PyzoFlex: Printed Piezoelectric Pressure Sensing Foil

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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. It is constructed with a sandwich structure of four layers that can be printed easily on any material. We use this material in combination with a high-resolution Anoto-sensing foil to support both hand and pen input tracking. The foil is bendable, energy-efficient, and it can be produced in a printing process. Even a hovering mode is feasible due to its pyroelectric effect. In this paper, we introduce this novel input technology and discuss its benefits and limitations.

ACM Classification: H.5.2 [Information interfaces and presentation]: User Interfaces. - Graphical user interfaces.

Keywords: piezoelectric, pyroelectric, pressure sensing, input device, bendable

INTRODUCTION
Over the last decade, touch sensing devices have become more and more important. Most researchers tried to improve multi-touch by introducing capacitive [5, 17], resistive [18], or optical [4, 10] sensing devices. Although most of them provide already a multi-touch sensing, it is still often not possible to track input pressure efficiently. Tracking pen and touch separately in combination with pressure tracking provides new possibilities for user interfaces and interaction design [1]. Hinkley et al. [11] point out that entirely new tools or even new interaction modes are possible due to the simultaneous use of pen and touch (e.g. touch input could be used for manipulations or navigation, whereas pen input could be used for accurate annotations). In 2009, Rosenberg and Perlin presented UnMousePad [18], a promising pressure-sensing device that was based on a paper-thin, resistive surface. Their setup had two impressive features: the sensing material was mounted on a paper-thin bendable/flexible material and it was able to accurately sense pressure input.

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In this paper, we present *PyzoFlex*, a novel sensing device that is based on a pyro- and piezoelectric sensor matrix, screen-printed on a flexible film (cf. Figure 1). Moreover, the sensor area can detect changes in pressure and temperature respectively.

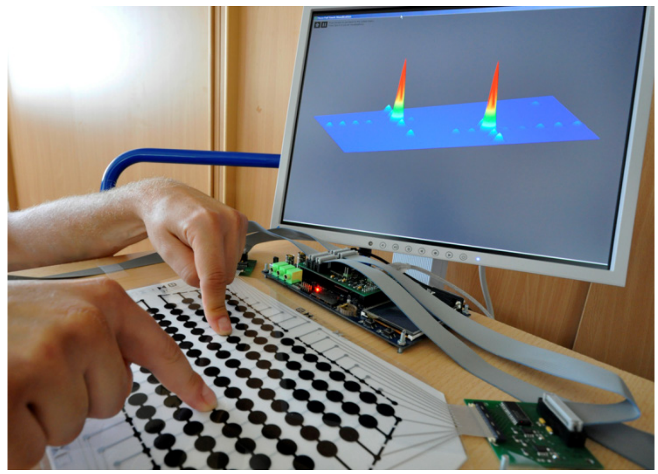

Figure 1: PyzoFlex in action. The current prototype is based on a DIN A4-sized foil that provides real-time pressure sensing feedback with a frame rate of 100 fps.

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. All ferroelectric materials also have a pyroelectric effect: a variation in temperature influences the distribution of the electrical charge, which is again measureable. As a result, ferroelectric materials can also be used to measure temperature changes.

The main contributions of this paper are:

- the technical implementation of a pressure sensing device based on piezo- and pyroelectric sensors,
- the presentation of material and sensor electronics,
- the combination with a high accurate pen tracking based on the Anoto[1] technology, and
- the presentation of the key features of PyzoFlex to discuss the pros and cons of the foil.

[1] www.anoto.com

In this paper, we demonstrate the concepts and the development of a novel sensing device based on ferroelectric materials. We will start with a discussion of the related work, followed by our sensing approach and foil design based on ferroelectric materials. Then, we will propose our implementation, including sensing electronics and signal processing. Subsequently, we will discuss interesting material properties and current limitations. Finally, we will conclude our work and give a short preview of the future work.

RELATED WORK

Over the last two decades, researchers tried to develop multi-touch input devices [3]. So far, multi-touch sensing devices are mostly divided into three different categories: optical, resistive, and capacitive tracking devices. The not so common piezoelectric sensing appears to be the fourth.

Optical Sensing

There exists a plenty of different solutions for vision-based multi-touch surfaces developed by researchers [10, 13, 21]. Han proposed a low-cost multi-touch sensing technology based on Frustrated Total Internal Reflection (FTIR) [10]. His back-projected prototype is able to acquire touch information at high spatial and temporal resolutions and is scalable to large surfaces. Matsushita and Rekimoto [13] presented a computer augmented wall, based on Diffused Illumination. With the appearance of the Microsoft Kinect sensor, new multi-touch and interaction solutions based on depth cameras have been developed [21]. However, all optical touch solutions are highly dependent on ambient lighting and the material of the tracking object. In addition, the separation of touch and pen input is not possible.

Resistive Sensing

Resistive array-based sensors usually consist of two layers of conductive material, one with horizontal lanes and one with vertical lanes. Whenever a user touches the surface the horizontal and vertical lanes are alternately connected and enabling the flow of current. This technique is called Force Sensitive Resistance [6, 18]. These solutions are inherently inexpensive and energy efficient, but the tracking resolution is limited to the space between the sensing lanes.

Capacitive Sensing

Capacitive touch sensors [5, 12, 20] consist of a thin conductive layer placed on an insulator, such as glasses. This layer serves as electrode of a capacitor. A touch on the surface results in a distortion of the panel’s electrostatic field and is measureable as changes in capacitance. There are several different technologies on to estimate the exact touch position. The DiamondTouch [5] is able to distinguish different users by incorporating them into a unique capacitive circuit. Capacitive sensing can only measure the contact area, so none of these solutions can be pressure sensitive. Another major disadvantage of this technique is that it relies on the dielectric properties of the human body; thus, styluses or objects cannot be tracked.

