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Multidirectional hemispherical dielectric elastomer proximity sensor for collision avoidance in Human-Robot Interaction applications

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ABSTRACT

Nowadays, several industrial manufacturing processes imply direct cooperation between human operators and robots. This increases production and quality while improving the working conditions. However, the possible presence of physical contact between humans and robots asks for the study and introduction of new technical solutions that aim at guaranteeing a safe Human-Robot Interaction (HRI). Specifically, in recent years, different sensing devices have been developed for collision avoidance monitoring in HRI applications. Generally, common solutions consist of distributed resistive or capacitive sensors networks connected to a central electronic reading board, resulting in a cumbersome layout covering the whole parts of the collaborative robots. In this context, this paper presents an innovative tactile and proximity sensing strategy based on a soft-sensor module that can be installed on the collaborative robot parts or surrounding workspace. The developed module consists of a capacitive sensor based on a silicone elastomer membrane with compliant electrodes attached to the surface, disposed homogeneously on a deformable hemisphere-shape made of silicone. Thanks to the geometrical layout, such a sensor allows multidirectional objects detection resulting in a promising non-invasive solution for collisions avoidance in HRI applications. This work reports the design, manufacturing, and preliminary experimental investigation of such a sensor module, evaluating the electrodes geometry and the most relevant features that optimize objects detection distance and directivity sensing performance.

Keywords: Human Robot Interaction, Dielectric Elastomer Sensor, proximity capacitive sensing

1. INTRODUCTION

In recent years, the introduction of collaborative robots in industrial sectors has paved the path for applications of Human Robot Interactions (HRI), improving the experience and performance of the workers by combining the operators' problem-solving skills with the efficiency provided by a robot in a shared workspace. However, HRI applications imply several strict safety restrictions to prevent harmful contact between robots and human operators must occur. This requirement leads to the need for sensing systems that can accurately monitor the relative position and movement of human operators with respect to the collaborative robots, which have to be able to activate safety protocols or an appropriate control in case of a hazardous situation occurrence and avoid unwanted contacts.

In order to enable HRI and resolve these safety issues, several sensing methodologies have been proposed in the scientific literature or as commercial solutions to detect the presence of human operators in the proximity of the robot. A first direct approach that does not need additional sensing equipment uses the measurements of the encoders and the torque sensors of collaborative robots to detect contacts with the environment[1]. Another conventional solution consists of vision monitoring systems[2], which allows monitoring the HRI in the shared workspace between operators and machines to avoid dangerous situations, but this also present some drawbacks. For example, it requires redundant fail-safe solutions to avoid that some parts of the workspace do not appear visible by the camera because of some obstacles, so it needs to use several cameras in parallel to guarantee that there are no occlusions. In addition, the effectiveness of visual methods can be diminished depending on the lighting conditions, making it more difficult to detect the human operator and/or the robot links and to estimate their mutual distance.

An alternative approach for collision avoidance in HRI consists of coating the external surfaces of the collaborative robot links and joints with sensing skin, i.e., a sensing layer capable of measuring the human presence in a proximity range. This kind of sensor is usually based on electrical transduction enabled by reading the rate of change of a specific electrical

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property of the sensor, such as the resistivity or capacitance. This sensor typology is generally used for touch and force sensor measurement[3,4] proximity detection[5,6], or a combination of the previous[7,8].

A promising technology for assembling these thin-layer devices for touch and proximity detection and collision avoidance in HRI applications are the Dielectric Elastomer Sensors (DES), which are electrostatic devices usually composed of a highly elastic dielectric elastomer membrane coupled with compliant electrodes, forming a deformable capacitor[9]. The electrodes can be easily bonded to the elastomeric membrane in several layouts, e.g., with parallel electrodes on the opposite sides of the DE surfaces or in an interdigitated disposition on the same side of the DE substrate[10]. Thanks to their advantages, such as a straightforward manufacturing and assembly process of their components made of affordable and low-cost soft materials, these types of sensors represent a promising solution as capacitive monitoring sensing layer for touch and proximity detection of HRI applications. Some examples of DESs employed for collision avoidance with collaborative robots as a wrapping membrane on the robot links can be found in[11] with a covering matrix layer of out-of-plane design DESs.

However, these sensors are usually conceived as coating membranes to be placed on the outer surfaces of a robot's links, which becomes a limitation if there are only small scattered areas to be monitored, not only on the robot but also in the workspace. Furthermore, since the most common fabrication process DES technology involves methods of 2D molding of the electrodes onto the DE substrate[12,13], the device often consists of a capacitive sensor encapsulated in a thin-layer planar structure, limiting the effectiveness of the contact proximity measurements in various directions relative to the normal to the sensor plane.

In this context, we propose an innovative solution that can address these issues and limitations by introducing the Hemispherical Dielectric Elastomer proximity Sensor (HDEPS), i.e., a modular sensing unit that can be arranged in cluster sensors to detect and prevent human-robot collisions over large workspace areas.

The HDEPS is obtained by assembling two main components: a DES membrane and a highly deformable hemispherical soft structure, and it demonstrated multiple advantages as detecting objects in all the areas surrounding the hemisphere, and a soft-compliant mechanical behavior in case of contact occurrences, thus avoiding generating high forces and behaving like a bumper.

In this work we present an efficient fabrication process in terms of complexity and assembly methodologies and a preliminary experimental analysis of an HDEPS of relevant sizes, testing both which electrode shape is most appropriate and its performance in comparison with an equal but planar structure of the sensor. The result of the analysis allowed us to validate the concept of the proposed sensor, discussing its ability to measure proximity in a multidirectional manner in HRI application.

