

A Flexible Piezoresistive/Self-Capacitive Hybrid Force and Proximity Sensor to Interface Collaborative Robots

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Abstract—Force and proximity sensors are key in robotics, especially when applied in collaborative robots that interact physically or cognitively with humans in real unstructured environments. However, most of the existing sensors for use in robotics are limited by: 1) their scope, measuring single parameters/events and often requiring multiple types of sensors; 2) being expensive to manufacture, limiting their use to where they are strictly necessary and often compromising redundancy; and 3) have null or reduced physical flexibility, requiring further costs with adaptation to a variety of robot structures. This article presents a novel mechanically flexible force and proximity hybrid sensor based on piezoresistive and self-capacitive phenomena. The sensor is inexpensive and easy to apply even on complex-shaped robot structures. The manufacturing process is described, including controlling circuits, mechanical design, and data acquisition. Experimental trials featuring the characterization of the sensor were conducted, focusing on both force–electrical resistance and self-capacitive proximity response. The sensor’s versatility, flexibility, thinness (1-mm thickness), accuracy (reduced drift), and repeatability demonstrated its applicability in several domains. Finally, the sensor was successfully applied in two distinct situations: hand-guiding a robot (by touch commands) and human–robot collision avoidance (by proximity detection).

Index Terms—Force-sensing resistor (FSR), force sensor, hybrid, piezoresistive sensor, proximity sensor, robotics.

I. INTRODUCTION

ADVANCED robots increasingly require more sensors to perceive their surroundings. Robot sensors are key to safe and intuitive human–robot interaction as well as robot autonomy. It is often the case, however, that existing conventional sensors

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do not fit specific robots or application requirements. Conventional sensors are often unable to detect events of interest either due to insufficient scope, accuracy, and/or robustness in working conditions. For example, vision sensors are constrained by light and suffer from occlusions. Other sensors may have excessive latency or limited repeatability. Frequently, researchers and engineers look for hybrid single-sensor devices that can measure a wide scope of variables to detect events of interest, while being easy to install on a robot’s structure (or in its surroundings). These sensors are, most often, not available. Existing devices frequently require costly alterations to reach hybrid integrated solutions, and they are usually not mechanically flexible, which further hampers their integration on structures with complex geometries.

The robotics and artificial intelligence markets are rapidly growing, and sensors have a leading role in their success [1]. Sensors become particularly important in a context where robots operate in more unstructured environments, often requiring interaction with humans. Tactile/force and proximity sensing are much-desired features for robot safety and interaction [2]. The ISO/TS 15066 standard for collaborative robot safety significantly depends on the capability to detect the presence of humans or objects within the robot’s surroundings, mainly for speed and separation monitoring [3]. In this context, hybrid force and proximity sensors, particularly ones that are easy to install on pre-existing robot systems, become extremely desirable.

This article proposes a novel mechanically flexible and self-adhesive piezoresistive/self-capacitive hybrid force and proximity sensor that is both inexpensive and easy to apply even on complex-shaped surfaces. The development process is described here step by step, including design, manufacturing, complementary circuitry, and signal processing. Experiments featuring sensor characterization were conducted, focusing on both its piezoresistive and self-capacitive operation modes. Finally, the proposed sensor is demonstrated in two distinct situations: 1) hand-guiding a robot (by touch commands) and 2) collision avoidance (by proximity detection). The contributions of this article are as follows:

- 1) a novel piezoresistive/self-capacitive hybrid force and proximity sensor;
- 2) the sensor’s structure is mechanically flexible and self-adhesive making it easy to install even on complex-shaped structures;

- 3) the sensor and its complementary circuitry are easy to manufacture, highly scalable, and inexpensive (the manufacturing process is explained here step by step);
- 4) the sensor provides reasonable accuracy and repeatability concerning force and proximity measurements. The presence of a human hand is detected at distances up to 100 mm away from an 8-cm² sensor, while the minimum detectable force is 0.5 N and the single point repeatability is about 11%;
- 5) the sensor's versatility, flexibility, and accuracy demonstrated its potential as an interface for collaborative robots.

A. Related Work

Dual-mode sensors (capacitive and inductive) have demonstrated the ability to measure tactile pressure of up to 330 kPa and sense proximity with a good spatial resolution (3 mm) at distances of up to 150 mm [4]. More recently, a dual proximity sensor combining the principles of inductive and capacitive proximity sensing was demonstrated, although with no pressure sensitivity [5]. Our proposed sensor requires significantly less complex signal processing and complementary hardware than those presented in both [4] and [5], albeit featuring a lower proximity resolution (30 mm). A soft force-sensing resistor (FSR) sensor capable of three-axial force measurements has been presented with interesting results, but is incapable of proximity detection [6]. Recent research has also shown the potential of using commercially available FSRs for proximity sensing, taking advantage of the electrodes already present in the FSR to perform capacitive proximity sensing [7]. A method for eliminating blind areas in piezoresistive sensor arrays has been presented, with moderate success [8]. A tactile sensor for smart prosthetics, based on giant magnetoimpedance material has shown very interesting results [9]. Its scalability, however, may be limited, and proximity detection is not featured. Smart conductive textiles are increasingly used in wearable electronics. Proximity measurements have been demonstrated by measuring the electrostatic capacity in conductive flexible fabrics [10]. Recently, conductive elastomers have been studied to address the challenges of sensing deformable soft structures [11]. Printable and stretchable elastic conductors, with initial conductivity of up to 738 S · cm⁻¹, have been shown to endure up to 215% strain while maintaining a conductivity of 182 S · cm⁻¹ [12]. Programmable sensor networks have been integrated modularly in the form of a tape (flexible electronics substrate) [13], achieving considerably higher precision than our proposed sensor. Our solution is, however, over 200 times less expensive (by area), easier to manufacture, and easier to scale. In a recent study, contact forces and proximity were measured by arrays of proximity sensors in flexible printed circuit boards embedded in silicone [14]. A robot skin composed of modularized hexagonally shaped cells is proposed in [15]. Each cell includes a set of sensors reporting vibrations (3-D accelerometer), pressure (three capacitive force sensors), pretouch (optical proximity sensor), and temperature (two temperature sensors). This skin has a wider scope than our proposed solution (which cannot measure neither

temperature nor acceleration). Once again, both [14] and [15] achieve higher resolutions particularly in the proximity detection, but with limited mechanical flexibility and manufacturing costs two to three orders of magnitude higher than the sensor proposed in this article. Electrostatic ultrathin flexible pressure sensors were successfully demonstrated in health-monitoring applications, such as breathing monitoring [16] and finger manipulation monitoring [17]. Flexible pressure sensors based on organic-transistor-driven active matrices have shown great potential in the past two decades. Features ranging from optical transparency and bending insensitivity [18] to simultaneous pressure and temperature mapping [19] have been demonstrated with promising results. All these solutions are significantly more complex to manufacture, although low-cost production should be achievable through high-volume production processes.

B. Background and Design Principles

When a conductive material is deformed, electrical resistance across it changes. Volume resistivity is often considered constant, making electrical resistance solely a function of geometric dimensions. This is the underlying principle behind various sensors, such as resistive strain gauges [20]. However, semi-conductive polymer composites, such as Caplinq's Lingstat or 3M's Velostat, behave differently. They feature a suspension of conductive filler particles randomly dispersed in a nonconductive polymeric matrix. Under strain, those particles move closer together in random movements known as micro-Brownian motion [21] [see Fig. 1(a)]. This effect increases the number of contacting particles, creating more paths for electricity to flow through. Simultaneously, noncontacting particles become, on average, separated by shorter distances, elevating the number of electrons tunneling through the nonconductive matrix between them [22]. Both the mechanisms contribute to a great reduction of the material's electrical resistivity under strain.

