Preliminary Study of a Capacitive Force Sensor for Soft Robotic Applications

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Abstract. The paper focuses on a preliminary study of an easy-to-customize capacitive soft sensor to measure forces that can enable soft robot features like sensitive skins or permits dexterous object manipulation thanks to the perception of the grasping force. The prototype has been realized overlapping five different layers choose among commercial and easy to find materials. The sensor is completely composed by customized or self-produced parts. The stack definition involves compatibility test to define the correct combination of layers and adhesives. An evaluation of the behavior has been performed applying weights in the range [20 – 5800] g finding a mean sensitivity of 0.143 pF/kg over an initial value C_0 of 3.151 pF. The sensor prototype showed good performance in term of sensitivity and hysteresis in the defined application range. Dielectric viscoelastic phenomena and decreasing repeatability have been observed in the upper part of the measuring range. The sensor proposed shows promising characteristics encouraging future developments.

Keywords: Capacitive Force Sensor, Conductive Inks, Customizable Force Sensor.

1 Introduction

Soft robotics involves the development of mechanical systems that take inspiration from nature and biology trying to mimic skills and strategies developed by living beings through evolution and natural selection. In soft robotics, movements [1], [2], sensing [3] and adaptation [4] mechanisms of the animal world are studied and replicated, to take advantage for robot development. An important theme in soft robots development concerns the characteristic defined context awareness [5], [6], that is, the ability of having the perception of the surrounding environmental parameters. The greater the awareness, the greater can be the robotic system autonomy in carrying out its tasks. This capability derives from the robot sensing skills obtained exploiting sensors. Soft sensor development is a promising field of research. The need for inte-

Bellitti, P., Caporaso, T., Grazioso, S., Lanzotti, A., Sardini, E., Serpelloni, M. (2023). Preliminary Study of a Capacitive Force Sensor for Soft Robotic Applications. In: Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., Roucoules, L. (eds) Advances on Mechanics, Design Engineering and Manufacturing IV. JCM 2022. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-15928-2_109

gration in soft robots establishes that the sensors must have adequate flexibility characteristics in addition to the classic metrological characteristics such as accuracy, repeatability. In soft robotics applications, soft force sensors enable robot features like the development of a sensitive skin or enable dexterous object manipulation [6] thanks to the perception of the grasping force. In this paper, a capacitive force sensor for soft robotic applications is shown and a preliminary analysis of the behavior is reported.

2 Capacitive force sensors design

2.1 Parallel-plate capacitor

Capacitive sensors enable the transduction of physical quantities in a change of the sensor capacitance from the nominal value. The most classic form of capacitor is made up by two conductive parallel plates separated by an insulating element called a dielectric [8] (Fig. 1).

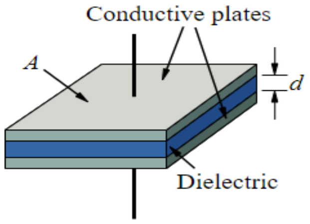


Fig. 1. Diagram of the parallel plates capacitor showing main elements and geometrical parameters

The characteristic parameters of the parallel plate capacitor determine the capacitance (*C*) according to the following formula (1):

$$C = \frac{\varepsilon \cdot A}{d} \tag{1}$$

where:

- *C* represents the capacitance
- ε is the dielectric permittivity
- *A* is the plates area
- *d* is the dielectric gap thickness.

The overall capacitance of the element is therefore dependent on both the geometric parameters and the permittivity of the material contained within the gap between the plates. Capacitive transducers can measure different quantities thanks to the variation of these parameters, for example capacitive humidity sensors use a hygroscopic dielectric, that absorb moisture and cause a change in dielectric permittivity [9]. Capacitive force sensors, as in this case, base their operation on the variation of parameter *d*. A compressible dielectric is chosen so that an external force acting on the plates can cause them to approach each other. Compression causes a reduction in the distance between the plates and a consequent increase in capacity.

In the proposed solution, the capacitive force sensor is developed ad-hoc by overlapping layers of different materials. The use of easily available materials and the realization method make it potentially easy to customize in terms of shape, size and measurement range. The description of the layers used is reported in Fig. 2.

Fig. 2. Stack diagram of the soft capacitive force sensor.

