INSTITUTO SUPERIOR TÉCNICO

PROJECTO MEFT

Smart fingertip tactile sensors for agrorobotics applications

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Research work performed for the Master in Engineering Physics

at

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July 4, 2020

1 Introduction

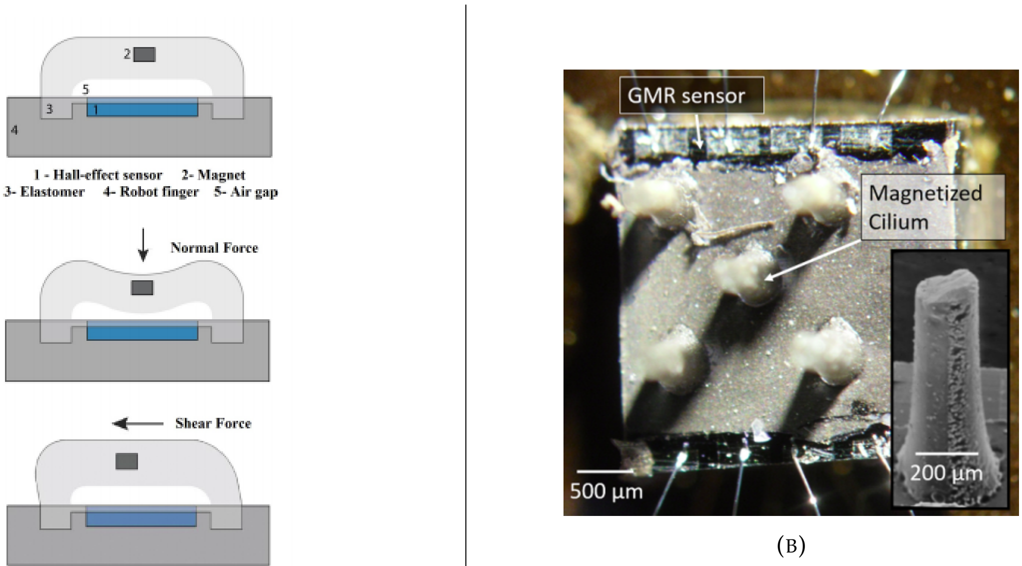
1.1 Motivation

In the agricultural business, as well as in distribution networks and packaging industry, food items suffer changes that need to be controlled. In particular, fruits and vegetables are handled multiple times starting from the harvest up until the point when they are sold. This manipulation facilitates damage in the food items, leading to a shorter shelf-life and overall loss of quality.

It has been demonstrated that appropriate handling is crucial to prevent spoilage and premature degrading of food items. Another crucial point to focus in is that fruits and vegetables should be harvested at the right stage of maturity: not to green, not too ripe. Therefore in fruit/vegetable handling, there is crescent effort to introduce automated technologies for manipulation and optical inspection of fruits/vegetables made possible by the increase of energy density and effectiveness of computing power. This is advantageous in the sense that it can present a quick and cost-effective way to harvest fruits without the need for seasonal labour force and its associated costs, but also and most importantly because it opens new doors for harvesting without damaging. This is where sensor technologies play a key role, for they facilitate the creation of agricultural robots that can effectively replace human labour in terms of speed and quality in handling.

1.2 Context

With this in mind, this work stems from the collaboration between INESC-MN and ISR-Robotics in magnetic-based tactile sensors. This collaboration has been fruitful in the study of such sensors, with the development of technologies such as ciliary structure GMR force sensors [25] and the hall effect 3-axis magnetic soft sensors developed by *Tiago Paulino* for the *Vizzy* robot hand [26]. With such works, experience was obtained in the design, optimization and testing of tactile sensors and the ground was laid for the study and implementation of other technologies.



(A) (B)

FIGURE 1: Design scheme of sensors for implementation in Vizzy robot 1a [26] and photograph of ciliary structure GMR sensor 1b [25]

1.3 Objectives

So, in this dissertation diverse options and detection strategies will be evaluated with the instrumentation of a robotic hand in view. The goal is to equip this robotic hand with sensors in strategic positions in such a way that provides tactile sensing abilities that allow for a quick evaluation of the quality and an increased precision in distinction of shape of the fruit/vegetable when being handled. In this way, we will dedicate to develop e-skin technologies and sensors embedded in elastomers and artificial skin, in a way that combines the tactile ability with a more sensitive perception of texture at the time of harvesting.