The article is organized as follows: Section 2 introduces the sensor model to account for the geometric deformation of the electrodes when the DES membrane is homogeneously stretched and disposed on the hemisphere structure; Section 3 describes the manufacturing and assembly of the HDEPS; Section 4 illustrates the test bench, the experimental procedure and the results of the tests; Section 5 reports the conclusions with an overall summary of this preliminary study.

2. SENSOR MODELLING

2.1 HDEPS geometrical model

The HDEPS is a device conceived to monitor the human presence that is small in size and can be distributed in a modular manner onto the most critical points of a robot or directly in selected workspace spots where the HRIs may occur. All of this without being invasive and ensuring soft contact in the case of direct interaction with the sensor. However, to keep the sensor design and fabrication methodology as simple as possible, the proposed device essentially consists of a membrane DES homogeneously placed on the hemispherical structure.

Therefore, for this work, it was required to define a geometric model to account for the electrode arrangement as a result of homogeneous deformation of the DES membrane when placed on a structure, moving the system layout from a 2D configuration into an out-of-plane one. Thanks to the proposed design based on a hemispherical, symmetric, and regular geometry, this goal was achieved by drawing inspiration from the reduced model for diaphragm deformations of dielectric elastomer generation devices[14]. Considering an elastomeric membrane of incompressible material with an annular electrode printed on it, as shown in Figure 1, the material points of these components can be described with respect to the reference center by the polar coordinates defined by a radius R and an angle of rotation φ. When this membrane is deformed into a hemispherical shape, it is possible to reconstruct the spatial position of the material points of the sphere through the reduced model of the equi-biaxial spherical diaphragm deformation[14]. The new positions will thus be defined by the same rotation angle φ, a radial coordinate r, and the height z, as schematically represented in Figure 1-b and c. For example, it can be shown that the spatial coordinates of the material points of the membrane described for each angle φ and radial coordinate R disposed on a hemispherical shape of radius R_H, are:

$$\begin{cases} r = \dfrac{2R_H^2 R}{R_H^2 + R^2} \\ z = \dfrac{R_H\left(R_H^2 - R\right)}{R_H^2 + R^2} \end{cases}. \tag{1}$$

Hence, it is possible to reconstruct the position of the electrodes that are printed in 2D and then set in the hemispherical out-of-plane shape, as in the example shown in Figure 1-b, c, and d. In this work, this model has been used to preliminarily identify the shape of the electrodes geometries once deformed on the base structure of the HDEPS.

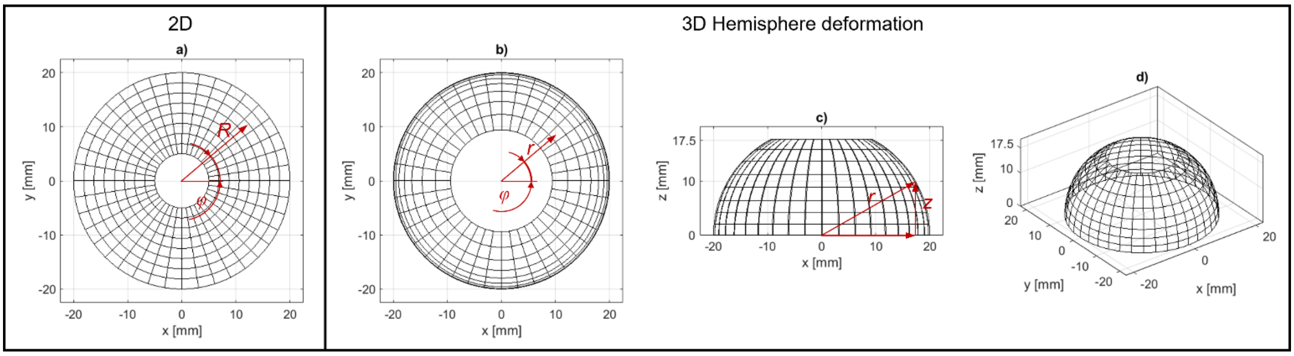

Figure 1. Representations of the planar (a)) and hemispherical (b), c) and d)) structures. The mesh represents an example of the electrode's material points, showing how the 2D membrane is deformed out-of-plane into a 3D hemispherical shape.

2.2 HDEPS electrodes and shape design

The preliminary experimental analysis presented in this work had the aim to evaluate the performance of the HDEPS with respect to two main parameters: the shape of the electrodes and the effectiveness of having an out-of-plane hemispherical structure compared to a fully planar system.

In order to measure the proximity of contact in multiple directions, it was chosen to have four distinct electrodes disposed as separate annular sectors with internal radius r_i = 5 mm, external raius r_e = 20 mm and separated by a gap g =3 mm, with a connection line of thickness c_w = 5 mm for the reading electronics, as represented in Figure 2-a. This electrode's layout has been compared with an identical one but with each single electrodes defined only by a contour of thickness t_{el} = 3 mm, as a hollow annular sector. These two layouts can be depicted in Figure 2-a, namely for the full and hollow electrodes configuration.

To complete the evaluation of the HDEPS design, the sensor's performance was tested with a hemispherical structure of outer radius R_H = 20 mm, compared to a fully planar one, for each of the two electrode configurations. These two structural configurations, planar and hemisphere, respectively, are shown schematically in Figure 2-b.

