Paper FSRs and Latex/Fabric Traction Sensors: Methods for the Development of Home-Made Touch Sensors

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ABSTRACT
This paper presents the development of novel "home-made" touch sensors using conductive pigments and various substrate materials. We show that it is possible to build one's own position, pressure and bend sensors with various electrical characteristics, sizes and shapes, and this for a very competitive price. We give examples and provide results from experimental tests of such developments.

Keywords
Touch sensors, piezoresistive technology, conductive pigments, sensitive materials, interface design

1. INTRODUCTION
Many technologies are used to develop sensors, most commonly using conductive inks, and numerous musical interfaces were developed with industrial sensors such as Interlink *Force Sensing Resistors* (FSR) or Tekscan's Flexiforce, among others. Although their electrical behaviour are not necessarily the same [1], commercial sensors have basically the same drawbacks: they are available in few normalised sizes and shapes, with pre-defined electrical characteristics. Researchers and interface designers then need to adapt the characteristics of their interface to these existing sensors. Many times, their work could certainly be more efficient if custom sensors were available.

2. HOME-MADE SENSORS-MATERIALS
In commercial touch sensors – force/pressure, bend and position sensors – conductive inks are used to make a surface or a whole material conductive. The idea is to mix pigments into a medium that will provide the desired electro-mechanical behaviour of the device. The process is similar in the development of home-made sensors.
The first type of material that we studied was conductive ink: Considering the fact that it is hard to find and expensive, it appeared much more clever to produce one's own conductive ink from carbon black pigments and various basic mediums like polyvinyl acetate, varnish or liquid black inks such as china inks or ink-jet inks[4]. As long as you reach a sufficient pigment concentration, you can easily produce a conductive ink with any medium.

The choice of medium is fundamental: a) it must keep the ink liquid enough to enable a uniform printing, b) it must remain flexible when dried (to be used on flexible surfaces), c) it must bond the pigments to the support efficiently. Also, the choice of the pigments, of the inking support and of the printing process (that can be manual) will influence the printed result.
It is important to notice that industrial conductive inks only exist for industrial printing process and not for personal printers using ink-jet or laser technologies. Indeed, the ink used for such machines are not conductive because their pigment concentration is too low or because their pigments are not conductive. The following table gives examples of the resistance we can reach on a coated paper.

Table 1 Ink resistance for various pigments' concentrations: we reached a saturation point for 16% pigments.

% of Carbon Black Pigments in China Ink	Obtained surface resistance for 5*1cm roll printed samples
2 %	0.2-0.4 MΩ
5 %	30-50 KΩ
8.5 %	9-11 KΩ
13.5%	1.8-2 KΩ
16% and more	1.6-1.8 KΩ

3. EXAMPLES OF HOME-MADE SENSORS

3.1. Linear Touch Potentiometer
Video Tape is a well-known material for home-made linear touch potentiometers. In fact, it is just a thin inked polymer strip: the ink is conductive and printed by a machine. Figure 1 shows the resulting evolution of the resistance with the tape length measured on a JVC sample with a multimeter.

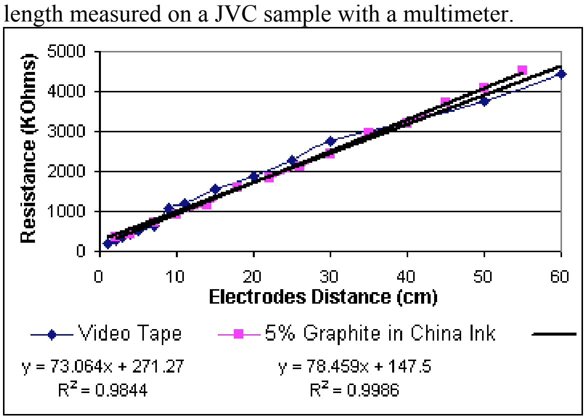

Figure 1 Comparison between 0.5 in width Video Tape and Inked band (the resistance of the inked material was multiplied by 20 for better comparison)

Videotape has a remarkably high resistivity, around hundreds of kΩ/cm (conductivity of 10^{-5} S/cm) and the printed process used to make it, provides it uniform conductivity. Furthermore, videotape is very fragile: any scratch on the inked surface will alter the resistance linearity.
It is then really easy to build a linear potentiometer such as the one represented below in figure 2[1]. In fact, several examples of position sensors using videotapes are available on the internet[1].