The lower layers (Fabric and Polyurethane) represent the sensor substrate while the three upper layers (Plate #1, Dielectric and Plate #2) represent the force sensitive element. The lower layer is realized from a 404-Revolutio-NAL® technical fabric produced by Carvico composed by 71% polyamide and 29% elastane. These choices allow good adaptability to the different surfaces and shapes on which the sensor could be adapted. The next layer is formed by polyurethane, and it is necessary to permits the fabric functionalization. The presence of the polyurethane layer makes the fabric waterproof and not allow the next layer to be absorbed into the fabric fibers.

2.2 Plate #1

The layer named Plate #1 is the first capacitor plate. To meet the requirements of simplicity of customization and realization, it is made depositing a conductive ink on the polyurethane layer. In this way, it is possible to obtain any shape and size simply by "painting" the desired shape with the ink. To evaluate the performance and compatibility of some of the inks available on the market, tests were made on fabric samples as shown in Fig. 3. In this phase, the samples are obtained depositing manually a certain quantity of conductive ink on small fabric pieces.

Fig. 3. Plate #1 realization: Conductive inks sample on polyurethane layer.

The conductive ink considered for the realization of the first capacitor plate are:

- Dupont PE874: stretchable silver-based conductive ink
- Creative materials 128-30 stretchable silver-based ink
- Dupont PE671: stretchable carbon-based ink

All the selected inks need a thermal curing process to make solvents evaporating and to make the silver or carbon microparticles melting together in order to create conductive paths. Dupont PE874 and DUPONT PE671 samples were placed in a thermostatic oven for 30 minutes at 130 °C, Creative Materials 128-30 sample was placed at 170 °C for 30 minutes. After the curing process the resistance across the sample has been measured to evaluate the conductivity: DUPONT PE874 shows a resistance of 1.1 Ω over a 30 x 15 mm area, Creative Materials 128-30 shows a resistance of 0.5 Ω over a 20 x 15 mm area and DUPONT PE671 shows a resistance of 1.3 k Ω over a 25 x 10 mm area. A cross hatch test was performed for all samples and good adhesion with the polyurethane layer is observed. The less conductive sample (DUPONT 671) was excluded from further test.

2.3 Dielectric layer

Dielectric layer is the insulator placed between the two plates that permits electrical and physical separation and contributes to define the overall sensor capacitance.
The dielectric shore must enable a thickness variation of the sensor in the force range [0 - 57] N. In addition, the insulator layer must show good adhesion with the plates. Dielectric layer is obtained with silicone produced by Zhermac Dental. The choose product is the Elite Double 16 Fast characterized by a Shore hardness of 16 and a declared elastic recovery of 99.95%. This silicone is a bicomponent product: when the two parts are mixed together the mixture start polymerizing reaching the final hardness in about 30 minutes.

In Fig. 4 is reported the dielectric layer realization. The polymerizing process take place inside a custom designed 3D-printed mold. The mold size is 100 x 100 x 3 mm. The pre-mixed silicon mixture is poured inside the mold, after the polymerization time the silicone sheet was extracted, and then cut into portions of the desired size.

The silicone elements were bonded on the plate #1 with a LOCTITE 406 adhesive specifically designed for plastics and rubbers helped with a polyolefin primer specific for promoting adhesion on difficult-to-bond plastics (LOCTITE 770). The bonded process was satisfying for both the DUPONT 874 and Creative Material 128-30 sample.

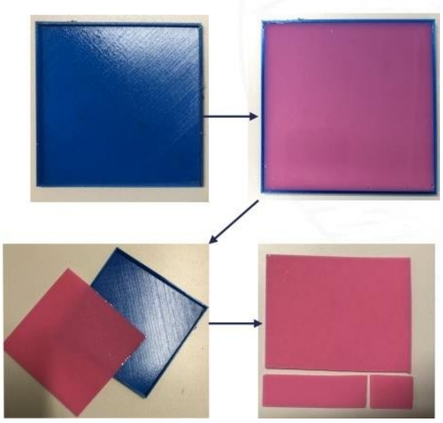


Fig. 4. 3D printed mold for silicon polymerization process.

After the bonding process the Creative Material 128-30 resistivity increases to some megaohm. Due to the incompatibility with the adhesive, this conductive past was excluded from further tests.

