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Properties of Tactile Sensors Based on Resistive Ink and the Dimension of Electrodes

Jaromír Volf, Viktor Novák, Vladimír Ryženko
and Stanislava Papežová

Abstract

This chapter presents the ongoing research, which aims to select suitable electrodes for their use in the pressure distribution measurement system Plantograf. In our research, we examine more materials, especially Yokohama conductive rubber CS57-7RSC and also conductive inks, which are represented type DZT-3 K, Graphit 33 and mixture of Loctite-Henkel conductive inks type Loctite 7004Hr and Loctite NCI 7002EC. All materials can be used as a converter between pressure and electrical quantities in the design of planar pressure transduces. We build on our previous works, where were examined the properties of conductive rubber, conductive inks and electrodes. Next part is focused on the newest results of our research. Due to the still incomplete results in the given issue, we decided to perform an extensive and original measurement of a total of 172 combinations of different electrode sizes, the ratio of conductive ink mixtures and the thickness of the applied ink layer. Thanks to this, it will be possible in the future to select a suitable combination of electrodes and inks when designing tactile pressure sensors for industrial or medical applications without the need to perform time-consuming preparatory measurements and exclude unsuitable ink-electrode combinations.

Keywords: conductive elastomer, conductive ink, tactile sensor, foil transducer, pressure distribution

1. Introduction

Foil transducers are devices that convert the applied pressure into an electric signal. Under the applied pressure, the electrical resistivity changes as the material of the transducer are deformed. The pressure can be calculated by knowing the dependency curves of pressure and resistivity. The principle of the transducer is similar to a microphone: under the applied pressure, microscopic conductive particles approach is getting closer, which causes a decrease of the resistivity of the material. A basic comparison of the electrical and physical properties of individual materials of the transducer is presented within this contribution, focusing on thin foils of conductive ink and conductive rubber.

In the previous versions of the device PLANTOGRAF – that measure the pressure distribution on a surface – conductive elastomer Yokohama Rubber

CS57-7RSC was initially used; this material was commonly used in the production of tactile sensors [1–6]; different polymers and their properties are nearly described in [7–10]. However, this material with a thickness of 0,5 mm exhibits a relatively large hysteresis in the range of some percent, which prevents the measuring of the absolute pressure acting on the electrodes' system. The main problem with conductive rubber is the mutual influence of nearby electrodes, i.e., the currents flow horizontally between individual electrodes so that they affect each other. This could be avoided by the creation of a corresponding matrix consisting of individually separated sensors. This technology is however quite expensive and technically very demanding, given the required density of sensors. Therefore, we further experimented with conductive inks that exhibit only a very small mutual influence of nearby electrodes. Ink could be applied to the electrodes directly by offset print which is a considerably simpler method of application than separation of sensors. During our preliminary experiments, we found out that ink may not adhere to the electrodes fully so that alternative methods have to be investigated. The properties of individual transducer materials and possible methods of their use are presented in further paragraphs.

We subsequently focused on the use of conductive ink. Four types of conductive inks were obtained for the tests: NGAP FI Ag-4101 from the Spanish firm NANOGAP, Luxor from the Taiwanese firm Luxor, KH WS SWCNT from the Korean firm KH Chemicals, and DZT-3 K. The last type of ink was the only used in the measurements since owing to its composition; it could form a relatively high-quality conductive layer compared to the others. This ink uses carbon particles as filler. The other inks did not meet the requirements, either they were too thin and they did not form a continuous layer, or they did not adhere to the substrate (first two, both water-based inks) or they were excessively conductive – as the third ink with silver particles as a filler – the resistance of the ink was only in units of Ohm. Later we tested as conductive ink Graphit 33 spray and last attention was intended on Loctite - Henkel conductive ink Loctite-NCI 7002EC and Loctite-7004HR [4].

Now is under development a new measuring system Plantograf V20F. It is a flexible transducer, which can measure the skew surfaces.

2. Materials and methods

2.1 Design and principle of the transducer

The basic principle, cross-section and top view of the transducer Plantograf V16 are shown in **Figures 1** and **2**; the principle is the same both for the conductive ink and conductive rubber layer.

The current, represented by red arrows, flows from the inner electrode through the conductive rubber to the outer electrode. The voltage U_x = 5 V is displayed in the first figure. The common electrode, supplied by a voltage of 1.8 V and marked as "screening" is a common method used in printed circuits. It provides - by hardware - the separation of individual sensors and it prevents the mutual interaction of nearby sensors. The electrodes are etched onto a Cuflex film placed on the bottom of the sensor matrix. Cuflex is a thin Teflon foil with an applied copper layer, copper layer thickness 0.07 mm, foil thickness 0.09 mm, but several individual thicknesses of the Cuflex film are available. The surface of each electrode is completely covered. The electrodes and the conductive elastomer are protected from mechanical wear by a protective coating, a non-conductive flexible
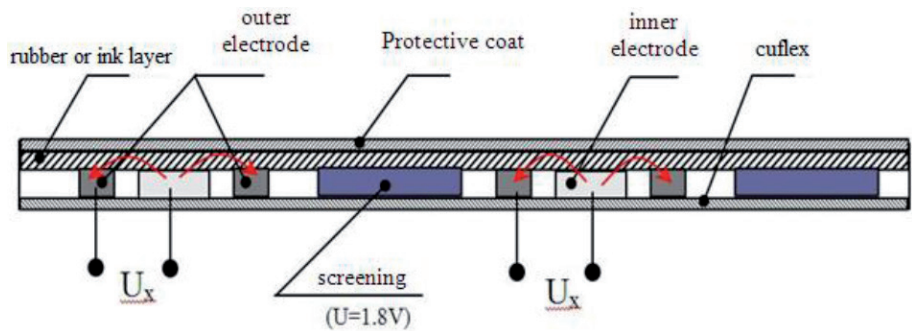
Figure 1.
Cross-section and top view of the transducer.
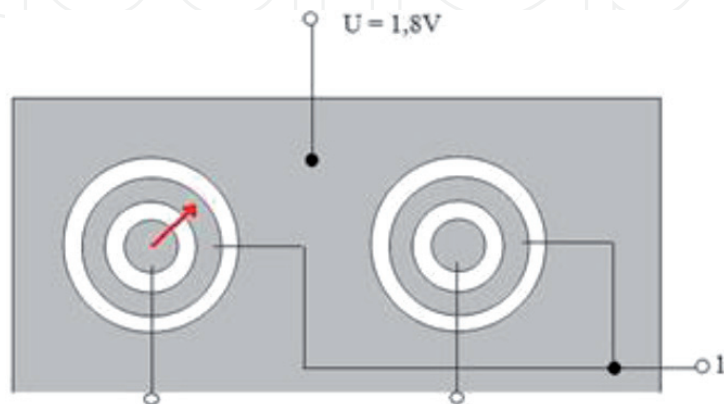
Figure 2.
Top view on the transducer.

material [5]. The resistance between the electrodes is measured, which is dependent on the deformation of the material under the pressure.

2.2 The Plantograf pressure measuring system and use of foil transducers

The foils are made of conductive ink or conductive rubber and are used in practice in the Plantograf measuring system. This is a tactile transducer which is picked up tactile information from a particular object and converts it into an electrical signal. The device is under steady development and improvement process of both the control electronic circuits and the transducer foil. Earlier versions of the device used conductive rubber, now we are still evaluating several conductive inks to meet all the required mechanical and electrical properties; thus, the use of the conductive ink is still rather experimental. First rubber-based sensors were used in 1978 wits USA made rubber Dynacon C for robot's hand. After 1982, the material was replaced with Yokohama Rubber with better mechanical and electrical. Plantograf, our transducer, was first designed in 1998. Since then, there were developed several versions of the transducer up to the current version Plantograf V16.

The system can process in real-time variable time pressure signals. It consists of 16,384 sensors (with a diameter of 2,5 mm each, in a 128 x 128 matrix arrangement) concentrated in the active area 0,5 x 0,5 m; it can sample and process up to 1000 fps. A full-frame is created by all 16,384 sensors. Plantograf measures the pressure distribution between the transducer and sole. Measured values are relative, where the analog output is converted on the digital signal by 8-bit A/D converter in 256 levels of gray. Every gray level was also assigned to pseudo colors. For exploitation full A/D convertor range is change get setting in range 0,5;1; 1,5; 2; 2,5; 3; 4; and

5. This way, the pressure distribution frame is represented in 256 color levels in a 2D or 3D model view. It is further possible to post-process the measured data via a dedicated program on a PC.

The system is used for dynamic and static measurements in various industrial or medical applications, described in more detail in [5, 11, 12]. Sample pictures of a graphic representation in the 2D and 3D view mode of the measured pressure distribution in a medical and industrial application of the device on a PC screen is shown in **Figures 3–5**.

2.3 Conductive rubber Yokohama CS57-7RSC

This transducer, made by Yokohama Rubber Co., labeled CS57-7RSC, represents a thin foil of conductive rubber (elastomer). This material is silicon-based and it is filled with small conductive pieces of pulverized graphite and as well as other additive particles (Iron (III) oxide and Silicon dioxide). The material is inert to water, methanol and ethanol and it is chemically stable. It exhibits relatively stable mechanical properties (thickness, elasticity) and values of electrical conductivity. The material has a tensile strength of 1.86 MPa, thickness of 0.5 mm, and a usable temperature range from −30–100°C [13].

These properties are fully appropriate for its use in the tactile sensor under normal operating conditions. A potential disadvantage of this material may be its low long-term stability of sensitivity and its known relatively high hysteresis. Hysteresis means the different values of the resistivity of the material in the process of loading and unloading under the same acting force, see also chart in **Figure 12**. These negative properties cannot be fully eliminated and they are given by the construction of the sensor and by the material itself [1–3]. A further issue is that rubber cannot be placed on individual electrodes separately or it would be technically extremely difficult by almost 16,500 electrodes.