Proximity sensors are usually based on optical, ultrasonic, or capacitive technology. We were aiming for a thin, highly scalable, and flexible sensor, so both the ultrasonic and optical solutions were considered impractical. The self-capacitance phenomenon was deemed adequate to meet our design criteria. In Fig. 1(b), a simple *RC* circuit is shown, where, after an initial transient period, a steady state is reached. The potential across the capacitor's terminals opposes the power supply voltage, and, at that point, no electric current flows through the circuit. A similar circuit may be considered [see Fig. 1(c)], where after a certain time, both the power supply and the capacitor will also tend to reach symmetric potentials. The resistor *R*, wired in series, increases the transient period (note that the time constant is directly proportional to the circuit's resistance). Consider now a third circuit [see Fig. 1(d)], in which electrostatic energy is stored not inside a capacitor, but in an electric field created between an electrode and a nearby conductive surface, such as a human hand. Two digital pins in a microcontroller board are connected to the ends of the circuit. The first pin is turned high (+5 V, in case of an Arduino Uno), and the second pin is set to input (without pull-up). A counter variable is incremented in a loop until the potential reaching the second pin triggers a high state

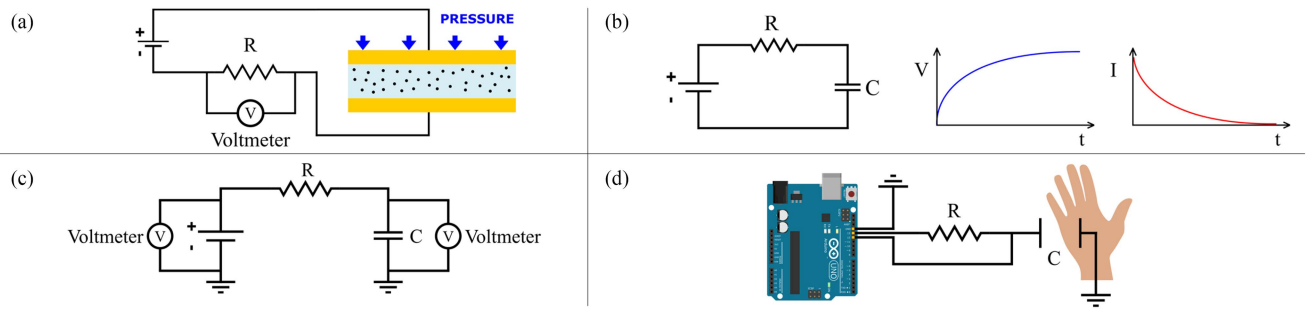


Fig. 1. (a) Compression of a semiconductive polymer. (b) Resistor–capacitor (RC) circuit. (c) RC circuit with common ground. (d) Self-capacitive proximity sensing circuit.

(at around 2.5 V). The final value of this counter variable will be directly proportional to the circuit's time constant and, in turn, to the circuit's capacitance (considering R to be constant). Higher resistance values increase the transient period, allowing for more sensitive measurements at the expense of longer response times. Capacitance is inversely proportional to the distance between the hand and the electrode, but it can no longer be determined by the parallel capacitor formula as a plethora of other variables become involved (skin conductivity, air humidity, interference from the surrounding environment, etc.). Voltage measurements are also dependent on the reference ground values, which may vary. This method is relatively imprecise for distance measuring, but it enables reliable human presence detection, is easy to implement, and requires only basic hardware, while also being highly scalable.

II. PIEZORESISTIVE/SELF-CAPACITIVE SENSOR

A. Design

The development of the proposed piezoresistive/self-capacitive hybrid sensor was driven by the following design goals:

- 1) easy and inexpensive manufacturability, with minimal specialized tooling;
- 2) good tactile resolution;
- 3) Force sensing range of up to 15 N;
- 4) human presence detection at distances up to 100 mm;
- 5) mechanical flexibility and reduced thickness.

Two sensor variants were developed: one featuring an FSR array with 16 prexels (i.e., unitary pressure-sensitive elements) of 48 mm^2 each, arranged in a 2×8 configuration, and a second higher resolution one, featuring 64 prexels of 81 mm^2 each, arranged in an 8×8 configuration. The blind area of each sensor can be practically eliminated by design (ensuring short distances between adjacent prexels) or by the application of the connected structure-based method presented by Wang [8]. We made our sensors compatible with Wang's method by designing a continuous layer of piezoresistive material (see Fig. 2). The area of each prexel was made similar to that of the tip of a human finger, ensuring adequate spatial resolution for tactile robot control (8.8-mm periodicity in the 8×8 version). A final design consideration was the area of the self-capacitive electrode to guarantee effective proximity detection. The maximum

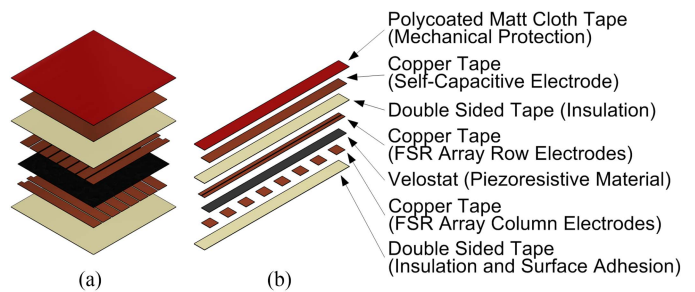


Fig. 2. Exploded view of the sensor's elements. (a) 64-prexel variant. (b) 16-prexel variant.

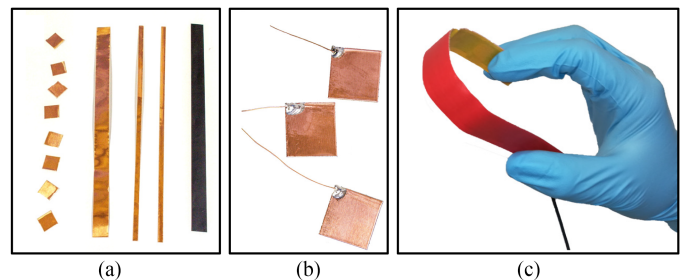


Fig. 3. (a) Copper electrodes and Velostat strip. (b) Detail of solder connections. (c) Assembled 16-prexel sensor.

detectable distance should be in the order of the size of the electrode. We implemented an 8-cm^2 electrode in the 64-prexel sensor, aiming for our goal of 100-mm proximity detection range.

B. Manufacturing

The manufacturing process is composed of nine steps, including assembly of all the sensor's elements (see Fig. 2). These steps are presented here for the 16-prexel variant, being analogous for the 64-prexel one.

