EVALUATION OF ELECTRODES WITH CONDUCTIVE INK FOR FLEXIBLE TACTILE SENSOR

Viktor NOVÁK[1], Jaromír VOLF[1], Vladimír RYŽENKO[1], Stanislava PAPEŽOVÁ[1]

[1]*Czech University of Life Sciences Prague, Faculty of Engineering, Department of Electrical Engineering and Automation, Kamýcká 129, 165 21 Prague 6, Czech Republic*

Abstract
This paper presents the ongoing research which aims to determine suitable combinations of dimensions of electrodes and of mixtures of conductive inks in the design of planar pressure transducers, and particularly in the design of the currently developed flexible tactile sensor SITSCAN CS. Here we continue in our previous work on planar pressure transducers by evaluating conductive inks. Due to the only partial results in this research field, we decided to perform an extensive and original measurement of totally 162 combinations of different electrode sizes, various conductive ink mixtures and ink layer thicknesses. Thanks to this, it will be possible to design various tactile sensors without the need to perform time-consuming preparatory measurements. The aim of the measurement is also to determine the usable working range of pressures and the corresponding sensitivity for certain combinations of electrodes and inks, and also to exclude those variants which are unsuitable for the given purposes. In the paper, we present the impact of the electrode dimensions on the measured electrical resistance.

Key words: *tactile sensor; communication bus; pressure; electrode; Sitscan; conductive ink.*

INTRODUCTION

In our previous work, we developed a planar measuring system PLANTOGRAF which evaluates the pressure distribution between the road, the soil and the tyre, or even within the soil itself; but the measuring system found its use in the medicine, too. Its current version consists of a large number of 16 400 individual sensors, that change their electrical resistance due to the applied pressure. Its predecessors also used individual electrodes to convert pressure into electric signals, however, they used different technology (originally conductive rubber, further conductive ink on a separate foil layer), for more detailed information about the previous research see e.g. (*Volf et al., 2015; Koder et al., 2019*). The main difference represents another method of applying ink to the electrodes and the flexibility of the transducer; any individual sensor represents a circle electrode with conductive ink applied directly to it, unlike previous solutions, where the ink was applied on a separate layer, more discussion about the application of the ink is described by (*Volf et al., 2019*). This was possible using a different ink type, namely polymer-based instead of water-based that did not adhere to the electrode. Now we are developing a new measuring system labelled SITSCAN CS, which is primarily designed to development of ergonomically shaped chairs. The main difference to its predecessors is the flexibility, i.e. its possibility to adopt to uneven surfaces, such as chair seats. This brings some innovative techniques of the design, such as using the printing technology by creating the sensor matrix.

A planar pressure transducer consists of a matrix of individual sensors, that are covered with the piezoresistive material. They originally came with conductive rubber based on the experiences described (*Barman & Guha, 2005*). As we focused our research to create a flexible transducer, we also reflect newer experiences teams experimenting with piezoresistive materials, e.g. by the design of FSR sensors discussed by (*Giovanelli. & Farella, 2016*) with lower pressure range. The properties of conductive inks are extensively described by (*Dimitriou E. & Michailidis, 2021*). The authors also focus on the electrical conductivity of conductive inks, which we will also reflect in further parts of our research, where different ink mixtures will be evaluated.

Before the final design of the new transducer SITSCAN CS, individual characteristics of various combinations of inks and different electrodes have to be measured; subsequently, their suitability for the intended use will be evaluated and the most suitable one will be implemented into the measuring system. The main motivation of our research is to perform the time-consuming preparatory measurements of the ink characteristics only once and to efficiently use the results in the design of a wide range of planar pressure transducers. This includes an extensive and original measurement of several combinations of different electrode sizes, various conductive ink mixtures and ink layer thicknesses. The aim of the study is to present the first part of the measurement, namely on the test sample plates Nr. 3 to Nr. 5 and to use the results to create a preliminary mathematical model that describes the relation between the electrodes and the electrical resistance.