FIGURE 2: Robotic hand for crop harvesting [23]

2 Tactile sensing transduction techniques

As mentioned briefly before, in this thesis we will evaluate various detection strategies for the construction of a tactile sensor. There are various techniques for tactile transduction, some of them commonly researched and a few used in agrorobotics.

Out of all of them, capacitive, piezoresistive, piezoelectric, inductive and optical methods show more potential for superior performance. Therefore, we give a brief overview of these transduction techniques [3].

2.1 Capacitive tactile sensors

Capacitive tactile sensors are one of the most used types of transducers used in tactile sensing. They are composed of 2 conductive plates (electrodes) with a layer of dielectric material between them.

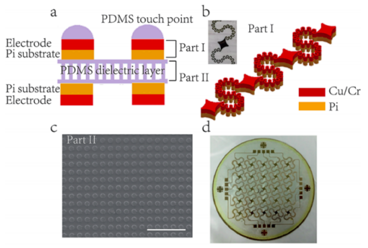
These sensors make use of the change in capacitance when a force is applied. The capacitance of a parallel plate capacitor is given by $C = \epsilon_0 \epsilon_r \frac{A}{d}$. Where ϵ_0 is the vacuum permittivity, η_r is the dielectric layer's relative permittivity, d is the distance between electrode plates, and A is the area in which both electrodes overlap.

One can measure the force applied on the sensor by tracking the changes either in A or d [1].

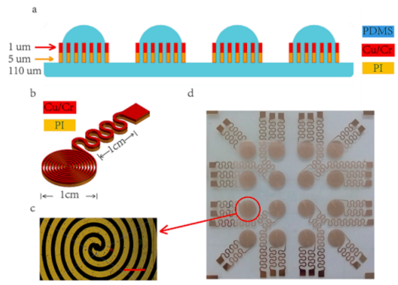
They usually have good frequency response, high sensitivity and large dynamic range, making them appealing to researchers, however they are more prone to noise (crosstalk) and require complex electronics for noise filtering [3].

Most research in capacitive sensing is being done in the design of the dielectric layer or the electrode structure. Tipically, using non-patterned PDMS for the dielectric layer the sensitivity is low, however with patterned layers of PDMS high sensitivity is easily achievable. For example, in [24] two structures were proposed for stretchable capacitive tactile sensors. One of them with a micropillar patterned PDMS layer between a vertical electrode - paralell plate structure (PPS)- and the other with a parallel serpentine electrode structure patterned in a PDMS layer - circular involution structure (CIS).

Both structures showed good linearity in measuring small pressures, and could withstand deformations of 90% (PPS) and 50% (CIS). A PPS sensor array was aditionally attached to a robotic finger



(A) **(a)** Cross sectional view; **(b)** Serpentine electrode lines connected to taxel; **(c)** Micro-pillar PDMS layer; **(d)** 5x5 PPS sensor array



(B) **(a)** Cross sectional view; **(b)**/**(c)** involution electrode; **(d)** 4x4 CIS sensor array

FIGURE 3: PPS (8a) and CIS (8b) sensors schematics (Taken from [24].)

and was demonstrated to achieve more than 90% accuracy in distinguishing objects with different form and stiffness.

2.2 Piezoelectric tactile sensors

Piezoelectric sensors make use of certain materials with piezoelectric properties, such as polymers like polyvinylidene fluoride (PVDF) and ceramics for tactile sensing. These materials generate a voltage potential proportional to the deforming external forces/pressures [1]. The tactile element is constructed by applying thin layers of metallization to both sides of the piezoelectric material, turning it into a parallel plate capacitor [2].

In [14], a sensor is proposed for detection of normal as well as shear force. A tactile unit composed of a unitary bottom electrode and a top electrode divided into 4 units, with a PVDF piezoelectric film layer between the electrodes was used to measure shear forces by the difference in change of charge between the 4 components of the electrode.