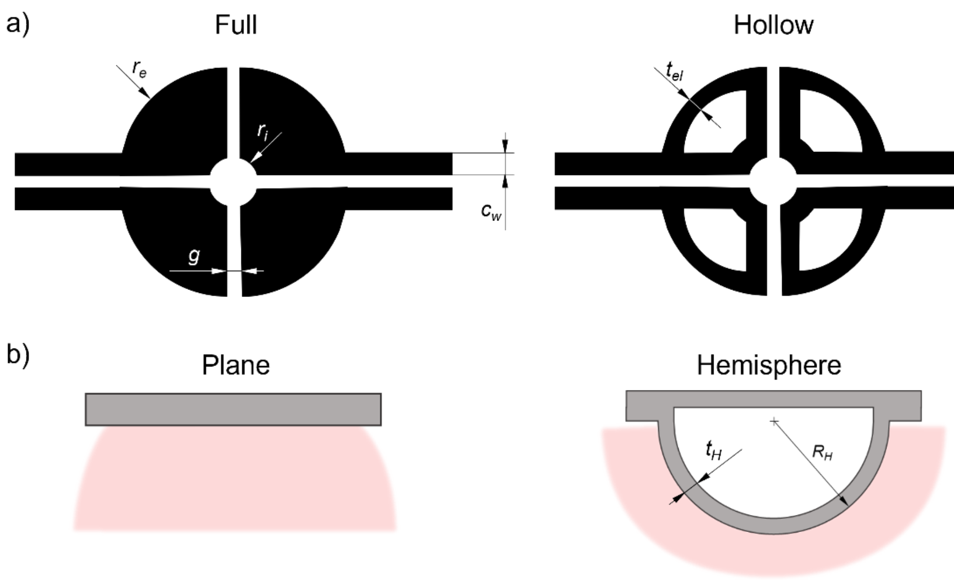

Figure 2. Design schematization of the electrodes and structure compared in this work. In a) the two different electrodes geometries. In b) the two structures.

3. FABRICATION PROCESS

This section outlines the manufacturing process and the assembly steps of the components composing the HEDPS, i.e., the DES membrane and the flexible hemisphere structure. For both, the choice of material, the fabrication methods, and the main passages for their coupling are presented. Such a process is schematically reported in Figure 3.

3.1 Manufacturing process

Both components of the HDEPS, i.e., the elastomeric membrane with the compliant electrodes on one surface and the hemispherical structure, require mechanical properties of high deformability. Indeed, the membrane needs to be stretched and disposed on the structure homogeneously, and the final device must be highly flexible when it comes into contact with an object in HRI operations. Therefore, the base material for all the components is a highly deformable elastomeric Polydimethylsiloxane (PDMS), with the electrode consisting of a mixture of Carbon black (CB) powder and a PDMS compound to conceive conductive electrical properties.

The electrode recipe consists of 12 g of Wacker ELASTOSIL® RT 625 and 0.8g of CB powder PRINTEX® XE2 B BEADS-ORION, all diluted in 15 g or IPA solvent. Such a compound is then blade-cast on a Polytetrafluoroethylene (PTFE) substrate, for both electrode configurations of Figure 2-a, following the manufacturing process and the time steps reported in [10]. The electrodes are attached through Saratoga sealing silicone on a Wacker ELASTOSIL® film 2030, a PDMS membrane with 100 µm thickness, posed onto a Polyethylene terephthalate (PET) substrate, as can be depicted from Figure 3-a. The manufacturing process of this component ends with a laser cut on the side of the PET substrate to remove it and leave the membrane-free, leaving only a circular PET ring to support the membrane handling and coupling on the hemispherical structure.