Therefore, we started to experiment with various conductive inks, which do not exhibit these negative proprieties. Conductive ink can be applied to individual electrodes directly without major difficulties; this way, the mutual interaction of electrodes can be eliminated substantially as we obtain separated conductive places.
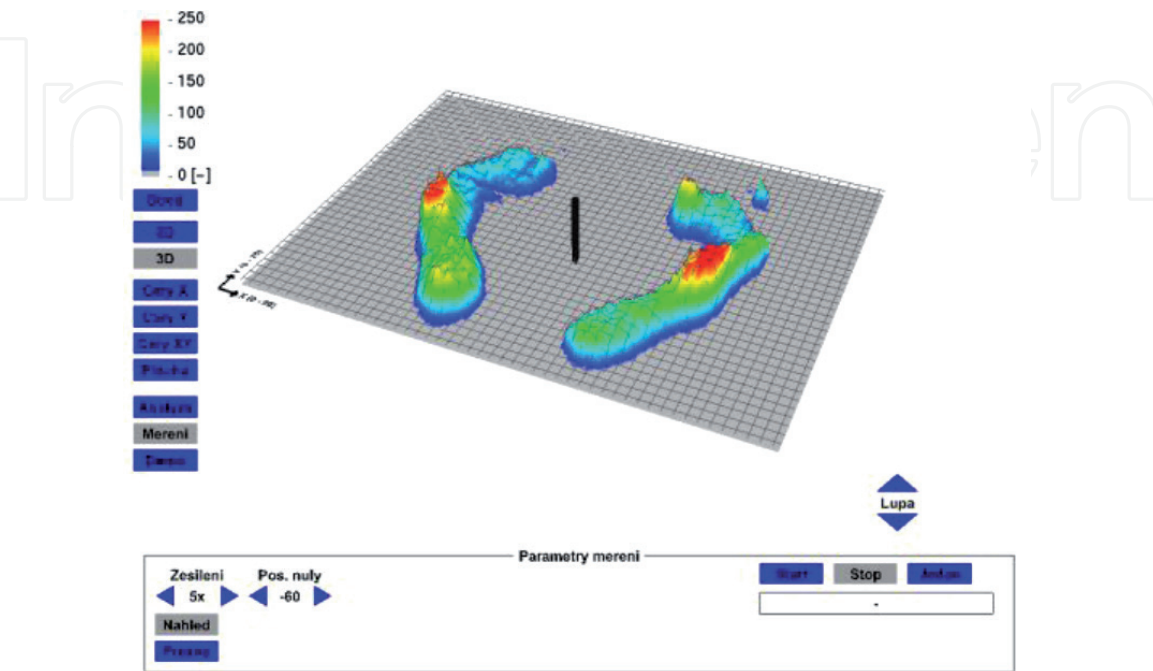
Figure 3.
Graphic representation of the distribution of pressure on a PC screen. Human foot in 3D.
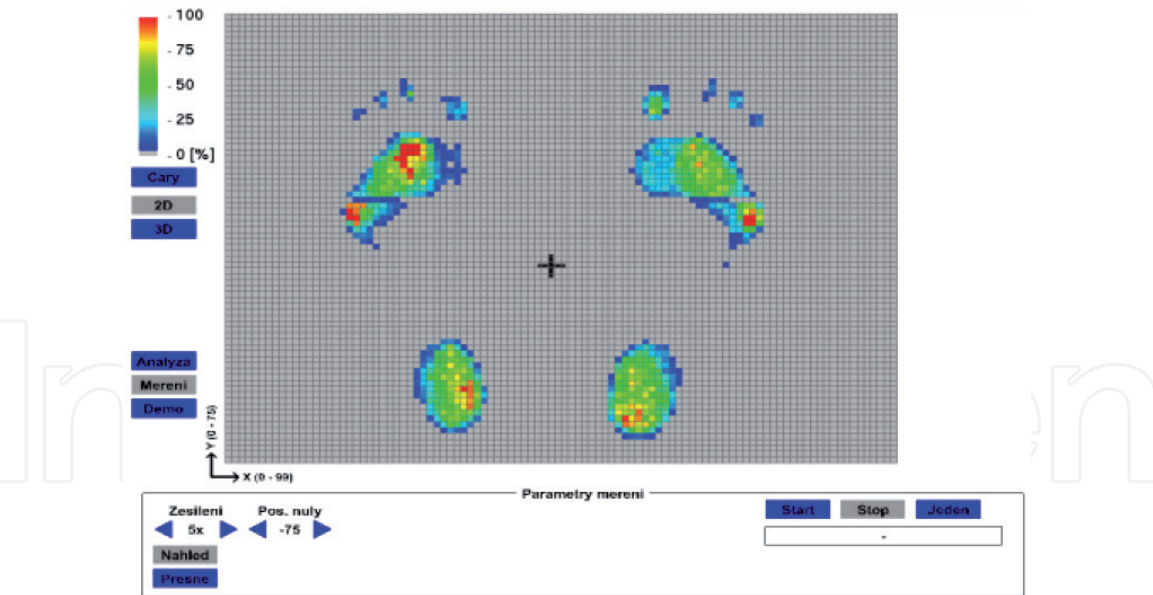
Figure 4.
Graphic representation of the distribution of pressure on a PC screen. Human foot in 2D.
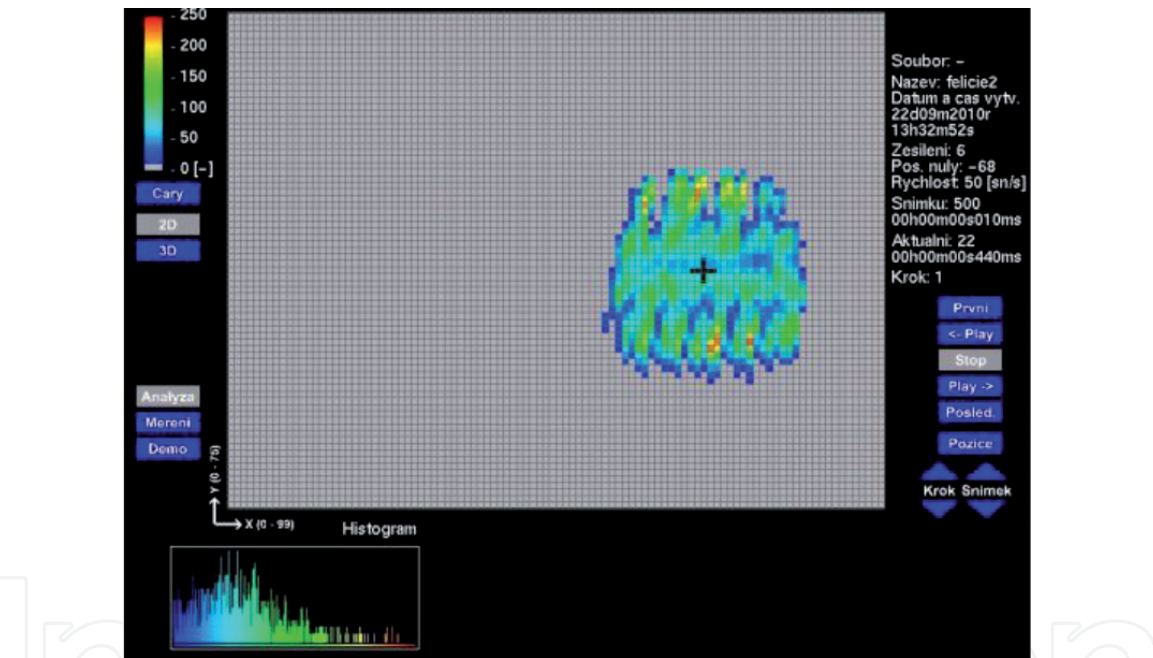

Figure 5.
Graphic representation of the distribution of pressure on a PC screen. Car Tyre.

2.4 Production of DZT-3 K ink specimens

Conductive ink is ink-filled with small pieces of conductive particles; we tested inks containing graphite and silver particles. For testing, we obtained four types of conductive inks: Luxor (Luxor, Taiwan), KH WS SWCNT (KH Chemicals, Korea), DZT-3 K (DZP Technologies, United Kingdom) and NGAP FI Ag-4101 (NANOGAP, Spain). The ink DZT-3 K was selected after preliminary evaluations and it was used in the measurements. This ink – using carbon particles as filler – could form a relatively high-quality conductive layer owing to its composition. The other inks did not meet the requirements: they were excessively conductive – as the third ink with silver particles as a filler – the resistance of the ink was only in units of Ohm. Other inks were too thin and they did not form a continuous layer or they did not adhere to the substrate (the first two - both water-based inks).

The electrical resistance of an unloaded ink layer should be optimally above 500 kΩ (at least 100 kΩ), and the resistance of the fully-loaded layer should be, optimally below 1 kΩ (usable range of hundreds of Ω). A possible disadvantage of the conductive ink compared with conductive rubber might be the difficulty of creating a compact and stable layer [5].

However, the selected ink DZT-3 K was unable to create a coherent conductive layer, i.e., to sustain its integrity when it was applied on the electrodes directly. Any negligible mechanical load caused the separation of the ink from the electrodes' surface. Additionally, we observed a certain deformation of the ink layer between the outer and inner electrodes. The measuring method – pushing with a force sensor tip on the ink layer – would not be applicable in this case.

We proceeded to an alternative procedure, as this setup proved not to be utilizable: the selected DZT-3 K ink was applied to the electrodes similarly as the conductive elastomer, by applying the ink on the surface of a 0,3 mm thick PET foil. TG 130 spray gun which can spray very low amounts of ink and enables fine control of spraying was used to deposit the ink on the foil. The ink DZT-3 K was diluted with water in the ratio of 1:1 to prevent the blocking of the jet. Three thicknesses of the deposited ink layer were selected: 7 μm, 15 μm and 23 μm. The spray applications were performed through a template made of the same foil with 3 mm holes given the 2.5 mm outer diameter of the circular electrodes for ink DZT-3 K. The thickness of the deposited ink layer was measured with a Mitutoyo SR44x1 digital micrometer with a measuring range of 0–25 mm and an accuracy of 1 μm. In a similar way was placed ink Graffiti 33 and Henkel ink, here was diameter to 3,5 mm.