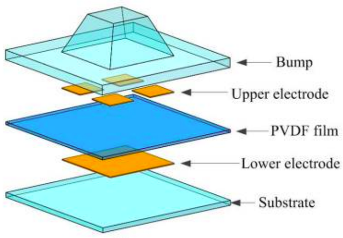


FIGURE 4: Schematics of piezoelectric sensor for 3 axis force measurement (Taken from [14].)

Sensors applying this transduction technique generally have a good high-frequency response with high sensitivity in dynamic environments. However, due to the quick dissipation of the charge induced on the piezoelectric material, they are unable to measure static forces only being able of detecting dynamic forces due to their large internal resistance [3]. Vibrating the sensor and detecting the change in vibration frequency when a force is applied is a way to overcome this problem [2].

2.3 Piezoresistive tactile sensors

Piezoresistive tactile sensors work by changing the electrical resistance of a material placed between or in touch with 2 electrodes when an external force is applied [2].

The sensitive material used in these sensors can be pressure sensitive conductive rubber, elastomer/elastomer cords in grid pattern or conductive ink. Usually the electronic setup to which they are integrated is a simple one, as a change in resistance is easy to quantify by $V = RI$, V being the voltage , I the current and R the resistance. They obtain good results in mesh configurations due to their low susceptibility to noise.

In [11] a pressure sensor is developed by patterning a Au resistor film in a PDMS flexible membrane. This membrane was then bonded to an air chamber made of PDMS walls used to put the desired pressure on the sensor by allowing the membrane to bend.

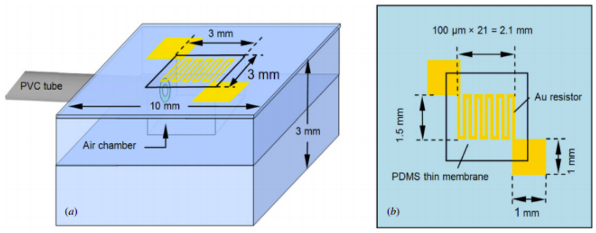


FIGURE 5: Schematics of sensor (Taken from [11].)

Ultrahigh sensitivity was achieved, owing to the strain-induced formation of microcracks on the resistor film (Sensitivity and other results exposed in *Table 2*).

However, this type of sensors suffer from hysteresis and low frequency response [3].

Furthermore, elastomer based sensors have a long nonlinear time constant, their force-resistance characteristic is highly nonlinear and they have poor long and medium term stability due to permanent deformation [2].

2.4 Strain gauges

Strain gauges are also resistive based, low cost tactile sensors, they are zig zag patterned metallic foil on flexible material. They change their resistance according to the external applied force that stretches or compresses the gauge [1].

We show here the fabrication process of a strain gauge sensor developed in [16], which was made double sided to compensate for the temperature induced resistance variation of the metal, in which the sensing part is the NiCr patterned in a square-wave shape.

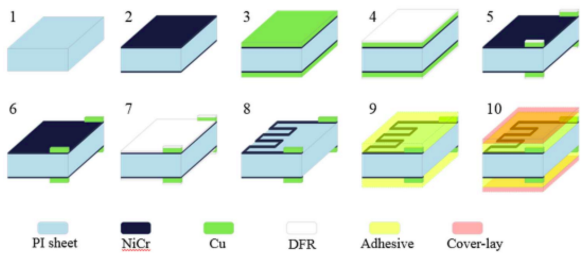


FIGURE 6: Fabrication process of sensor (Taken from [16].)

Usually gauges are used to wrap cantilevers, however these method can lack sensitivity and sensing area.

Metallic or alloy gauges generally have good sensitivity and spacial resolution but lack flexibility.

They are highly sensitive and susceptible to humidity and temperature changes. Their response is nonlinear and they suffer from high hysteresis due to their mechanical nature [3].

2.5 Magnetic tactile sensors

Magnetic tactile sensors measure changes in magnetic flux or magnetic field using a Hall effect sensor or a magneto resistance, respectively. These are able to detect 3D forces/pressures with just one taxel (by means of 3D Hall sensors, for example) which allows for high-resolution and low power consumption [1].

