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Flexible Textile Printed Piezoresistive Pressure Sensors

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Abstract. The combination of sensor technology and textiles substantially extends the range of textile applications. Smart textiles, especially clothing, might increasingly be equipped with pressure sensors. They could be used in the sports or health sector to measure body activities or other activities which are close to the body. Therefore, it is essential to develop flexible sensors which allow to adapt to the properties of textile materials which are in contact with the body or surrounding it. In this paper a pressure sensor based on piezoresistive ink and conductive fabric with high flexibility is reported. Preliminary pressure sensors have been fabricated and tested on a universal testing machine. The sensors show to be functional, but also showing some aspects to improve, such as its hysteretic behaviour.

Introduction and State-of-the-Art

One of the methods for manufacturing a textile piezoresistive pressure sensor is based on a 3-layer structure. The outer layers form the electrodes through which the electrical conditioning circuit is connected. A conductive, moreover piezoresistive layer is placed between the electrodes. A piezoresistive material is able to change its electrical resistance if pressure is applied to it. The variations of resistance in the piezoresistive layer are proportional to the pressure applied on it, and thus an appropriate signal conditioning circuit is able to convert these variations into an electrical signal. Figure 1 shows a setup in which the inner layer is a polymeric piezoresistive film [1].

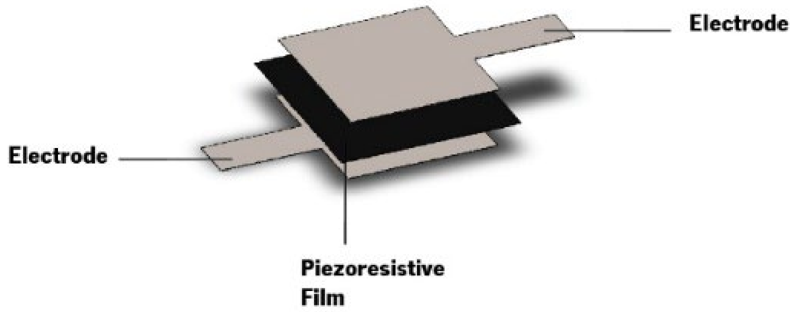

Figure 1. Construction of the flexible pressure sensors [1]

To realize the pressure sensitive layer, several piezoresistive materials can be used, which are able to change their resistance under mechanical deformation. To obtain a piezoresistive textile, various conductive materials are applied on textile fabrics or fibers, such as carbon nanoparticles [2], metallic nanoparticles or nanowires [3] and conductive polymers [4].

A piezoresistive material can be made out of conductive nanoparticles which are placed in a matrix of non-conductive polymer. When pressure is applied to this material, the particles move closer together and thus resistance between the electrodes decreases as the current is conducted more easily through the particles, which is explained in Figure 2 [5].

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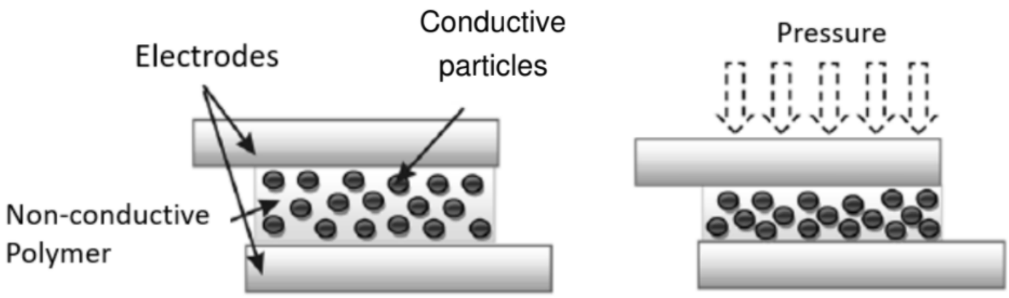


Figure 2. Functionality of the piezoresistive effect [5]

One of the most known and utilized materials is Velostat by 3M. It is a common piezoresistive material, which consists of a carbon loaded polymeric foil [4]. In [6], a setup using Velostat with silver-plated woven polyamide fabric is described. Earlier work [1] has been presented using this setup, as well as copper film and knitted polyamide silver-plated fabric as electrodes. In [7] a similar configuration using copper fabric and Velostat is described. The EeonTex fabric produced by EEONYX has revealed piezoresistive properties as well. In [8], a pressure sensing matrix using this fabric as piezoresistive layer and striped copper-based conductive fabrics to form the electrode matrix have been proposed.