Piezoelectric Sensing

Existing input devices exploiting the piezoelectric effect are few and very expensive due to the dependence on non-printable piezoelectric materials. Usually they provide only limited user interaction. 3M introduced a system which utilizes the dispersion of touch-generated surface waves across a chemically treated glass plate using piezoelectric sensor elements placed in each corner for detection. Software algorithms then interpret this information and provide the actual location of the touch[2]. The technology claims to be unaffected by dust and scratches, and it works for both fingers and styluses. However, it cannot detect a motionless finger. A similar detection system for surface acoustic waves based on polymer piezoelectric sensors has been introduced by Reis et al. [16]. RIM’s Blackberry Storm 2 has embedded a piezoelectric crystalline layer between two glass plates for triggering a haptic feedback. However, the detection of the touch location is not provided by the piezoelectric layer.

Fujita et al. patented a ferroelectric liquid crystal touch panel in 1992 [8]. The touch position gets detected by electrodes measuring the electromotive force which is generated by pushing the ferroelectric crystal layer. Compared to our work, their setup cannot detect different pressure levels. Instead they can only distinguish between touch and no touch.

The company Murata presented a twistable remote controller and a touch-pressure panel which are both based on a piezoelectric film[3]. In contrast to their remote controller, we do detect neither bending nor twisting (which however would be possible with our setup). For their touch panel, they use an additional capacitive approach for position detection and a piezoelectric film for pressure detection. This results in two different hardware components for touch sensing. We avoid this keeping both complexity and costs low. The barely information suggests that only their remote control is transparent, but not their "touch pressure pad".

Pen and Touch

Several research studies consider touch input or pen input in isolation. Only a few systems support both, the simultaneous interaction with pen and touch [1, 11, 22, 23]. Hinkley et al. [11] refined the use of pen and touch by contextual information. Pen input always draws and touch input always manipulates, but if they are used together in the context of an object a new implicit mode is triggered. Yee [23] used single-touch and stylus input on a tablet to support simultaneous drawing and panning within a canvas. Brandl et al. [1] explored the effects of bi-manual pen and touch input on a horizontal tabletop surface, while assigning the pen to the preferred hand and touch to the non-preferred hand. Pen and touch gestures were explored in [2, 7, 22].

[2] www.3Mtouch.com

[3] www.murata.com/new/news_release/2011/0921/

The benefits of combining pen and touch input for digital surfaces have been explored in several research projects [1, 22]. However, many of these systems limit users through their technical restrictions such as constrained scalability. For example, touchscreens overlaid on tablet computers that provide simultaneous pen and touch interaction have been proposed in [23]. Solutions such as the small-scale capacitive multi-touch screen from N-Trig have already been commercialized. They support user-input for both pen and capacitive touch in one single device. For the pen tracking, the developers of the N-Trig device use an electrostatic stylus and an active digitizer that is embedded in the screen.

UnMousePad [18] is a resistive, pressure-sensitive touch-based input device for tracking both touches as well as pens based on Interpolating Force Sensitive Resistance (IFSR), which is completely different to our approach from a technology point of view. The thin and transparent foil can acquire high-quality, anti-aliased pressure images and is able to distinguish touches, objects, or pens. In contrast to UnMousePad our setup is based on ferroelectric material that provides hover capability. Moreover, our transparent foil prototype is ITO-free.

PYZOFLEX APPROACH

Piezoelectric Effect

Piezoelectric materials are like wet sponges, once you squeeze them water/charge pours out. The amplitude and frequency of the signal is directly proportional to the mechanical deformation of the piezoelectric material [14]. The induced deformation of the piezo-element causes a change in the surface charge density of the material resulting in a voltage appearing between the electrodes (cf., Figure 2). The piezoelectric coefficient describes the amount of electrical charge generated per applied force unit.

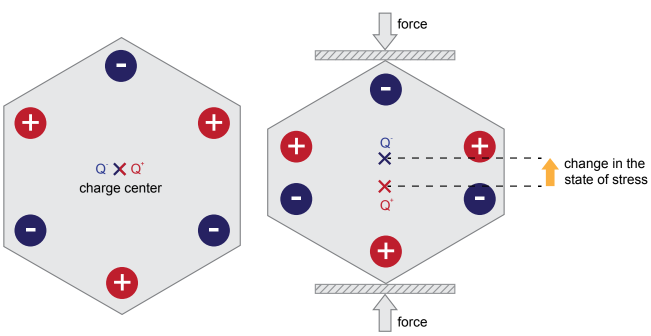

Figure 2: The Piezoelectric Pressure Sensing Effect. *(Left)* Distribution and centers of positive and negative charges. *(Right)* Shifting of the charge centers in the state of stress/force.

Piezoelectricity was discovered over 100 years ago by the Curie brothers studying the dimensional changes of quartz at different electric fields. In the 60's, piezoelectricity was detected in organic materials studying whale bones and tendon thus initiating intense search for piezoelectricity at organic materials. In 1969, Kwai discovered that a stretched and poled film of polyvinylidene fluoride (PVDF) shows large piezoelectric activity (5 pC/N) [9].

A PVDF film, like all piezoelectric materials, is a dynamic material developing an electrical charge proportional to a change in mechanical stress. As a consequence, piezoelectric materials itself are not suitable for static measurements due to their internal resistance. The electric charges generated in the polymer film decay with a time constant determined by the dielectric constant, the internal resistance of the film and the input impedance of the interface electronics to which the film is connected (cf. Figure 3) [14].