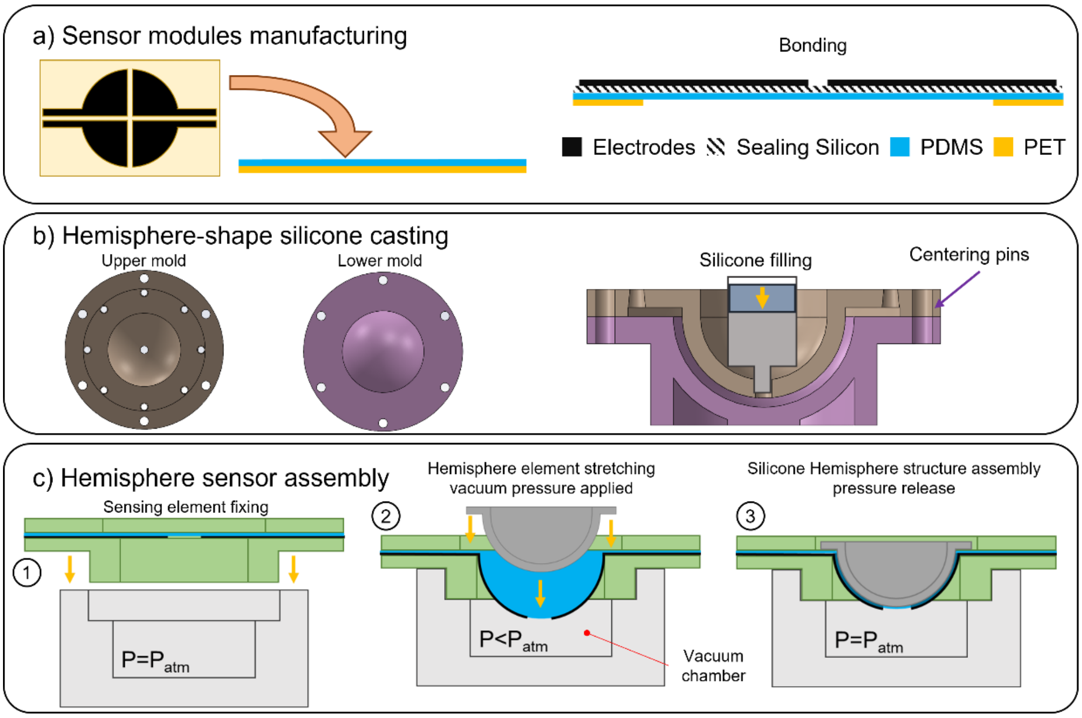

Figure 3. Schematic representation of the main manufacturing and assembly process steps: a) sensing element manufacturing process; b) Hemisphere-shape silicone casting process; c) Hemisphere-shape silicone assembly with sensing element.

Concerning the flexible hemispherical PDMS structure, this has been obtained through a casting process of Dragon Skin 30 PDMS, mixed as reported in [10], in a resin mold SLA obtained with the 3D printer Formlabs Form 2. This mold is composed of two parts centered using two centering pins and screwed with 6 M4 bolts, as represented in Figure 3-b. When assembled, these form a hemispherical cavity of thickness t_H = 2 mm, in which it is possible to pour the silicone from a casting hole placed at the center of the upper mold, in which a syringe pushes the PDMS until it evacuates from the foundry sprues. After a curing time at 60°C for 4 hours, the PDMS hemispherical structure is completely cured, the mold and the syringe are disassembled, and the residual appendices (from foundry sprues and syringe filling hole) are removed with a cutter.

3.2 HDEPS assembly procedure

The last step for the fabrication of the HDEPS is to assemble the silicone membrane, coupled with the compliant electrodes and the hemispherical silicone structure. Therefore, it was necessary to find an appropriate methodology to deform the membrane homogeneously and then fix it on the external surface of the structure. The best strategy to respect this constraint is to generate a homogeneous depression force acting on the membrane when placed as an interfacing layer between an atmospheric pressure environment P_{atm} and a lower pressure chamber, P. The assembly process is reported in Figure 3-c, and it is divided into three main steps:

1. The vacuum chamber is closed hermetically with the membrane component, after blocking it between two rigid supports made of Polymethyl methacrylate (PMMA), profiled with a laser cutter machine Epilog® Laser Fusion M2 - 75 W, Figure 3-c.

2. The chamber pressure P is manually adjusted with a vacuum pump (Rocker 300) such that $P<P_{atm}$, deforming the membrane as a diaphragm and thus creating space for the insertion of the hemispherical structure, Figure 3-c.

3. Finally, the structural component is inserted into the clearance space, and the pressure P is regulated in order to have $P=P_{atm}$, releasing the membrane homogeneously on the outer surface of the hemisphere, which was previously covered by Saratoga sealing silicone, Figure 3-c.

In this context, a total of four devices have been fabricated, one for each of the configurations defined as in Figure 2, respectively:

- With full electrodes on the planar (FP) or hemispherical (FH) structure layouts;
- With hollow electrodes on the planar (HP) or hemispherical (HH) structure layouts.

The overall schematical configurations and the four manufactured HDEPS devices are reported in Figure 4. As can be noticed, all the obtained devices are attached to a PMMA frame comprised of a threaded M6 insert in order to be able to connect the electrodes to the reading electronics via copper plates attached to a PMMA backplate, ensuring the electrical connections mechanically. The measured internal radius r_i of the FH and HH devices results respectively equal to 7 and 8 mm, which are slightly different from the expected one of 9.4 mm, computed via equation (1). This difference must be pointed to manufacturing process inaccuracies, e.g., the electrode's influence on the membrane deformation. The real radius of the silicone hemispherical structure, which is 19.75 mm, its deformation during the assembly phase, and the membrane relief cause discrepancies in the real r_i obtained. It is worth mentioning that in the computation of r_i of the hemisphere, the membrane thickness is neglected. Even though the manufacturing process issue, the resulting sensor modules turn out with acceptable accuracy.