Another possibility of producing pressure sensor using piezoresistive materials is using interdigitated electrodes, as shown in Figure 3 [6]. In this case, conduction is made between electrodes places on the same plane, as opposed to conduction in the z direction that occurs in the previously presented works.

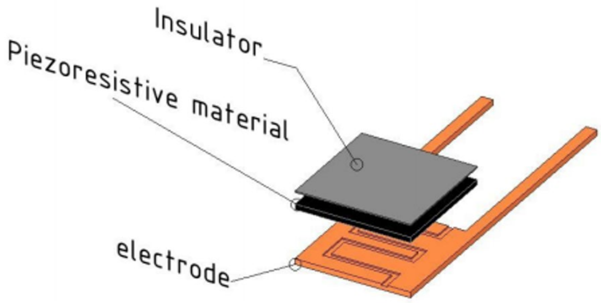


Figure 3. Piezoresistive sensor using interdigitated electrodes [6]

In this work, conductive fabrics are used combined with a piezoresistive ink printed on cotton fabric using a screen-printing process. To achieve a mechanical stability between layers of the sensor, a net-shaped adhesive is used between layers. This should allow achieving stable performance of the sensor even in sensors with larger areas.

Materials and Methods

In this work, piezoresistive ink from Nanopaint, commercial name PR 2, is printed on a cotton plain weave to achieve a piezoresistive layer. First tests showed that the piezoresistive sensor exhibits very low resistance after a certain level of applied force, which makes signal conditioning tricky in these ranges. For this reason, a non-conductive additive provided by Nanopaint, with the intention of increasing resistance values and thus measurement ranges, was used in some experiments.

As studied in [9], woven structures result in more stable sensors regarding reproducibility and dynamic properties of the measured signals, when compared to knitted structures. Therefore, a plain weave is used as first choice for this work. Cotton is chosen as material due to its thermal stability, considering that the printing and bonding processes to which the material is subjected induce some thermal stress that should not impair the original fabric properties. The fabric has been tested and has the following properties

Table 1. Properties of fabric used for printing of piezoresistive layer

Property	Value	Test method
Yarn fineness	Warp: 19,5 tex Weft: 21 tex	DIN EN ISO 2060:1995-04
Thickness	0,54 mm	DIN EN ISO 5084
Mass per unit area	116,2 g/m^2	DIN EN 12127
Weave density	Warp: 30 threads/cm Weft: 25 threads/cm	DIN EN ISO 1049-2

The application of the piezoresistive ink on the textile is accomplished by screen-printing. Before using, the ink is subjected to mechanical stirring between 30-60 minutes. It is at this time that the additive is mixed with the ink, in various mixture ratios.

A screen with the mesh size of 81 Threads Per Inch (TPI) is used. Samples were screen printed on a Zimmer Mini MD-F R541, a flat screen-printing table with a magnetic system that allows the rolling of a metallic rod-squeegee over the screen, applying the ink at an even pressure, as shown in Figure 4. The magnetic field level can be chosen from a range of 1 to 6, low to high pressure respectively, therefore affecting the ink's layer thickness. The dimensions of the printed sensors are 3 x 3 cm.

The economical screen-printing process is perfectly qualified for the production of mass articles. The opportunities for designs are unlimited and the textile properties remain unchanged by screen printing. Screen printing is considered a direct printing process because the ink is applied directly to the textile through the screen, as can be seen in Figure 4.