- 1) Copper tape and Velostat pieces were cut to form the sensor's internal elements. These include eight prexel column electrodes, two prexel row electrodes, one Velostat layer, and one self-capacitive copper electrode [see Fig. 3(a)].
- 2) Enamelled copper wires were soldered to each copper electrode [see Fig. 3(b)]. It is important to avoid the flow of solder to areas that will be in direct contact with the

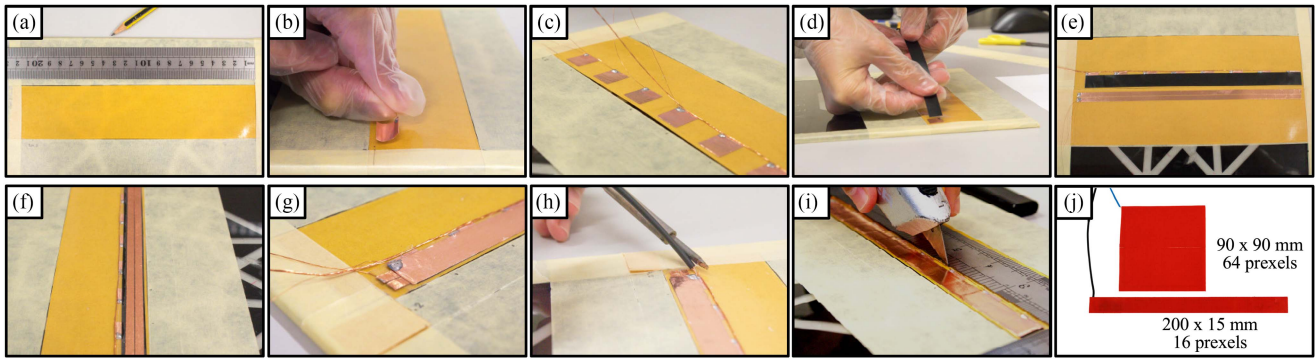


Fig. 4. (a) Base layer. (b) Gluing the column electrodes of the FSR array. (c) Wire management (twisted and glued to the base layer beneath). (d) Semiconductive polymer installation. (e) Lower and upper halves of the FSR array, before assembly. (f) Completed FSR array. (g) Self-capacitive electrode. (h) Heat shrink tube installation. (i) Cutting the sensor assembly to final dimensions. (j) Completed sensors.

semiconductive polymer. Solder build-ups outside those areas should also be kept to the bare minimum, as they will create pressure concentration zones and promote layer separation, decreasing the sensor's low-pressure sensitivity through a sharp increase in the electrical contact resistance between layers. Finally, all the copper parts were thoroughly cleaned with isopropyl alcohol, both before and after the soldering process.

- 3) To make the sensor's base layer, a strip of double-sided tape was unrolled on top of a flat surface with its adhesive side up and held in place with strips of painter's tape. We used a pencil to mark the measurements [see Fig. 4(a)].
- 4) The eight column electrodes were glued to the base layer [see Fig. 4(b)]. Their enameled wires were also twisted and glued to the base layer beneath [see Fig. 4(c)]. All the wires must be inside the sensor's design dimensions.
- 5) The Velostat layer was laid on top of the eight column electrodes [see Fig. 4(d)]. It is essential to ensure proper insertion at the first attempt. Unsticking and relocating the polymer may result in contamination of its surface with adhesive residues.
- 6) A second strip of double-sided tape was placed on the workbench with its uncovered sticky side up. This will be the sensor's middle insulating layer, separating the FSR array's row electrodes from the self-capacitive electrode. After appropriate measurements, both array's row electrodes were glued in place [see Fig. 4(e)];
- 7) The middle insulating layer, with the two previously installed electrodes, was placed on top of the Velostat layer and the lower cover of the adhesive was removed [see Fig. 4(f)].
- 8) The self-capacitive electrode was then installed, and all the wires were arranged as flat as possible to reduce the risk of layer delamination [see Fig. 4(g)]. A heat shrink tube was installed to provide further insulation and surface protection to the enameled wires [see Fig. 4(h)].
- 9) The sensor was cut to shape and covered with its final layer of polycoated matt cloth tape, which will provide surface protection [see Fig. 4(i)]. The fully assembled prototype is shown in Fig. 4(j).

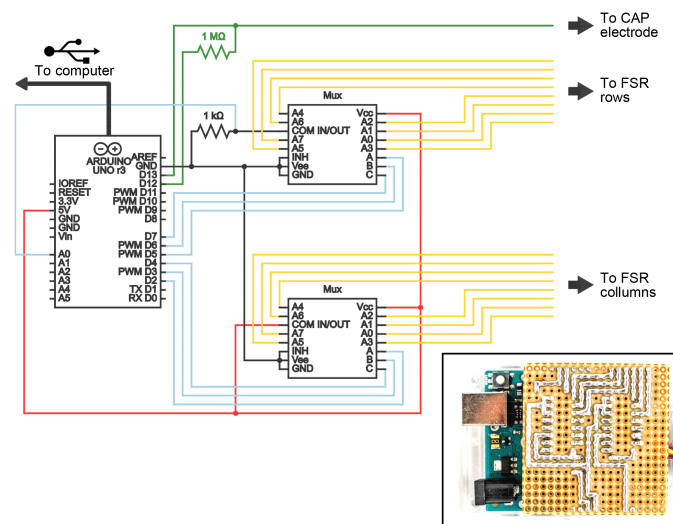


Fig. 5. DAQ circuit diagram (center) and assembled DAQ system (right).

C. Data Acquisition System

The data acquisition system (DAQ) is composed of three main components:

- 1) a custom-made Arduino shield;
- 2) the Arduino itself, which runs the sensor's transfer functions and communicates with an external serial client;
- 3) an external computer, which receives sensor data and interfaces with the robot's controller.

The shield, circuit in Fig. 5, features two 3-bit multiplexers (STMicroelectronics M74HC4051) to address the column–row pairs in the FSR array. This enables a maximum array size of $2^3 \times 2^3 = 64$ prexels. Higher bit multiplexers will enable exponentially larger sensor arrays. We used a voltage divider circuit with a reference resistor of $1\text{ k}\Omega$ to measure the electrical resistance across each prexel. A $1\text{-M}\Omega$ resistor, connected between the sending and receiving pins of the proximity sensing circuit, allows for adequate proximity sensitivity.

The Arduino (Uno) was used to: 1) establish the connection to the serial client; 2) measure the transient period of the self-capacitive circuit (and apply a transfer function to determine

the approximate distance in millimeters); 3) address both the multiplexers to connect to each prexel in the FSR array; 4) measure voltage drop across each prexel, calculate corresponding resistance, and apply a transfer function to determine the force being applied; 5) send all the values to the serial client; and 6) return to point 2).

Self-capacitance measurements were performed using the algorithm developed by Paul Badger and released to the public domain in the form of the Arduino “CapacitiveSensor” Library (version v0.4) [23]. In short, a counter variable is first set to zero. Then, the send pin is set to high (+5 V) and the counter is incremented in a loop until the self-capacitive electrode’s potential reaches +2.5 V, causing the receive pin’s state to turn high. This charge cycle is then repeated a predefined n number of times to smooth out high-frequency noise (we found $n = 70$ to be appropriate), with the counter variable being further incremented in each cycle. The increment frequency of the counter variable was determined to be $f = 270$ kHz, so each unitary counter value corresponds to approximately $3.7 \mu\text{s}$. The counter’s final value is then used as a relative measure of transient time and, thus, a relative measure of capacitance, according to

$$C = \frac{-\Delta t}{R \times \ln(1/2)} = \frac{-\text{counter}}{n \times f \times R \times \ln(1/2)} \quad (1)$$

where C is the capacitance, Δt is the transient period, R is the value of the resistor connected in series with the self-capacitive electrode, n is the number of charge cycles, and f is the frequency at which the counter variable is incremented during each charge cycle. Every time someone approaches the sensor, its self-capacitance increases, resulting in higher transient times and thus higher counter values.

Finally, an external computer was used to receive real-time data from the Arduino using a MATLAB-based platform, allowing for simultaneous real-time robot motion control using the KUKA Sunrise Toolbox (KST) [24].