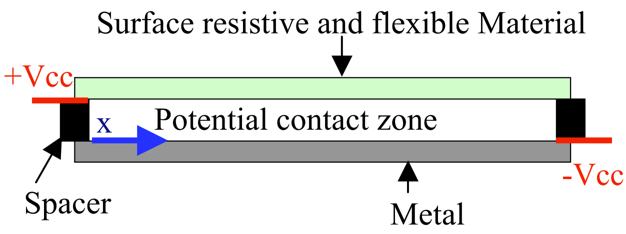

Figure 2 Home-made linear potentiometer along the x-axis

Separated connexions are placed on opposite ends of each band. The sensor resistance increases with the distance of the compressed zone from the connector on the resistive band.
Video tape is the best disposable material for such a sensor. However it can only be found in limited sizes. Home-made conductive surfaces were successfully performed replacing videotape by other conductive materials (tissues, papers, printer rolls,..), inked band or even pigments stacked on tape (less efficient and dirty) and enabling a much wider range of size possibilities.

3.2. Home-made Bend Sensors

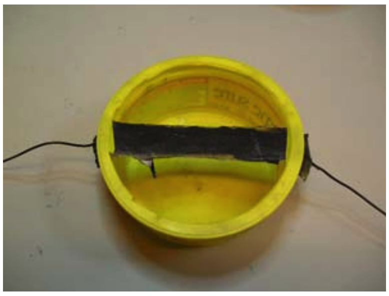

Figure 3 Multi-Couch Bend sensor: a pigment line is stuck between two latex layers making a sort of tube

Initial bend sensors were developed using conductive ink onto a flexible and elastic substrate (a 0.2 inch thick PET polymer sheet), the bending of the support increasing the ink resistance. This trial was not very successful, as we could not find any medium that would prevent the dried ink from cracking under strain.
We replaced the ink medium by elastic polymers such as latex, and silicone-based products. There was no need for support any more as the pigments were mixed with the polymers and moulded into the appropriate shape. A similar method was used by Mikael Fernström for the development of a pressure sensitive floor called "ForSeFIELDS" [3]. However, this method was not completely successful, as it required a high pigment load (from 15 to 20%) to prevent from the insulating effect of the various polymers. For such a pigment loading, the resulting material looses much of its mechanical strength.

Because pigments were insulated when mixed with polymers, we found it was a better idea to insert a pigments line inside 2 polymers layers. The polymers would then provide the material elasticity needed and confine pigments into a defined zone. Figure 3 shows a similar sensor mounted on a plastic support.
Traction along the sensor's length decreases the local pigment concentration along the line, thus decreasing conductance. Figure 4 shows the evolution of this conductance with a traction of 50% of the sensor length at initial state.

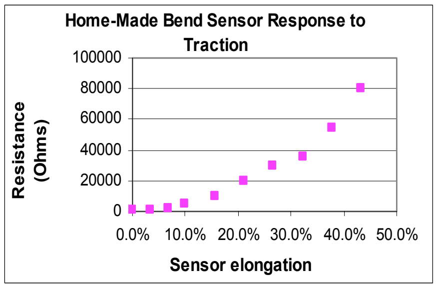

Figure 4 Multi-layer Sensor response to traction

We can see that for 50% traction, a continuous variation from 1 to 80 kOhms is obtained: although this sensor appeared to be very sensitive, the configuration did not provide a good repeatability. Indeed, pigments are quite free inside the tube and so any mechanical stress on the sensor will randomly change the pigment distribution, therefore affecting its resistance. Moreover the choice of latex as elastic material is not optimal: Silicone or Polyurethane based polymers should provide less viscosity and fragility.
We then decided to use a porous and elastic matrix that was tinted with conductive pigments; such porous materials can be papers, foams, tissues or polymers.[2] The use of a fibre skeleton limits the distribution possibilities of pigments into the elastic material and therefore provides better repeatability. Latex or silicone (or any other flexible container) might then be used to embed the sensor and so protect and prevent it from variations due to temperature, moisture or bad manipulation, as well as preventing pigments from leaking from the sensor. Figure 5 is an example of a medical care bandage that was tinted with carbon black and specific chemical products (retention aids, flocculants...) to improve the pigments bonding. The sensor is set on three various positions into a transparent plastic envelope.

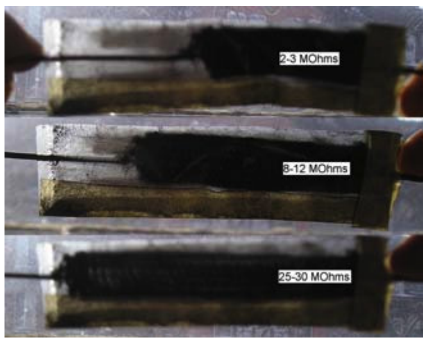

Figure 5 Tissue Bend Sensor under Strain: the resistance increases with traction

[1] Websites for instructions on how to build linear position sensors:
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

[2] Many fibres can bond pigments through hydrogen bonding or other chemical forces: a process that is more complex than mixing pigments with mediums, requiring specific chemical component used in the paper or textile industry. This implies that research with porous materials be realized in specialized research centres.