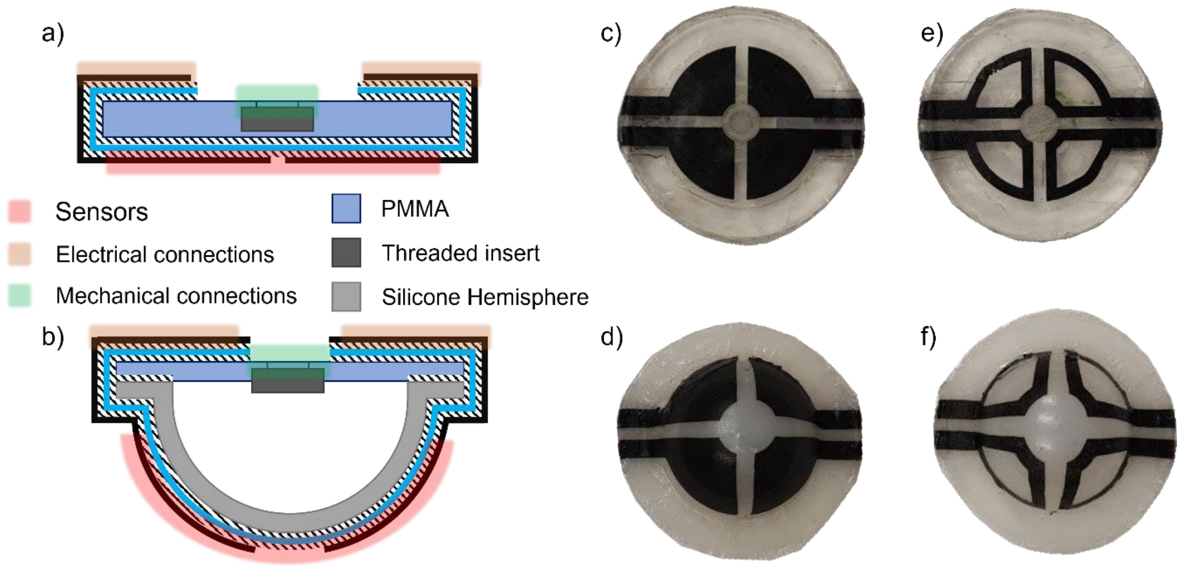

Figure 4. Schematic representation of planar a) and hemisphere b) sensors. Manufactured sensors: c) FP d) FH, e) HP and f) HH.

4. EXPERIMENTAL VALIDATION

This section reports the results of the experimental campaign for the four described sensor layouts (HP, FP, HH and FH). The objective of the tests is to assess if the sensors can detect obstacles in their proximity, considering the increase in the capacitance read. Two types of tests have been implemented, vertical and horizontal: in the first case, it is verified if the sensor can detect an object placed beyond itself, while in the second case, the area of interest is the one surrounding the sensor, thus checking if the hemispherical geometry provides better directionality information compared to the traditional planar geometry. In the following two paragraphs, a brief description of the test bench and the experimental procedures is presented, then the results of vertical and horizontal tests are shown and discussed

4.1 Test bench description

In this work, the two test typologies, i.e., vertical and horizontal, have been conducted using the seven-degree-of-freedom Franka Emika Panda robotic arm, with a six-axis force/torque sensor (FTE-AXIA80-DUAL SI-200-8/SI-500-20) mounted on the last link of the arm in series to a custom clamp where the HDEPS can be mounted. The force/torque sensor measures the force exchanged with the sensor when in contact with another object as a body in HRI applications. A ProtoCentral FDC1004 breakout board, connected to an Arduino Nano, performs the capacitance reading of the HDEPS. This board can read the capacitance of up to four channels connected to the electrodes of the HDEPS.

The tests are made with two connection configurations: each electrode connected to respective channels and the other with all electrodes short-circuited and connected to only one channel.

An L-shaped conductive plate made of brass and connected to the ground is used to simulate the human body's response to capacitive sensing. Thus, the robot can approach it vertically or horizontally.

Therefore, the channel measurement is nothing else than the capacitance value between the ground and the electrode (or electrodes) of the HDEPS. All the data from the robot, the force/torque sensor, and the capacitance board are read and saved on a workstation PC.

A view of the test bench is presented in Figure 5.

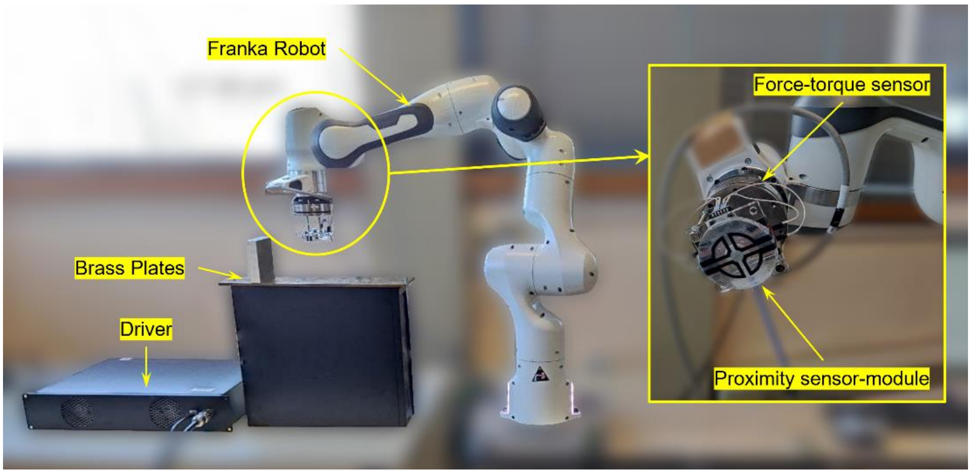

Figure 5. Experimental setup for the planar and hemispherical DEPS validation

4.2 Test procedure

Whether the test direction is vertical or horizontal, the testing procedure consists of the following steps:

1) Move the end effector to a position close to the desired initial position for the test under consideration and oriented with the manufactured device (FP, FH, HP, or HH) facing downwards.

2) Manually move the end effector to the initial position for the test under consideration (see Figure 6), using the manual guidance functionality provided by the robot. The definition of the initial position depends on the direction of the test (vertical/horizontal) and the geometry of the sensor (planar/hemispherical), as shown in Figure 6: for vertical tests with planar sensors, the initial position is when the surface of the sensor adheres to the horizontal plate (Figure 6-c); for vertical tests with HDEPS the initial position is when the sensor touches the horizontal plate (Figure 6-e); for horizontal tests with planar sensors, in the initial position the edge of the vertical element of the conductive L-shaped structure is tangent to the electrodes (Figure 6-d); for horizontal tests with HDEPS the edge of the wall is placed at the base of the hemisphere tangent to the electrodes (Figure 6-f).