III. SENSOR CHARACTERIZATION AND EXPERIMENTS

A comprehensive theoretical approach for FSR modeling was proposed in [25]. However, it requires advanced material analysis techniques, which may be inaccessible to some researchers. For that reason, we propose an empirical approach. The characterization of the self-capacitive proximity response was achieved using a semiempirical model. Table I details some of the main specifications and characteristics of the sensor.

A. FSR Empirical Model

1) *Force–Electrical Resistance*: The force–electrical resistance relationship was evaluated using a compression test stand designed for the purpose (see Fig. 6). It features a rubber pressure test tip designed to closely emulate the area and pressure distribution of a human finger touching the sensor. In the first experiment, the sensor was subjected to forces ranging from 0 to 15 N in step increments of approximately 0.4 N. The resulting values of electrical resistance were recorded and plotted in Fig. 7. The test was repeated six times at an average room temperature of 25 °C. Operation at higher temperatures will increase the sensor’s force

TABLE I
SENSOR SPECIFICATIONS AND CHARACTERISTICS

Parameter	Value
Size of tactile elements	$4 \times 12 \text{ mm}^2$
Thickness	1 mm
Minimal detectable force (force sensing)	0.5 N
Single point repeatability (at 8.1 N)	11.3%
Static loading (relative to measured force)	6.1% (after 3 h)
Drift (3 h at a constant force of 8.1 N)	5.8% per log(min)
Presence detection range (proximity sensing)	0–100 mm
Hysteresis (force sensing)	15%
Rise time (force sensing)	34.5 ms
Delay time (force sensing)	4.8 ms
Sensitivity (force sensing)	$1.38 \times 10^{-4} \text{ S/N}$
Precision (force sensing)	7%
Resolution (force sensing)	0.07–2.3 N

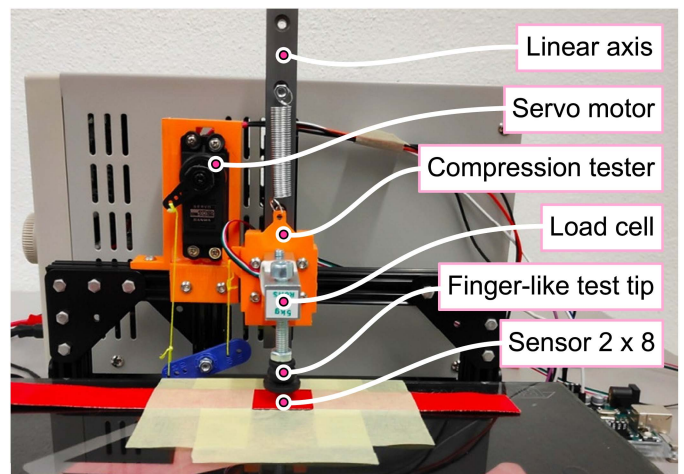


Fig. 6. Experimental setup of the force–electrical resistance compression/hysteresis test.

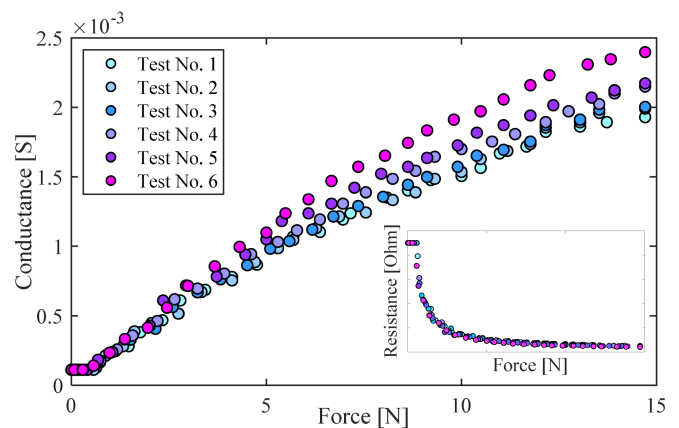


Fig. 7. Measured electrical conductance and electrical resistance.

sensitivity, due to the softening of the piezoresistive polymer layer. This phenomenon was not modeled in this article, and no significant variation was observed in the 18–25 °C range. The sensor is expected to endure operation at temperatures ranging from –50 up to 80 °C, according to specifications provided by the manufacturers of both the piezoresistive layer (3M) and the adhesive tapes forming the sensor’s structure (Advance Tapes).

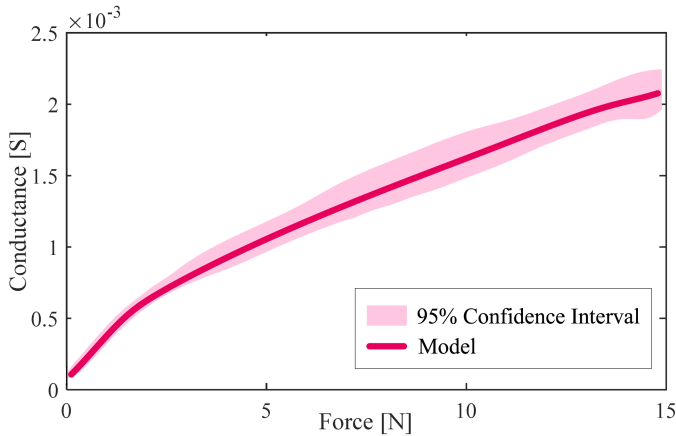


Fig. 8. Force–conductance FSR model with 95% confidence intervals.

Force–conductance data show an approximately linear behavior, making linear regressions a good solution to obtain simple and computationally inexpensive empirical models. There are, however, some pointwise exceptions consistent to all six recorded datasets. These deviations occur mainly due to the layer delamination caused by manufacturing imperfections inside the sensor. To account for these deviations, high-degree polynomial regressions can be used to better fit the force–conductance data. Choosing between linear and higher degree regressions requires a balance between computational cost and model accuracy. In addition, as expected, the sensor proved to be inaccurate when subjected to forces lower than 0.5 N, mainly due to the delamination phenomena. Small pockets of air get between the semi-conductive polymer and the electrodes inside the sensor, creating an unpredictable increase of contact electrical resistance. We did not take these low force/conductance values into consideration in our model, as they represent an unpredictable behavior and were considered nonsignificant data. For our specific model, a high-degree polynomial was fitted to the average force–conductance values across all the six tests, and the standard deviations for each point were calculated. Confidence intervals of 95% were also calculated, assuming that multiple measures of the same force follow a normal distribution (see Fig. 8).

2) *Signal Drift*: In a second experiment, a constant force was applied during a 3-h test, to determine the sensor’s signal drift. The data resulting from this test show an asymptotic decrease in electrical resistance over time (see Fig. 9). Velostat’s electrical resistance is mostly a function of material strain. This explains why the graph in Fig. 9 shows a similar behavior to the stress–time graph of a viscoelastic material undergoing stress relaxation. Such behavior can be modeled by a critically damped spring–damper system, whose position could be determined by

$$x(t) = (x_0 + (\dot{x}_0 + \omega_n x_0) \times t) \times e^{-\omega_n t} \quad (2)$$

where x_0 is the system’s initial position, \dot{x}_0 is the system’s initial velocity, and ω_n is the system’s natural angular frequency. Adapting (2) to model the signal drift of our sensor, we have

$$R(t) = (\Delta R + (A + B \times \Delta R) \times t) \times e^{-Bt} + R_0 - \Delta R \quad (3)$$

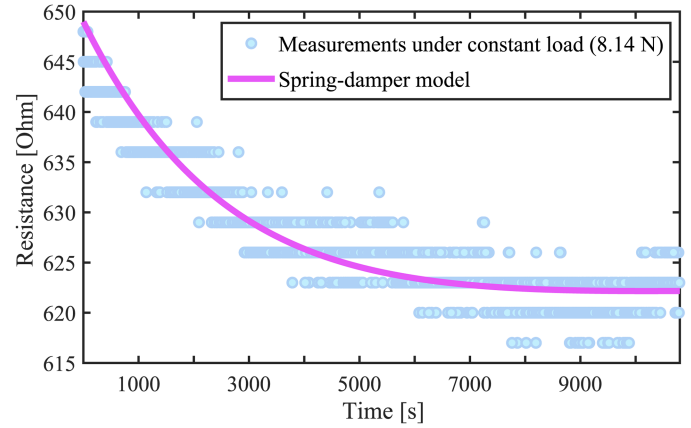


Fig. 9. Signal drift during a 3-h test and the spring–damper model.