2.4 Plate #2

The second plate is realized bonding a conductive fabric (Shieldex® Nora Dell) on the silicon layer with the same combination of LOCTITE 406 + LOCTITE 770 adhesive and primer used in paragraph 2.4. The bonding between the silicon layer and the fabric is strong enough to guarantee good adhesion between the layers.

This step concludes the first part in which the material compatibility is verified, and the stack is defined.

3 Sensor prototype fabrication

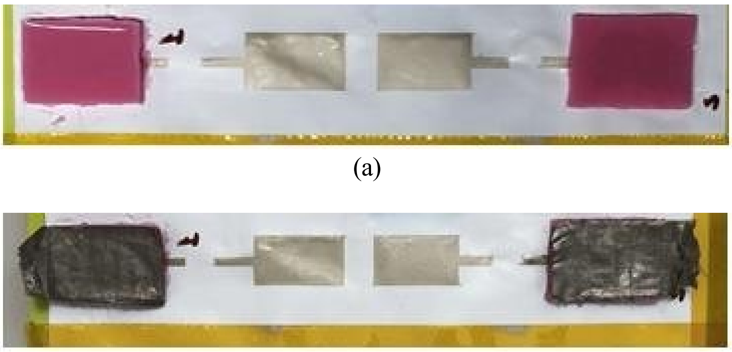
The second phase regards the sensor prototype fabrication process. Twelve different sensors have been realized overlapping the layers described in the previous paragraph. The process starts with a big rectangular fabric piece (27 x 18 cm) with polyurethane layer. The polyurethane layer was applied with a professional heat press for t-shirts.

The size of the first plate, in this series of prototype is 14 x 22 mm with a little extension for electrical connection. The geometrical size has been defined with kapton tape (Fig. 5a), the DUONT PE874 conductive ink has been sprayed with an airbrush (Fig. 5b) and then cured in a thermostatic oven for 30 minutes at 130 °C (Fig. 5c).

(a) (b) (c)

Fig. 5. Realization of the first conductive plate: (a) masking with kapton tape, (b) spraying conductive ink with airbrush, (c) plates after the curing process.

The 3-mm dielectric layer composed by the pre-polymerized Elite Double 16 Fast silicon was cut in rectangular pieces whose size are: 15 x 23 mm and bonded to the first plate using the primer and adhesive combination (Fig. 6a). Then the last layer composed by the conductive fabric is bonded with the same adhesive (Fig. 6b).



(a)

(b)

Fig. 6. Last two steps of the sensor prototype realization: (a) silicon and (b) fabric bonding.

4 Preliminary experimental tests

The tests on the sensors are currently in progress, in this section are presented the preliminary results obtained analyzing data retrieved from repeated tests on a single sensor.

The experimental setup is showed in Fig. 7. The selected sensor was connected to a HP4194A Impedance/Gain-Phase Analyzer set to measure the sensor impedance while the sensor has been loaded with different weights. The sensor capacitance is then calculated from the impedance at 100 kHz. A mechanical structure has been realized to uniformly distribute the force on the sensor surface and the sensor has been placed on a scale to verify the load.

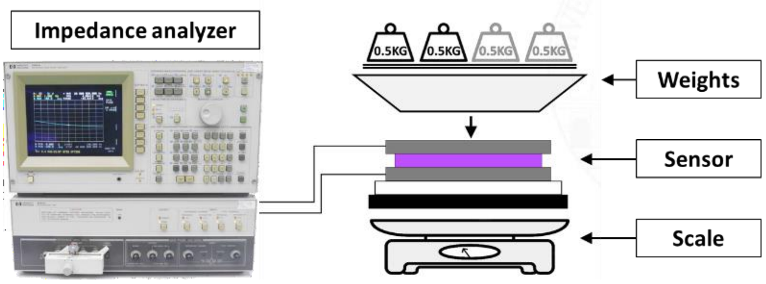


Fig. 7. Experimental setup used to load the sensor and measure the capacitance.

The test protocol is here explained: starting from the sensor unload, the weight has been increased in steps of about 500 g from 20 g to 5800 g. The first weight value is about 20 g (weight of the first part of the mechanical structure), the second weight value is 660 g (weight of the full mechanical structure), and the last weight is 5800 g (scale full scale). The weight path has been made 5 times: 3 times for increasing weights and 2 times for decreasing weight values.