MATERIALS AND METHODS

As we started the development of the new transducer, we ordered at the Faculty of Chemical Technology, University of Pardubice, Czech Republic, 2 + 9 individual samples (see Fig. 1) in shape of a plate, that includes 18 individual circular electrodes with different dimensions. The samples were made using printing technology and each one has a unique combination of thickness of the ink layer and the ratio of the inks in the mixture. The electric output signal is obtained via three busses that are connected to the electrodes. As the piezoresistive layer were selected conductive inks HENKEL NCI 7002 and ECI 7004HR in the specified ratios in the mixture. The ink 7002 is non conductive, whereby the ink 7004 is conductive with carbon particles as filler. The inks are designed to blend with each other to obtain the required level of resistivity, they are suitable for the printing technology (LOCLITE NCI 7002 and LOCLITE NCI 7002 product sheets).

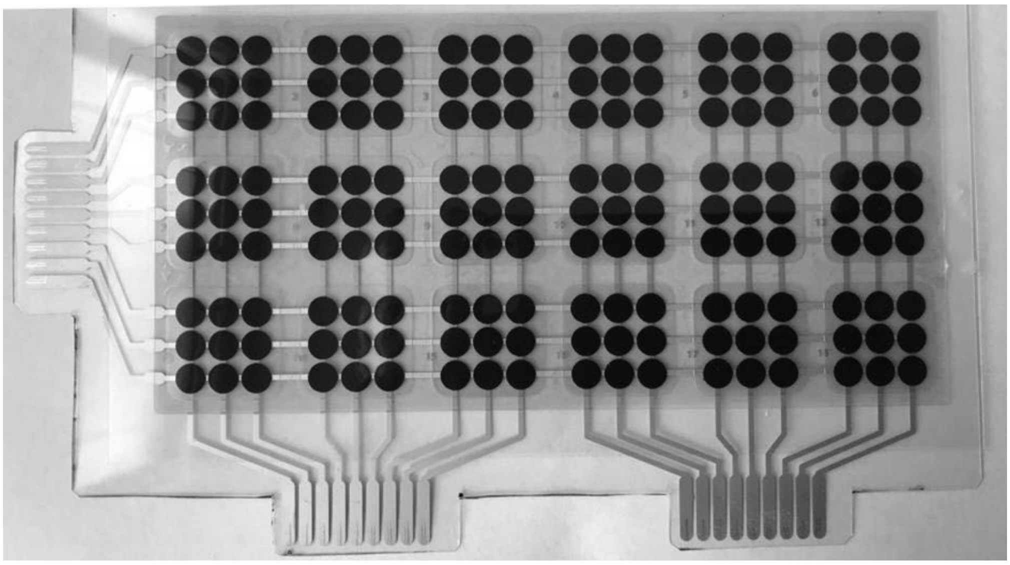

Fig. 1 Sample plate with circular electrodes.

Due to the proposed extend 162 ink – electrode combinations, we decided to perform the measurement as automatically as possible. This included four key parts, namely using a robotized arm to extend selected force on the electrode, a control program to set the exerted force automatically, an electric circuit to determinate the electrical resistance as the output variable and a LabView program to collect the data and calculate the quantities. More detail about the used methodology can be found in (*Volf et al., 2019*). Measurements of the dependency of the output voltage (or else electrical resistance) 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. Pressure was applied by the measuring tip with 3 mm in diameter by means of the vertical motion of the robot's arm. The arm was moved in 0.02 mm increments for a general overview of the behaviour of an electrode and further in 0.01 mm step for a more detailed analysis; this more detailed course was measured only on selected (the most convenient) electrodes and will be presented separately. The loading force was exerted from 0,37 N up to cca. 17,6 N. The pressure applied on the electrodes was calculated from the known area of the surface of the measuring tip and the exerted force. This resulted in the measured range of pressure values approximately from 30 kPa up to 1 400 kPa for the particular measuring tip. A photograph of the robotized measuring workspace is depicted in Fig. 2.