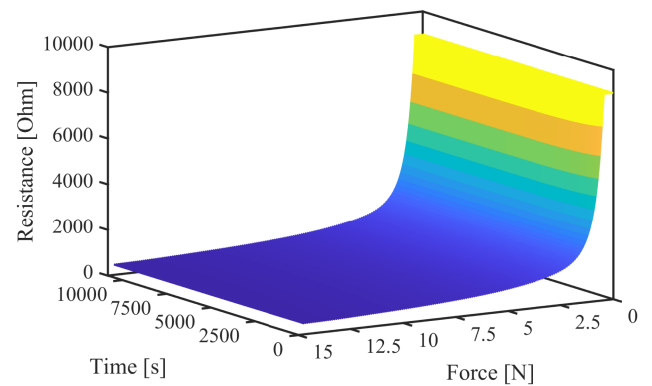


Fig. 10. Three-dimensional FSR model considering stress relaxation.

where R_0 is the initial electrical resistance, ΔR is the difference between the initial and final electrical resistance measured, and A and B are parameters that can be determined by a numeric method. The previous force–resistance and resistance–time models were then combined, generating a complete 3-D empirical model (see Fig. 10).

B. FSR Dynamic Response

1) *Hysteresis*: Using the same setup shown in Fig. 6, 16 load–unload cycles were performed with forces ranging from 0 to 15 N at a rate of approximately 0.7 N/s (see Fig. 11). Hysteresis errors ranged from 12% to 17%, averaging 15% across all 16 cycles. These values are in line with those of commercially available FSRs, suggesting that our sensor’s additional layers and capacitive electrode do not significantly affect performance.

2) *Step Response*: We have also evaluated the sensor’s response to a tactile step load. The inherent elasticity of either a human finger or the rubber test tip in the experimental setup would overshadow the sensor’s response delay, so a rigid 1.1-kg wooden sphere was used instead the rubber test tip. The sphere was rested on top of one prexel, with a nylon cable supporting part of its weight. Then, the cable was cut so that the whole weight of the sphere was applied to the sensor. Measured conductance–time data are shown in Fig. 12. As would

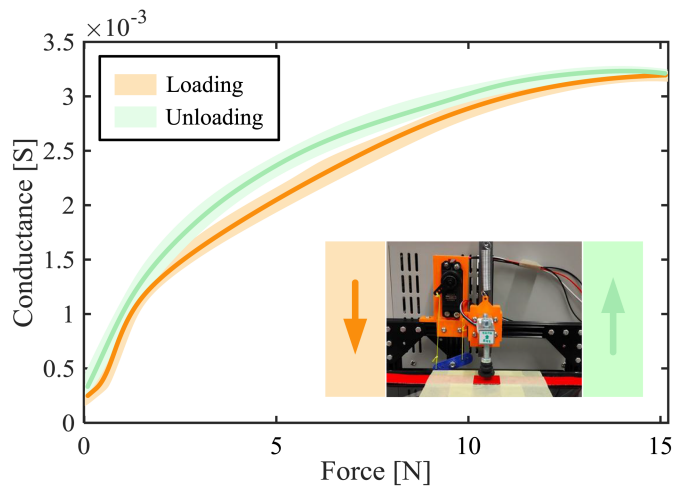


Fig. 11. Hysteresis curve during loading and unloading (16 cycles).

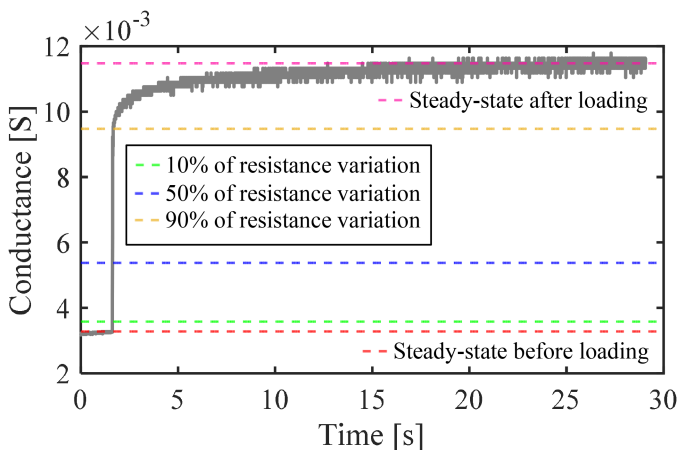


Fig. 12. Dynamic step response to point load.

be expected from any FSR, conductance values in Fig. 12 are significantly higher than the ones previously observed in Fig. 7. This is due to the higher pressure created from by the sphere's small contact area. The delay time (from 0% to 50% of the steady state value) is 4.8 ms and the rise time (from 10% to 90% of the steady state value) is 34.5 ms (see Table I).

C. Self-Capacitive Proximity Response

The 16-pxel ($15 \times 200 \text{ mm}^2$) sensor proved reasonably effective at detecting the presence of a human hand up to 50 mm away, while the larger 64-pxel variant ($90 \times 90 \text{ mm}^2$) could detect presence at 100 mm. Being hybrid sensors, featuring both the FSR and self-capacitive modes, they are able to distinguish between the presence and the touch of a human hand in their surroundings. As previously discussed, proximity readings start as a dimensionless time value, the counter. A semiempirical model will directly correlate this value with distance values, in millimeters. Three different experiments were conducted.

In the first experiment, both the sensors were placed on top of a nonconductive surface without any objects in close proximity. Proximity data were then recorded. This allowed us to determine a base value for each sensor. Results were an average counter

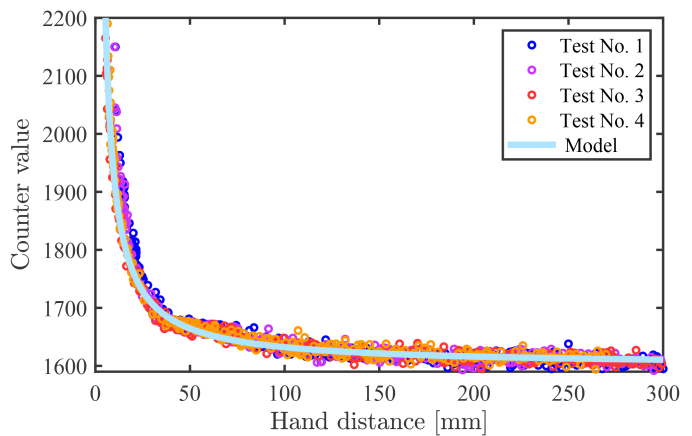


Fig. 13. Second experiment for the detection of a hand at different distances from the sensor. The hand is reliably detected at distances up to 100 mm.

value of 1486, with a standard deviation of 29 for the 16-pxel sensor, and 1610 with a standard deviation of 9.6 for the 64-pxel variant.