2.5 Conductive ink Graphit 33

Graphit 33 is ink consisting of graphite particles, with organic solvent as a filler. The main properties of the ink are stated in the following **Table 1**.

This ink exhibited the same mechanical deficiencies as the previous specimen - poor adherence and incoherent conductive layer while applied to the electrodes directly, Therefore, we repeated the previous procedure and we deposited the ink on the surface of a 0,4 mm thick PET foil and it was applied to the electrodes similarly as rubber.

The ink was deposited on the foil in 20 μm, 50 μm and 80 μm layers (corresponding with 3x, 6x and 9x multiple spraying). There were used four types of electrodes for the measurement: LD, PD, LH, PH, the electrodes and their dimensions according to the following **Table 2**. The general design of the electrodes is depicted in **Figure 7**.

GRAPHIT 33	
Minimal full coverage layer thickness	**10–20μm**
Surface coverage	up to 4 m^2/l
Packing	200 ml can
Drying time	<20 min
Color	black
Temperature limit of the graphite film	250–300°C
Temperature limit of the paint	±90°C
Surface resistivity	1000–2000 Ω

Table 1.
Properties of ink Graphit 33 [14].

Technology	Thermoplastic
Appearance	Black
Filler type	Carbon
Cure	Heat cure
Operating temperature maximum	100 °C
Product benefits	Screen printable Excellent screen residence time Flexible low-temperature drying cycles
Application	Conductive ink
Typical assembly applications	Force-sensitive modules, Printed resistors and Sensing devices
Key Substrates	Treated polyester and Polyimide
Emulsion thickness	20 to 40 μm
Viscosity, Brookfield, Speed 20 rpm, @ 20 °C	25,000 mPa·s (cP)
Density	1100 kg cm^{-2}
Shelf Life @ 5 to 30 °C (from date of manufacture)	365 days
Flash Point DIN 53213	78 °C

Table 2.
Properties of ink Loctite-7004HR [15].

2.6 Loctite - Henkel conductive ink Loctite-NCI 7002EC and Loctite-7004HR

We cooperate with the Faculty of Chemical Technology, University of Pardubice by creating test boards (see **Figure 6**) and developing of the new flexible transducer. These samples were made using printing technology. Each one of nine samples of electrode boards include 18 individual circular electrodes with different dimensions stated in **Table 3**; corresponding dimensions are graphically explained in **Figure 7**. Each test plate is created for the different mix of inks and thickness of ink.

Any of the nine samples test boards will have a different combination of the factors that may influence the sensitivity of the sensor, namely:

- thickness of the ink layer

- proportion of two conductive inks in the mixture

- dimension of the electrode

Before we have received the complete set of all nine test boards, we obtained a "pre-sample plate" to evaluate the design and the suitability for further measurements of the full set of samples. This "pre-sample" has ink thickness 25 (±1) μm and the proportion of the inks 60:40% in the mixture. The proportion of both conductive ink effects resultant resistance of the sensor. The ink Loctite-7004HR has by ink thickness 0,25 μm for loading state resistivity of about 3500 Ω/sq./mil. Properties of this ink are shown in **Table 2**.

The second used ink is Loctite-NCI 7002EC. This is ink with very high resistance. The ink Loctite-NCI 7002EC is non-conductive in the unloading state. Properties of this ink show **Table 4**.
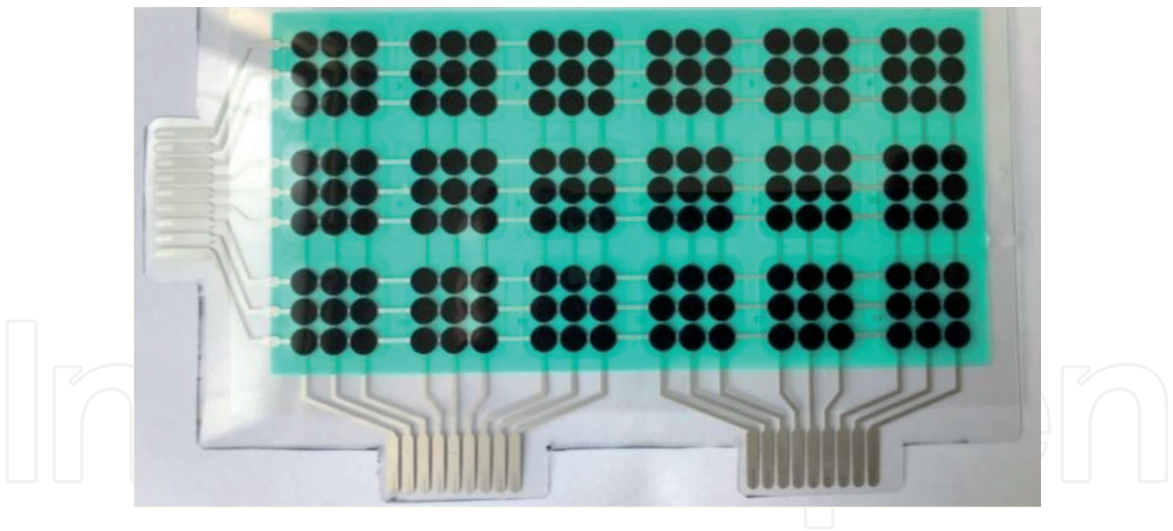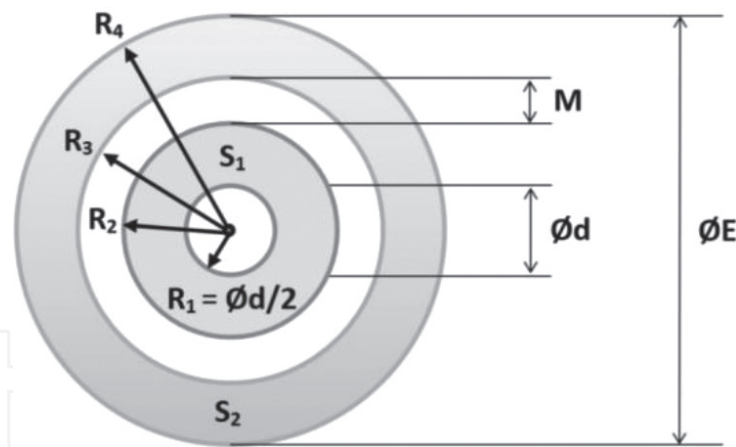
Figure 6.
Sample with circular electrodes.

Electrode number	R1	R2	R3	R4	E	M	S1	S2	Final S
1 - LH	0,2	0,45	0,55	1	2	0,1	0,5105	21,909	27,014
2 - PH	0,05	0,45	0,55	1	2	0,1	0,6282	21,909	28,191
3 - LD	0,2	0,5	0,75	1,25	2,5	0,25	0,6597	3141	38,007
4 - PD	0,05	0,5	0,75	1,25	2,5	0,25	0,7774	3141	39,184
5	0,05	0,825	0,925	1,75	3,5	0,1	2,13	69,318	90,618
6	0,05	0,8	0,95	1,75	3,5	0,15	20,024	67,846	8787
7	0,05	0,775	0,975	1,75	3,5	0,2	18,788	66,334	85,122
8	0,05	0,75	1	1,75	3,5	0,25	1759	64,784	82,374
9	0,05	0,725	1025	1,75	3,5	0,3	16,432	63,193	79,625
10	0,05	0,7	1,05	1,75	3,5	0,35	15,313	61,564	76,877
11	0,05	0,675	1075	1,75	3,5	0,4	14,233	59,895	74,128
12	0,05	0,75	0,85	1,6	3,2	0,1	1759	57,716	75,306
13	0,05	0,725	0,875	1,6	3,2	0,15	16,432	56,362	72,794
14	0,05	0,7	0,9	1,6	3,2	0,2	15,313	54,968	70,281
15	0,05	0,675	0,925	1,6	3,2	0,25	14,233	53,535	67,768
16	0,05	0,65	0,95	1,6	3,2	0,3	13,193	52,063	65,256
17	0,05	0,625	0,975	1,6	3,2	0,35	12,192	50,551	62,743
18	0,05	0,6	1	1,6	3,2	0,4	1123	4,9	6023

Table 3.
Parameters of electrodes.

2.7 Shape of the measured electrodes

The measurements of individual electrodes were performed on a scanning matrix comprising circular electrodes with a 2–3,5 mm diameter; the electrodes were placed on an elastic printed circuit board. The same sizes and design of the electrodes as described were used to enable the comparison of the properties of tactile sensors with a conductive elastomer with those with a conductive ink [5]. Conductors were soldered to the outlets of lines and columns which enabled the easy choice of a particular electrode. The dimensions of the measured electrodes are presented in **Figure** 7.

Figure 7.
*Dimensions of the measured electrodes.*

Technology	Thermoplastic
Appearance	Black
Cure	Heat cure
Operating temperature maximum	100 °C
Product benefits	Non-conductive Screen printable Flexible resistive Excellent screen residence time Flexible low-temperature drying cycles Good adhesion
Application	Non-Conductive ink
Typical assembly applications	Printed resistors Sensing devices Heating elements Protection against electrostatic discharge (ESD)
Key Substrates	Treated polyester and Polyimide
Solid's content	37.5 to 40.0%
Viscosity, Brookfield, Speed 20 rpm, @ 20°C	10,000 to 25,000 mPa·s (cP)
Density	1270 kg cm^{-3}
Theoretical coverage, @ 10 μm dry coating thickness	14 m^2 kg^{-1}
Shelf Life @ 5 to 30°C (from date of qualification in original seal)	365 days
Flash Point DIN 53213	78 °C

Table 4.
Properties of ink Loctite-NCI 7002EC [16].