4.1 Preliminary experimental results

The first data series represented in Fig. 8 is obtained for weight increasing values from 20 g to 5800 g.

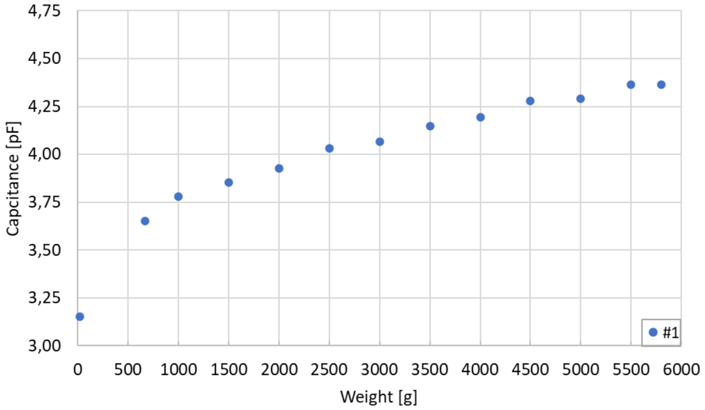


Fig. 8. Capacitance vs. weight graph of the first set of data for increasing weights.

Analyzing data there is a clear increasing trend in the capacitance as the weight applied rises. Between the first (20 g) and the second (688 g) weight values there is a considerable capacitance increase from 3.151 pF to 3.654 pF, this gap is greater than all the following steps. A more detailed characterization is needed in this range to evaluate the sensor behavior. In the range [1000 – 5500] g the mean sensitivity is 0.143 pF/kg. Between 4500 g and 5000 g a considerable reduction in sensitivity can be observed (0.024 pF/kg), this behavior could be associated to viscoelastic property of the silicone.

In Fig. 9 is reported the capacitance versus weight graph for increasing (#1) and decreasing (#2des) weights. The same consideration about the two phenomena observed in the previous graph (Fig. 8) can also be found in the decreasing dataset. It can be observed qualitatively that no relevant hysteresis behavior appears.

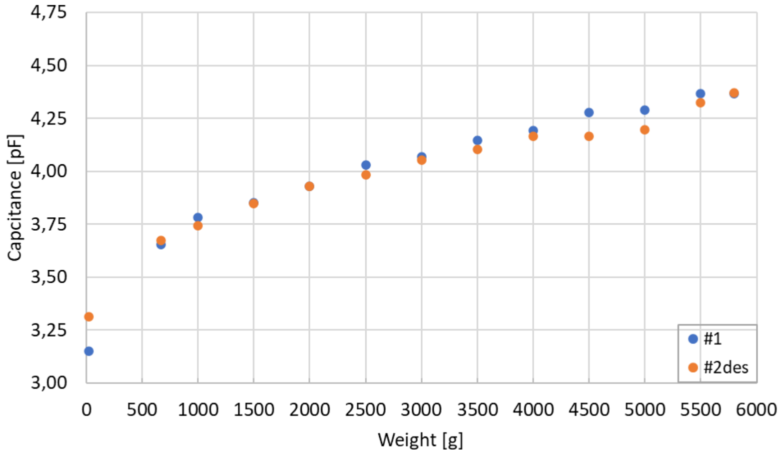


Fig. 9. Capacitance vs. weight graph for increasing (#1) and decreasing (#2des) weights.

Finally, all the 5 datasets retrieved are analyzed in term of mean values and standard deviation (Fig. 10). The results show a significant spread about the mean value. The spread appears growing as the weight increase.