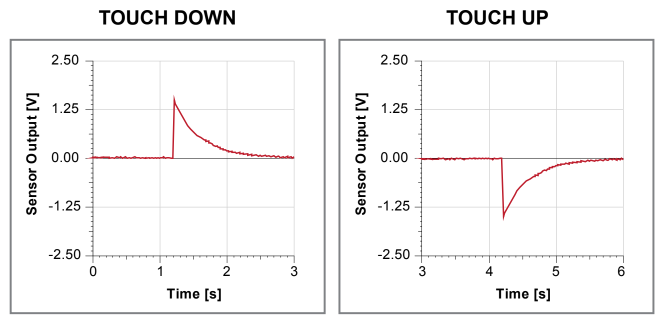

Figure 3: Piezoelectric output voltage once the user is touching the surface *(Left)* and lifting the finger *(Right)*.

Pyroelectric Effect

The pyroelectric effect in orientated and poled PVDF was found in 1971, where a pyroelectric coefficient of about $20\mu C/m^2K$ was identified, comparable to crystalline pyroelectrics [9]. Pyroelectric sensor materials are usually dielectric materials with a temperature-dependent molecular dipole moment. As these materials absorb thermal energy, they expand (or contract). Due to the expansion an indirect piezoelectric signal is caused [14]. A reduction of the average polarization of the film (sum of molecular dipole moments) is caused by random motion of the dipoles upon heating; this generates a charge built up on the film surface. Analog to piezoelectricity and stress, the pyroelectric output current is proportional to the rate of temperature change. The pyroelectric charge coefficient describes the amount of electrical charge generated per degree of temperature change.

Utilizing the afore-mentioned material properties, piezo- and pyroelectric polymer films can be used for sensing of pressure and temperature changes in a large area. By developing a printable formulation of a piezo- and pyroelectric polymer ink, as well as considering a sufficient layout of sensors, the fabrication of cost efficient, large-area sensors by screen printing processes is possible. These sensors are capable of pressure sensing and tracking (touch and/or pen input) as well as detecting the approaching of IR-emitters such as human hands (hovering interaction).

In Figure 4 the piezoelectric and pyroelectric effect are compared, showing a touch with a duration of about five seconds. As seen in the right side of Figure 4, it is highly complex to distinguish the warming and cooling effects from the touch signals. Moreover, in some situations, these effects can get even more blended. Usually, the piezoelectric foil is highly sensitive against any external light sources.

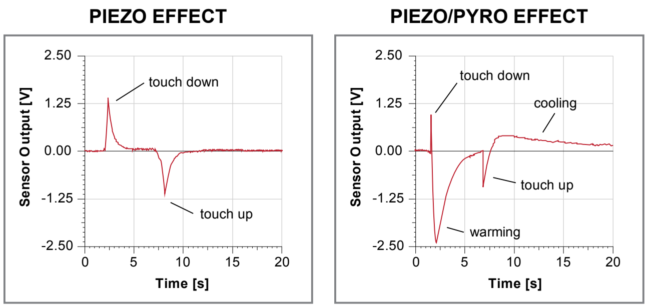

Figure 4: Output signals from the PyzoFlex sensor: Piezoelectric response without pyro effect *(Left)* and combined piezo- and pyroelectric response *(Right)*.

These problems can be solved either by adding a temperature absorbing layer – losing the pyroelectric response - or by changing the general foil design. A foil design, which has both piezo- and pyroelectric effects, is discussed later.

Current Foil Design

The current sensing foil is based on a 16 × 8 array of screen printed, flexible, capacitive, circular sensor spots having a diameter of 10 mm (cf., Figure 5). The 128 sensor spots currently cover a 210×130 mm² area.

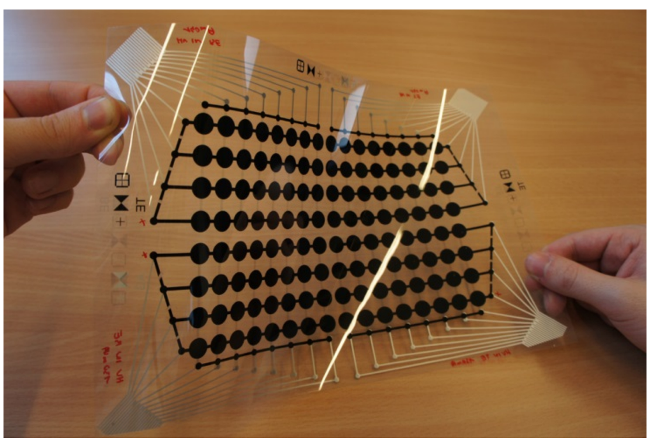

Figure 5: The current version is a 16 x 8 array of printed, piezoelectric sensor spots with a size of 10 mm.

The basis of our touch foil is the transparent plastic substrate, which serves as carrier for the printed materials. In the first step 128 circular spots (electrodes) are printed to the carrier material, which are connected horizontally. Subsequently, the whole plastic substrate gets continuously coated with the ferroelectric material. After that, the second layer with vertically connected electrodes is printed.

The two layers of electrodes are forming a capacitor. Charge changes in the ferroelectric sensor layer cause measureable voltages between the electrodes. Figure 6 shows the sandwich design of our foil prototype.

For our prototype, we used the following materials:

- the first layer is a transparent polyethylene terephthalate substrate (*PET*),
- the electrodes in the second layer consist of a semi-transparent *conductive polymer* material,
- the piezo- and pyroelectric sensor material forms a polyvinylidene fluoride (*PVDF*), which has a transparency of about 85 percent, and
- the top electrodes consist of either non-transparent *carbon* (cf., Figure 5) or again of *conductive polymer* (cf., Figure 16).

