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A SPIRAL CAPACITIVE SENSOR FOR ROBOTIC FINGER TACTILE FEEDBACK AND FUTURE LOW-COST INTRAOCULAR PRESSURE MONITORING

Nguyen Dac Hai, Le Manh Long, Tran Van Tung
Hanoi University of Industry, Ha Noi, Viet Nam

Keywords: pressure sensors, capacitance sensor, tactile feedback, robotic finger, intraocular pressure, coplanar electrodes.
Abstract. This paper presents the research, design, and simulation of a coplanar capacitive pressure sensor for robotic finger tactile sensing during object manipulation. The proposed sensor is capable of detecting applied forces up to 1 N. As the force increases from 0 N to 1 N, the sensor's capacitance shifts from 0 fF to 112 fF. The sensor performance was investigated using ANSYS Maxwell in conjunction with ANSYS Mechanical. Simulation results demonstrate a clear capacitance variation in response to the applied force. This sensor can be integrated into industrial applications to measure contact pressure in robotic fingers, enhancing their tactile sensing capabilities during grasping tasks.

СПИРАЛЬНЫЙ ЕМКОСТНЫЙ ДАТЧИК ДЛЯ ТАКТИЛЬНОЙ ОБРАТНОЙ СВЯЗИ НА КОНЧИКАХ ПАЛЬЦЕВ РОБОТА И ПЕРСПЕКТИВНЫЙ НЕДОРОГОЙ МЕТОД МОНИТОРИНГА ВНУТРИГЛАЗНОГО ДАВЛЕНИЯ

Нгуен Дак Хай, Ле Мань Лонг, Чан Ван Тунг
Ханойский промышленный университет, Ханой, Вьетнам

Ключевые слова: датчики давления, емкостной датчик, тактильная обратная связь, роботизированный палец, внутриглазное давление, копланарные электроды.
Аннотация. В данной статье представлены результаты исследования, проектирования и моделирования копланарного емкостного датчика давления, предназначенного для тактильного восприятия роботизированными пальцами при манипулировании объектами. Предложенный датчик способен обнаруживать приложенные силы до 1 Н. При увеличении силы от 0 Н до 1 Н емкость датчика изменяется в диапазоне от 0 фФ до 112 фФ. Рабочие характеристики датчика были исследованы с использованием программных средств ANSYS Maxwell в сочетании с ANSYS Mechanical. Результаты моделирования демонстрируют отчетливое изменение емкости в ответ на приложенную силу. Разработанный датчик может быть интегрирован в промышленные робототехнические системы для измерения контактного давления на кончиках роботизированных пальцев, расширяя их возможности тактильного восприятия при выполнении задач захвата.

1. Introduction

Measurement of force or pressure is a critical feature in numerous applications, including robotic manipulation [1, 2], surgical operations [2, 3], breast cancer identification [4], and various other fields. These sensors operate based on different physical principles, such as piezoresistivity, capacitance, and diffraction, with resistive and capacitive sensors being the most widely used. Capacitive sensors are extensively employed in sensing technology as well as in the manufacturing and automotive industries. Unlike resistive sensors, they exhibit lower sensitivity to temperature fluctuations and thermal noise. Today, capacitive pressure sensors are utilized in diverse areas, ranging from biology for measuring intraocular pressure [5] to cardiovascular treatments, such as continuous monitoring of ventricular pressure [6]. Furthermore, micro-capacitive pressure sensors can be embedded into cuff electrodes for in-situ monitoring of the interface pressure between the implanted cuff and neural tissue [7].

In this study, a coplanar capacitive force sensor is proposed, designed with full biocompatibility for industrial environments. The sensor is capable of measuring contact pressure for robotic finger tactile sensing during grasping tasks. Its specific geometry enhances sensitivity toward force applied in a particular direction. The sensor surface is fabricated on a 171 μm flexible polyimide substrate. When force is applied, the surface deforms, altering the distance between the electrodes and inducing a change in capacitance. This research offers a cost-effective solution for polymer-based capacitive force sensors.

2. Theoretical Framework and Sensor Design

The coplanar capacitor is designed with a width (*w*), height (*h*), and electrode spacing (*d*), as illustrated in Figure 1. In the current configuration, the sensor is designed for single-sided sensitivity. This is achieved by placing an electrode plate at the bottom and connecting it to the ground (Fig. 2).