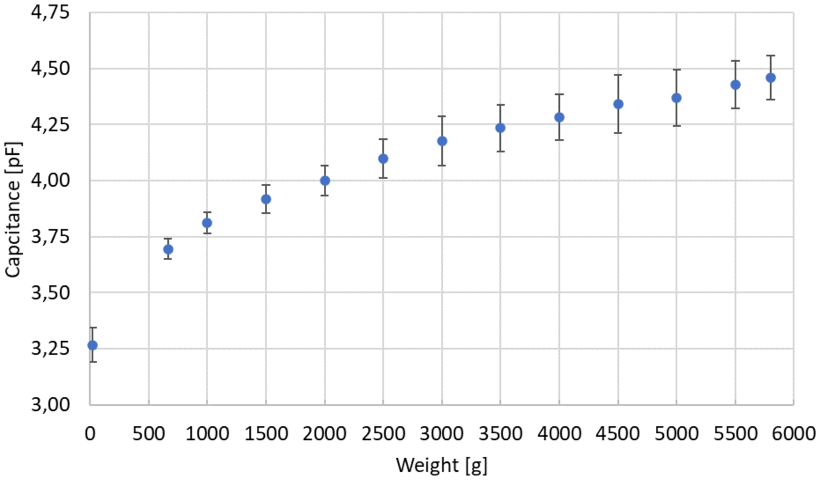


Fig. 10. Capacitance vs. weight graph for the 5 datasets express in terms of mean values and standard deviations.

5 Conclusions and future works

An easy-to-customize capacitive force sensor has been realized overlapping different structural and functional layers. The compatibility of the different layers has been preliminarily analyzed both in terms of application suitability and compatibility with the adhesives. The final stack defined is composed by 404-Revolutio-NAL® technical fabric, polyurethane layer, Dupont PE874, Double 16 Fast silicone by Zhermac Dental and Dell's Shieldex® Nora conductive fabric. A preliminary analysis was performed to observe the capacitance dependence by the pressure applied on the sensor, obtaining an average sensitivity of 0.143 pF/kg in the range [1000 — 5500] g. Repeated tests were performed for the qualitative evaluation of hysteresis and repeatability. Although further studies are needed to deepen the viscoelastic phenomena observed and better characterize the lower range [0 — 1000] g, the prototype is promising for use in soft robot applications like sensitive-skins or soft grippers. Further studies on different sensor prototypes will be performed to assess the repeatability of the production process. Stiffness and deformation test will also be performed.

References

1. Wu, Q., Yang, X., Wu, Y., Zhou, Z., Wang, J., Zhang, B., Luo, Y., Chepinskiy, S. A., Zhilenkov, A. A.: A novel underwater bipedal walking soft robot bio-inspired by the coconut octopus, Bioinspir. Biomim, vol. 16, p. 46007, 2021
2. Liao, B., Zang, H., Chen, M., Wang, Y., Lang, X., Zhu, N., Yang, Z., Yi, Y.: Soft Rod-Climbing Robot Inspired by Winding Locomotion of Snake, Soft Robot., vol. 7, no. 4, pp. 500–511, Aug. 2020
3. Zhang, R., Shen, Z., Zhong, H., Tan, J., Hu, Y., Wang, Z.: A Cephalopod-Inspired Soft-Robotic Siphon for Thrust Vectoring and Flow Rate Regulation," Soft Robot., vol. 8, no. 4, pp. 416–431, Aug. 2021
4. Malley, M., Haghighat, B., Houe, L., Nagpal, R.: Eciton robotica: Design and Algorithms for an Adaptive Self-Assembling Soft Robot Collective Proc. - IEEE Int. Conf. Robot. Autom., pp. 4565–4571, May 2020
5. Liu, H., Wang, L.: Collision-free human-robot collaboration based on context awareness, Robot. Comput. Integr. Manuf., vol. 67, p. 101997, Feb. 2021
6. Liu, K., Wu, Y., Wang, S., Wang, H., Chen, H., Chen, B., Yao, J.: Artificial Sensitive Skin for Robotics Based on Electrical Impedance Tomography, Adv. Intell. Syst., vol. 2, no. 4, p. 1900161, Apr. 2020
7. Yang, W.-T., Kuang, Z., Wang, C., Tomizuka, M.: Development of Soft Tactile Sensor for Force Measurement and Position Detection, May 2021
8. Grove, T. T., Masters, M. F., Miers, R. E.: Determining dielectric constants using a parallel plate capacitor, Cit. Am. J. Phys., vol. 73, p. 52, 2005
9. Chaudhary, P., Maurya, D. K., Yadav, S., Pandey, A., Tripathi, R. K., Yadav, B. C.: Ultra-fast responsive humidity sensor based on roasted gram derived carbon quantum dots: Experimental and theoretical study, Sensors Actuators B Chem., vol. 329, p. 129116, Feb. 2021