Novel Capacitive-Based Sensor Technology for Augmented Proximity Detection

Marcello Chiurazzi, Member, IEEE, Guido Giuseppe Garozzo, Paolo Dario, Fellow, IEEE, and Gastone Ciuti, Member, IEEE

Abstract—In this paper, the authors developed a capacitive-based sensor technology for high-range proximity detection, composed of multiple active units. The single sensor unit consists of a multi-layer compliant structure with a coplanar plate capacitor configuration. A prototype, composed of two single active units, was designed using, for each one, conductive electrodes printed on a polyimide layer and positioned in the middle of soft polymeric insulating substrates, either acting as shock-absorber and for sensor electrical and mechanical protection. For an in-depth theoretical analysis of the physical capacitive principle, a conditioning electronic circuit (i.e. data collection, conversion, amplification and filtering modules) was built in order to collect a digital voltage output proportional to the variable sensed capacitance. Experiments were performed to characterize the single capacitive sensor and the multi-unit sensor technology (i.e. curve of response, dynamic response, accuracy and precision). The results confirmed the outcomes originally achieved through FEM simulations and the effectiveness of the technology in high-range detection. Using a combination of two active sensor units, an operating range was achieved of up to 15 times the performance of a single commercial capacitive sensor with comparable dimensions.

Index Terms— Collaborative robotics, human-robot collaboration, capacitive sensors, high-range proximity detection.

I. INTRODUCTION

Research institutes and companies worldwide are focusing on autonomous self-adaptive robotic machines capable of collaborating with humans (e.g. autonomous vehicles, collaborative robots). Consequently, awareness of the operating environment is greatly needed. Sensor technologies are thus widely used to compute and provide information on crowded and non-static scenarios. However, the main drawback preventing the rapid diffusion of collaborative machines, both in medical or industrial fields, remains in the limitations of a robust 3D reconstruction of the workspace [1].

The success of human robot collaboration (HRC) is greatly dependent on the number and type of sensor technologies used, i.e. the accuracy and reliability of the computational awareness in the collaborative workspace. Sensor technologies for computing distances between robotic machines and objects within a common area currently belong to two main classes, i.e. embedded and environmental [2]. Although this classification might be further detailed, for the sake of simplicity, authors decided to analyse and compare technologies belonging to these two classes, i.e. environmental and embedded, the last one integrated into or onto a robotic machine.

Environmental sensors, such as RGB-D cameras, are effective in HRC for industrial applications in terms of, for example, global information and high sensitivity. However, their application has real-time constraints. In fact, a single camera approach does not provide a robust awareness of the entire working environment due to shadow effects or simply due to the limited field of view of the camera itself [3]–[5]. Multiple cameras are therefore needed to guarantee a robust and redundant reconstruction of the environment in order for objects to be detected. However, this involves a high computational cost that entails merging information belonging to different cameras in order to re-map obstacles, especially human beings, by exploiting a convex approximation of their geometries. Phan and Ferrie [6] proposed a model based on a popular graphical representation to compute a high-resolution 3D reconstruction of the human model. On the other hand,
Safeea et al. reconstructed humans and manipulators using cylindrical geometries, with a closed form solution to compute the distances between them [7]. Nevertheless, these algorithms usually require a computational time (at least 0.5 s) that is not always suitable for real-time applications, such as HRC scenarios, where a rapid reaction is needed to avoid collisions and to manage interactions [8].

On the other hand, embedded sensor technologies integrated into robotic machines however, such as torque sensors, have a fast-dynamic response and are also not affected by environmental conditions, such as shadow effects. An unpredicted collision or a voluntary physical interaction, can be recognized, in the simplest manner, through monitoring the current on each motor; in this case, the current is higher if compared to a manipulator intrinsic dynamic, not affected by external perturbations. Exploiting this approach, Geravand et al. demonstrated how to distinguish between an accidental collision and an intended physical interaction using a continuous online monitoring of the motor currents [9]; however, this approach is able to provide only local information on the obstacle during a physical collision with the robot.

Using a different approach, but still relying on sensor technologies embedded into robotic systems for contact detection, Tonietti et al. [10] developed a human-robot interaction strategy based on variable impedance actuators (VILAs) embedded into the joints of an anthropomorphic manipulator.

Although the effectiveness of all the solutions presented so far on force detection, have been proven, the limitations are based on the capability of detecting the presence of an obstacle once the collision or interaction is generated. Thus, they cannot be used to predict and avoid unpredicted contacts. This means that when entrusting these sensor technologies to an HRC scenario, human safety can only be ensured by stopping the robot once a collision has been detected. In this case, a passive compliant layer, externally covering the manipulator, such as the ABB YuMi or FANUC CR-35iA, can be further integrated in order to reduce the energy during the impact.

Moving to embedded sensor technologies integrated onto robotic machines, but still relying on physical contact detection, De Maria et al. [11] developed a tactile technology aimed at monitoring the interaction forces between the robot’s end-effector and the surrounding environment. In addition, Mazzocchi et al. [12] developed a compliant sensorized skin composed of multiple sensing units for covering non-collaborative industrial robots. Based on a piezoresistive technology for contact detection in a 2D configuration, the skin was used to provide pressure/force information regarding a human-robot collision with an overall procedure time of 50ms.

Collaborative robots embedding contact detection skins and embedded technologies integrated into robotic machines are usually characterized by both a low inertia (e.g. lightweight structure) and reduced motion speed, in order to keep the energy transferred during the impact lower than an imposed safety threshold; see ISO/TS 15066:2016 [8].