2.5.1 Inductive tactile sensors

They can also measure changes in magnetic induction of coupled coils when affected by an external force, being then called inductive tactile sensors.

They use Faraday's law of induction [1]. A primary coil induces a magnetic field sensed by a secondary coil. By applying an external force one modulates the mutual induction between those coils, which in turn modulates the voltage measured in the sensing coil [3].

The sensor below, developed in [19] is composed of a coil array separated from a rigid stainless steel sheet sensing interface. Normal forces are detected by the change of inductance when the gap between them is reduced, and shear forces when the coil area covered by the stainless steel is reduced on one side and increased in the other.

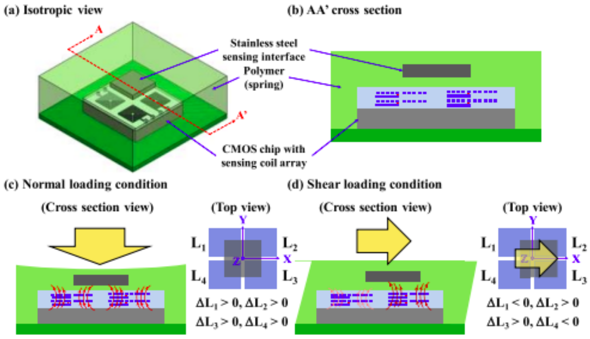


FIGURE 7: **(a)/(b)** Schematics of sensor; **(c)/(d)** Principle of operation for normal and shear forces; (Taken from [19].)

These sensors are flexible, highly sensitive and easy to fabricate, being a good choice for robotic artificial skin. Nonetheless, when compared to other kinds of sensors, they are power consuming, require more complex electronics, are prone to stray capacitance, and have low repeatability due to the coils not always returning to the exact same place after actuated on [3]

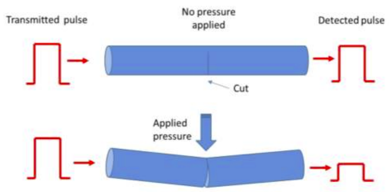
2.6 Optical tactile sensors

Optical tactile sensors work by measuring changes in light. Usually, optical fibers are used as the transmission medium for light. When an external force is applied the transmitting medium (optical fibers) is bent and such sensors can, for example, measure the change in light intensity at the output of optical fibers [1] using a camera or a photodiode for this job. A merit of these sensors is that, besides the intensity, they can also measure the position of the force.

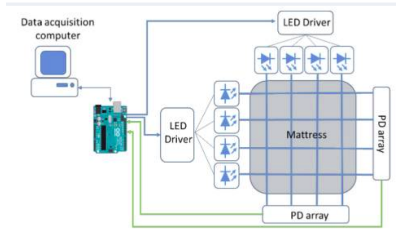
In [22] a simple pressure sensor was developed for vital signal monitoring, using cuts in fiber optics cables, that reduce the light intensity that arrives at the photodiodes in the output side when pressure is applied, as showed in the figure below.

These sensors can also include fiber Bragg gratings in the cores of the optical fibbers, and measure the force by the displacement of the frequency of the transmitted light at the output of optical fibers.

Advantages of these sensors include light weight, immunity to electromagnetic phenomenons and high spatial resolution [3]. However, they require a lot of processing power and their rigidness is a major disadvantage.



(A) Principle of operation



(B) Application schematics

FIGURE 8: (Taken from [22].)

3 Timeline of dissertation work

- **September:** Reevaluating possibilities and deciding over which technologies, materials and design to implement in the tactile sensor;
- **October and November:** Design and fabrication of the tactile sensor in the INESC facilities;
- **December - mid January**: Calibration and testing of the sensor apparatus;
- **mid January - February**: Experimental sensor data acquisition and analysis with machine learning algorithms and posterior discussion of results;
- **March-mid May**: Writing and delivery of the dissertation.