In the second experiment, a human hand gradually approached the 64-pxel sensor until physical contact was established. Real-time hand distance was recorded using an electromagnetic tracker (Polhemus Liberty), which is accurate within $\pm 0.5 \text{ mm}$. The whole process was repeated four times. Sensor counts plotted against tracker readings can be seen in Fig. 13. A sixth-order Butterworth low-pass filter with a cutoff frequency of 1 Hz proved effective at smoothing the signal, although higher cutoff frequencies may be required depending on specific application. The voltage across a charging capacitor can be determined by

$$V(t) = V_{\infty} \left(1 - \exp\left(\frac{-t}{RC}\right) \right) \quad (4)$$

where $V(t)$ is the voltage across the capacitor, V_{∞} is the applied voltage, and R and C are the circuit's resistance and capacitance, respectively.

From (4), it can be shown that the time necessary to reach a certain voltage across a capacitor is linearly dependent on its capacitance (i.e., the time constant $\tau \propto C$). In a parallel-plate capacitor, C is inversely proportional to the distance between electrodes. It is reasonable to assume that our sensor's self-capacitance is also inversely proportional to the hand's distance from it. Finally, the value of the counter variable is proportional to time, leading to

$$\text{counter} = n \times f \times \Delta t = \frac{a}{x} + b \quad (5)$$

where n is the number of charge cycles, f is the incrementing frequency of counter, Δt is the transient period, x is the distance from the hand to the sensor, b is the previously determined counter base value, and a is a calibration parameter that can be determined experimentally using sensor readings over known distances. Experiments showed $a \approx 2b$ to be a good first approximation. Fig. 13 shows the application of (5) to experimental data.

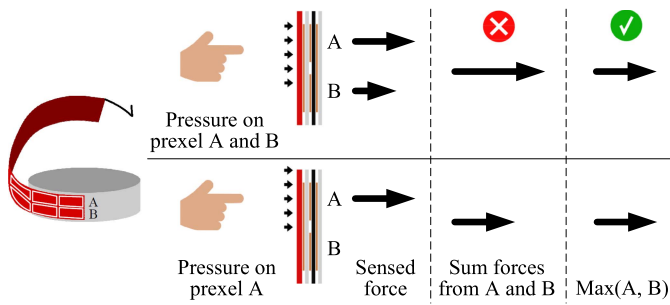


Fig. 14. For xy -axis robot commands, only the maximum forces sensed across all lines of each column of the FSR array are considered, to avoid accidental overmeasures.

The third and final experiment was similar to the second, but with several objects instead of a human hand approaching the sensor: a small anodized aluminium rod, an aluminium caliper, a steel hammer, and a 500-mL plastic water bottle (full). The sensor could not reliably detect the presence of any of these objects. This represents a limitation of the proposed sensor, but some interesting side effects arise: the sensor becomes capable of easily distinguishing the touch of a human hand from the touch of any of these objects, by comparing values between its piezoresistive and self-capacitive modes of operation.

IV. APPLICATION IN REAL ROBOTIC SYSTEMS

The sensor was applied in two distinct robotic case studies: guiding a robot by hand (using tactile commands) and human–robot collision avoidance (measuring hand proximity). Owing to its flexibility, the 16-prexel sensor was installed around the robot end-effector as if it was masking tape (see Fig. 14). The collaborative robot is a seven-degree-of-freedom KUKA iiwa R800 equipped with the Sunrise controller and interfaced using the KST Toolbox. Data were acquired from the sensor at 10 Hz for proximity readings and 100 Hz for tactile robot control.

A. Robot Hand Guidance

For the robot hand-guiding application, force-sensing measurements are acquired, treated, and transformed into robot motion commands, i.e., translations in Cartesian space. Proximity sensing was also used to trigger the robot hand-guiding control mode.

The 16-prexel sensor variant features a 2×8 FSR array with two rows (A and B) and eight columns (1, 2, ..., 8) (see Fig. 14). Each column of the array, when touched, triggers a corresponding robot motion in the xy Cartesian space. Each finger touching the sensor spreads the pressure between one or both rows in the array (A and B) (see Fig. 14). Only the maximum force, applied to prexel (A, n) or prexel (B, n) is considered. Adding forces sensed across both rows would result in overmeasures. The sensor's width (15 mm) ensures that at least one of the two prexels in each column is fully covered by the human finger. To hand guide the robot along the z -axis, we calculate the pressure difference between both rows of prexels. The human finger tends to touch the sensor in the center (the sensor's 15-mm width forces that scenario), leading

to an approximately equal pressure distribution between FSR array rows. When the hand tries to push the robot upward, or downward, an angular momentum is created between the skin's surface (where a traction force is applied) and the bone inside. This momentum changes the balance of pressures, which can be calculated and used to indicate the human's intention to move the robot end-effector along the z -axis. The sensor is calibrated by attaching a reference frame to its structure (matrix of prexels whose position is fixed and known). The relative position of each prexel is calculated in relation to the robot's local reference frame using homogeneous transformations. The sensor is stucked around the robot's tool flange in a known position and orientation relative to the robot's end-effector reference frame [see Fig. 15(b)].

The experimental test is shown in time lapse [see Fig. 15(b)]. The robot end-effector position along the x -axis is plotted against sensor force measurements in Fig. 16. This analysis along a single axis, x -axis in this case, facilitates the visualization and understanding of the system's behavior, which can be extrapolated to the other axes.

Five different users indicated that they found the hand-guiding process to be more intuitive than the traditional teach-in robot programming (using the teach pendant). Three users are researchers and two are project engineers, all of them with basic skills in robotics. They were informed that the robot's end-effector could be moved by simply pushing on its tool flange (where the sensor was installed), without further explanation. As the robot started to move, all the users intuitively pushed or pulled the robot flange in different directions, immediately and intuitively realizing how the system behaves/operates.

B. Human–Robot Collision Avoidance

In order to avoid human–robot collisions, the hand proximity to the robot was monitored using the sensor's self-capacitive operational mode. For this specific experimental test, the sensor was attached to the robot gripper in a relatively flat surface. Experiments demonstrated that it can be applied in various locations of the robot arm, in both flat and moderately curved surfaces, keeping an efficient monitoring. Fig. 15(c) shows that when the sensor detects a human hand in close proximity, a command is issued to the robot controller, immediately moving the robot to a safe predetermined position. The system latency is approximately 100 ms, and the maximum human–robot relative speed during the test was 60 mm/s. Fig. 17 shows the distance between the hand and the robot, measured by both the proposed sensor and an electromagnetic tracker (Polhemus Liberty), as well as the robot end-effector position. All data are unfiltered.

Results demonstrate that the sensor provides human–robot relative proximity data, and by this way, the robot reacts to avoid collision.