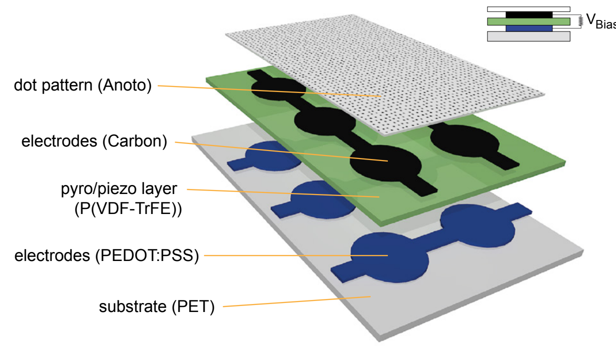

Figure 6: PyzoFlex sensor sandwich technology.

For applications with a strict pen and touch separation, a stable separation of both inputs is highly necessary. A separation based on the blob information of touches [18] is not highly robust, because slight pen and finger contacts result in similar blob sizes and pressure values. Moreover, an accurate pen tracking requires ultra-high input resolutions (e.g., 677 dpi with Anoto[4]), which are hard to achieve with multi-touch sensing technology. We decided to combine the PyzoFlex foil Anoto pen tracking to provide a stable pen and touch tracking. Furthermore, the additional Anoto foil acts as a temperature absorbing layer to reduce the pyroelectric response.

IMPLEMENTATION

PyzoFlex fabrication

The fabrication is done by low-cost printing of a smart active matrix sensor array with four functional inks [24]:

- the fluoropolymer sensor ink[5],
- the conductive polymer ink[6],
- the conductive carbon paste[7], and
- the conductive silver ink[8].

The substrate is formed by a transparent, flexible (175 µm thick) plastic foil[9], thus guaranteeing high flexibility and

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[4] http://www.anoto.com/why-anoto.aspx

[5] P(VDF-TrFE) (poly(vinylidene fluoride trifluoroethylene)

[6] PEDOT:PSS(poly(3,4-ethylenedioxythiophene): poly(styrene sulfonic acid)) ink (HC Starck SV3)

[7] DuPont 7201

[8] DuPont 5000

[9] Melinex™ ST725

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 - can be printed on the foil thus forming a 5µm thick transparent layer. Silver conductive lines are printed for connecting the sensor electrodes to a Molex 1.00 mm Pitch FFC/FPC connector. 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.

For achieving piezo- and pyroelectric response, the randomly ordered and dipole containing nano-crystallites that are embedded in an amorphous constellation must be aligned vertically to the sensor electrodes. This can be achieved by hysteresis poling of the sensors using a Sawyer-Tower-Circuit [15]. For sufficient 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/m^2 at a poling frequency of 10 Hz.

PyzoFlex provides printed, large-area, flexible and durable polymer sensors, showing a piezoelectric coefficient d_{33} of 20-30 pC/N, a pyroelectric coefficient p_{33} of 40 µC/m^{2}K at room temperature, and a Curie temperature of 125 °C.

PyzoFlex sensing electronics

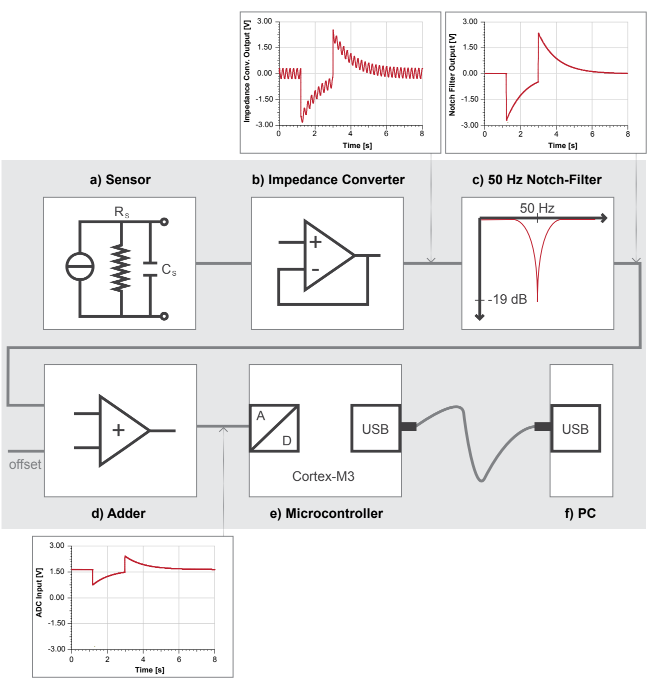

Figure 7: Sensing electronics of the current prototype as block diagram.

The equivalent circuit of a piezoelectric sensor is a current source with an internal resistance R_s (1 GΩ) and an internal capacitance C_s (1 nF), as depicted in Figure 7a. 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 7b). 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 the 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).

In the next step, the signal noise gets reduced. According to the surrounding mains voltage, the electrical noise is around 50 Hz in the signal spectrum. Therefore, a 50 Hz Notch filter is used to remove this noise (cf., Figure 7c).

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 micro-controller's internal analog to digital converter (cf., Figure 7d).

For the current prototype, we chose a highly energy-efficient 32-bit Cortex-M3 microcontroller from ATMEL (cf., Figure 7e). 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.

Scanning the sensor matrix

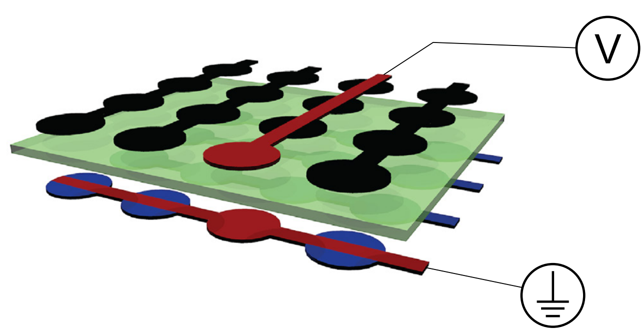

Figure 8: Scanning a single touch point.

The current prototype of PyzoFlex 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 one horizontal row to ground. Meanwhile, all other rows are on high impedance (cf., Figure 8).