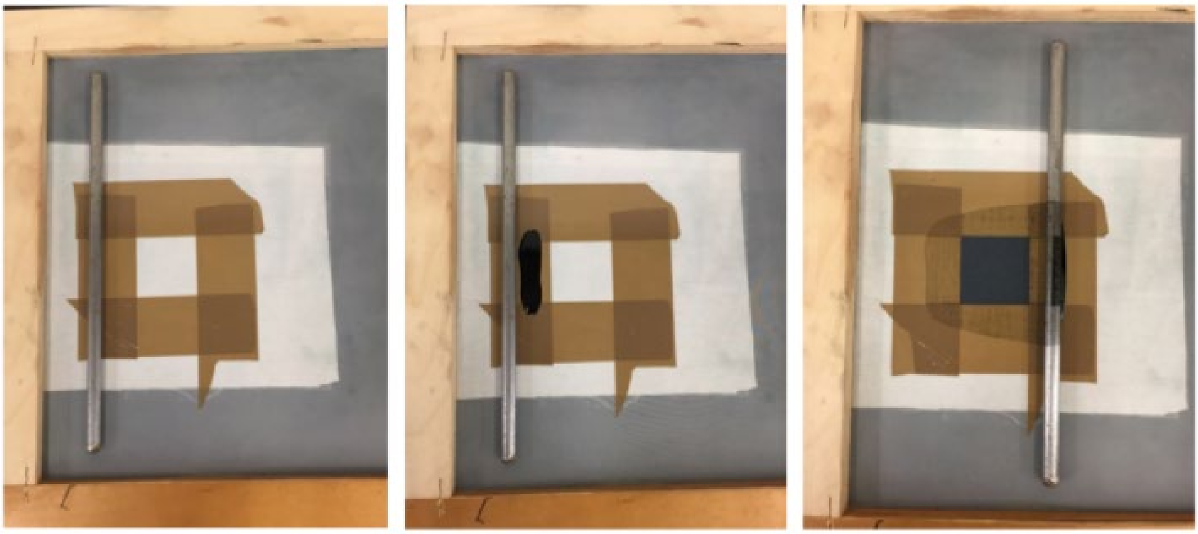


Figure 4. Printing the piezoresistive ink on the cotton fabric

After printing, the ink has to be cured in an oven for 10 minutes at 60°C.

To allow the electrical connection to the piezoresistive layer a silver-plated woven nylon fabric (Statex Bremen from Shieldex) is proofed to be functional as an electrode material. The woven silver fabric has high conductivity and is extremely flexible, fully preserving the textile properties required in this work.

In order to stabilize the assembly of fabrics, the individual layers should be joined in some way. With the use of the silver-plated conductive fabric, however, joining the layers by sewing is not functional. By stabbing the fabric with a needle, individual threads can be damaged and pulled through the seam hole to the other side. This causes a short circuit between the electrodes.

To overcome this problem, a thermoplastic bonding net, UT1 from Protechnic, shown in Figure 6, is used to bond the silver fabric and the cotton together. The material is non-conductive. However, as it is in a net shape, there is still electrical contact between the electrodes and the ink, which is fundamental for the sensor to work. The electrode fabric layers must be smaller than the middle layer in order to avoid a short circuit. The bonding net consists of polyurethane ester aliphatic which is very elastic and transparent. This thermoplastic bonding net, therefore, is supposed to have an excellent bonding on TPU, PVC, polyamide, polyester, fabrics and leather. Since the material for the electrodes is based on polyamide and the piezoresistive ink is printed on cotton fabric, this bonding material promises to be quite suitable for this application.

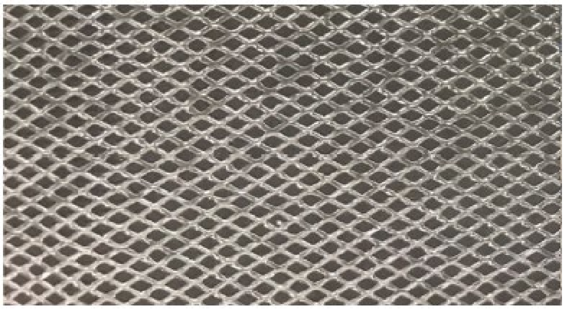
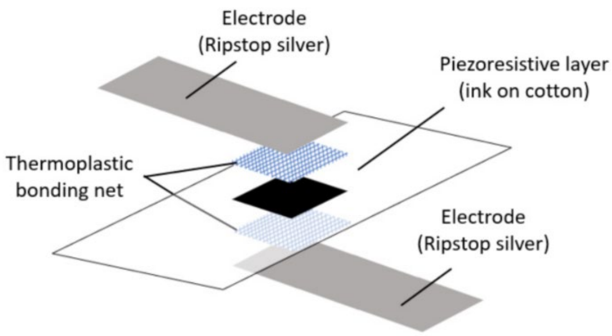


Figure 6. Thermoplastic bonding net

For bonding the 3 layers of the sensor the bonding net is placed on both sides of the piezoresistive layer and pressed in a heating press at 110°C for 10 seconds at a pressure of 2.5 bar (Figure 7). Although the melting point of the thermoplastic net is reached at lower temperature, a sufficient cross-linking is only achieved with the mentioned settings.