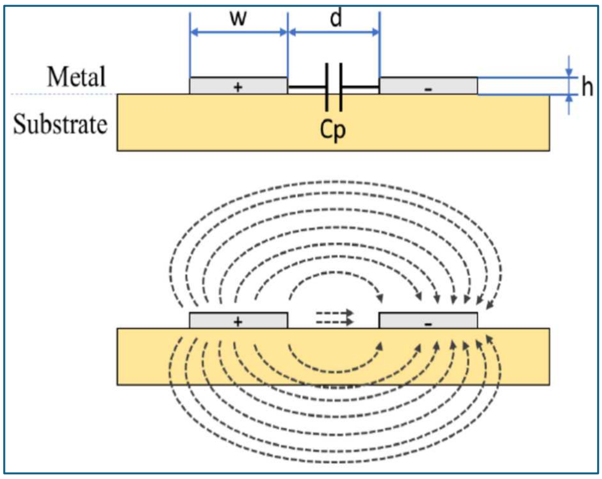

Fig. 1. Coplanar sensor architecture

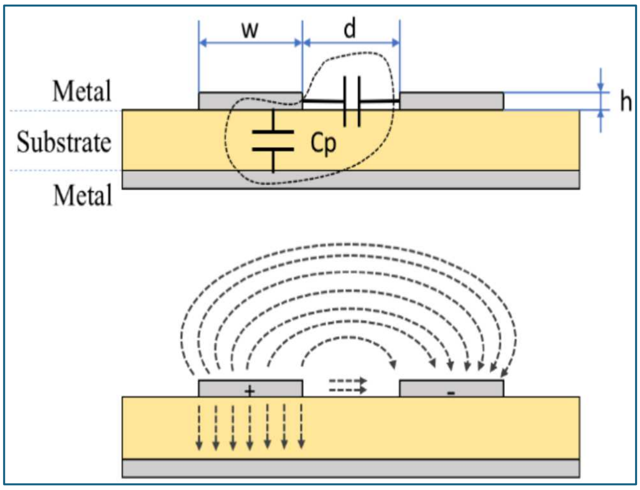

Fig. 2. Coplanar sensor model featuring a grounded plate

As shown in Figure 2, the grounded bottom plate in this coplanar configuration causes the electric field lines to be denser at the top. This results in decreased sensitivity on the underside, achieving single-sided detection. A spiral configuration was adopted to maximize the active sensing surface, as illustrated in Figure 3.

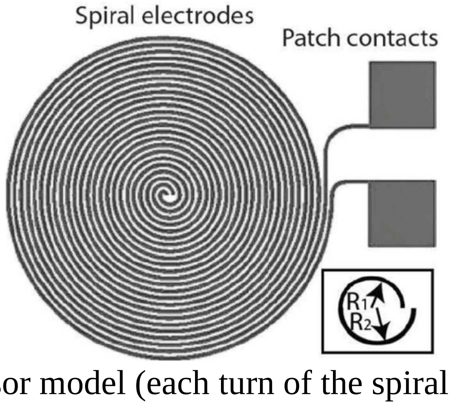

Fig. 3. Spiral capacitive sensor model (each turn of the spiral consists of two semicircles)