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. The scan for all 128 sensors takes 4.352 ms (128×34 µs). To sum up, it takes approximately 1µs 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 higher touch point density.

Touch Processing

Every pressure-change on a sensor spot generates a charge and eventuates in a measurable voltage. 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

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

With a sampling rate of 100 Hz, t would be 10 ms. 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.

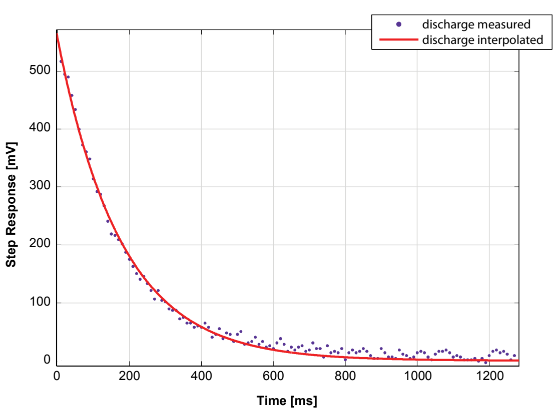

Figure 9: Interpolation of the step response.

The time constant τ of the exponential function depends on the internal resistance and capacitance of the sensor as well as the input impedance of the measurement circuit. We use a pneumatic measurement setup (cf., Figure 11) 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 (cf., Figure 9).

The interpolated exponential function has a τ of 177.2 ms. After that, all parameters, which are required to process the pressure progress from the sensor output, are known. Figure 10 shows the back-calculation from the sensor output to calculate the pressure. The applied pressure is illustrated in the first graph. The second graph shows the measured output voltage of the sensor. The deviations between the predicted and the actual values are shown in the third chart. Finally, an integration of the deviations is plotted in the last chart. Notice, that the voltage progress is proportional to the applied pressure.

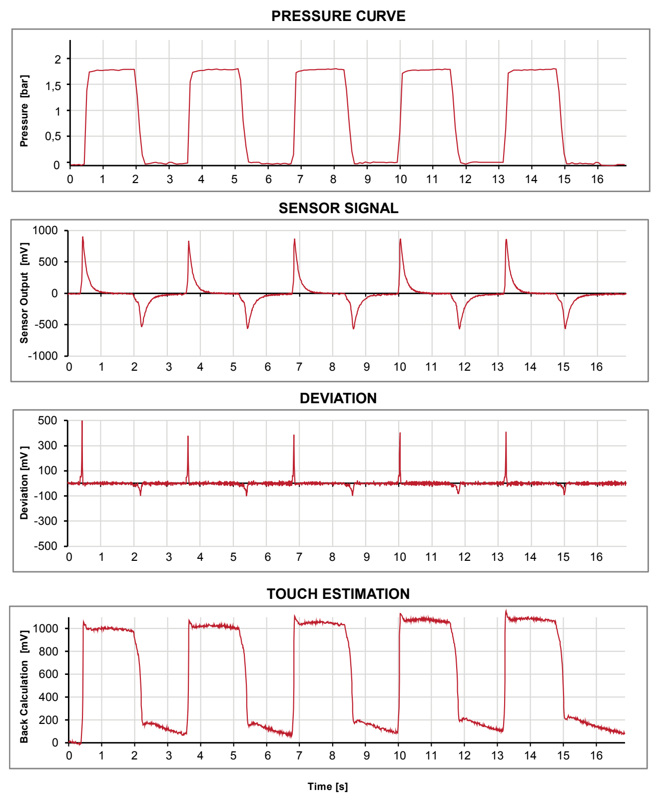

Figure 10: The touch processing. Applied pressure curve *(First)*; resulting in a piezoelectric sensor signal *(Second)*; the deviation between the next estimated and measured signal value *(Third)*; the estimated touch signal, which is achieved by integrating the deviation curve *(Fourth)*.

Pen & touch tracking

To provide a stable solution for a pen and touch tracking, we combine different technologies: the PyzoFlex foil with an additional Anoto dot pattern (cf., Figure 6). The pen and touch separation is realized through software-based solution in the second step. A combined input driver analyses both pen and touch input data synchronously. Whenever a new touch is performed, the input driver waits for about 50 ms for a pen input at the same spot (within a small threshold). This works properly, since each Anoto event has an initial lag of 50 ms as a result of the Bluetooth transmission. During this period, all touch data gets temporarily stored in the input driver. Whenever a pen input is noticed, the input driver forwards only the pen input and ignores the touch input. Otherwise, the temporarily stored touch data gets regularly forwarded to the applications. However, the problem of palm rejection [11] is not yet solved with the suggested separation procedure.

PERFORMANCE OF PYZOFLEX

The piezoelectric response was measured with a special developed air-pressure driven setup shown in Figure 11.

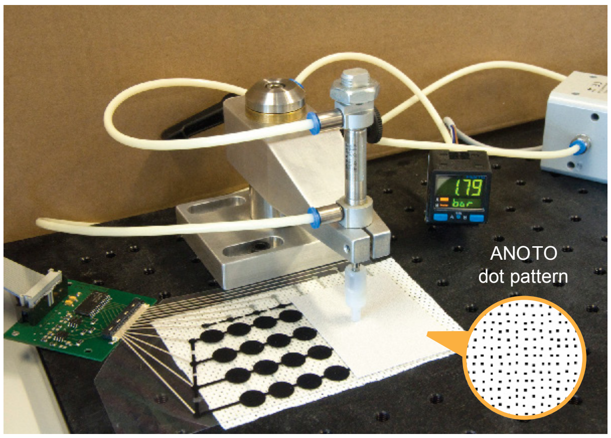

Figure 11: Setup for the piezoelectric measurements. Currently an Anoto covered sensor-spot is excited at 1.8 bar. As a compressable substrate, a thin fabric is used.