	Advantages	**Disadvantages**
Capacitive	High sensitivity High spacial resolution Good dynamic range Independence of temperature	Susceptible to noise Stray capacitance Cross-talk Complexity of electronics
Piezoresistive	High spatial resolution Low cost Simple electronics Low susceptibility to noise	Hysteresis High power consumption Low repeatibility
Piezoelectric	High frequency response High dynamic range High sensitivity	Poor spatial resolution Only dynamic sensing
Magnetic (inductive)	Linear output High dynamic range High sensitivity	Poor reliability Low frequency response High power consumption Stray capacitance
Strain Gauges	Good sensing range High sensitivity Low cost	Hysteresis Nonlinear response Susceptible to temperature Susceptible to humidity Complex design
Optical	Reliable Large sensing range High repeatability High spatial resolution Immunity to EMI	Bulky Non-conformable Processing power requirements

TABLE 1: Relative advantages and disadvantages of transduction techniques [1-3]

	Instance	Sensitivity	Range	Det. Limit	Response time	Sensor Spacing	No of taxels
Capacitive	[7]	1.2 kPa^{-1}		<0.8 Pa	36 ms		
	[6]	6.583 kPa^{-1} $(0-100$ Pa) 0.125 kPa^{-1} $(100-1000$ Pa)		3 Pa	48 ms	1 mm	5 x 5
	[5]	0.815 kPa^{-1}	50 N		38 ms		4 x 4
	[4]	50 mN (shear force) (2N) 190 mN (normal force) (8N)				3 mm	2 x 2
Piezoresitive	[8]	11.60–1108.75 kPa^{-1}	600 kPa	40 Pa	$<$ 60 ms		1
	[9]	516.74 kPa^{-1}		24.5 Pa			1
	[10]	$16.9-5.41$ kPa^{-1} (<300 Pa) $>$ 0.5 kPa^{-1} (1300 Pa)			<10 ms		6 x 8
	[11]	0.23 kPa^{-1}	6.7 kPa		200 ms		1
Piezoelectric	[14]	14.93 pC/N (x axis) (0-0.5 N) 14.92 pC/N (y axis) $(0-0.5$ N) 6.62 pC/N (z axis) $(0-1.5$ N)				8 mm	3 x 2
	[12]	$0.578-0.821$ V/N					1 x 3
	[13]	430 mV/N	2 N				1
Strain gauges	[15]	0.12 V/N	100 N	0.3 N			1
	[16]	4.9×10^{-5} Pa^{-1} $(0-380$ kPa) 1.66×10^{-4} Pa^{-1} $(380-930$ kPa)	930 kPa	6.25 Pa			1
	[17]	0.0229 Ω kPa^{-1}	2000 kPa	14 kPa			1
Inductive	[20]	9.22 %/N	1.4 N				1
	[18]	1.25 nH/kPa	150 kPa	30 Pa			1
	[19]	2.9 nH/N (normal force) 17.4 nH/N (x-axis) 15.3 nH/N (y-axis)					2 x 2
Optical	[21]	0.08 N	0.5 N				1
	[22]	$2.2-4.5$%/N					4x4

TABLE 2: Figure of merit of state-of-art tactile sensors

References

[1] Chi C, Sun X, Xue N, Li T, Liu C. Recent Progress in Technologies for Tactile Sensors. Sensors (Basel). 2018;18(4):948. Published 2018 Mar 22. doi:10.3390/s18040948

[2] Girão P, Ramos P, Postolache O, Miguel Dias Pereira J. Tactile sensors for robotic applications. Measurement. 2013;46(3):1257-1271. doi:10.1016/j.measurement.2012.11.015

[3] Tiwana M, Redmond S, Lovell N. A review of tactile sensing technologies with applications in biomedical engineering. Sensors and Actuators A: Physical. 2012;179:17-31. doi:10.1016/j.sna.2012.02.051

[1, 2, 3] - Review of tactile sensing technologies including principle of operation, merits and challenges.

[4] Charalambides A, Bergbreiter S. A novel all-elastomer MEMS tactile sensor for high dynamic range shear and normal force sensing. Journal of Micromechanics and Microengineering. 2015;25(9):095009. doi:10.1088/0960-1317/25/9/095009

Description of the development of a capacitive tactile sensor for both shear and normal force sensing.