The electrodes are denoted accordingly to their marking: S1 – inside electrodes area, S2 – outside electrodes area, S – both electrodes area. The parameters of the electrodes are listed in **Table 3**, dimensions are stated in mm.

2.8 Determination of electrical resistance of the ink

The measurement circuit diagram is depicted in **Figure 8**. It represents a stabilized circuit, that supplies a voltage divider. One resistor of the divider is constant
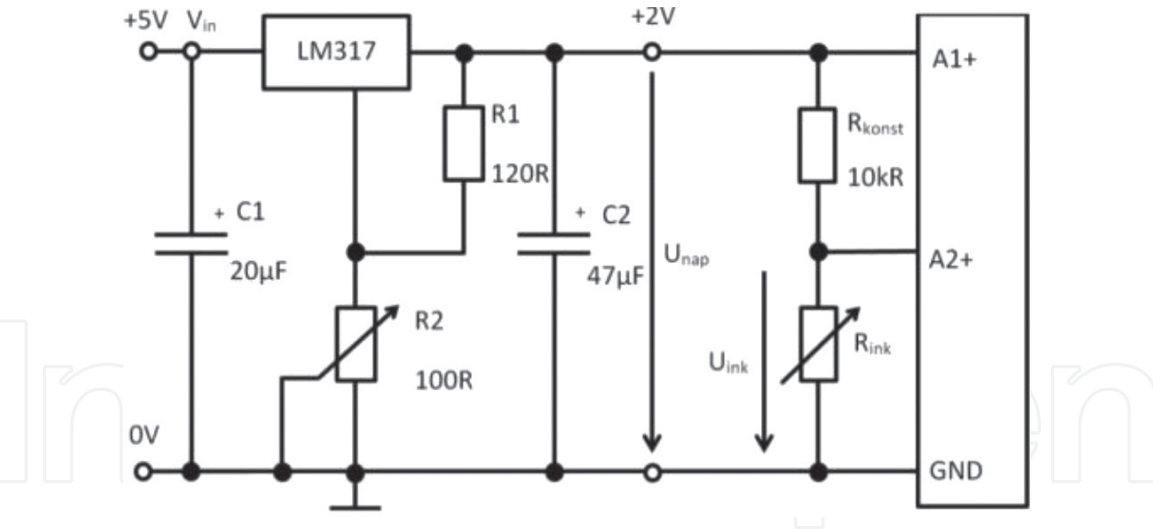
Figure 8.
Circuit diagram for measuring the conductive ink resistance.

and the other one is variable, represented by the resistance of the conductive ink. The supply circuit, is LM317 voltage stabilizer, enables the setting of the supply voltage to 2 V and its fine adjustment. The low value of the supply voltage ensures that only a small current flow through the circuit, and thus it avoids the heat of the conductive ink. The electrical resistance of the constant resistor in the divider is 10 kΩ, to ensure a constant current in the divider circuit. The electrical resistance of the ink was calculated using the formula (1):

$$R_{ink} = \frac{R_{konst} \cdot U_{ink}}{U_{nap} - U_{ink}} \tag{1}$$

where
R_{ink} resistance value of sensor
R_{konst} resistor with constant resistance value 10 kΩ
U_{ink} voltage on sensor
U_{nap} power voltage

The measurement of the voltage on the conductive ink – needed to calculate the resistance values in the divider – was determined by the measuring card NI 6008. The voltage UINK was connected to an analog input of the card and it was measured by the RSE method (Reference Single Ended) against ground potential. On the other analog input of the card was connected to the output voltage UNAP from the stabilizer in the same way. The output of the measuring card was connected to a PC via USB. The entire measuring station was controlled by the NI LabView program. A LabView application was also created, which enables the recording and the calculation of the electrical resistance of the conductive ink [5].

2.9 Measurement procedure

Measurements of the properties of conductive ink were performed at a robotized workplace equipped with a Turbo Scara SR60 robot. The basic step of the vertical motion of the robot's arm is 0.01 mm. The pressure was applied by the measuring tip 3 mm in diameter using the vertical motion of the robot's arm. The arm was moved in 0.02 mm increments for a general overview of the behavior of an electrode and further in 0.01 mm step for a more detailed analysis. The pressure was applied using the vertical motion of the robot's arm, at which the Hottinger DF2S-3 tensometer force sensor was fixed. The measuring tip is a circular surface with ϕ3

mm or ϕ4 mm diameter. The output voltage of the type DF2S-3 tensometer force sensor was measured by an Almemo 2890–9 Data Logger.

This force sensor was chosen because of its appropriate range and high sensitivity. Its accuracy is 0,03%, nonlinearity is 0,03%, max. Loading is 200 N, and sensitivity 2 mV/V, power supply 5 V, see [17]. For connecting to data logger was used connector Ahlborn Almemo ZA9105650FS1V with input range ± 2,6 V, resolution 1 μV, precision class AA. Detailed technical parameters see in [18]. This way the electrical resistance of the conductive ink was measured.

The control unit is set up to display the values in grams; the conversion into the pressure values was made subsequently. The foil with the deposited ink was placed on the electrode field. The measuring tip touched down on the surface of one tactile point and pressed on the conductive ink deposited on the foil against the circular electrodes. The pressure imposed on the electrodes was calculated from actually exerted force and the known area of the surface of the measuring tip. **Figure 10** presents the overall layout of the measuring post. **Figure 9** shows the detailed view on the measuring head: (1) is for the conductive ink deposited on a foil, (2) indicates the measuring tip, (3) is the force sensor DF2S-3 and (4) indicates the robot's head.

The movement of the robot's arm was controlled by a dedicated remote control. The foil with deposited ink layer and the tactile field with circular electrodes was put into the workspace of the robot's arm and it was placed on a hard, plastic pad. The positioning of the measuring tip was performed by manual control of the robot. After checking that the measuring tip covers the entire surface of the electrodes, the Almemo 2890–9 data logger was reset to zero in an unloaded condition. For a correct measuring, the stable "unloaded" resistance value of the ink layer, depending on the thickness of the layer and the electrodes' design, was determined before further loading of the electrodes. This value and the matching vertical coordinate were recorded as a start value. Subsequently, the robot's arm was gradually lowered using the + and – buttons on the remote control.

After a couple of test measurements, the maximum vertical shift of 180 μm was determined, representing 18 down steps of the robot's arm. That was sufficient to measure the boundaries when loading force does not more decrease the resistance of the ink. From this value, the backward (up) movement by the same number of steps was carried out (unloading). Loading and unloading procedures were performed to measure the hysteresis of the conductive ink. Corresponding resistance and pressure
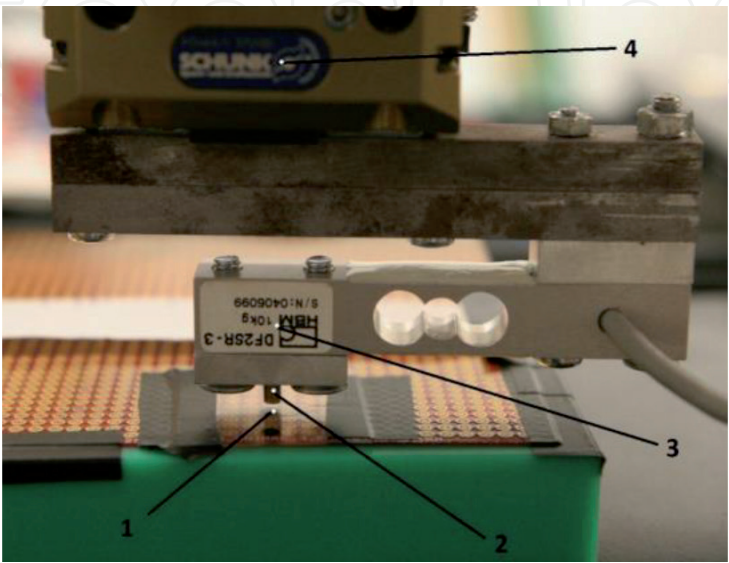
Figure 9.
Detailed view on the measuring head.
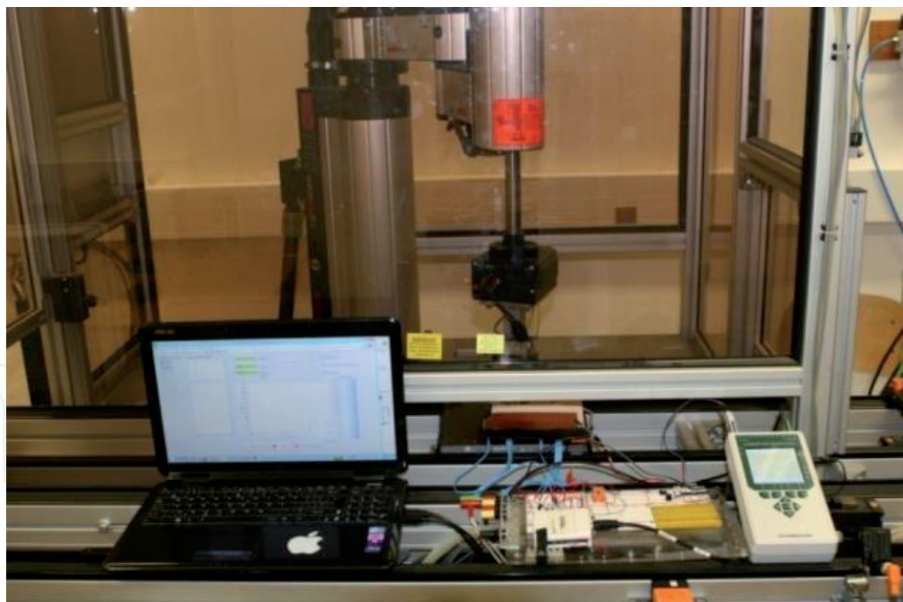
Figure 10.
The layout of the robotized measuring post.

values were logged by the Lab-View application after each shift. For measurement, we used LabView measure card NI USB 6009 with the common GND and with inside A/D convertor 13 bits and input range 5 V [4, 19]. One measurement cycle thus contained 37 values. Between the individual measurement cycles, there was a five-minute break, so that the material could relax unloaded. The measurements were repeated 10 times for all types of electrodes and each ink layer thickness.

