PyzoFlex®: a printed piezoelectric pressure sensing foil for human machine interfaces

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ABSTRACT

Ferroelectric material supports both pyro- and piezoelectric effects that can be used for sensing pressures on large, bended surfaces. We present PyzoFlex®, a pressure-sensing input device that is based on a ferroelectric material (PVDF:TrFE). It is constructed by a sandwich structure of four layers that can easily be printed on any substrate. The PyzoFlex® foil is sensitive to pressure- and temperature changes, bendable, energy-efficient, and it can easily be produced by a screen-printing routine. Even a hovering input-mode is feasible due to its pyroelectric effect. In this paper, we introduce this novel, fully printed input technology and discuss its benefits and limitations.

Keywords: printed sensors, piezoelectricity, ferroelectricity, pressure sensing, touch interface, PVDF:TrFE, HMI

1. INTRODUCTION

We have seen a large rise of novel and user-friendly interfaces that move beyond the paradigm of mouse and keyboard for input. Multi-touch screens are now the de-facto standard in mobile devices such as phones and tablets, depth cameras are increasingly being used to capture gestural input in the living room and beyond. This rise in adoption of such ‘natural’ user interfaces shows there is a great deal of user demand for simpler ways of navigating information and content, where the computer interface is not a barrier, but enables them to accomplish tasks more quickly and easily.

Over the last decade, touch sensing devices have become more and more important. Most researchers tried to improve the multi-touch sensing technology by introducing capacitive[1][2], resistive[3], or optical[4][5] sensing devices. Although most of them provide already a multi-touch sensing, it still is often not possible to track the pressure of the input efficiently. In 2009, Rosenberg and Perlin presented UnMousePad[3], a promising pressure-sensing device that was based on a paper-thin, resistive-sensing surface. Their setup had two impressive features: (i) the sensing material was mounted on a paper-thin flexible/bendable material and (ii) it was able to accurately sense pressure input.

In this paper, we present PyzoFlex®, a novel sensing device that is based on a pyro- and piezoelectric sensor matrix, which is fully printed on a flexible substrate (Figure 1). This sensor array can detect changes in temperature and pressure respectively.

Figure 1: Screen Printed PyzoFlex® Sensor Array directly after printing (left) and its illustrated response to touch events.
We developed an early PyzoFlex® prototype, a novel sensing device that is based on a ferroelectric copolymer (PVDF:TrFE) sensor matrix, which is fabricated by a screen printing routine on a flexible substrate. So far, the sensor area can detect changes in pressure and temperature respectively. The piezoelectric effect can be found in any ferroelectric material. Any mechanic stress or force (e.g. touch) applied will result in a change of the electric field. This electric field variation is proportional to the mechanic deformation. Therefore, the piezoelectric effect can be used to measure pressure changes efficiently (Figure 7). All ferroelectric materials also have a pyroelectric effect: a variation in temperature influences the distribution of the electrical charge, which is measureable as well. As a result, ferroelectric materials can also be used to measure temperature changes. PyzoFlex® is a bendable sensor technology, meaning that the sensor can be mounted on different curved surfaces. Since the ferroelectric material is printed on a substrate, even other materials beyond a foil are possible (e.g. even on paper). Fabrication by printing further facilitates the scale-up of the technology and is very cost-effective; the fabrication of PyzoFlex® sensors on square meters in a roll-to-roll machine is feasible.

Figure 2: quasi-transparent PyzoFlex Sensors by using PEDOT:PSS electrodes.

Another crucial advantage of PyzoFlex® is its quasi-transparency (Figure 2), which of course is an important feature for touchscreen applications in mobile devices (e.g. smartphones or tablets). Moreover, our approach provides an energy-efficient implementation, since every touch generates a small amount of voltage. Under certain conditions the multi-touch sensing setup could additionally serve as energy harvesting resource.