Fig. 2 Robotized measuring workspace.

The electrical resistance of a particular electrode depends on several variables, namely on the dimension of the used electrode, on the used ink or ink mixture and on the thickness of the applied ink layer. We expect a significant impact of the thickness of the ink layer on the electrical resistance; within a thinner ink layer, there are created less conductive paths and the resistance should theoretically increase. The impact of the dimensions of an electrode on the electrical resistance is more complex and will be evaluated statistically in the next chapter. Theoretically, the electrical resistance should increase with the area size, as there are created more conductive paths within the ink, and it should also decrease with smaller gap between the inner and outer electrode as the conductive path shortens.

RESULTS AND DISCUSSION

The aim of this evaluation is to determine the dependency of the electrical resistance on the dimension of the electrodes and to make a mathematical model of this dependency. As the variables area of the electrode and the gap between the inner and outer electrode are not independent on each other, a direct statistical evaluation of the impact of the gap size and of the electrode area itself on the electric conductivity is not possible. Therefore, we introduce a new variable called Active Electrode Area P_A, that includes both parameters (1), where the others (ink thickness, mixture) are kept constant. The values of $R_1 - R_4$ are graphically explained in Fig. 2; the calculated values of P_A (%) for individual electrodes are stated in Tab. 1.

$$P_a = \frac{\pi R_4^2 - \pi R_3^2 + \pi R_2^2 - \pi R_1^2}{\pi R_4^2} = \frac{R_4^2 - R_3^2 + R_2^2 - R_1^2}{R_4^2} \quad (1)$$

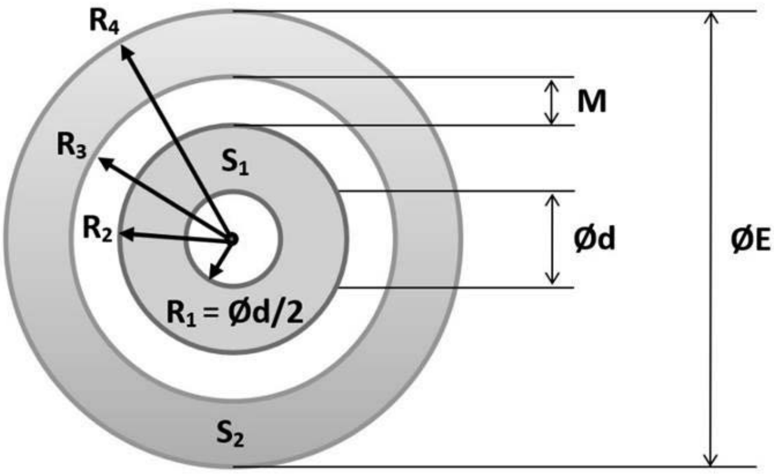

Fig. 2 Dimensions of the electrodes.

Tab. 1 Active electrode area P_A for individual electrodes

Electrode	E1	E2	E3	E4	E5	E6	E7	E8	E9
P_A (%)	86	89,75	77,44	79,84	94,20	91,35	88,49	85,63	82,78
Electrode	E10	E11	E12	E13	E14	E15	E16	E17	E18
P_A (%)	79,92	77,06	93,65	90,53	87,40	84,28	81,15	78,03	74,90

An arithmetic mean of measured electrical resistances of individual electrodes has been calculated and depicted by a scatter graph. Subsequently we used regression analysis to find a model, that describes the dependency of the electrical resistance on the Active Electrode Area. In following graphs in Figs. 3 and 4, there are depicted two models with the regression function and with the coefficient of determination R^2.

