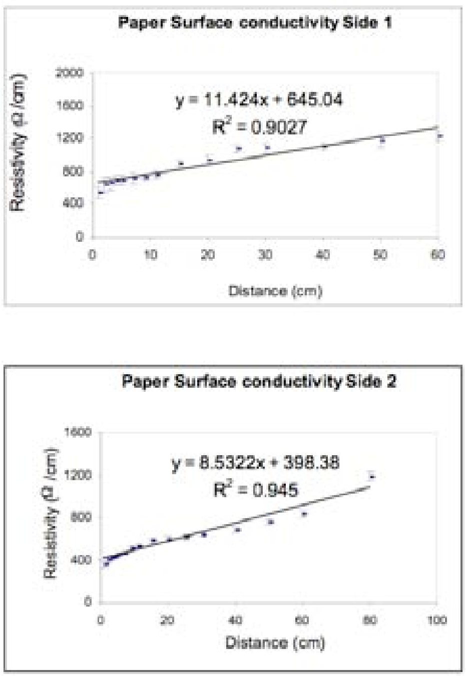

Fig. 9. Electrical properties of one type of stained paper.

As predicted, the conductivity is higher on one side (Side 2), which is the wire side of the paper. The linearity is not as good as with video tape, since in stained paper current might travel along the fiber network as opposed to linearly[7].

Paper	R at 100 g [Ω]	R at 5 kg [Ω]	Voltage range [V]
1G	280	13	3.2
5G	750	36	3.2
15G	1.5k	73	3.2
1R	2k	19	4.1
2R	4k	42	4.1
4G + 3F	7M	28k	4.5

TABLE I
MEASUREMENTS OF THE RESISTANCE OF SEVERAL PAPER FORCE SENSING RESISTORS.

[7]Ideally, one should also compare conductivity in both directions of the paper as fibers tend to orientate through the machine direction during the production process.

Measurements of the samples resistance for 100 g and for 5 kg are presented in Table I. All measurements were performed using a simple voltage divider using a common operational amplifier. Resistance values used for each sample measurement were selected to correspond to the sample's resistance range.

One can notice the wide variation of ranges obtained depending on the number of paper sheets stacked and on the types of paper. Minimum resistance ranges around a few hundreds of Ohms was obtained using paper type *G*, while using only one or two sheets of paper *R* increased the resistance to a few thousand Ohms, also increasing the range. The highest resistance values were obtained using a combination of 4 sheets of paper *G* and three sheets of paper *F*, with a variation between 7 MΩ and 28 kΩ. Voltage excursions were acceptable for use with common sensor-to-MIDI interfaces on the market.

VII. Practical Issues with Developing Touch Sensors

Not all the methods of producing homemade sensors described above can easily be done at home by inexperienced designers, although all can be developed in minimal laboratory conditions, provided that a minimally experienced designer has access to the materials needed[8].

Position sensors can easily be created with videotape or conductive fabric. Notwithstanding exceptional cases – specific sizes and shapes or when higher conductivity is needed – it is easier to develop a position sensor from these readily available and inexpensive materials than to create one's own complex material.

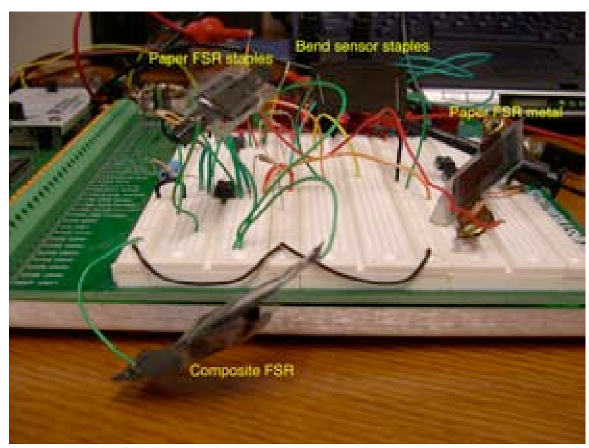

Fig. 10. Four homemade sensors: paper FSR with staples, paper bend sensor with staples, paper FSR with metal tape, and composite FSR.