Loctite inks were measured via LabView card full automatically using a robot control program. The full set consists of 172 samples of combination electrode dimension, a mix of inks and thickness of ink layers. The voltage on sensors was measured by LabView card. Were calculated average value, standard deviation and then standard uncertainties – type A, B and combination standard uncertainties type C. These uncertainties are marked for lucidity only in separate graphs of dependencies. This same process was used for conductive ink DZT-3 K, too. For Yokohama, conductive rubber uncertainties were not measured. In lucid graph with more curves was used only average values.

3. Results

3.1 Results with conductive elastomer Yokohama CS57-7RSC

The measurements were carried out ten times on the same sensor point for conductive elastomer and each type of electrode, i.e., both LD and PD. The diagrams below this paragraph show the dependence of the measured electrical resistance on the applied pressure, as an average from each of the ten sets of measurements. The electrical resistance should decrease due to the applied pressure, based on the principle explained at the beginning of the chapter. Now the course of the electrical resistance for selected combinations of materials and electrodes must be studied and their appropriateness for the described device assessed.

The first diagram in **Figure 11** presents the dependence of electrical resistance on the applied pressure for conductive Yokohama CS57-7RSC. In the diagram, the behavior of the dependence for a PD electrode by the red curve and for an LD electrode is given by the green curve.
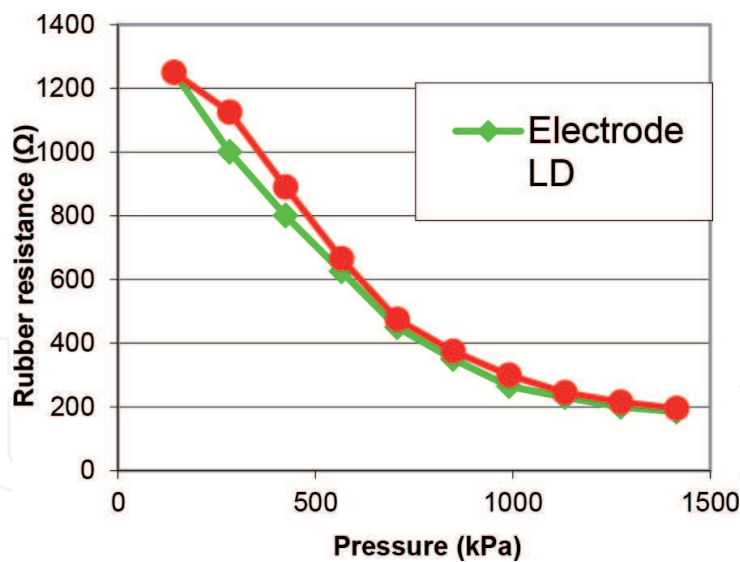
Figure 11.
Dependence of electrical resistance on the applied pressure – Conductive rubber, LD and PD electrodes.

Yokohama elastomer was tested on electrodes 1–4, see **Table 3**. The resistivity changes between 200 and 1300 Ω by pressure between 100 and 1400 kPa.

Further, the hysteresis curve of elastic material Yokohama was measured. Hysteresis curves measured by loading (red curve) and unloading (green curve) cycle shows **Figure 12**.

3.2 Results with conductive ink DZT-3 K

The measured data for LD-type and PD-type electrodes for all 3 thicknesses of the ink layers - 7 μm, 15 μm and 23 μm – are represented graphically in the following graphs. All measurements were repeated 10x and the total (combined) measurement uncertainty was calculated and graphically represented by respective intervals for each measured value.
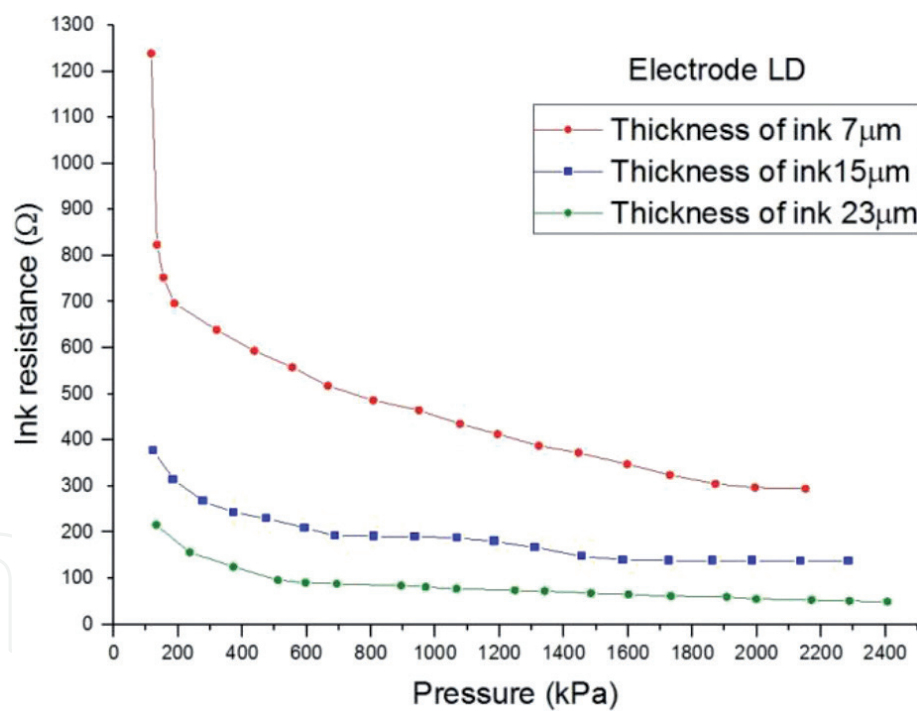
Figures 13 and **14** present the graphical result for the conductive ink of thickness 7 μm in the loading and unloading cycle for LD electrode types. Initial insensitivity is
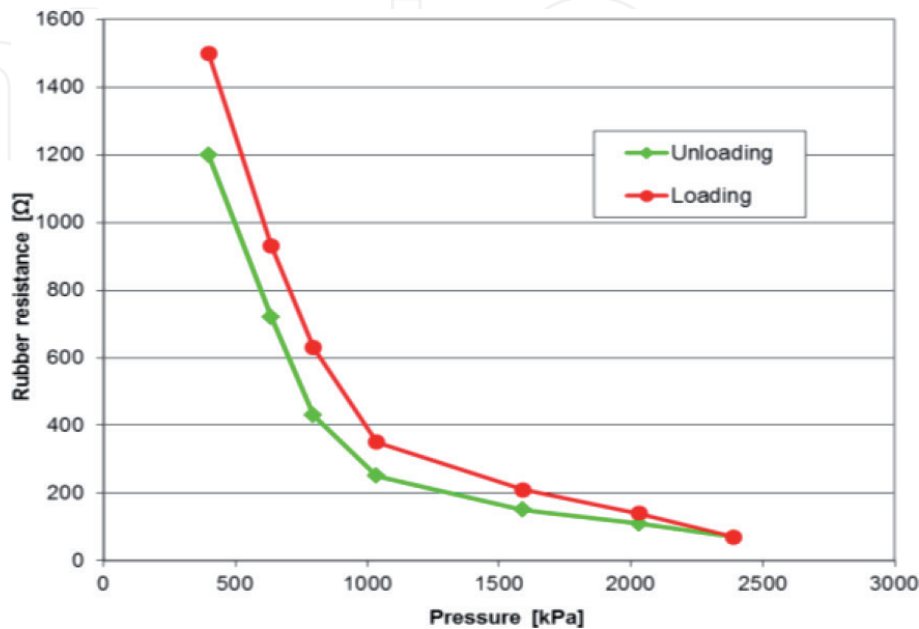
Figure 12.
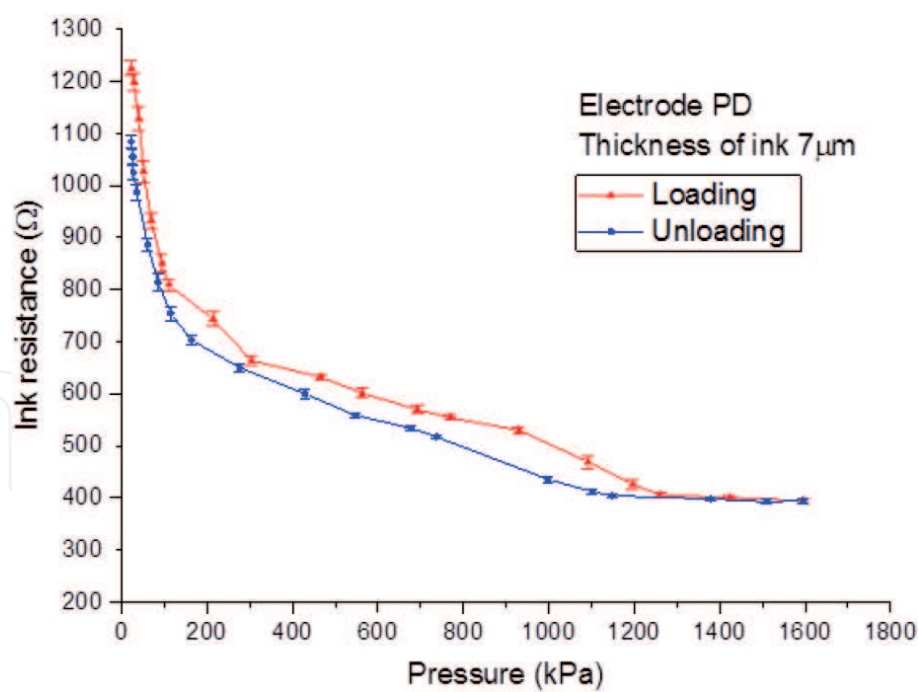*Hysteresis of the conductive elastomer.*
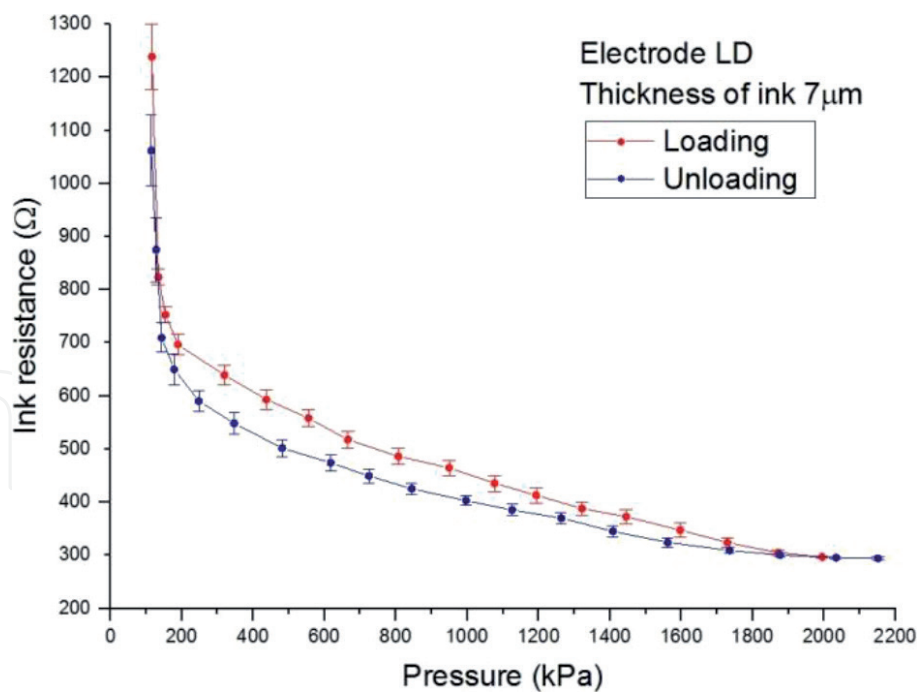
Figure 13.
Dependency of the resistance of a 7 μm ink layer in the loading and unloading cycle of LD electrode.
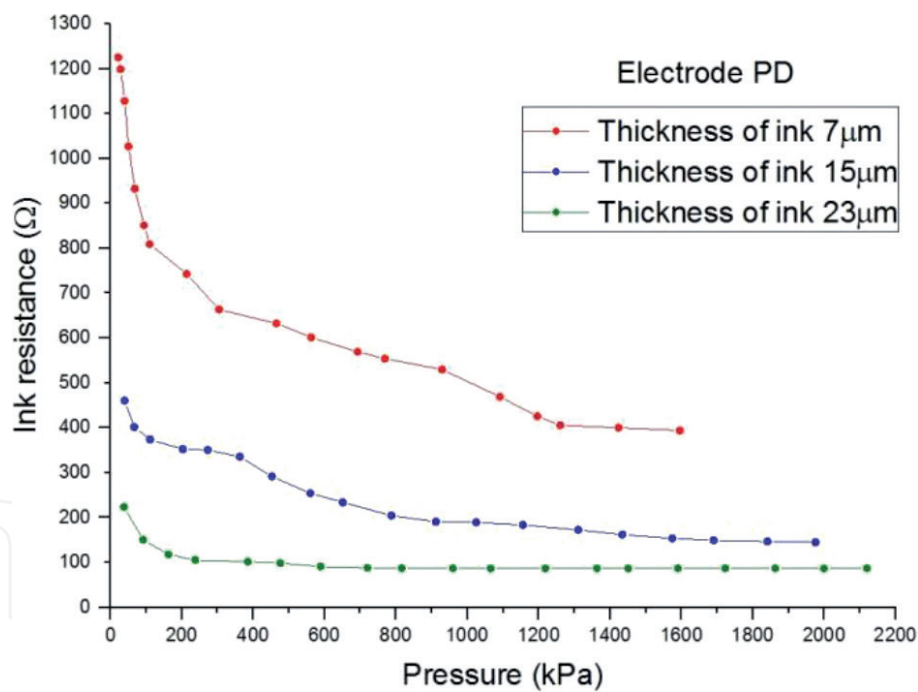