2. EXPERIMENTAL

2.1 Ferroelectric Material

Several materials are known to have piezo- and pyroelectric properties, among them fluoropolymers like polyvinylidenefluoride (PVDF) and its copolymers (P(VDF:TrFE)). Screen printed piezoelectric films based on PVDF were reported by Papakostas and White[9]. However, details on the paste are not given in the paper. Printable precursors for piezo- and pyroelectric inks are reported in [10] and [11]. In both cases the precursors are particle suspensions which eventually require a temperature treatment at high temperatures. Piezo- and pyroelectricity was not investigated in any of the papers, but due to the poor homogeneity in comparison to solution based materials, poorer properties have to be expected. Hung et al.[12] fabricated piezoelectric PVDF films via ink jet printing. The polymer was dissolved in highly toxic N,N- dimethylacetamide. A new fabrication method for PVDF inks was developed recently by Helbig, Stadlober, Domann et al.[13]. The novel process being used for fabrication of PyzoFlex®-sensors offers the possibility to dissolve the fluoropolymer in less hazardous solvents at lower temperatures. The viscosity of the paste can be adjusted by the solid content, thus enabling application of the layers by spin coating, bar coating and screen printing.

2.2 Fabrication

The fabrication is done by low-cost printing of a smart active matrix sensor array with four functional inks[6]: (i) a conductive polymer ink (Heraeus PEDOT SV3/4), (ii) the fluoropolymer sensor ink, (iii) the conductive carbon paste (DuPont 7201), and (iv) the conductive silver ink (DuPont 5000). The substrate is formed by a transparent, flexible (175 µm thick) plastic foil (Melinex ST 726), thus guaranteeing high flexibility and good adhesion of the functional materials applied during the screen printing process. The sensor ink is based on the pyro- and piezoelectric copolymer P(VDF-TrFE) which has a semicrystalline structure and - in a special formulation[13] - and is printed on the foil thus forming a
5 µm thick transparent layer. Silver conductive lines are printed for connecting the sensor electrodes to a Molex 1.00 mm Pitch FFC/FPC connector for signal read out. After the printing step, each layer needs a short annealing treatment at 100 °C only. This calcination guarantees complete solvent evaporation thus increasing the functional properties (conductivity, piezo- and pyroelectric response) of each layer. Owing to the humble thermal requirements, the overall process can be considered being a low temperature fabrication. A detailed description of the sensor buildup and its fabrication can be found in Scheipl et al. [7].

Figure 3: Scheme of the PyzoFlex® layer composition fabricated by screen-printing (left) and close-up of a printed PyzoFlex® sensor foil (right).

For achieving piezo- and pyroelectric response, the randomly ordered and dipole containing nano-crystallites that are embedded in an amorphous polymer matrix must be aligned vertically to the sensor electrodes. This can be achieved by hysteresis poling of the sensors using a Sawyer-Tower-Circuit [8]. For sufficient and durable dipole alignment, an electric field in the range of 140 MV/m being twice as much as the coercive field strength is needed. This procedure leads to a very high remnant polarization of 70 mC/m² at a poling frequency of 10 Hz.

PyzoFlex® provides printed, large-area, flexible and durable polymer sensors, showing a piezoelectric coefficient d33 of 20-30 pC/N, a pyroelectric coefficient p33 of 40 µC/m²K at room temperature, and a Curie temperature of 125 °C.

2.3 Electronics

The equivalent circuit of a piezoelectric sensor is a current source with an internal resistance Rs (1 GΩ) and an internal capacitance Cs (1 nF), as depicted in Figure 4a. The internal resistance and the internal capacitance of the sensor are dependent on the physical dimensions, the electrical conductivity and the permittivity of the used material.

Touching the foil generates only a small amount of energy, which is difficult to measure. Therefore, an impedance converter is used to amplify the sensor signal (cf., Figure 4b). It forwards the input voltage to the output voltage but amplifies the signal power. In the ideal case the input current should be close to zero Ampere. Hence, an operational amplifier that supports an ultra-low input current (less than 10 fA) would be preferable. The disadvantage of this type of operational amplifiers is their temperature dependency. Therefore, we used a less temperature-dependent operational amplifier with 1 pA input current and added an additional 100 MΩ input resistance. Additionally, the known input resistance provides the back calculation from the signal to the touch force (Newton).

Figure 4: Sensing electronics as block diagram. For detailed description see text.
In the next step, the signal noise gets reduced. According to the surrounding mains voltage, the electrical noise is in the range of 50 Hz in the signal spectrum. Therefore, a 50 Hz Notch filter is used to remove this noise (cf., Figure 4c). In the final step, an offset and attenuation is applied to the signal to satisfy the measurement range (0 to 3.3 V) of the microcontroller’s internal analog to digital converter (cf., Figure 4d).