3) For vertical tests, move the end effector 10 cm in the positive *z*-direction. For horizontal tests, move the end effector in the *z* and y-direction, since these tests are performed at different heights with respect to the initial position to check directionality. Let *h* be the height of the test and $Distance_{max}$ the length of the testing path (10 cm). Then, when the tested sensor is planar, the end effector is moved *h* in the positive *z*-direction and *d* in the positive *y*-direction; instead, when the tested sensor is hemispherical, the end effector is moved *h* in the positive *z*-direction and $Distance_{max} – (R_H – R_H\cos(\arcsin(h/R_H)))$ in the positive *y*-direction.

4) Move the end effector in the negative *z*/*y* direction depending on whether the test is vertical or horizontal at a constant speed (0.001 m/s) while recording the data from the manufactured sensing modules and the force/torque sensor. Horizontal tests are stopped once the end effector has moved 10 cm in the negative *y*-direction. Vertical tests, instead, are stopped when one of the two following conditions occurs: 1) the end effector has moved 10.5 cm in the negative *z*-direction; 2) the measured force in the *z*-direction from force/torque sensor has exceeded 40 N.

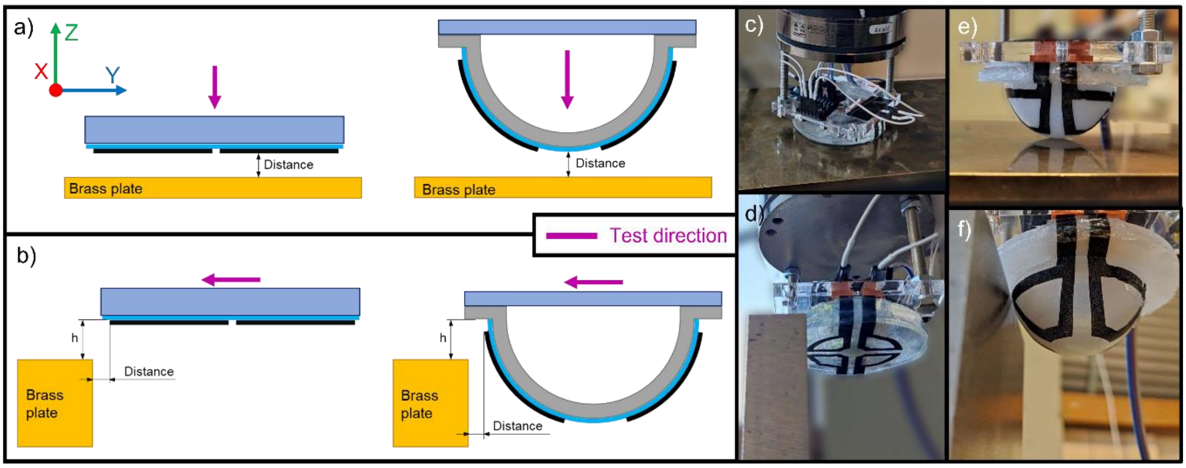

Figure 6. a) Schematic representation of the initial test position of vertical tests. b) horizontal. c) picture of initial position for planar sensor vertical test. d) planar sensor horizontal test. e)HDEPS vertical test. f) hemispherical horizontal test.

4.3 Results vertical test

In this section, the results of vertical proximity tests are presented. The plots show the value of the capacitance as a function of the distance from the obstacle. It has to be remarked that the offset capacitance that is measured when the sensor is far from any external object is subtracted from the actual measurement.

Figure 7 shows the results of vertical tests for all four sensor types (FP, FH, HP, or HH). The tests were performed with both the four-channel and the one-channel connection configuration. The zero distance indicated in the plots corresponds to the contact point. The following observations can be made:

- The capacitance measurement observed for planar sensors is higher with respect to HDEPS due to the more extensive coverage of the four electrodes in a parallel position to the brass plate. However, the increase in the measured capacitance value for the HDEPS is relevant and allows the detection of an object.
- As expected, the four channels show approximately the same capacitance because the sensing electrodes are at the same distance from the conductive plate while approaching it; there are only some differences due to manufacturing imperfections
- There is not a significant difference between the hollow and the full sensors.
- With the one-channel connection, the measured capacitance is significantly higher both for planar and for hemispherical sensors since a higher area of the overall electrode connected to a single channel of the reading electronics

Moreover, a test was conducted with a human hand instead of a conductive plate to assess the brass plate's equivalence with the human body for the HRI applications. Therefore, the results of two vertical tests, one with a human hand and one with a conductive plate, were compared. Since the outcomes are very similar (green line and dashed line of the plot relative to the FP sensor in Figure 7), it can be concluded that the grounded conductive structure is a good approximation of the human body and can be used for all the tests.