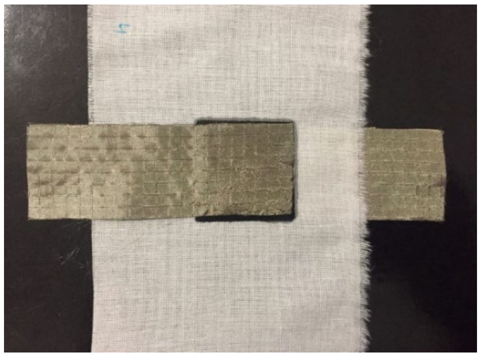


Figure 7. Exploded view of the sensor (left) and sensor (right)

Using the described materials, sensors are manufactured and tested in the further course. During the manufacturing process, different parameters such as piezoresistive ink layer thickness are varied in order to gain knowledge about the design showing the best functionality.

The fastest way to test the sensors for simple functionality is to use a multimeter to which the electrodes are connected, and the resistance is measured. This enables immediate determination of whether sensors are functional by changing their resistance as soon as pressure is applied. If this does not happen and the resistance is close to 0 or remains the same when pressure is applied, it indicates that the sensor is not functional, and a short circuit probably occurred. For more detailed and significant measurements, the Hounsfield universal testing machine is used. This method is used to test the behavior of the sensor when a force is applied in a cyclic process, shown in Figure 8.

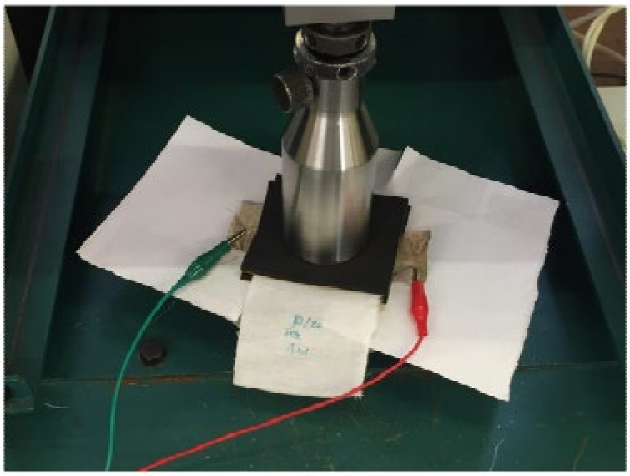


Figure 8. Setup for compression test

The printed pressure sensor is subjected to a cyclic compression test in a Hounsfield universal testing machine. To protect the sensor and the equipment from mechanical impairment during the test, as well as to distribute pressure evenly over the surface of the sensing area, a layer of 3 mm EPDM (ethylene propylene diene monomer rubber) is placed on each side of the sensor.

The machine is equipped with a movable traverse with adjustable speed. For the compression test, a 2.5 kN force cell and a compression stamp are attached on the bottom of the traverse. As a counterpart a fixed plate is used on the bottom of the machine on which the sensor is placed. By connecting the electrodes to a multimeter or to the sensor signal conditioning equipment, the sensor is tested using a speed of 30mm/min and force ranges between 0 to 200N. Resistance is measured by a multimeter connected to a PV via RS-232, whilst the signal conditioning circuit described in Figure 9 outputs a voltage that is acquired with a data acquisition board (DAQ) and software developed in LabVIEW. The output voltage depends on the resistance R and on the sensor`s resistance R_s (Figure 9).

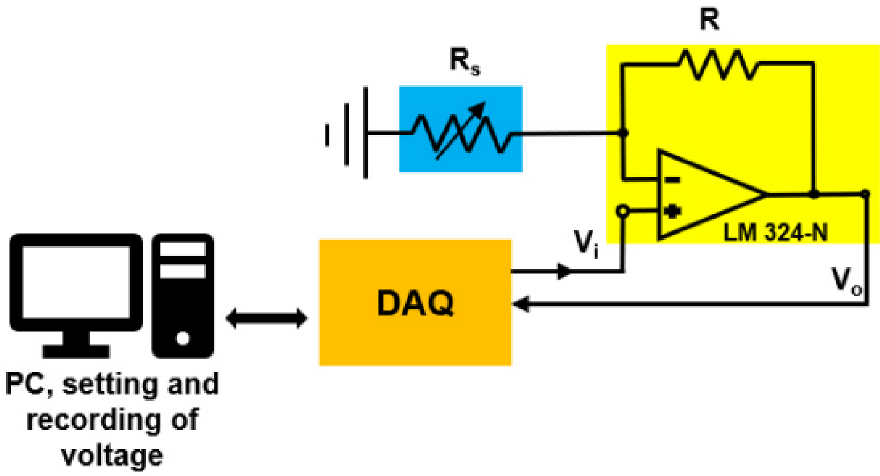


Figure 9. Conditioning circuit for the piezoresistive sensors, implemented with a non-inverting amplifier with gain dependent on the sensor resistance R_S