Figure 14.
Comparison of LD-type electrodes.

apparent, it may be caused by the force necessary for the touch-down of the foil with the deposited ink on the electrodes. Hysteresis is apparent in all electrodes, similarly as in the case when a conductive elastic material was used, however, it is much lower.

Figures 15 and **16** give the comparison of the courses of electrical resistance during loading of LD-type and PD-type electrodes for various thicknesses of the deposited ink layer. From the diagrams, it is apparent that maximum sensitivity is achieved for a 7 μm thickness of the deposited ink layer for both types of electrodes.
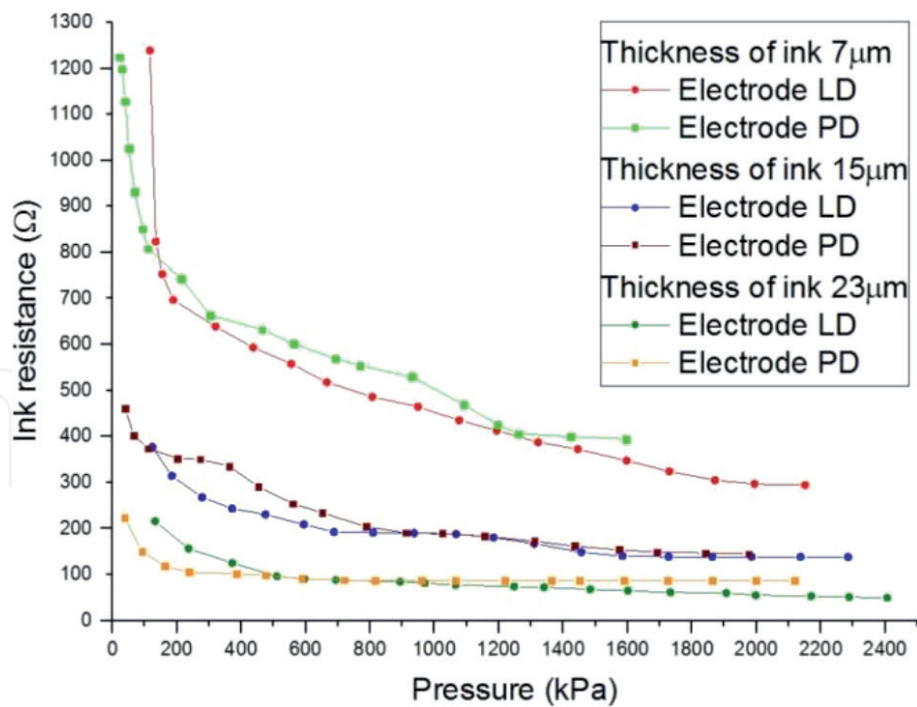
Figure 15.
Dependency of the resistance of a 7 µm ink layer in the loading and unloading cycle of PD electrode.

Figure 16.
Comparison of PD-type electrodes.

The last graph in **Figure 17** presents the overall results of the measurements; the graph shows a comparison of changes in resistance depending on the pressure for the LD and PD-type electrodes for different thicknesses of the applied conductive ink. The greatest sensitivity is achieved for a 7 µm ink layer. The comparison of LD and PD electrode types shows a somewhat smoother curve course of the PD electrode for the ink layers of 15 µm and 23 µm. Contrarily, the curve is smoother for the LD electrode and the ink layer of 7 µm.

Figure 17.
Overall comparison of LD and PD electrode types.

3.3 Results with Loctite - Henkel conductive ink Loctite -NCI 7002EC and Loctite-7004HR

The loading force was exerted from 0,37 N up to cca. 17,6 N. This resulted in the measured range of pressure values approx. From 30 kPa up to 1400 kPa for the particular measuring tip.

For measuring these inks, we prepared nine test desks (**Figure 6**), each with the 18 electrodes types, see **Table 3** and **Figure 7**. Each test desk was prepared with a different mix of inks (40:60, 50:50 and 60:40) and three different ink layer thicknesses (10 μm, 20 μm, 30 μm).

The presented results were measured on the test desk Nr. 10, where mix of inks ECI7004HR:NCI7002 is 60:40% and the thickness of the ink is 20 μm. The initial loading pressure varies significantly, as every electrode has own threshold, when it starts to react to the applied pressure (i.e., when the resistance starts to drop). The scale on the graphs has been maintained the same to enable visual comparison of the courses. The graph on **Figure 18** shows the electrode 3 - LD and **Figure 19** show the electrode 4 - PD.

The course of the electrode LD is very particular compared to other electrodes. It has a very steep beginning part and later the resistance is almost linear.

The course of electrode 4 has a similar course as electrode 3, but the run part is more sheer. **Figure 20** show resistance dependence on pressure for both electrodes with uncertainties.

The next graphs show resistance dependence on pressure for all electrodes 1 to 18. It represents the most extensive measurements, which we ever made. Fully we made about 172 measurements of different full courses for different 18 electrodes, mix conductive inks and different thicknesses of these inks. Every course was measured 10 times, it presents more than 1700 number measurements full graphs. The way of measurement is described in Chapters 2.8 and 2.9. The comparison of all individual electrodes is shown in following **Figures 21** and **22**.