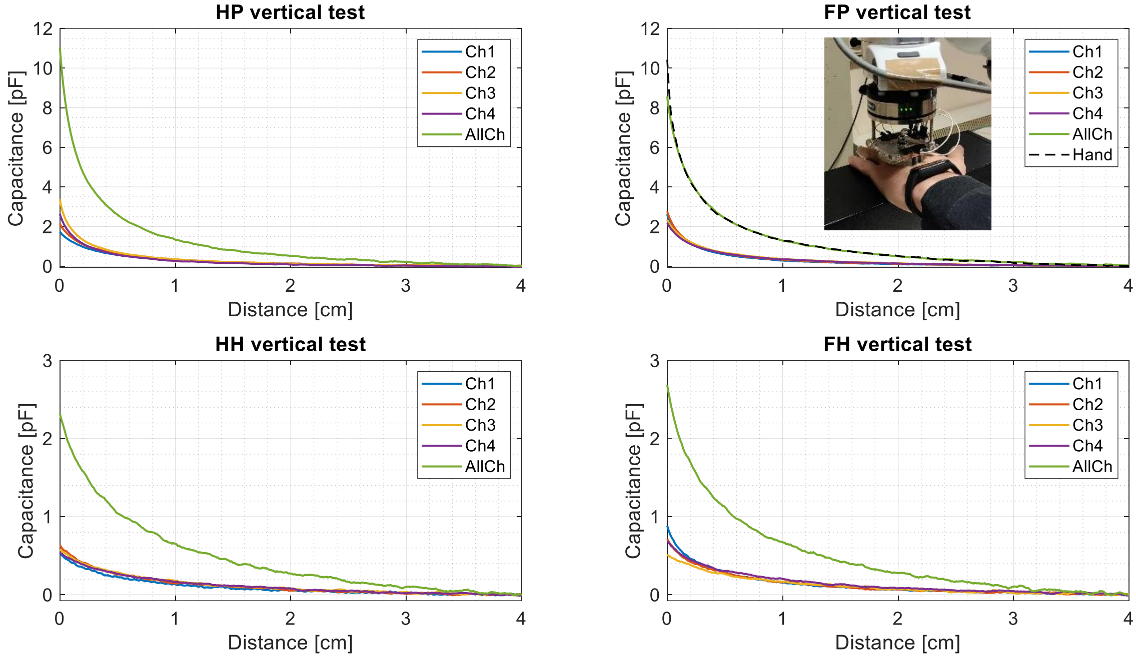

Figure 7. Results of vertical tests in four channels and one-channel connection configurations. The initial position for the test with the human hand is shown in the FP vertical test plot

4.4 Results horizontal test

In this section, the results of horizontal proximity tests are presented, showing the results in Figure 8, only with the four-channels configuration. For the tests with planar sensors, the zero distance indicated in the plots corresponds to the initial position as shown in Figure 6, while for the tests with HDEPS, the zero distance corresponds to the contact point between the conductive structure and the hemispherical surface. Moreover, only the measurements data relative to the two electrodes approaching the conductive structure are shown because the other two are null. The tests are performed at multiple heights in the *z*-direction as defined in section 4.1: in particular, 3 mm, 5 mm, 10 mm, 15 mm, and 17.5 mm. The following observations can be made:

- The planar sensors can detect an object only if it is very close in the *z*-direction. Indeed, at a distance of 1 cm, the capacitance value is already negligible, as can be depicted in Figure 8, which shows a decrement in sensor performance of the planar shape sensors for all the tested heights.
- On the contrary, the HDEPS can detect obstacles in the whole area surrounding the hemisphere, as represented in Figure 2. The increase in the capacitance value of the HH e FH sensors is almost equal for all the heights, as can be noticed from Figure 8, which shows a similar performance of the HDEPS for all the tested heights.
- The highest distance at which tests were performed is 17.5 mm, because this is the maximum height of the electrodes in the *z*-direction on the hemispherical out-of-plane structure, corresponding to the *z* value calculated from (1) for the internal radius r_i of the electrodes and schematically reported in Figure 1-c.
- There is no relevant difference between hollow or full electrodes.