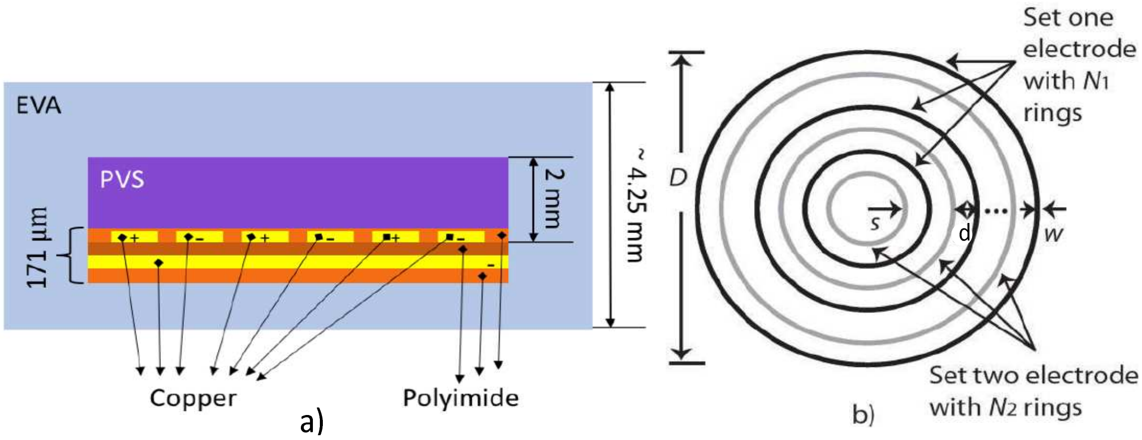

Fig. 4. Detailed geometry of the sensor

Tab. 1. Geometric dimensions and material specifications of the proposed sensor

Component	*w*	*d*	*D*	*s*	Polyimide	Poly-vinyl siloxane (PVS)	Ethylene vinyl acetate (EVA)
Value	0.203 mm	0.1778 mm	8.5 mm	0.2 mm	25 µm	2 mm	3 mm

The sensor is modeled as a number of concentric annular rings: *N*1 annular rings are charged to the same potential to form one electrode, while the other *N*2 rings form the other electrode with opposite charges. For the spiral configuration, the sensor is actually formed by two groups of concentric semi-annular rings with different *s* values (*R*1 and *R*2) but identical *w* and *d* (see Figures 3 and 4). The capacitance C_{con} of the concentric sensor is a linear function of *s* for fixed *d* and *w*, i.e., $C_{con} = ks$, where *k* is a slope coefficient determined solely by the properties of the test material. Therefore, the capacitance of the spiral sensor can be expressed as follows [8]:

$$C_{spiral} = \frac{1}{2}C_{con1} + \frac{1}{2}C_{con2} = \frac{1}{2}ks_1 + \frac{1}{2}ks_2 = k\frac{s_1 + s_2}{2}. \quad (1)$$

In other words, a spiral turn formed by two consecutive semicircles can be modeled equivalently with $s = (s_i + s_{i+1}) / 2$.

3. Simulations and Discussion

The sensor's operation was investigated using ANSYS Maxwell simulation software in conjunction with ANSYS Mechanical. The results from this simulation were imported into ANSYS Mechanical as force density, and mechanical deformation was simulated by applying an inclined force to the top plate. The mechanically deformed structure was then imported back into ANSYS Maxwell to calculate the differential capacitance values.

The sensor model consists of a copper spiral sensor. The signals from the two electrodes of the sensor are fed into a signal processing unit to obtain the output (output voltage), which is then sent to a data acquisition and storage system (Fig. 5).

In Figure 6 the simulation results show that as the applied force on the sensor varies from 0 N to 1 N, the output differential capacitance changes from 0 pF to 0.112 pF. The output capacitance of the sensor varies depending on the applied force with a linear correlation coefficient of R^2 = 0,963.