Force sensors, on the other hand, appear to be the most interesting homemade touch sensors as it is possible to arbitrarily choose the dimensions of the sensor one requires. Furthermore, there are no simple ways to create them except for the use of conductive foam, which has a very slow response time.

[8]Although it may sound strange, it is not always easy to obtain – by donation or purchase – samples of conductive inks from manufacturers. In some cases, manufacturer's refused to give or to sell us products because we work at a university!

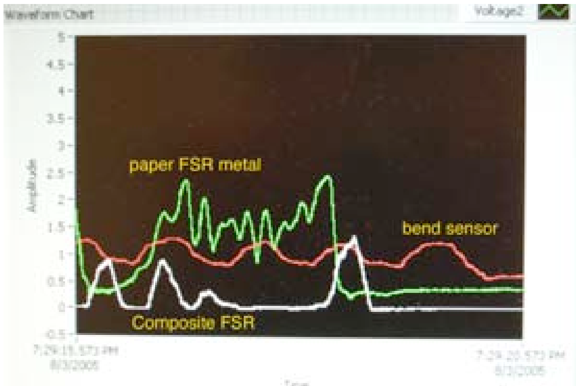

Fig. 11. Signals from three of the sensors showed in Figure 10. Note that the voltage excursion obtained using simple voltage dividers is sufficient to be used with available sensor-to-MIDI interfaces, except for the case of the bend sensor, which requires a better conditioning system such as a Wheatstone Bridge.

A. Paper FSRs

Comparing the various materials studied above, the simplest and most straightforward material to use to construct an FSR is stained paper. By stacking many sheets together and connecting each side of the stack one can obtain an excellent variable resistor that is sensitive to the force applied to it. Indeed, paper is a material that is 40 to 60 percent porous and highly compressible, the compression zone being in the elastic limit of the paper, preventing any material destruction (at least along the paper thickness).

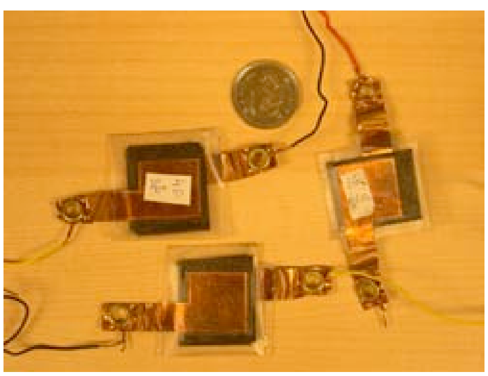

Fig. 12. Three homemade paper FSRs using metal contacts. Each FSR has different electrical characteristics dependent on the number of paper sheets stacked.

Stacking papers increases the resistivity range. An interesting question, then, is how big one can make such a sensor. The answer is linked to the surface conductivity of the material, the way connections are designed, and also the characteristics of the sensor such as possible hysteresis due to the air flow in and out of the paper [10].

B. Problems with connections

As we are not working with metals, we cannot solder connections. Various techniques were developed using special commercial rivets, or a simple stapler and metallic staples. We also experimented with inexpensive aluminum tape, but it was found to generate noise. This can either be attributed to dust on its surface or to the fact that aluminum always forms an oxide layer on its surface. Our choice was to use other metal tapes and/or silver filled conductive glue, although these are quite expensive and not always easy to find.

C. Life Span

One of the limitations of our approach is the life span of such sensors. Specifically, when using paper and depending on the application, sensors may break mainly due to problems in connections.

This is not necessarily a major drawback if compared to industrial sensors, for two main reasons: a) commercial touch sensors are also quite fragile, being very sensitive to bends and twists, and b) the difference in costs involved in purchasing a commercial sensor and in making an alternative version of it (several dollars and few cents US per sensor, respectively), as well as to the simplicity in making some of the alternative sensors presented above. Even with the eventuality of sensor damage, it is still beneficial to use alternative sensors in many applications that involve rapid prototyping, specifically in new instrument design.