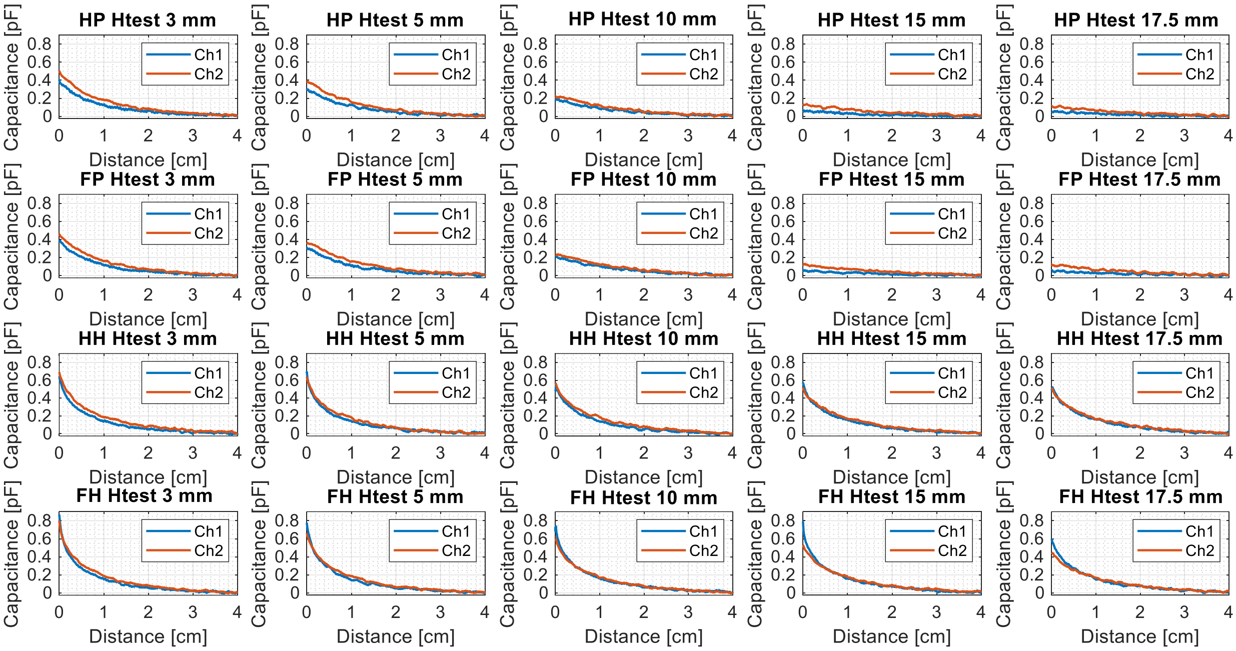

Figure 8. Results of horizontal proximity tests

4.5 Discussion

From the previous results, it can be concluded that the HDEPS show a suitable performance for capacitive proximity detection. The directionality of the sensor depends on the coverage area of the electrode contour. Indeed, the planar geometry best detects objects located beyond the sensor. HDEPS can still detect an object approaching vertically, though less prompt and reliable detection. On the other hand, planar sensors cannot detect an object approaching laterally, unless it is very close. Another important conclusion is that hollow electrode geometries should be preferred over full electrodes geometries since the latter require more material without providing any noticeable improvement in the capacitance value when approaching the conductive structure.

A characteristic of HDEPSs that makes them suitable for HRI application is that their silicone hemisphere is soft and compliant, and as a result, if contact happens, the generated forces are relatively small. Thus, this type of sensor can be used as a proximity and contact detection bumper. In this regard, Figure 9 shows the force applied by the robot on the plate after a contact happens during vertical tests. The plots show the value of the force along the *z*-direction. Like for the vertical tests shown in Figure 7, the zero position is the contact position between the plate and the sensor, which corresponds to the initial position set with the manual guidance functionality of the robot. Data are also shown for negative distances because the vertical tests are stopped when either the end effector has moved 10.5 cm in the negative *z*-direction (i.e., when the distance is -0.5 mm with respect to the zero position) or the force measured in the *z*-direction with the force/torque sensor has exceeded a threshold of 40 N. The first condition is met during the test with the HDEPS. In contrast, the second occurs with the planar sensor device (the threshold is reached at 2.35 mm after the contact position).

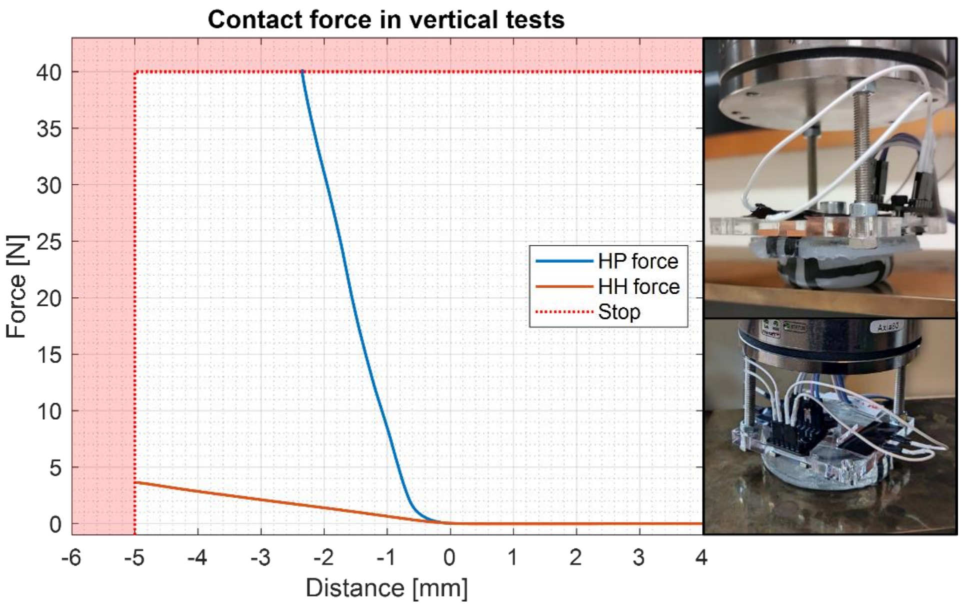

Figure 9. Contact forces in vertical tests: planar sensor stops 1.35 mm after the contact because it reached the threshold force of 40 N; hemispherical sensor stops 5 mm after the contact. The pictures on the right of the plots show the compressed sensors at the end of the contact force tests.

5. CONCLUSION

This work proposes an innovative sensor concept for robot proximity detection in human-robot interaction (HRI) applications. The proposed device, namely the Hemispherical Dielectric Elastomer Proximity Sensor (HDEPS), consists of a dielectric elastomer membrane coupled with compliant electrodes and homogeneously disposed on a soft hemispherical structure, capable of multidirectional object detection and suitable for HRI applications. A straightforward manufacturing process is developed and presented, and four different sensor configurations are produced: with full and hollow annular sector electrode layouts and a planar or hemispherical structure (HDEPS). These devices are mounted on a robotic arm capable of freely moving them on the testbench, conducting an experimental campaign to assess their performance. The experimental results of all tests show that the HDEPS manages to detect conductive objects in its proximity and acts like a soft bumper for collision events, demonstrating low interaction force at contact. In conclusion, the HDEPS shows to be a suitable sensing device for HRI applications, to be placed on the links or joints of the robot or directly on specific spots around the workplace where hazardous conditions for human safety can occur. Future work will focus on improving the manufacturing process and scaling down the device dimensions to allow a modular HDEPS distributed network capable of monitoring the surrounding environment in HRI applications.

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