From graphs appear that some electrodes are suitable for low loading, e.g., electrodes 5, 7, 8, 9, 11 and 13, see **Figures 21** and **22**. Electrode 5, see **Figure 15**, exhibits
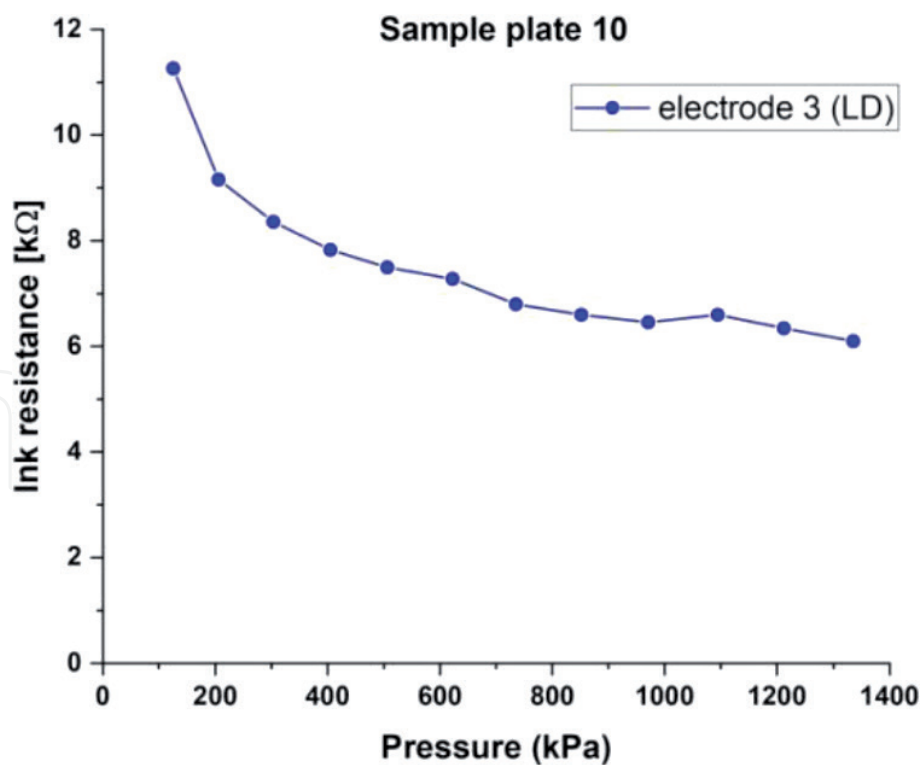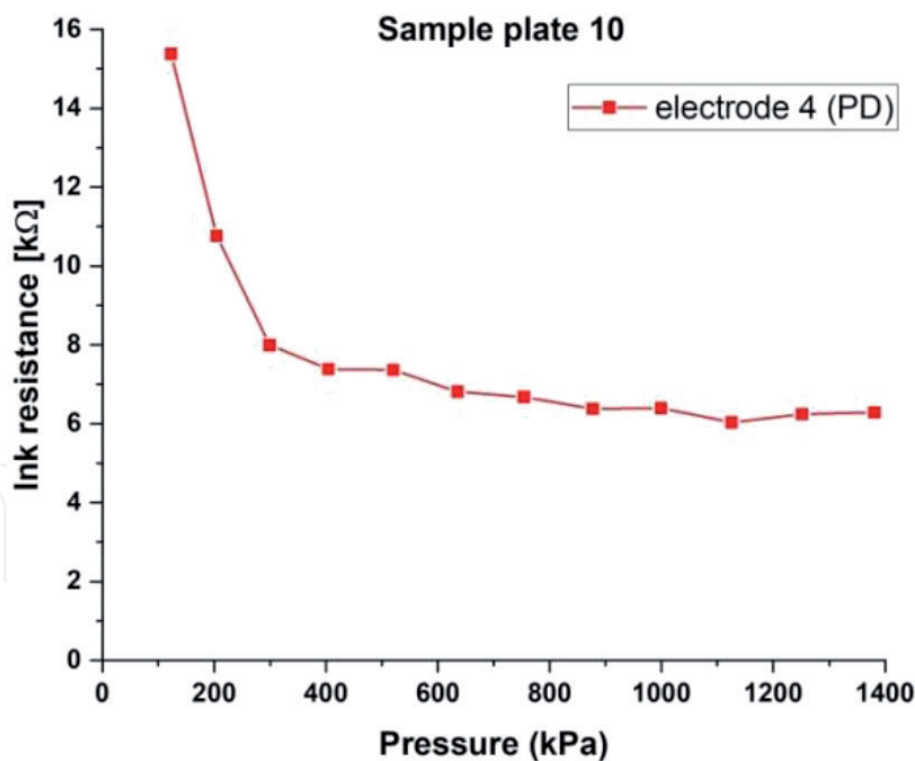
Figure 18.
Electrode 3 – LD.

Figure 19.
Electrode 4 – PD.

a typical course as demonstrated by most of the electrodes – initial steep descent in the resistance, turn and following little loss in resistance with stagnation towards the end. Electrode 10 has a gradual decrease in resistance up to cca. 400 kPa, followed by stagnation. Electrode 12 exhibits a typical course; notable is that its construction enabled the measurement starting at cca. 50 kPa. Electrode 15 exhibits similar behavior as electrode 10, the measurement is loaded with significantly
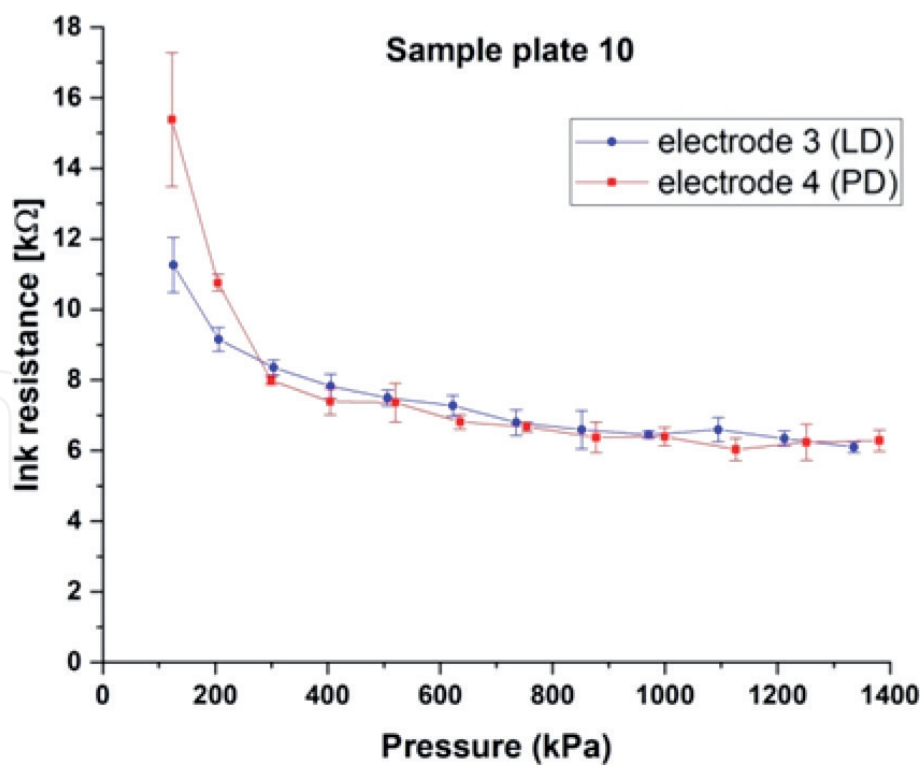
Figure 20.
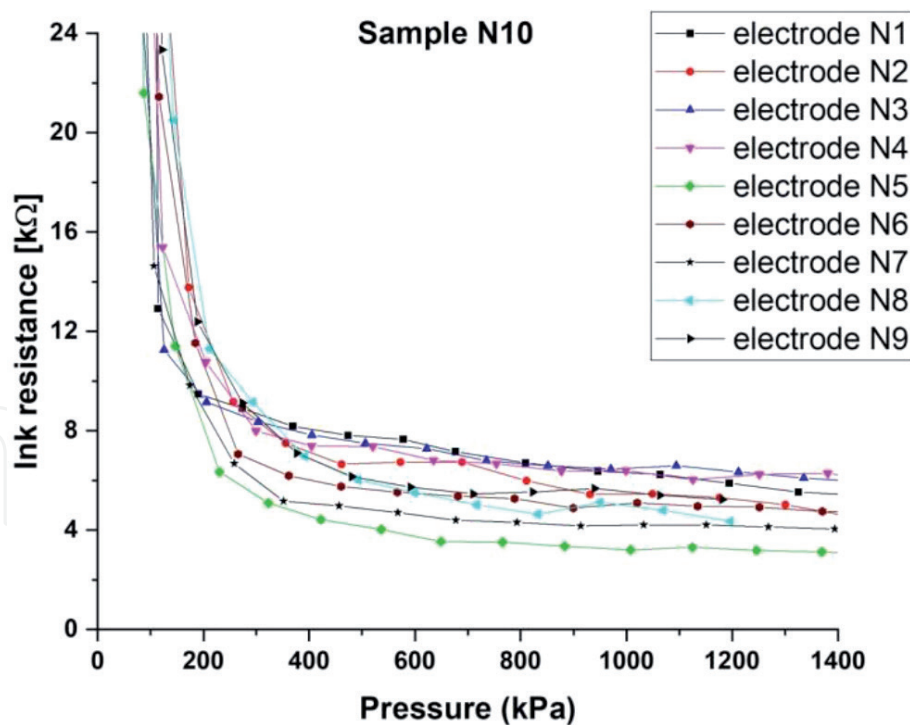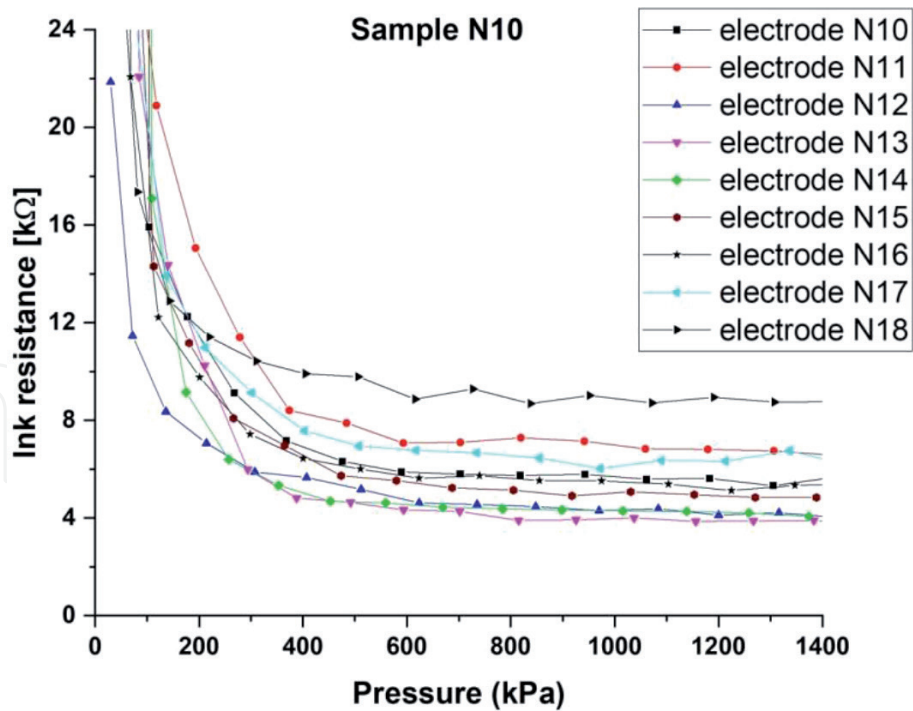*Resistance dependence on pressure for both electrodes LD and PD with uncertainties.*