D. Application Example: The CheapStick

One application example of the use of paper FSRs is the *CheapStick*, developed by Alexander Jensenius and the authors [11]. It consists of a position sensors using videotape and a squared paper FSR with dimensions of several centimeters. By using the electronics of a commercial USB game controller that provides 4 analog input channels – used by the small joysticks in the gamepad – and various digital inputs, the controller's total cost was below US$10. This is basically the price of one FSR if purchased from a commercial manufacturer.

Fig. 13. The *CheapStick*, a low-cost USB controller using alternative touch sensors.

VIII. Conclusions

In this work we presented results of a systematic study on the feasibility of developing alternative touch sensors for musical applications. Specifically, we have studied three types of conductive materials: complex, composite and porous, and described ways to use them as integral parts of alternative touch sensors. Using several variations of these materials, we built prototypes of force and position sensors and measured their electrical characteristics. Results obtained were comparable to those as obtained using commercially available industrial sensors, showing that it is possible to develop low-cost and easy-to-make sensors with various shapes and sizes. Applications of this work are far reaching, including musical interface design, augmented instruments, and robotics.

ACKNOWLEDGMENTS

We would like to thank the various manufacturers who graciously send us samples of various conductive materials.

We would like to thank Professors Theodorus van de Ven, Jorge Viñals, and Mikael Fernström for comments and suggestions. Thanks also to Eric Johnstone for innumerable technical tips, to Alexander Refsum Jensenius and to Mark Marshall for their collaboration, and to Bertrand Scherer for his invaluable help with sensor measurements in LabView. Thanks to David Birnbaum for proofreading this text.

This work is supported by the Natural Sciences and Engineering Research Council of Canada, through a Discovery Grant to the first author.

REFERENCES

[1] B. Bongers, ch. "Physical Interfaces in the Electronic Arts. Interaction Theory and Interfacing Techniques for Real-time Performance", In M. M. Wanderley and M. Battier, *Trends in Gestural Control of Music*. Ircam - Centre Pompidou, 2000.

[2] E. R. Miranda and M. M. Wanderley, *New Digital Musical Instruments: Control and Interaction beyond the Keyboard*. A/R Editions, 2005.

[3] M. Marshall, "A Survey of Sensor Use in Digital Musical Instruments," Sound Processing and Control Laboratory, McGill University, Tech. Rep., 2004.

[4] Interlink Electronics, "FSR - Force Sensing Resistor Integration Guide and Evaluation Parts Catalog," version 1.0, Revision D.

[5] J. Fraden, *Handbook of Modern Sensors. Physics, Design and Applications*, 3rd ed. Springer Verlag, 2004.

[6] Infusion Systems, "Sensors," webpages with electrical characteristics of various sensors distributed by Infusion Systems.

[7] L. Haken, K. Fritz, E. Tellmann, P. Wolfe, and P. Christensen, "A Continuous Music Keyboard Controlling Polyphonic Morphing Using Bandwidth Enhanced Oscillators," in *Proc. of the 1997 International Computer Music Conference. San Francisco, Calif.: International Computer Music Association*, 1997, pp. 375–378.

[8] L. McElligott, M. Dixon, M. Fernström, B. Richardson, and K. Leydon, "ForSeFIELDS: Force Sensors for Interactive Environments," in *Proceedings of UBIComp02*, 2002, pp. 168–176.

[9] R. Koehly, "Study of Various Technologies for Home-Made Sensors," Master's thesis, Sound Processing and Control Laboratory, McGill University, 2005, Master AST 2004-2005, Grenoble, France.

[10] R. Koehly and M. M. Wanderley, "Alternative Low-Cost Force and Position Sensors," Manuscript in preparation.

[11] A. R. Jensenius, R. Koehly, and M. M. Wanderley, "Building Low-Cost Music Controllers." in *Proc. of Computer Music Modeling and Retrieval 2005 Conference*, Pisa, Italy, 2005.