For the current prototype, we chose a highly energy-efficient 32-bit Cortex-M3 micro-controller from ATMEL (cf., Figure 4e). In comparison with other common micro-controllers, the signal processing can be performed on the board more efficiently, because data types are up to 32-bit and high-performance multiplications are supported. Furthermore, it features a 12-bit analog to digital converter (one million samples per second) and an integrated USB core unit.

2.4 Scanning the sensor matrix

The PyzoFlex® prototype shown in Figure 1 has 128 sensor spots covering a 210×130 mm² area. The electrodes on the bottom are connected horizontally and the electrodes on the top are connected vertically. An ultra-low leakage analog multiplexer is used to connect the horizontal row to ground. Meanwhile, all other rows are on high impedance. Every column is connected to an impedance converter circuit. Additional analog multiplexers are used to switch one of the impedance converter outputs to one of the analog digital converters’ inputs of the micro-controller. Other components between the impedance converter and the A/D converter are described in the sensing electronics section. All sensor spots are measured and their output voltage is sent to the PC every 10 ms. Scanning all 128 sensors takes 4.352 ms (128×34 µs). In summary, it takes approximately 1 µs for driving the analog multiplexer, 25 µs for waiting for the multiplexer and filtering circuits to settle to the new sensor output, and finally 8 µs for the A/D conversions. After scanning all sensors, it takes additional 2 µs to configure the DMA controller of the USB core to send the results to the PC. Due to the short processing time enough capacity is left for larger foils or a higher touch point density.

3. RESULTS

3.1 Sensor output

Since the PyzoFlex® sensor acts as a piezoelectric energy converter, any deformation of the sensor foil caused by – e.g. a touch of a human finger – is converted into electric energy (see Figure 6). The charges being generated by such a deformation can be measured as a voltage between the electrodes of the sensor setup. The generated voltage output from the PyzoFlex® foil is perfectly linear (cf., Figure 5). This is important for two reasons: (i) on the one hand it facilitates the tracking of the touch location and (ii) on the other hand it enables to utilize the absolute magnitude of the touch force for a selection of different user modi in the context of HMIs. The exerted pressure is an additional and independent interaction parameter that helps to distinguish intuitively and efficiently between the selection and the movement of an object when realizing novel user interactions by using a PyzoFlex® touch-foil.

![Figure 5: Linearity of the pressure dependent response of the PyzoFlex® foil.](image-url)
consumption in mobile devices is a crucial topic, a multi-layer approach (separation of sensing- and harvesting layer) could facilitate the prolongation of charging cycles of mobile devices (Figure 6).

Figure 6: Multi-layer PyzoFlex®. The graph indicates the generated electrical output of a 1-layer and a 2-layer PyzoFlex® sensor being excited with a pneumatic stamp. The generated charges of a double layer setup are twice as many as of a single layer design.

3.2 Processing the touches

For useful implementation of a piezoelectric touch foil into a user interface, dynamic pressure changes (being typical for piezoelectric sensing principles) are limiting the possibilities of user interaction compared to sensing static pressure levels. Those limitations can be overcome by using a smart signal processing as described below.

Every pressure-change on a sensor spot – e.g. by touching the sensor with a human finger – generates a charge and eventuates in a measurable voltage (see Figure 7). If no further pressure-change occurs, the voltage discharges through internal resistance of the piezoelectric film and the input resistance of the measurement circuit. This discharge follows an exponential function and is well predictable once the parameters of the exponential function are known. Every upcoming sensor value can be predicted with

$$U_{predicted} = U_{current} \cdot e^{-\frac{t}{\tau}}$$

Every deviation of the predicted value must be caused by a new pressure change on the sensor. This helps us to process the pressure changes from the sensor signal. In an additional step, the pressure progress can be calculated by integrating all pressure changes.