Figure 21.
Dependence of resistance on pressure for electrodes 1–9.

less uncertainty and starts at lower pressures. Electrode 14 has a typical course; its dimensions do not differ significantly to others. The courses are convenient for measuring the lower pressure range. Also, note the similar dimensions of both electrodes 16 and 17.

Figure 22.
Dependence of resistance on pressure for electrodes 10–18.

4. Discussion

In this chapter, we will discuss the comparison of the conductive ink and elastomer material, various electrode types and respective ink layer thicknesses. Generally, it may be stated that the measured electrical resistance of the material depends on the applied force and the contact area of the object with the transducer. The main issue is the mutual interaction between nearby sensors which is significant mainly in the rubber material.

Yokohama conductive rubber CS57-7RSC was loaded with a lower maximum pressure than ink according to the manufacturer's technical specification. Higher pressures may decrease the accuracy of the measurement and may destroy the rubber. The usability of this material in the Plantograf planar transducer was confirmed with good results within a relevant data output for both types of electrodes in the pressure ranges from 200 kPa up to 1400 kPa. From loads of approx. 1000 kPa the slope of the curve decreases which causes a lower sensitivity of the transducer for higher pressures. Due to mutual interaction of the nearby electrodes, it cannot be used to measure the absolute value of the pressure on the surface directly but only the pressure in a relative scale, e.g., 0–255 kPa on an 8-bit converter like the Plantograf can be determined. The absolute value of the pressure over every electrode may be determined using transcendental equations.

After preliminary measurements with different types of electrodes we found out that the electrical resistance is influenced mainly by the space between the inner and outer electrode and by the size of the electrode itself – see **Figure 7**. However, PD and LD electrodes differ only in the diameter of the inner opening – i.e., 0.1 mm (PD) and 0.4 mm (LD). Due to their similar parameters, the difference in the electrical resistance of these two electrodes is therefore not significant; only the behavior of the dependence slightly varies, as can be seen in **Figures 14** and **16**. A thicker ink layer contains so many carbon particles that after applying pressure on the ink layer, its behavior is approaching that of a conductor with an insignificant resistivity change.

Mutual interaction with conductive ink DZT-3 K is very low (max. up to 3%), demonstrated by measuring on the 5x5 and 3x3 sensor matrix. At loads above 600 kPa with thicker ink layers (here 15 μm and 23 μm) there is only a slight change of the electrical resistivity. Therefore, these configurations are not appropriate for higher loads. The best sensitivity was achieved with the 7 μm ink layer. The curve of the PD-type electrode is less smooth than that of the electrode LD, with a nearly linear dependence in the range from 200 kPa to 2000 kPa. The setup with an LD electrode and a 7 μm ink layer was assessed as the best transducer in the experiment [20].

DZT-3 K ink showed significantly higher sensitivity than Graphit 33 ink, when it reacted to a change in resistance at a lower pressure around 22 kPa. Graphit 33 reacted at a pressure of 267 kPa. For this comparison, it is necessary to add that the measured thinnest layer of DZT-3 K ink had half the thickness of the thinnest layer measured in this work. Even with a larger layer thickness, Graphit 33 showed a higher resolution. The resistance for the thinnest layer varied from 3.4 kΩ to 380 Ω and the other two thicknesses had a lower but still acceptable resolution. This fact was stated by the author in his work, i.e., that the DZT-3 K ink has high conductivity and thus a low resolution. When measured on the thinnest layer, its resistance ranged between 1.2 kΩ and 390 Ω. For wider layers, the resistance varied minimally.

In general, every electrode exhibits an initial steep decrease in the electrical resistance followed by a turn, when the resistance decreases significantly more slowly with the rising pressure. This turn is situated in the pressure range 200–400 kPa, depending on the electrode, also the turn is differently sharp. This phenomenon is caused due to the exponential dependency of the resistance on the pressure, which bases on the composition of the material; as the pressure is high enough, there are created significantly fewer conductive paths, thus the resistance drops only a little.

Further, the uncertainties are generally much greater in the range of lower pressures, particularly in pressure ranges under the described turn. These are given first by the light contact of the measuring tip with the surface and secondly by the light contact of the conductive layers itself with the electrode.

Most electrodes exhibit also stagnation in the loss of electrical resistance towards high-pressure levels. This is caused due to the saturation of the material as the particles are compressed to their maximum so the electrical resistance cannot drop anymore. The usable range of the electrodes is therefore limited to pressure ranges below the saturation level.

The particularity of electrode 1 was probably caused due to its different dimensions compared to other electrodes. After verifying the course with a more detailed measurement, it may be a suitable electrode for measuring higher pressure ranges due to its almost linear characteristics and better sensitivity in the higher-pressure ranges.

From the courses of the resistance, it can be seen, that the electrodes are not "universal", i.e., usable in the whole pressure range (with the exception of the electrode 1). Also, the upper value of pressure is limited to cca 500 kPa, then the drop in resistance is negligible. However, this poses no problem, as such high pressures are not expected to be measured in common industrial or agricultural applications.

5. Conclusion

Based on our experiments, we conclude that both materials – conductive ink and conductive rubber – are suitable as transducers of pressure and electrical quantities, however, with some limitations. Conductive rubber does not meet the requirements of the Plantograf, as it has a limited pressure range for higher loads. Furthermore, there is significant hysteresis of this material, which appeared during the loading and unloading of the rubber. It is a limiting factor for its use in newer versions of

the Plantograf measuring system, which are capable of the real-time measurement of applied pressure up to 1000 frames per second. This phenomenon also prevents the measuring of the absolute pressure acting on the electrode system.

Conductive ink exhibited better results than conductive rubber, namely in the setup with the LD electrode and the 7 μm ink layer. However, there is another problem: the used ink can be wiped off the electrodes very easily. This water-based ink sinks into the gaps between electrodes and it and exhibits small adherence to the electrodes. Thus, we had to select an alternative procedure by spraying the ink on the foil. To allow direct application of the ink to the electrodes, different, polymer-based types of ink may get better mechanical properties. Inks with polymer-based binders adhere to the electrodes much better and the layer is not excessively destructed by the applied pressure [5, 13, 21, 22].

From a comparison of the properties of two types of conductive inks DZT-3 K and Graphit 33, it can be concluded that neither of them is the most suitable choice for tactile sensors. Each would be suitable in a different application where either greater or lesser sensitivity would be required. It is possible to take into account the fact that if the ink with graphite particles were measured on the same thin layer as the second type of ink, it could show greater sensitivity. In addition, the life of the ink layer that will be required when used in a tactile sensor needs to be taken into account. When measuring ink with carbon particles, there is no mention of damage to the surface of the layer. In the measurement of ink with graphite particles, there were cases of a deformed layer. It is, therefore, necessary to consider the cause of the deformation; whether the layer is poorly applied or, for example, the load pressure is too high.

Based on the performed preliminary measurement of the sample plate, we can conclude that the measuring methodology and computer processing of the data is adequate, however, to measure the full set of the samples, there have to be done some minor adjustments. First, more focus is to be given to lower pressure ranges up to cca. 500 kPa, hence the electrical resistance does not change significantly with higher pressures, given the saturation of the material. For more detailed measurement, a smaller step (0,01 mm) may be considered for some electrodes to determine the course more accurately, this applies particularly for low-pressure loads (below 200 kPa). The control program of the robot will have to be adjusted accordingly. The dimensions of the electrodes have a partial impact on the course of the resistance-pressure curve, which is mainly demonstrated with electrode 1, which has significantly different dimensions than others. This electrode is also the most suitable for measuring higher pressures up to 1000 kPa. Other electrodes have their working range up to cca 500 kPa, which is sufficient for their proposed applications.

Generally, the range of the pressures that can be measured using both conductive rubber (earlier research) and various setups with conductive ink (our current research) is from tenths of kPa up to cca 2000 kPa. There are visible some significant dependencies (electrode size, thickness of ink layer, mixture composition) on the sensitivity and applicable pressure range. We preliminary found out, that for instance thinner ink layer causes significantly higher sensitivity of the transducer; the size of the gap between the inner and outer ring of the electrode extends the measurable pressure range; the drop of electrical resistance is less steep with a growing gap. However, these factors are still subject to ongoing research and statistical evaluation, final results will be available probably within 2 years.

In any case, the new design of the electrodes proved to be capable for the proposed use in foil transducers between pressure and electrical resistance, the main concern is now the usable pressure range. In further measurements, other significant dependencies may be discovered, namely the impact of the thickness of the ink layer and the ratio of the ink mixture on the sensitivity and usable range of the electrodes.

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