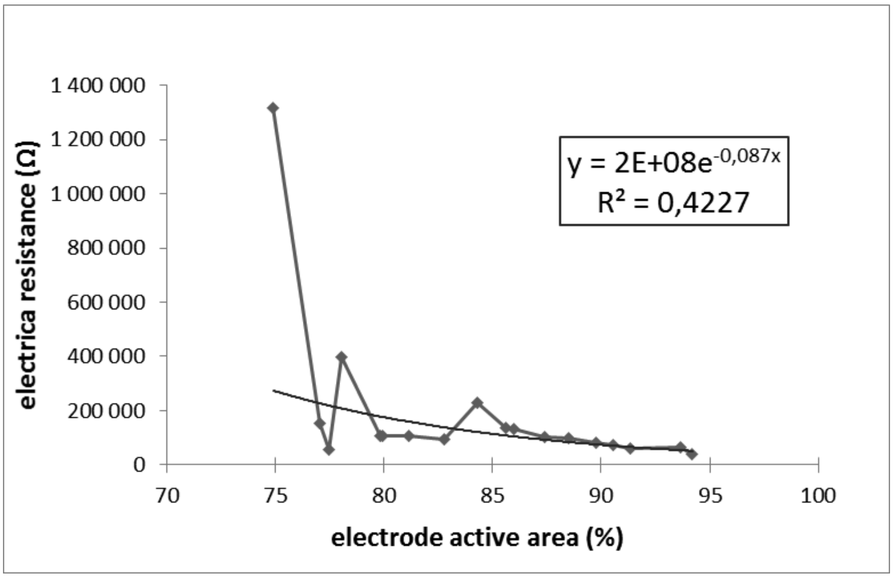

Fig. 3 Regression analysis – exponential.

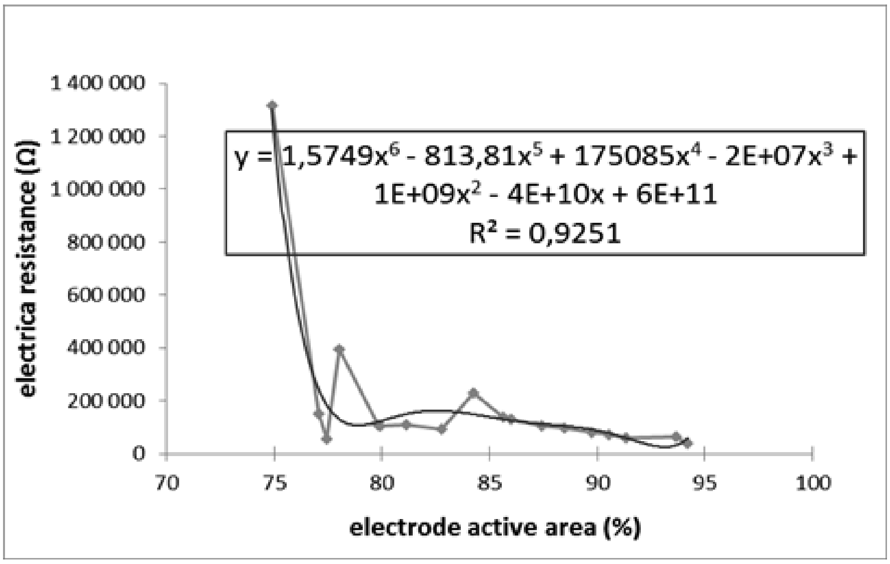

Fig. 4 Regression analysis – polynomial.

The dependency is better captured by a 6th degree polynomial (Fig. 4 above). With increasing Active Electrode Area P_A the electrical resistance decreases significantly, up to values under 100 kΩ. This is a very important finding for the design and selection of the electrodes for the transducer. According to the requirements on the designed transducer (expected pressure range, control electronics), electrodes with higher or lower active electrode area should be selected. This is in accordance with our introductory measurements with conductive inks and circular electrodes, where the PD electrode exhibited slightly higher electrical resistance by constant outer dimensions (*Volf et al., 2019*). More discussion about the impact of the electrode shape and dimensions on their resistivity can be found in (*Yang et al., 2021*). It is also important to keep the variable Active Electrode Area P_A constant when designing same sensitive transducers with different resolution (i.e. with bigger or smaller electrodes), as the dimensions of the electrode are not independent.