The relation between the sensor's resistance (R_S) and the voltage output (V_O) for the circuit used is expressed by equation 1:

$$V_o = V_i(1 + \frac{R}{R_S}). \quad (1)$$

with

V_o : Output voltage (V)
V_i : Input Voltage (V)
R_S : Sensor resistance (Ω)
R : Feedback resistance (Ω)

The force is recorded by the Universal testing machine, voltage and force signals are later synchronised in the developed Labview software.

Results and Discussion

The first result obtained is that of resistance versus force, depicted in Figure 10.

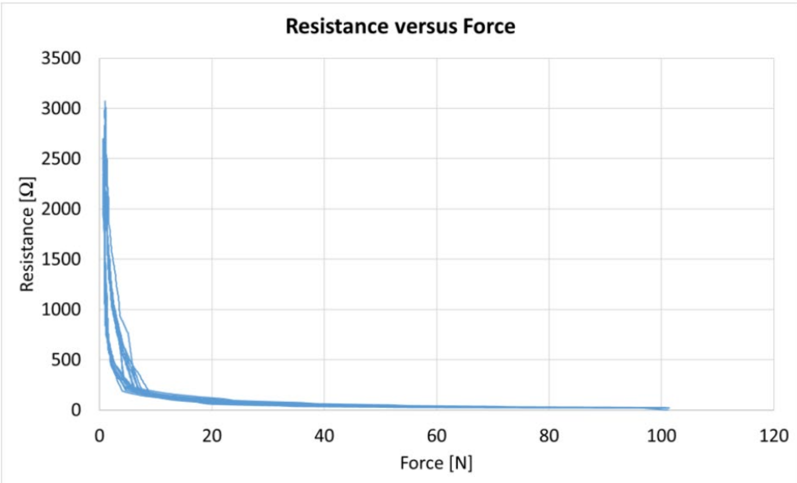


Figure 10. Characteristic of resistance versus force in a cyclic test

As can be observed, the characteristic is highly non-linear, and sensitivity is much higher at low forces than at higher ones. The processing of these variations becomes much easier when the sensor is connected to the signal conditioning circuit and output voltage is measured. The transfer function of the circuit, when applied to the characteristic that can be observed in Figure 10, has the ability to linearize the force-output voltage relation to a certain extent. A typical relation is shown in Figure 11.