[5] Li T, Luo H, Qin L et al. Flexible Capacitive Tactile Sensor Based on Micropatterned Dielectric Layer. Small. 2016;12(36):5042-5048. doi:10.1002/smll.201600760

Description of development of a capacitive tactile sensor on a flexible substrate.

[6] Niu H, Gao S, Yue W, Li Y, Zhou W, Liu H. Highly Morphology Controllable and Highly Sensitive Capacitive Tactile Sensor Based on Epidermis/ Dermis Inspired Interlocked Asymmetric Nanocone Arrays for Detection of Tiny Pressure. Small. 2019;16(4):1904774. doi:10.1002/smll.201904774

Description of the development of a capacitive tactile sensor based on human skin characteristics for small pressure detection.

[7] Wan Y, Qiu Z, Hong Y et al. A Highly Sensitive Flexible Capacitive Tactile Sensor with Sparse and High-Aspect-Ratio Microstructures. Adv Electron Mater. 2018;4(4):1700586. doi:10.1002/aelm.201700586

Description of the development of a micropatterned PDMS based capacitive tactile sensor.

[8] Wu C, Zhang T, Zhang J et al. A new approach for an ultrasensitive tactile sensor covering an ultrawide pressure range based on the hierarchical pressure-peak effect. Nanoscale Horiz. 2020;5(3):541-552. doi:10.1039/c9nh00671k

Development of a piezoresistive tactile sensor using a novel approach based on the HPP effect presenting ultrahigh sensitivity and an ultrahigh pressure range.

[9] Chen L, Feng J, Li T, Li X, Zhang J. High-Tactile Sensitivity of Piezoresistive Sensors With a Micro-Crack Structure Induced by Thin Film Tension. IEEE Electron Device Letters. 2019;40(9):1519-1521. doi:10.1109/led.2019.2927720

Development of piezoresistive tactile sensor with enhanced sensitivity due to thin-film tension induced micro-cracks.

[10] Sun X, Wang C, Chi C, Xue N, Liu C. A highly-sensitive flexible tactile sensor array utilizing piezoresistive carbon nanotube–polydimethylsiloxane composite. Journal of Micromechanics and Microengineering. 2018;28(10):105011. doi:10.1088/1361-6439/aaceb9

Development of piezoresistive tactile sensor array using a nanotube-PDMS composite.

[11] Liu X, Zhu Y, Nomani M, Wen X, Hsia T, Koley G. A highly sensitive pressure sensor using a Au-patterned polydimethylsiloxane membrane for biosensing applications. Journal of Micromechanics and Microengineering. 2013;23(2):025022. doi:10.1088/0960-1317/23/2/025022

Development of piezoresistive pressure sensor by Au deposition on PDMS membrane with high sensitivity achieved due to strain induced micro-cracks.

[12] Acer, M., Yildiz, A. and Bazzaz, F., 2017. Development of a soft PZT based tactile sensor array for force localization. 2017 XXVI International Conference on Information, Communication and Automation Technologies (ICAT),.

Development of a ceramics piezoelectric sensor array for force measurement and localization.

[13] Maita, F., Maiolo, L., Minotti, A., Pecora, A., Ricci, D., Metta, G., Scandurra, G., Giusi, G., Ciofi, C. and Fortunato, G., 2015. Ultraflexible Tactile Piezoelectric Sensor Based on Low-Temperature Polycrystalline Silicon Thin-Film Transistor Technology. IEEE Sensors Journal, 15(7), pp.3819-3826.

Development of an ultraflexible piezoelectric sensor in a piezo-eletricoxide-semiconductor FET configuration with enhanced piezoelectric properties.

[14] Yu, P., Liu, W., Gu, C., Cheng, X. and Fu, X., 2016. Flexible Piezoelectric Tactile Sensor Array for Dynamic Three-Axis Force Measurement. Sensors, 16(6), p.819.

Development of piezoelectric tactile sensor array with ability to measure normal and shear forces with good sensitivity.