A pressurized bar was loaded on the polymer film while the piezoelectrically generated charges were measured with the afore described PyzoFlex sensing electronics. The proportional pressure valve (Festo MS6-LRE-1) regulating the waveform and pressure load applied on the sample is controlled by a function generator (Keithley 6221). The pressure in the air-pipe is monitored with a Festo SPAB-P10R-R18 pressure sensor. The stamp itself consists of a Teflon cylinder with a diameter of 4.5 mm.

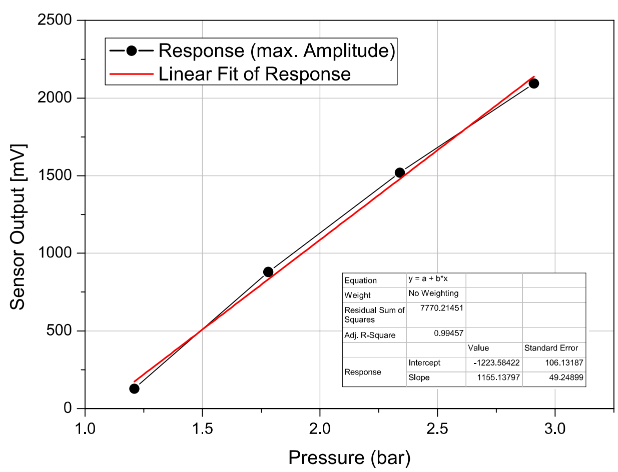

Figure 12: Linearity of the pressure dependent response of the PyzoFlex foil.

Linearity

The generated voltage output from the PyzoFlex foil is perfectly linear (cf., Figure 12). This is important for two reasons: On the one hand it facilitates the tracking of the touch location and on the other hand it enables to utilize the absolute magnitude of the touch force for a selection of different user modi. 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.

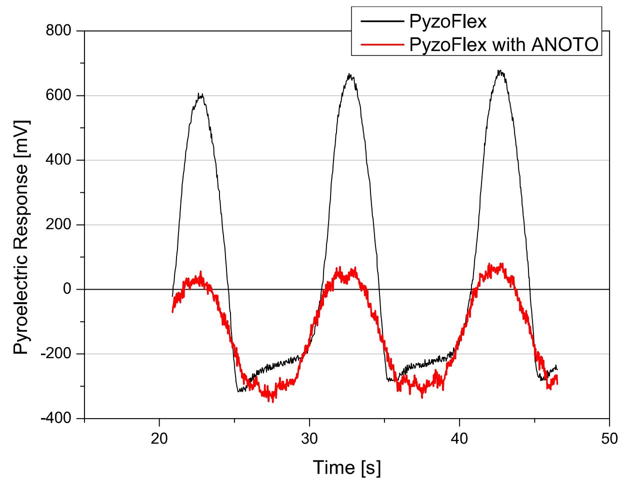

Figure 13: Pyroelectric response to a 70 mW laser diode with a wavelength of 890 nm. The combination with the Anoto pattern significantly reduces the generated (positive) response influencing the touch-signals.

Noise due to external light sources

As shown in Figure 13 the PyzoFlex sensor foil is sensitive to IR-radiation introduced by ambient light.

Thus inducing temperature variations in the pyroelectric layer and therefore generating charges and a detectable voltage signal response.

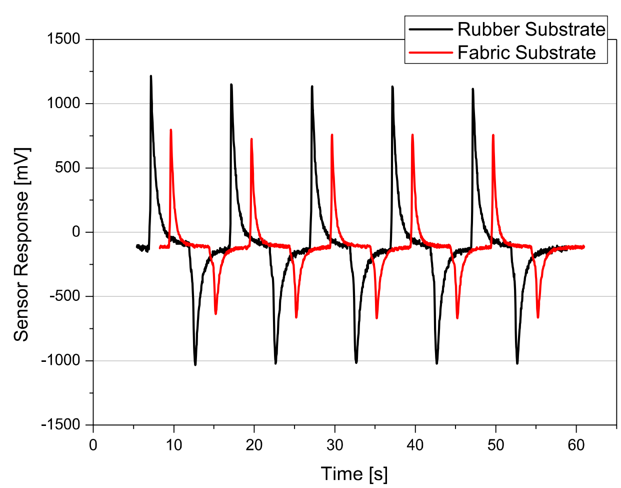

Figure 14: Influence of different substrates to the piezoelectric response. The less elastic fabric-substrate shows only 65 % of the signal generated using the more compressible rubber substrate.

This is an effect that might cause troubles for a multi-touch environment. A combination of the PyzoFlex with the Anoto foil decreases the parasitic pyroelectric effect by several orders of magnitude thus enabling pure touch-based control of the surface (cf., Figure 13). The Anoto foil screens both the IR-radiation from light sources as well as the heat induced by a human body (finger).

Different substrate materials

The type of substrate material is crucial for the magnitude of the harvested piezoelectric signal height. A slightly compressible and/or perforated substrate provides a larger degree of freedom (= stronger bending) in applying a vertical mechanical stress due to the lack of surface confinement (cf., Figure 14).

Geometry

PyzoFlex is a bendable sensor technology, meaning that the sensor can be mounted on different curved surfaces (cf., Figure 15).

Figure 15: The PyzoFlex foil can be also attached to curved surfaces. The metal cylinder has a diameter of 16 cm.

The bending radius depends on the size and the distance of the printed piezoelectric spots. We currently implemented a matrix of circular spots with 10 mm diameter and about 15 mm distance. The spot size is related to the maximum diameter of a human finger-touch. The highest response signal is expected for a fully activated spot surface area (least parasitics). However, too large spot sizes would be detrimental with respect to resolution and higher noise signals trapped from ambient heat sources. Optimization on testing different spot sizes and spot shapes is ongoing.