C. Sensor Robustness and Shortcomings

The sensor showed significant deviations (over 50%) on proximity measurements, when placed at less than 100 mm from the robot's actuators (while the robot was moving). Preliminary simulations show a vast reduction electrostatic potential behind

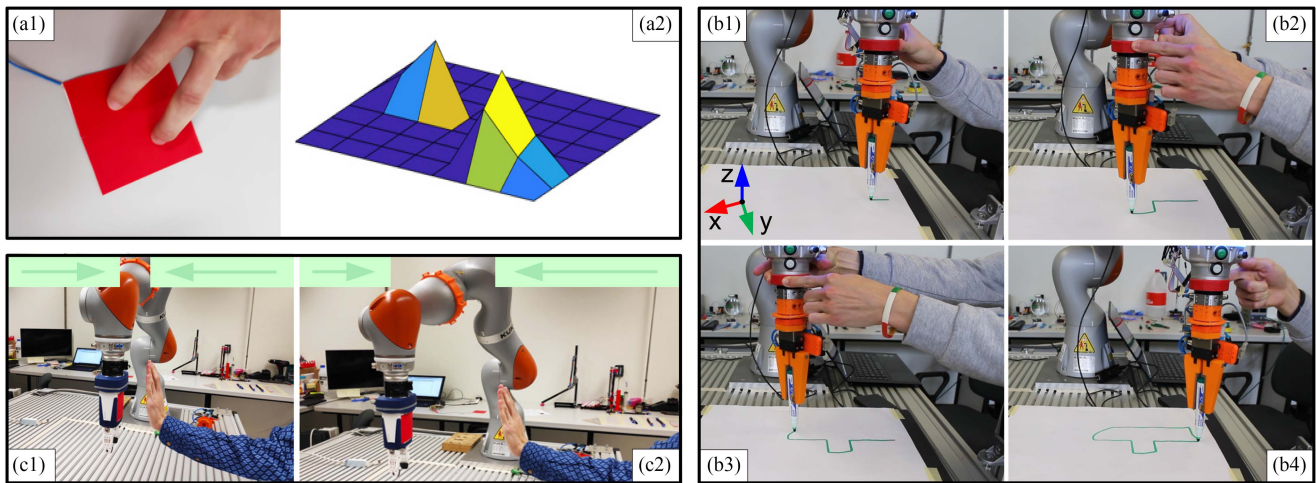


Fig. 15. (a) Two fingers touching the 64-pxel sensor (left) and corresponding response plot (right). (b) Robot hand-guiding with the smaller 16-pxel sensor installed around the robot's end-effector. (c) Human-robot collision avoidance test with the 64-pxel sensor: an emergency command is triggered when the hand reaches within 100 mm from sensor. The robot moves to a safe position to avoid collisions.

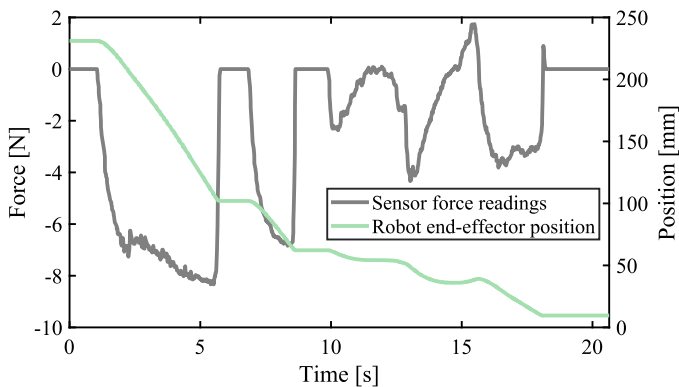


Fig. 16. Data recorded during robot hand-guiding demonstration. Plotted forces and end-effector position are both relative to the x -axis direction, being the robot's response analogous for the y - and z -axis directions.

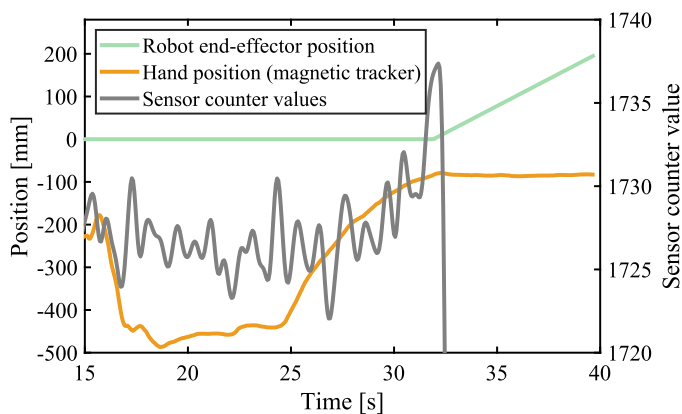


Fig. 17. Human-robot collision avoidance demonstration. The 64-pxel sensor triggers an emergency command to the robot when a human hand reaches within 100 mm of the robot's end-effector. All data are unfiltered.

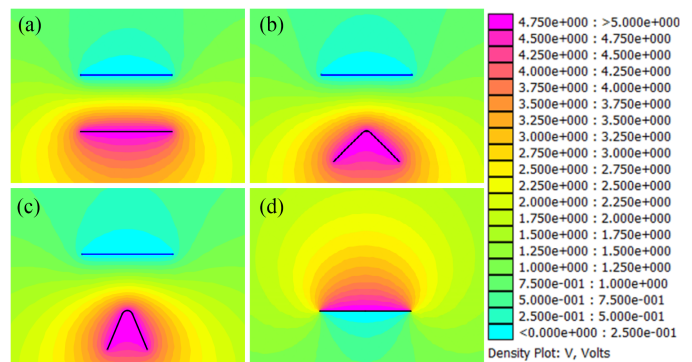


Fig. 18. (a)–(c) Electrostatic potential around 8-cm^2 self-capacitive electrode with 8-cm^2 test grounded electrode in close proximity. (d) Electrostatic potential around 8×8 sensor with FSR layers being used as active electrostatic shields.

the shielded side of the 8×8 sensor [see Fig. 18(d)]. This is expected to increase the sensor's robustness to electrostatic interference originated from behind it. Although the implementation of this feature requires no modification to the sensor, further development of the DAQ circuit will be required. The current circuit is unable to simultaneously address all the FSR electrodes, a feature that would be necessary to use them as active shields.

Stress concentration and prestress may occur when the sensor is applied to curved surfaces. The sensor was mounted on a 30-mm constant-radius curved surface. In this case, we simply tared the sensor and achieved results within the same $\sim 10\%$ error margin obtained over a flat surface. Creasing prexels around sharp edges should be avoided where possible to prevent stress concentration in the piezoresistive polymer. In cases where this is not feasible, local calibration of the creased prexels must be performed, and a decrease in maximum measurable force is to be expected due to the increased stress resultant from the reduced contact area between the object/human and the edge on

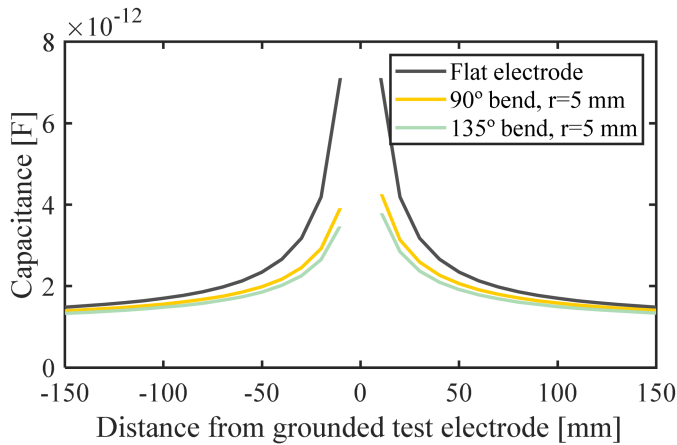


Fig. 19. Capacitance measured in the 8-cm² electrode.

which the sensor is applied. When applied to complex geometry surfaces, the normal distance between a hand within proximity range and the sensor varies according to surface topography, causing self-capacitance measurements to fluctuate accordingly. This effect can be simulated using the method of moments for electrostatics [26]. To illustrate this point, capacitance on the 8-cm² electrode was calculated when another 8-cm² grounded conductor is placed within the proximity range, simulating a hand at distances ranging from 10 up to 150 mm [see Fig. 18(a)]. The same simulation was then repeated with the self-capacitive electrode bent 90° and 135° around a 5-mm curvature radius [see Fig. 18(b) and (c), respectively]. Results are presented in Fig. 19, where the capacitance reduction with increasing curvature becomes clear. In practical terms, this results in the sensor not being capable of accurately determining hand-to-surface distance when applied to highly curved surfaces, being, however, still moderately effective at detecting hand presence within its proximity range.