[15] da Silva, J., de Carvalho, A. and da Silva, D., 2002. A strain gauge tactile sensor for finger-mounted applications. IEEE Transactions on Instrumentation and Measurement, 51(1), pp.18-22.

Development of strain gauge tactile sensor for finger force measurement.

[16] Kwak, Y., Kim, W., Park, K., Kim, K. and Seo, S., 2017. Flexible heartbeat sensor for wearable device. Biosensors and Bioelectronics, 94, pp.250-255.

Development of a flexible strain gauge flexible sensor for application in heartbeat monitoring in wearable device, with good sensing range and detection limit.

[17] Manjunath, M., Nagarjuna, N., Uma, G., Umapathy, M., Nayak, M. and Rajanna, K., 2018. Design, fabrication and testing of reduced graphene oxide strain gauge based pressure sensor with increased sensitivity. Microsystem Technologies, 24(7), pp.2969-2981.

Development of a strain gauge tactile sensor where the effect of temperature is nullified and which presents a high sensitivity and a wide sensing range

[18] H. Wang, M. Totaro and L. Beccai, "Development of Fully Shielded Soft Inductive Tactile Sensors," 2019 26th IEEE International Conference on Electronics, Circuits and Systems (ICECS), Genoa, Italy, 2019, pp. 246-249, doi: 10.1109/ICECS46596.2019.8964922.

Development of inductive tactile sensor which doesn't suffer effects of EMI and uses same material for sensing and EM shielding.

[19] Yeh, S. and Fang, W., 2019. Inductive Micro Tri-Axial Tactile Sensor Using a CMOS Chip With a Coil Array. IEEE Electron Device Letters, 40(4), pp.620-623.

Development of an inductive tactile sensor using a simple aproach based on polymer encapsulation.

[20] Yeh, S., Chang, H. and Fang, W., 2018. Development of CMOS MEMS inductive type tactile sensor with the integration of chrome steel ball force interface. Journal of Micromechanics and Microengineering, 28(4), p.044005.

Development of an inductive tactile sensor using a simple aproach based on polymer encapsulation but wuaing a steel ball as the sensing interface.

[21] E. Fujiwara, F. D. Paula, Y. T. Wu, M. F. M. Santos, E. A. Schenkel and C. K. Suzuki, "Optical fiber tactile sensor based on fiber specklegram analysis," 2017 25th Optical Fiber Sensors Conference (OFS), Jeju, 2017, pp. 1-4, doi: 10.1117/12.2263454.

Development of an optical fiber-based tactile sensor.

[22] Sartiano, D. and Sales, S., 2017. Low Cost Plastic Optical Fiber Pressure Sensor Embedded in Mattress for Vital Signal Monitoring. Sensors, 17(12), p.2900.

Development of simple optical fiber-based sensor array embedded in matrix for vital signal monitoring.

[23] Nancy S. Giges, “Smart Robots for Picking Fruit”, American Society of Mechanical Engineers (ASME), May 2013, https://www.asme.org/topics-resources/content/smart-robots-for-picking-fruit

[24] Wang, X., Xu, T., Dong, S., Li, S., Yu, L., Guo, W., Jin, H., Luo, J., Wu, Z. and King, J., 2017. Development of a flexible and stretchable tactile sensor array with two different structures for robotic hand application. RSC Adv., 7(76), pp.48461-48465.

Development of a capacitive tactile sensor based on 2 different structures that provide great flexibility proved to distinguish objects with different characteristics.

[25] Ribeiro, P., Khan, M., Alfadhel, A., Kosel, J., Franco, F., Cardoso, S., Bernardino, A., Schmitz, A., Santos-Victor, J. and Jamone, L., 2017. Bioinspired Ciliary Force Sensor for Robotic Platforms. IEEE Robotics and Automation Letters, 2(2), pp.971-976.

Development of ciliary structure magnetic force sensors (collaboration between INESC and ISR-Robotics)

[26] T. Paulino et al., "Low-cost 3-axis soft tactile sensors for the human-friendly robot Vizzy," 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017, pp. 966-971, doi: 10.1109/ICRA.2017.7989118.

Development of GMR-based magnetic sensor for robotic hand application (collaboration between INESC and ISR-Robotics)