Transparency

An important topic of touch sensing is transparency, which of course is an important feature for touchscreen applications in mobile devices (e.g. smartphones or tablets). Since the P(VDF-TrFE) sensing layer itself has a transparency over 85 percent, the main limitations come from the black carbon electrodes (cf., Figure 6). One possibility is to replace them by nearly transparent PEDOT:PSS electrodes with the advantage that these are also printable (cf., Figure 16). A further possibility is a high-transparent but less mature metal nanoparticle ink.

Figure 16: Replacing the black carbon electrodes with PEDOT:PSS electrodes results in a quasi-transparent foil.

Economical tracking & ITO-free

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 even serve as energy harvesting resource [19]. Another major economic advantage is the ITO-free (*indium tin oxide*) implementation, because common used indium is a very limited resource in our world.

DISCUSSION

We have showed how printed pyro- and piezoelectric materials can be used to produce a pressure and temperature sensitive touch foil. Nevertheless, the following problems have to be solved.

Multi-Touch & Crosstalk problems

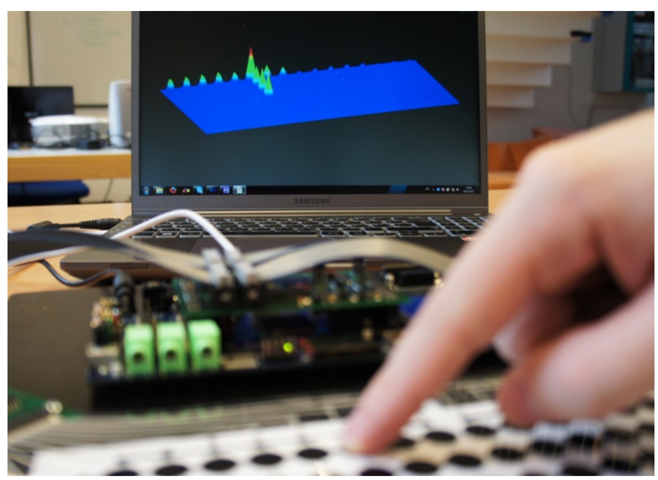

Figure 17: Crosstalk problems caused through the matrix-based wiring of the sensor foil.

For a single touch point the back-propagation of the pressure progress works without any problems. Although we are able to capture each sensor point simultaneously with 100 Hz, the recognition of multiple adjacent touches is currently problematic due to *crosstalk problems* between the sensor spots (cf., Figure 17).

The crosstalk is caused by the matrix-based wiring and the used materials. Several solutions are possible. In the next step, we plan to improve our signal-processing algorithm to mathematically remove the crosstalk. We will analyze the crosstalk for characteristic patterns, which can then be subtracted from the original signal. Furthermore, a new sensor design could effectively eliminate crosstalk since a matrix configuration is avoided and each sensor element is separately connected; thus, causing a higher number of connection lines to the electronics. Additional to the previous two solutions, the conductivity of the electrodes (highly conductive printing pastes) could be increased or insensitive discharging elements could be introduced (by applying inactive sensor spots as discharging elements in between the active sensor spots). We are currently working on reducing the crosstalk to mitigate this issue.

Higher Resolution

In the current prototype, 128 circular sensor points with a diameter of 10 mm are arranged in a distance of about 15 mm. The main focus of the current foil design was to prove the concept of using a printed ferroelectric sensor array for pressure sensing. In order to achieve a high-resolution touch foil, we plan to decrease the diameter and distance of the sensor points, since there is enough capacity on the microcontroller left. The current microcontroller can handle easily up to 1024 sensor spots. Furthermore, the use of additional A/D converters will allow us to parallelize the sampling of sensor values, resulting in an even higher resolution.

The current foil uses a different spacing for the horizontal lines (16 mm) of the matrix than the vertical (13 mm). An informal experiment showed that a distance of 13 mm provides accurate linear interpolation, whereas a distance of 16 mm is too large. Thus, by increasing the pixel density of the foil design, we can use a linear interpolation routine to increase the resolution to modern standards. Of course a linear interpolation requires a crosstalk free sensor signal.

Cross-Sensitivity of Piezo- and Pyro-Response

With the current foil design, there is a trade-off between hovering mode and pen input. Currently the additional Anoto pattern (cf., Figure 6) serves as a light reflecting and temperature diffusion layer. By printing the pattern directly on the touch foil, this issue can be solved. To handle piezo- and pyroelectric responses (pressure and hovering) simultaneously, a complete new foil design is required. In the new design, each touch point consists of two side-by-side layers (as half circle electrodes), which are wired separately to the sensing electronics. Whereas one is tuned on piezoelectricity, the other one is tuned on pyroelectricity. This can be accomplished by adding inorganic piezoelectric nanoparticles to the sensing material. Through a smart poling procedure, either pyro- or piezoelectricity can be suppressed, owing to the opposite sign of the piezoelectric coefficient for sensing material and the nanoparticles. This would lead to two separate signals for each touch point and simplifies the signal processing. Currently, we are working on a corresponding foil design.

CONCLUSION & FUTURE WORK

In this paper, we have demonstrated that piezo- and pyro-electric materials are a promising alternative to the existing optical, resistive, and capacitive sensing materials. In comparison to common touch solutions, the proposed approach can sense pressure accurately using piezoelectric materials. Even a hovering mode is feasible due to its pyroelectric effect. Furthermore, the foil is produced by simple low-cost printing. No cleanroom, vacuum or evaporation is required in the manufacturing process. The sensing electronics is able to sample each of the 128 sensor spots with 100 Hz. A software-based input driver calculates the applied pressure from the sensor output. By combining the pressure sensitive touch foil with a high-resolution pen technology (Anoto), a powerful pen and touch solution is achieved. This provides new possibilities for user interfaces and interaction design [1, 11]. We foresee our technology beneficial to the development and use of large surfaces, where pen and touch are used simultaneously (e.g., whiteboards or tabletops). There is also high potential for mobile touch devices due to the quasi-transparency (85%) of the foil.