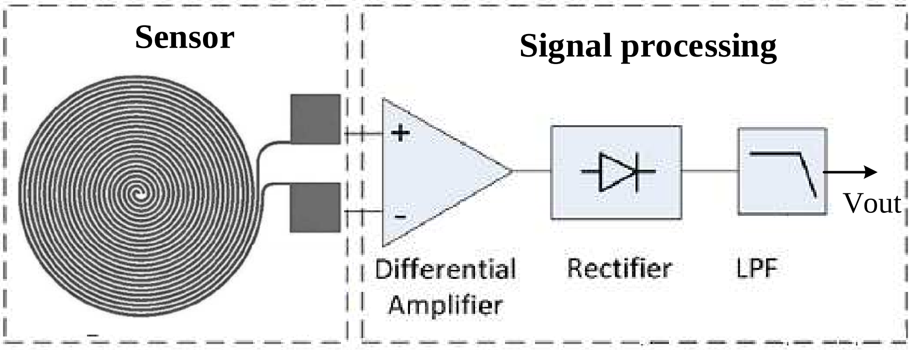

Fig. 5. Block diagram of the sensor signal processing

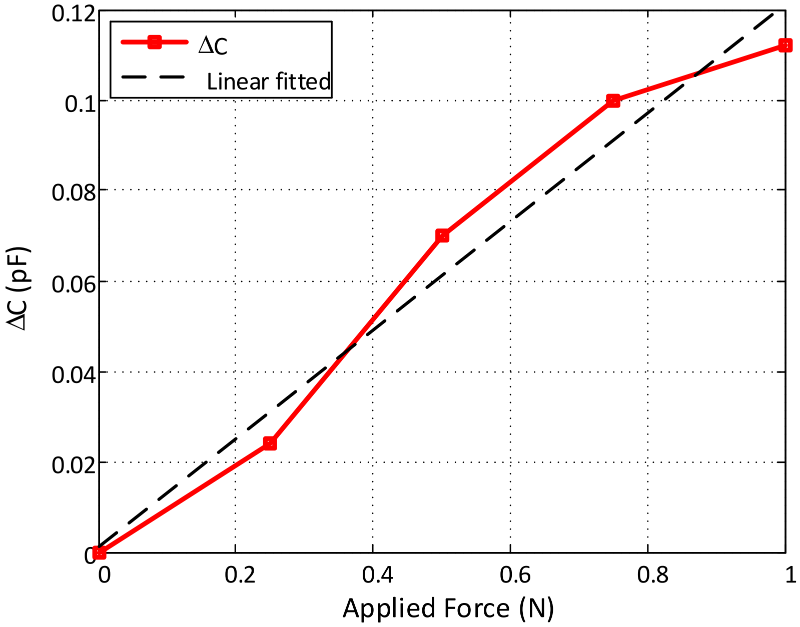

Fig. 6. Dependence of sensor capacitance on the applied force

4. Conclusions

A capacitive pressure sensor has been designed and simulated, with results evaluated under a maximum applied force of 1 N. Due to its specific geometry, the sensor is primarily sensitive to unidirectional excitation and can also function as a position sensor, where the maximum capacitance change varies relative to the distance from the spiral center. Under an applied force of 1 N, the sensor exhibits capacitance variations with high repeatability and low hysteresis, achieving a sensitivity of 112 fF/N. Given this performance, the sensor is well-suited for applications in robotic tactile sensing for object manipulation. In future research, the authors aim to scale down the sensor dimensions to the micrometer range to investigate its potential for low-cost intraocular pressure (IOP) monitoring.

References / Список литературы

1. Wei. Y., Xu. Q. Design of a PVDF-MFC force sensor for robot-assisted single cell microinjection // IEEE Sensors Journal. 2017, vol. 17, no. 13, pp. 3975-3982. doi.org/10.1109/JSEN.2017.2701835.
2. Dai Y., Abiri A., Liu S., Paydar O., Sohn H., Dutson E.P., Grundfest W.S., Candler R.N. Grasper integrated tri-axial force sensor system for robotic minimally invasive surgery // Conference: Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). 2017, pp. 3936-3939. doi.org/10.1109/EMBC.2017.8037717.

3. Kim S., Kim C., Park S., Lee D.Y. A 3-DOF Sensor to Estimate the Force Applied to the Tip of a Surgical Instrument // 18th International Conference on Advanced Robotics (ICAR), Hong Kong, China, 2017, pp. 143-148. doi.org/10.1109/ICAR.2017.8023509.
4. Fernandes J, Jiang H. Three-Axis Capacitive Touch-Force Sensor for Clinical Breast Examination Simulators // IEEE Sensors Journal. 2017, vol. 17, no. 22, pp. 7231-7238. doi.org/10.1109/JSEN.2017.2755596.
5. Ha. D, de Vries. W.N, John S.W.M, Irazoqui P.P., Chappell W.J. Polymer-based miniature flexible capacitive pressure sensor for intraocular pressure (IOP) monitoring inside a mouse eye // Biomedical Microdevices. 2012, vol. 14, no. 1, pp. 207-215. doi.org/10.1007/s10544-011-9598-3.
6. Hernández-Sebastián. N, Díaz-Alonso. D, Renero-Carrillo. F.J, Villa-Villaseñor. N, and Calleja-Arriaga. W. Design and Simulation of an Integrated Wireless Capacitive Sensors Array for Measuring Ventricular Pressure // Sensors. 2018, vol. 18, no. 9, p. 2781. doi.org/10.3390/s18092781.
7. Chiang. C.-C, Lin. C.-C. K, Ju. M.-S. An implantable capacitive pressure sensor for biomedical applications // Sensors and Actuators A: Physical. 2007, vol. 134, no. 2, pp. 382-388. doi.org/10.1016/j.sna.2006.06.007.
8. Chen. T, Bowler N. Design of Interdigital Spiral and Concentric Capacitive Sensors for Materials Evaluation // AIP Conference Proceedings. 2013, vol. 1511, pp. 851-858. doi.org/10.1063/1.4789232.

Сведения об авторах:
Нгуен Дак Хай – к.т.н., преподаватель;
Ле Мань Лонг – магистр, преподаватель;
Чан Ван Тунг – к.т.н., преподаватель.