The repeatability of this material was still not optimised, as the tissue was not enough elastic. However, "smart textile" development recently became a highly active research field ("WEALTHY" European Project [7]) and strain fabric sensors were already successfully performed by other researchers, such as F. Lorussi & Al [8].

4. HOME-MADE PRESSURE SENSORS

Various techniques can be used to develop touch sensors sensitive to force and/or pressure. One of these techniques consists in embedding pigments into latex or other materials. Some of these sensors provided excellent sensitivity, as shown in figure 6.

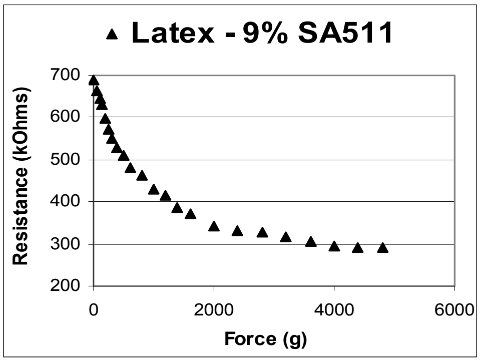

Figure 6 Latex Pressure Sensor [4]

Nevertheless, depending on the pigments used and on their concentration, the mixing process was not always successful.
Tinted porous materials appeared to be more efficient for pressure sensing. Any tinted polymer or organic foam, tissue or fibre network could provide an efficient pressure sensor, depending on its elasticity. However, the tinting process is not obvious and it requires some chemical knowledge and the use of specific products to optimise the bonding of pigments into the fibres.
We focused on tinted paper and succeeded in developing efficient paper pressure sensors, as seen in figure 7: as paper is around 50% porous and quite compressible and elastic, the compression of a stack of tinted sheets will increase the contact between pigments, thus increasing conductivity inside the sheets thickness.

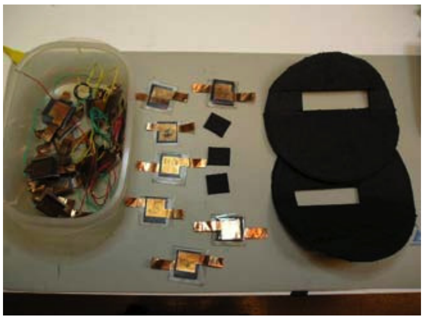

Figure 7 Home-made paper pressure sensors

As you can see, the design can be pretty simple : the sensitive material basically just requires connectors on each side of the pressure direction which can be made with metal foils or totally conductive ink. A plethora of tricks it would be too long too add here can be easily found using more complex designs. Also a major point of discussion would be connection systems as it must not generate noise. Soldering is not possible with ink, paper and some metal foils. Hopefully, one can find efficient alternatives such as mechanical connecting systems.

5. THE EFFICIENCY OF HOME-MADE SENSORS

The quality of sensors for musical performance can be evaluated through a few parameters: linearity, repeatability, resolution, drift and time-response. Home-made sensors' performance will mainly depend on material uniformity, design, and connexions' quality.
We can already notice from figure 1, that it is feasible to create surface conductive bands with home-made conductive inks, their range and linearity being sufficient for the making linear touch potentiometers.
Home-made bend sensors are not optimised in terms of repeatability: however there is a good potential for multi-layer latex bend sensors, as shown in figure 8.

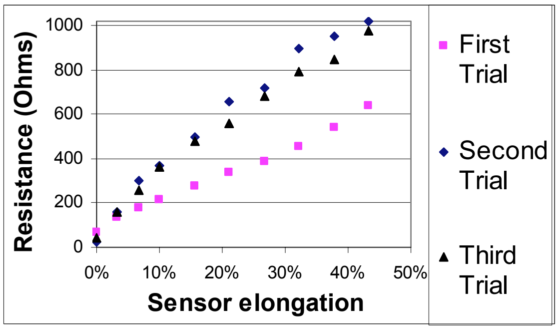

Figure 8 Repeatability of a multi-layer bend sensor response to 3 consecutive tractions [5]

The response is highly linear and the range is quite sufficient to be treated through a simple tension divider. Unfortunately, it presents a slow time-response (around 3s max). We can also see that the first trial is different from the other 2, a fact that is quite frequent with visco-elastic materials. During the first trial, we reached a plastic deformation state: the limit of elastic deformation of the material is then moved to this point and then as long as we remain in this deformation limit we can hope to get repeatable results. This sensor can then be used efficiently to sense, for instance, the bending of a finger, of the elbows or of the knees.
Results concerning paper pressure sensors are also quite impressive. A special laboratory testing machine was designed at EFPG, Grenoble, to observe the evolution of the sensor resistance under compression between 100g and 5kg on a 10*2cm paper sample with clipped copper foils as connectors on each end of the paper. Figure 9 shows the testing results.