CONCLUSIONS

Within our research, we evaluated the impact of the dimensions of the electrodes and of the ink layer thickness on the measured electrical resistance. The results will be applicable in the design of the new transducer SITSCAN CS, that converts the applied pressure into electric signal. Furthermore, the results can be used in design of any tactile transducer basing on an ink-based piezorezistive layer. We performed an extensive set of measurements of 162 individual combinations of ink layer thickness – electrode size – ink mixture ratio. The results should simplify the design of tactile pressure transducers in the future, as there will be no need for the time-demanding preparatory measurements and evaluations of the electrodes.

Within the first part of our work, we concentrated on the test sample plates Nr. 3 to Nr. 5, with constant ratio of ink mixture and with 3 different ink thickness layers. The impact of the dimensions of the electrodes on the electrical resistance has been investigated and modelled. Due to the dependency of the individual dimensions of an electrode on each other, a new variable called Active Electrode Area has been introduced. This variable determinates the ratio between the area of the gap and the area of the electrode. Using a regression analysis, the course is better captured using a 6th degree polynomial. With the increasing the Active Electrode Area the electrical resistance decreases up to values below 100 kΩ. This properties of the electrodes have to be taken into account by designing a new tactile transducer, too. The first set of electrodes proved them to be suitable for use in the new developed tactile sensor SITSCAN CS. The main limitation is now the partially limited pressure range, i.e. big uncertainties for low pressure ranges and zero sensitivity for high pressure ranges. The thinnest ink layer can be preliminary excluded for the use in the tactile sensor. We will continue on the measurements with different ink mixtures to obtain the full set of 162 electrode – ink mixture – ink ratio combinations.

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REFERENCES

1. Volf, J.; Svatos, J.; Koder, P.; Novak, V.; Papezova, S.; Ryzhenko, V. & Hurtecak, J. (2015). Pressure Distribution Measurement System PLANTOGRAF V12 and its Electrodes Configuration. *Agronomy Research* 13(3), 732–738.
2. Koder, P.; Novak, V.; Ryzhenko, V.; Hruby, D.; Volf, J. & Novak, D. (2018). Plantograf V18 - New construction and properties. *Agronomy Research* 16(Special issue 1), 1085–1094.
3. Volf, J.; Novak, D.; Novak, V. & Papezova, S. (2019). Evaluation of foil transducers and their use in tactile sensors. *Measurement* 136, 573–578.
4. Barman, S. & Guha, S.K. (2006). Analysis of a new combined stretch and pressure sensor for internal nodule palpation. *Sensors and Actuators A-Physical*, 125 (2), 210-216.
5. Giovanelli, D. & Farella, E. (2016). Force Sensing Resistor and Evaluation of Technology for Wearable Body Pressure Sensing. *Journal of Sensors*, Article number 9391850.
6. Dimitriou E. & Michailidis, N. (2021). Printable conductive inks used for the fabrication of electronics: An overview. *Nanotechnology*, 32(50), Article number 502009.
7. Yang, E.-C., Chen, Y.-W., Wu, J.-Y., Chen, R. & Lo, C.-Y. (2021). Enhancing the Detection Sensitivity in Capacitive Tactile Sensors with Optimized Electrode Shapes. *IEEE Sensors Journal*, 21(23), 26294-26303.
8. LOCLITE NCI 7002. Available online: https://www.henkel-adhesives.com/cz/cs/produkt/industrial-inks-and-coatings/loctite_nci_7002ec.html (accessed on 11.4.2022).
9. LOCLITE NCI 7004. Available online: https://www.henkel-adhesives.com/cz/cs/produkt/industrial-inks-and-coatings/loctite_nci_7004hr.html (accessed on 11.4.2022).

Corresponding author:
Ing. Viktor Novák, Department of Electrical Engineering and Automation, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16521, Czech Republic, e-mail: novakviktor@tf.czu.cz