For future work, we plan to eliminate the discussed problems, including the crosstalk and the cross-sensitivity of the piezo- and pyroelectric response. Furthermore, we want to increase the resolution by changing the sensor arrangement and interpolating between the sensor points. Another goal will be to improve the scalability of the sensor foil – since it can be printed on really large surfaces. In our final version, we would like to fabricate the sensor foil over several square meters in an in-line roll-to-roll process at low cost. Finally, we plan to develop a more transparent sensor foil by experimenting with new materials (e.g., for the use in mobile devices).

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REFERENCES

1. Brandl, P., Forlines, C., Wigdor, D., Haller, M. and Shen, C. 2008. Combining and measuring the benefits of bimanual pen and direct-touch interaction on horizontal interfaces. In *Proc. AVI 2008*, 154-161.
2. Brandl, P., Haller, M., Hurnaus, M., Lugmayr, V., Oberngruber, J., Oster, C., Schafleitner, C. and Billinghurst, M. 2007. An Adaptable Rear-Projection Screen Using Digital Pens And Hand Gestures. In *Proc. ICAT 2007,* 49-54.
3. Buxton, W., Hill, R. and Rowley, P. 1985. Issues and techniques in touch-sensitive tablet input. In *Proc. SIGGRAPH 1985*, 215-224.

4. De los Reyes, I., Roberton, N., Calvery, B., Turner, T. J. E., Chandley, A., Makosi, D., Henderson, P., Nikitin, E., Elabbady, T. and Joe, P. 2007. Function oriented user interface. *U.S. Patent No. 7730426B2.*
5. Dietz, P. and Darren, L. 2001. DiamondTouch: a multi-user touch technology. In *Proc. UIST 2001*, 219-226.
6. Eventoff, F. N. 1979. Electronic pressure sensitive transducer apparatus. *U.S. Patent No. 4313227*.
7. Frisch, M., Heydekorn J. and Dachselt, R., 2009. Investigating multi-touch and pen gestures for diagram editing on interactive surfaces. In *ITS 2009,* 149-156.
8. Fujita, M., et al. 1992. Ferroelectric liquid crystal touch panel. *U.S. Patent No. 5122787.*
9. Fukada, E. 1989. Introduction: Early Studies in Piezoelectricity, Pyroelectricity, and Ferroelectricity in Polymers. *Phase Transitions: A Multinational Journal*, Volume 18, Issue 3-4, 135–141.
10. Han, J. 2005. Low-cost multi-touch sensing through frustrated total internal reflection. In *Proc. UIST 2005*, 115-118.
11. Hinckley, K., Yatani, K., Pahud, M., Coddington, N., Rodenhouse, J., Wilson, A., Benko, H. and Buxton, B. 2010. Pen + touch = new tools. In *Proc. UIST 2010*, 27-36.
12. Jobs, S. P., et al. 2008. Touch screen device, method, and graphical user interface for determining commands by applying heuristics. *U.S. Patent No. 7479949B2*.
13. Matsushita, N. and Rekimoto, J. 1997. HoloWall: designing a finger, hand, body, and object sensitive wall. In *Proc. UIST 1997*, 209-210.
14. Measurement Specialities, Inc. 1999. Piezo Film Sensors. *Tech Report*, Sensor Products Division, Norristown.
15. Naber, R. C. G., Asadi, K., Blom, P. W. M., de Leeuw, D. M. and de Boer, B. 2010. Organic nonvolatile memory devices based on ferroelectricity. *Advanced materials*, Volume 22, Issue 9, 933–945.
16. Reis, S., Correira, M., Martins, M., Barbosa, G., Sousa, M., Minas, G., Lanceros-Mendez, S. and Rocha, J. G. 2010. Touchscreen based on acoustic pulse recognition with piezoelectric polymer sensors. In *ISIE 2010*, 516-520.
17. Rekimoto, J. 2002. SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In *Proc. CHI 2002*, 113-120.
18. Rosenberg, I. and Perlin, K. 2009. The UnMousePad: an interpolating multi-touch force-sensing input pad. In *Proc. SIGGRAPH 2009*, 65:1-65:9.
19. Sodano, H. A., Inman, D. J. and Park, G. 2005. Comparison of Piezoelectric Energy Harvesting Devices for Recharging Batteries. *Intelligent Material Systems and Structures*, Volume 16, Number 10, 799-807.
20. Westerman, W. 1999. Hand Tracking, Finger Identification and Chordic Manipulation on a Multi-Touch Surface. *PhD thesis*, University of Delaware.
21. Wilson, A. 2010. Using a depth camera as a touch sensor. In *Proc. ITS 2010*, 69-72.
22. Wu, M., Shen, C., Ryall, K., Forlines, C. and Balakrishnan, R. 2006. Gesture registration, relaxation, and reuse for multi-point direct-touch surfaces. In *Proc. TABLETOP 2006*.
23. Yee, K. 2004. Two-handed interaction on a tablet display. In *Proc. CHI EA 2005*, 1493-1496.
24. Zirkl, M., Sawatdee, A., Helbig, U., Krause, M., Scheipl, G., Kraker, E., Ersman, P. A., Nilsson, D., Platt, D., Bodö, P., Domann, G. and Stadlober, B. 2011. An All-Printed Ferroelectric Active Matrix Sensor Network Based on Only Five Functional Materials Forming a Touchless Control Interface. *Advanced Materials*, Volume 23, Issue 18, 2069–2074.