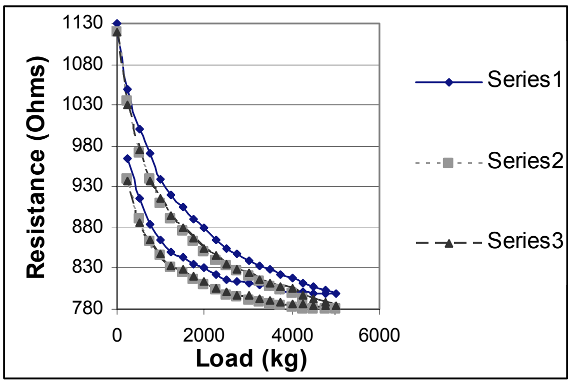

Figure 9 Repeatability testing of a paper pressure sensor under 3 series of gradual strain from 0 to 5 kg and return [6].

After a first trial during which there was a plastic deformation of the paper (like for the bend sensors), the following tests were similar: the sensor has an excellent repeatability, comparable to commercial ones [1].
Let's first notice the poor range we get in comparison with the range announced for Interlink FSR. The resistance range given in figure 8 would only provide 0.5 volt range with a simple voltage divider. Hopefully, a Wheatston bridge or an Op-Amp would increase this range. Also, more complex designs of paper and spacer stacks, as well as paper repulping enabled to provide an even more linear range of up to 4 volts (out of 5 in input) with a simple 1kOhm tension divider.
We can notice from this experiment that the hysteresis represents at worse 15% of the full range, which is better than for the Interlink FSR sensors (15 to 25% variation specified in the Interlink FSR user guide).
Second, the force resolution, which is the smallest measurable difference in force, is also competing with the FSR resolution. Even for high loads, there is a difference of 0.3 Ohms for 5g variation. We can then say that the resolution is lower than 0.1% of the full scale (5/5000g). The resolution given for FSR is 0.5% of the full scale.
A third experiment, drift testing, consisted in placing a 1kg load on the sensor for 1 minute. The conductive response of the material stabilised in a few seconds and remained the same at +/- 2% during the whole time, which is once again comparable to FSR specifications.
Last, the time-response was measured through an oscilloscope: a 3 kg load was exerted on the sensor and the screen of the oscilloscope was shot during the load release. The following picture shows that it took 75ms for the paper to recover its original state. This time-response is not totally satisfying for musical applications, as for instance, if we used such a sensor for percussion sensing, it would enable to sense only 6 beats per second to satisfy the Nyquist theorem.

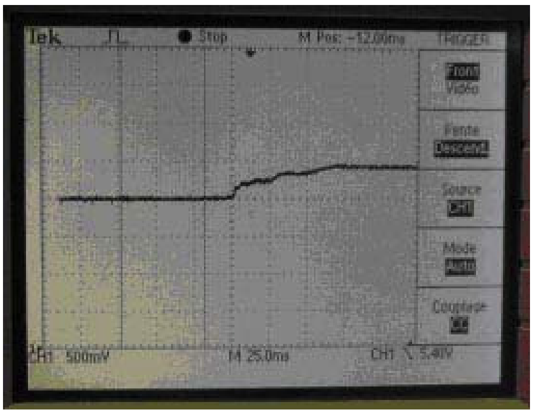

Figure 10 Time-response detection of a paper pressure sensor for 3kg load release.

6. CONCLUSION

To get its own custom sensors, it is worth spending some handwork time: this will make one save money and improve the quality and originality of the interfaces such as the one of Figure 11 [5]. These interfaces can even be granted an environmental-friendly label as one can use only recycled materials to produce them. This work shows once more that creativity not only exists in musical performance but also in development of technology.

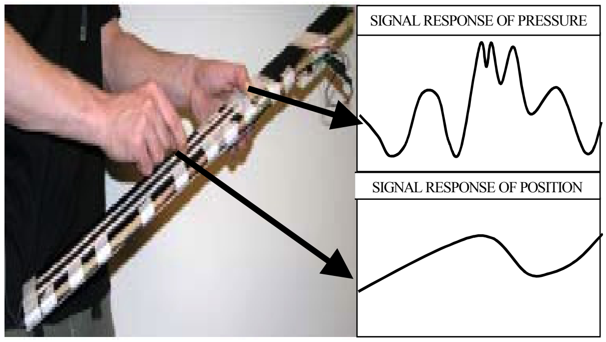

Figure 11 A performance with the Cheapstick, composed of one Paper pressure Sensor and one Linear touch potentiometer with Video Tape [7]

7. ACKNOWLEDGEMENTS

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