Figure 7: Piezoelectric output voltage once the user is touching the surface (Left) and lifting the finger (Right). The graphs also show the exponential signal decrease described in equation (1).
By using a sampling rate of 100 Hz, it is corresponding to 10 ms. The time constant $\tau$ of the exponential function depends on the internal resistance and capacitance of the sensor as well as on the input impedance of the measurement circuit. We use a pneumatic measurement setup to apply repeatable forces to a sensor spot. This setup helps to measure the step response of one single sensor spot. We used a fitting tool to interpolate the step response with an exponential function.

The interpolated exponential function of the used PyzoFlex® foil has a $\tau$ of 17.72 ms. By knowing these values, all parameters being required to process the pressure progress implied to the sensor spot are known. Figure 8 shows the back-calculation from the sensor output to the pressure progression. The applied pressure is illustrated in the first graph (a). The second graph shows the measured output voltage of the sensor (b). The deviations between the predicted and the actual values are shown in the third chart (c). Finally, an integration of the deviations is plotted in the last chart (d). Notice, that the voltage progress is proportional to the applied pressure.

Processing piezoelectric touch signals in such a way enables the detection of distinct, static pressure levels by continuously monitoring the piezoelectric signals being generated within the PyzoFlex® sensor matrix.

![Figure 8](http://proceedings.spiedigitallibrary.org) The touch processing. Applied pressure curve (a); resulting in a piezoelectric sensor signal (b); the deviation between the next estimated and measured signal value (c) (the deviation of the signal amplitude arises from the differences in the time constant between active excitation and passive relaxation. Nevertheless, the integrated areas below the peaks are equal); the estimated touch signal, which is achieved by integrating the deviation curve (d).

4. **OUTLOOK**

Until recently, the limitations of display and interface technologies have restricted the potential for human interaction and collaboration with computers. Desktop computer style interfaces, for example, still tend to leave the user one step removed from interacting with content. The emergence of large multi-touch displays has pointed to new possibilities for using display technology for interaction and collaboration\cite{14}\cite{15}\cite{16}. A range of emerging technologies and applications could enable more natural and human-centered interfaces so that interacting with computers and content becomes more intuitive. This will be important as computing moves from the desktop to be embedded in objects, devices and locations around us and as our “desktop” and data are no longer device dependent but follow us across multiple platforms and locations.

![Figure 9](http://proceedings.spiedigitallibrary.org) Novel user interaction scenarios being enabled by flexible PyzoFlex® HMIs in combination with flexible displays.
The increasing number of natural interfaces shows that users' expectations about using these devices in their daily life have increased. The reaction to these natural interface implementations has been very dramatic. This is because people are still interested in a simpler way of navigating information and content where the computer interface is not a barrier, but enables them to accomplish tasks more quickly and easily. Multiple metaphors and interaction paradigms using pen, touch, and visual recognition are coming together with the other elements to create a new experience. With the increasing development of interactive surfaces both companies and academics are evaluating their potential for wider use. These newly emerging form factors require novel human–computer interaction techniques. Although related natural large surfaces\cite{15-17-19} popularized the idea of futuristic, off-the-desktop gesture-based human–computer interaction and direct manipulation-based interfaces, in reality, making these interfaces is still a challenge. Conventional metaphors and underlying interface infrastructures for single-user desktop systems have been traditionally geared towards single mouse and keyboard-based WIMP (Window, Icon, Menu, Pointing) interface design.

Besides that, the new ability to manufacture flexible displays with technologies such as E-ink or Organic Light Emitting Diodes (OLED) will drastically change the design of mobile electronic devices. Therefore, future form factors will include light-weight mobile electronic devices that are bendable, rollable, foldable and even stretchable as well as large-area interactive information and learning environments. Flexible printed displays are increasingly being integrated into a variety of everyday products including password information on credit cards or other plastic cards which fit easily into one’s wallet, product packaging with smart labels that allow for electronic text and images to be applied to anything from milk cartons to cereal or remotely updatable price tags in supermarkets as well as other application fields like home-health diagnostics or smart clothing.

Within this context, novel PyzoFlex® user interfaces in combination with flexible displays will allow for completely novel, user friendly and intuitive interaction concepts as being shown in Figure 9. This topic will be investigated within a European funded Project (FLASHED, FP- ICT-2013.3.3, 7th European Framework Programme) starting in October 2013.

REFERENCES