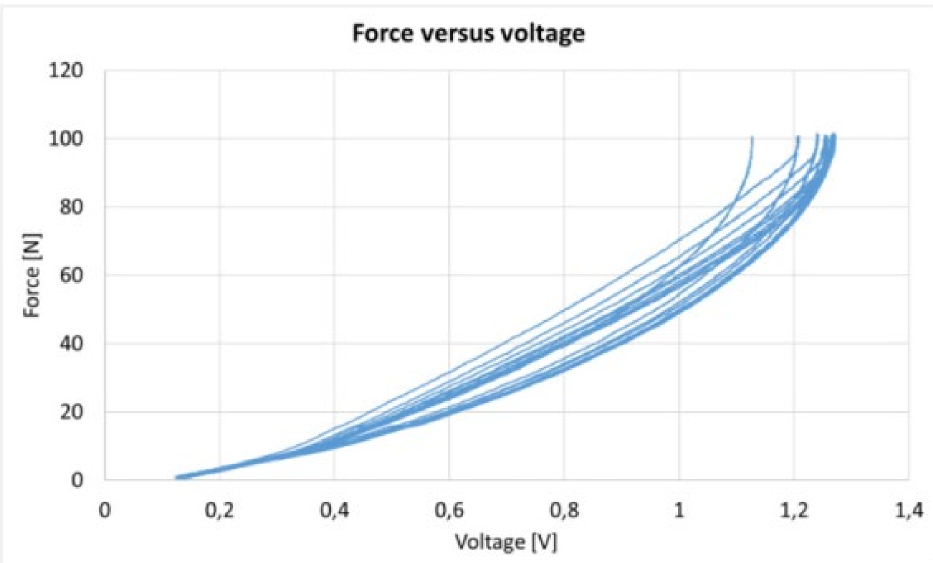


Figure 11. Force-Voltage diagram

Although the sensor is functional, it shows some hysteresis during the cyclic compression test, which is marked in red in Figure 12. In general, hysteresis is a phenomenon in physical systems, which describes that a physical property, caused by a change of another variable, is delayed. In addition, the output variable is not only dependent on the input variable, but also on the previous state of the output variable. In this case, a reason why the hysteresis appears, could be that the sensor layers do not fully recover from compression before new pressure is applied in the cyclic compression test.

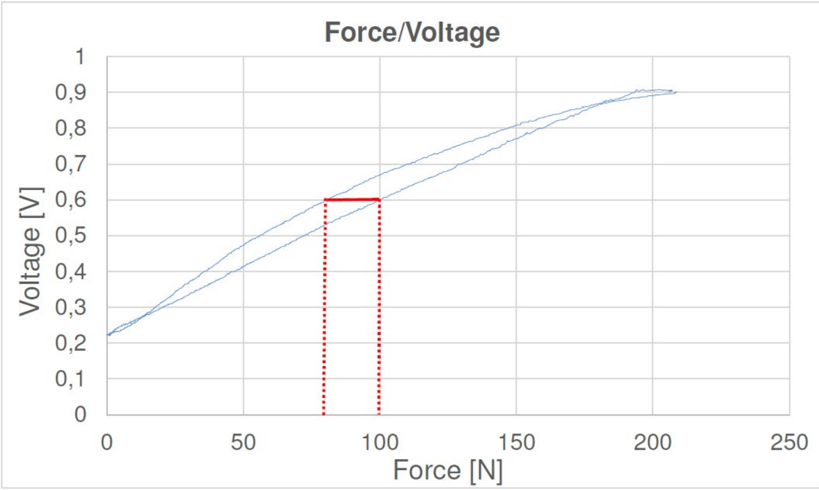


Figure 12. Hysteresis (red)

Hysteresis is a problem, because it is not possible to determine exactly at which force a certain voltage occurs.

Furthermore, with increasing number of cycles the voltage signal shows an increase of the peak magnitude that results from a decrease of the resistance (Figure 12). This behavior was observed for all the manufactured sensors and had already occurred with other sensors using Velostat. It is most probably due to mechanical creep of the piezoresistive material and substrate.

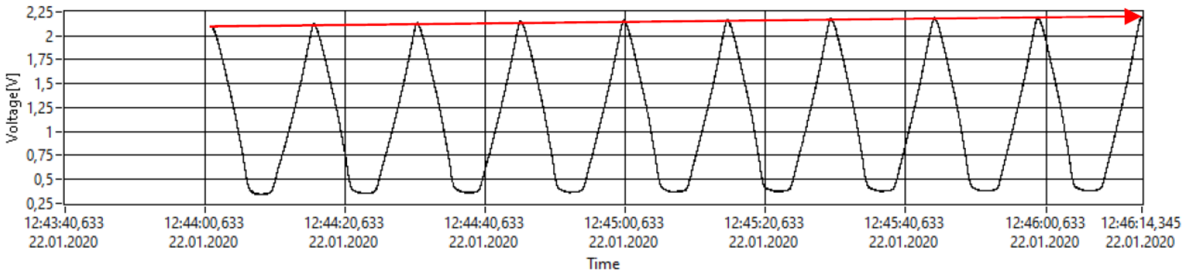


Figure 13. Time signal of output voltage over several cycles - Increase of the voltage peak

Nevertheless, some very interesting results could be obtained using several percentages of additive and using bonding. Figure 14 shows the comparison of a non-bonded (sensor layers not joined using the bonding net, just superimposed) versus a bonded sensor produced using ink with 20% of additive:

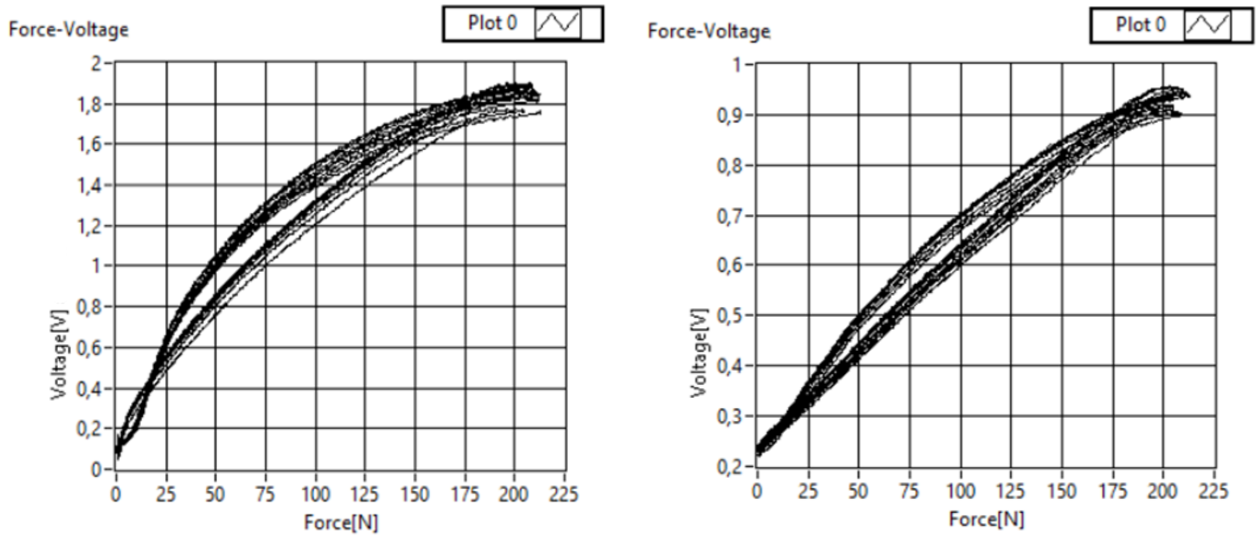


Figure 14. Sensor using ink with 20% of additive, non-bonded (left) and bonded (right)

As can be observed, the voltage range produced by the bonded sensor is lower than that of the non-bonded sensor. This is due the effect that the bonding net has on the resistance of the sensor, increasing it and thus lowering the output voltage (see Equation 1). This is no actual problem, because it can be easily solved by increasing the gain of the amplifier using a larger resistance R.

On the other side, bonding shows to contribute to lower hysteresis and a more linear characteristic of the sensor, besides the improved mechanical stability of the sensor. It can also be observed that the sensor is more stable for low forces (between 0 and 20 N).

Conclusions and Future Work

The main goal of the present research work was to create a textile based flexible piezoresistive pressure sensor for the integration into smart textiles. To achieve this, a basic overview and understanding about the existing methods and materials was inevitable. The research shows that the materials currently used for the manufacture of sensors for smart textiles do not yet meet all requirements for flexibility, washability and other desired properties.

Measurement results show almost linear behavior for sensors with lower conductivity in the ink and using bonding. Furthermore, an interesting range of resistance could be measured, from over 3kΩ to under 200Ω which allows the sensor to be used in different areas of sensitivity. However, hysteresis, some non-linearity and spreading of the measurement results are still existing and are to be improved. In conclusion, the piezoresistive ink is proved to be functional to produce a flexible, piezoresistive pressure sensor with reasonable stability and accuracy.

For further applications of flexible textile pressure sensors, it is recommended to perform the same test procedure with other materials and compare their results. In sectors where natural fibers are not or only barely used, the cotton material could thus be replaced by synthetic alternatives such as polyester. This material exhibits different properties than cotton and may therefore be used advantageously. Polyester is considered to be very easy-care and dries very quickly. Due to its high flexibility and strength, polyester is particularly suitable for bedclothes or clothing in outdoor areas. Up to now, only textiles in the form of woven fabrics have been considered in this work. In future investigations, experiments with knitted fabrics or nonwovens could provide further insights.

In this research work, sensors with an area of 9 cm^2 were manufactured and examined. In the future it is expected that the knowledge gained from these results can be used to produce wide-area sensors, to be applied in sports and health applications.

The next step could be a punctiform pattern application of the ink. If the electrodes continue to cover the entire surface, the measurement principle remains the same, but the manufacturing process becomes cheaper and more sustainable by using less ink.

Besides pressure sensors, extension sensors are also feasible using this ink. Different combinations of materials and forms of textiles could result in sensors with the ability to behave in a very specific way and thus applicable in very specific applications.

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