V. CONCLUSION

This article presented a novel mechanically flexible piezoresistive/self-capacitive hybrid force and proximity sensor, which proved to be multifunctional, easy to fabricate, highly inexpensive, and easy to apply to complex-shaped robot structures. These characteristics demonstrated its potential application in collaborative robot interfaces. Experimental results for both the piezoresistive and self-capacitive operation modes showed the sensor's versatility, flexibility (1 mm thickness), accuracy (reduced drift), and repeatability. Its fabrication method is simple and highly scalable while being flexible enough to accept process variations. Finally, the sensor was successfully applied in real-world scenarios, namely, robot hand-guiding and human-robot collision avoidance. Future work will be dedicated to testing 3-D printer-based manufacturing processes based on conductive filaments and improvement of the sensor's proximity range and robustness to electromagnetic interference by utilizing the aforementioned FSR electrodes as active electrostatic shields during proximity measurement cycles.

REFERENCES

- [1] G.-Z. Yang *et al.*, "The grand challenges of Science Robotics," *Sci. Robot.*, vol. 3, no. 14, 2018, Art. no. eaar7650.
- [2] J. A. Marvel, "Sensors for safe, collaborative robots in smart manufacturing," in *Proc. IEEE SENSORS*, 2017, pp. 1–3.
- [3] S. José *et al.*, "Methods for considering safety in design of robotics applications featuring human-robot collaboration," *Int J. Adv. Manuf. Technol.*, vol. 107, pp. 2313–2331, 2020.
- [4] H. S. Han *et al.*, "A flexible dual mode tactile and proximity sensor using carbon microcoils," *Proc. SPIE*, vol. 9798, 2016, Art. no. 979838.
- [5] T. D. Nguyen, T. Kim, J. Noh, H. Phung, G. Kang, and H. R. Choi, "Skin-type proximity sensor by using the change of electromagnetic field," *IEEE Trans. Ind. Electron.*, vol. 68, no. 3, pp. 2379–2388, Mar. 2021.
- [6] L. Viry *et al.*, "Flexible three-axial force sensor for soft and highly sensitive artificial touch," *Adv. Mater.*, vol. 26, no. 17, pp. 2659–2664, 2014.
- [7] J. C. Ramos *et al.*, "Adding proximity sensing capability to tactile array based on off-the-shelf FSR and PSoC," *IEEE Trans. Instrum. Meas.*, vol. 69, no. 7, pp. 4238–4250, Jul. 2020.
- [8] L. Wang, "Usage of connected structure to eliminate blind area of piezoresistive sensor array," *IEEE Trans. Ind. Electron.*, vol. 65, no. 4, pp. 3568–3575, Apr. 2018.
- [9] Y. Wu *et al.*, "A skin-inspired tactile sensor for smart prosthetics," *Sci. Robot.*, vol. 3, no. 22, 2018, Art. no. eaat0429.
- [10] T. Matsuno, Z. Wang, K. Althoefer, and S. Hirai, "Adaptive update of reference capacitances in conductive fabric based robotic skin," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 2212–2219, Apr. 2019.
- [11] J. Hughes and F. Iida, "Tactile sensing applied to the universal gripper using conductive thermoplastic elastomer," *Soft Robot.*, vol. 5, no. 5, pp. 512–526, 2018.
- [12] N. Matsuhisa *et al.*, "Printable elastic conductors with a high conductivity for electronic textile applications," *Nature Commun.*, vol. 6, no. 1, Jun. 2015, Art. no. 7461.
- [13] A. Dementyev, H.-L. C. Kao, and J. A. Paradiso, "SensorTape: Modular and programmable 3D-aware dense sensor network on a tape," in *Proc. 28th Annu. ACM Symp. User Interface Softw. Technol.*, 2015, pp. 649–658.
- [14] D. Hughes, J. Lammie, and N. Correll, "A robotic skin for collision avoidance and affective touch recognition," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 1386–1393, Jul. 2018.
- [15] E. Dean-Leon, K. Ramirez-Amaro, F. Bergner, I. Dianov, and G. Cheng, "Integration of robotic technologies for rapidly deployable robots," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1691–1700, Apr. 2018.
- [16] J. Zhong *et al.*, "Smart face mask based on an ultrathin pressure sensor for wireless monitoring of breath conditions," *Adv. Mater.*, vol. 34, no. 6, 2022, Art. no. 2107758.
- [17] S. Lee *et al.*, "Nanomesh pressure sensor for monitoring finger manipulation without sensory interference," *Science*, vol. 370, no. 6519, pp. 966–970, 2020.
- [18] S. Lee *et al.*, "A transparent bending-insensitive pressure sensor," *Nature Nanotechnol.*, vol. 11, no. 5, pp. 472–478, May 2016.
- [19] T. Someya and T. Sekitani, "Printed skin-like large-area flexible sensors and actuators," *Procedia Chem.*, vol. 1, no. 1, pp. 9–12, 2009.
- [20] D. Giovanelli and E. Farella, "Force sensing resistor and evaluation of technology for wearable body pressure sensing," *J. Sens.*, vol. 2016, 2016, Art. no. 9391850.
- [21] L. Wang, T. Ding, and P. Wang, "Influence of carbon black concentration on piezoresistivity for carbon-black-filled silicone rubber composite," *Carbon*, vol. 47, pp. 3151–3157, 2009.
- [22] J. G. Simmons, "Generalized formula for the electric tunnel effect between similar electrodes separated by a thin insulating film," *J. Appl. Phys.*, vol. 34, no. 6, pp. 1793–1803, 1963.
- [23] P. Badger and P. Stoffregen, "Capacitive sensing library," May 20, 2022. [Online]. Available: <https://www.arduino-libraries.info/libraries/capacitive-sensor>
- [24] M. Safaea and P. Neto, "KUKA sunrise toolbox: Interfacing collaborative robots with MATLAB," *IEEE Robot. Autom. Mag.*, vol. 26, no. 1, pp. 91–96, Mar. 2019.
- [25] M. Kalantari, J. Dargahi, J. Kövecses, M. G. Mardasi, and S. Nouri, "A new approach for modeling piezoresistive force sensors based on semiconductive polymer composites," *IEEE/ASME Trans. Mechatronics*, vol. 17, no. 3, pp. 572–581, Jun. 2012.
- [26] T. K. Sarkar and R. F. Harrington, "The electrostatic field of conducting bodies in multiple dielectric media," *IEEE Trans. Microw. Theory Techn.*, vol. 32, no. 11, pp. 1441–1448, Nov. 1984.



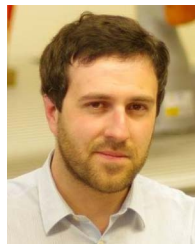
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