Resulting in a high-range proximity detection, and still relying on embeddable technologies onto the robotic machine, Lee et al. [13] developed a dual-mode multigrid capacitive sensor technology used for contact and human’s hand proximity detection of up to 170 mm. On the other hand, Ye et al. [14] developed capacitive sensor technologies based on coplanar plate capacitors; these sensors were capable of detecting an iron bullet at a distance up to 600 mm. This demonstrated that promising results can be achieved by investigating smart geometries (e.g. combs, spirals, circles) and intrinsic parameters, such as the dimension of the plates or the pitch between them in order to optimize the curve of response of the sensor. However, an important limitation of the aforementioned technologies is represented by the single sensor dimension (310 mm × 190 mm), which is not always suitable for covering any non-regular surfaces, and which also affects the overall sensor resolution.

Sensors using a coplanar capacitive principle measure the distortion, due to the interaction with an approaching object, of the electrical field generated by the sensor itself. They can be used to detect both conductive and non-conductive materials (Fig. 1A). On the other hand, a different capacitive principle is based on parallel plate capacitors, where the transduced parameter is the oscillation frequency of an LC circuit, and C is the capacitance measured between an active plate, potentially embedded into a robotic skin. A detected (grounded and conductive) object acting as the second plate of the sensor is needed (Fig. 1B).

In terms of the market, commercial skin sensor technologies for human-robot proximity detection have been developed by COMAU SpA (Turin, Italy) and FOGALE nanotech (FOGALE Robotics, Nîmes, France), integrating their proprietary concepts onto a COMAU NJ4-170 and Universal Robot UR5, respectively.

Other technologies, such as optical, inductive, ultrasound and laser ones are mainly applied in mobile robotic platforms for multi agent navigation, as presented in [15]–[19], where the geometry and the material of the object to be detected strongly affect the sensor performance, especially for 2D optical sensors. Table I summarizes and qualitatively evaluates the aforementioned technologies according to some of their main features and applications. Costs of the different technologies, reported into Table I, have to be intended in a quantitative but reasonably generic and not-detailed manner since strictly dependent by different aspects, such as the application the technologies are used for, different performances, business companies’ strategy for selling the technology or the application-driven sensors and specifications requested (e.g. sensitivity range, resolution, dimension). Therefore, reported
| Sensor Technology / Features | Proximity | Force/Pressure | Material | Cost | Refs |
|-----------------------------|-----------|----------------|----------|------|------|
| Force                       | o         | +              | --       | $$   | [11], [12], [19] |
| Piezo                       | o         | +              | o        | $$$  | [12], [19] |
| Capacitive                  | +         | +              | +        | $    | [20], [21] |
| Optical                     | +         | o              | -        | $$   | [15] |
| Laser                       | +         | o              | -        | $$   | [16] |
| Ultrasound                  | ++        | o              | +        | $$$  | [17] |

Note that the low sensitivity achieved with most of the embedded sensor technologies, as well as the limitations of single environmental optical sensors, cannot ensure that the robot will perform the task continuously, and also avoid potential obstacles. Moreover, since contact or pre-contact information does not enable the collision to be reliably avoided, robotic systems are forced to move at low speeds within the collaborative workspace, thus affecting the efficiency of the entire process and the overall procedural time.

Nevertheless, among the aforementioned technologies and concerning a human-robot interactive scenario, capacitive sensors still seem to have a high hidden potential. For the best of our knowledge, these sensors, if compact in size (i.e. smaller than 2 cm²), are currently used for contact and pre-contact detection. Braun et al. [20] showed that these sensors can be used for several applications, such as gesture recognition, physiological sensing or motion analysis for rehabilitation, as well as human gait cycle analysis as demonstrated by Zheng et al. in [21]. As also highlighted by Braun et al., capacitive technologies are mostly adopted in applications where a low sensitivity range is needed. John Ulmen and Mark Cutkosky [22] developed a capacitive sensor for pressure/force sensing that can measure forces of up to 100 N with a resolution of 0.2 N. Each sensor has an area of 11 mm² and they are arranged according to a parallel plate capacitor technology. Following the same approach, Xu et al. developed and presented in [23] a capacitive technology composed of a 3 × 3 array of sensor units with a dimension of 36 mm² for the single unit and a resolution of 2 mN. In such applications, capacitive technologies for pressure detection exploit a parallel plate capacitor, where the sensors are made up of a soft compliant structure that hosts the two plates of a capacitance at a specific distance. When the soft structure is stimulated, due to mechanical stresses, the relative distance between the plates changes, leading to a variation in capacitance, measured as:

\[ C = \frac{\varepsilon_0 A}{d} \] (1)

The present paper outlines the design of a new capacitive technology based on the interaction of multiple sensing coplanar capacitive units for high-range proximity and contact detection in HRC applications. Our technology aims to overcome current limitations in terms of modular and compliant integration, sensitivity range and cost. The paper is organized as follows: Section II.A explains, from a theoretical point of view, the physics behind the presented concept. Section II.B describes the capacitive system design and the fabrication process. The design of the electronics and the experimental set-up are reported in Sections II.C and II.D, respectively. Section III describes the results achieved in comparison with the current state of the art. Sections IV and V contain the conclusions and proposals for future directions.

II. MATERIALS & METHODS

Our capacitive technology exploits the combination of a minimum of two capacitive sensor units. First, there is a master unit, named “reading sensor”, which provides distance information computing the distortion of its own generated electrical field. The second (or more) slave element(s), named “emitting unit(s)”, generates a secondary electrical field that interacts with the one produced by the reading sensor in order to increase the proximity detection range.

The sensing elements can be used either individually or together and were designed to be integrated onto any non-regular surface. The multi-sensor configuration increases the proximity sensitivity range, thus enabling control strategies based, for example, on collision avoidance, and 3D reconstruction. In addition, impedance control, can be enabled thanks to the contact detection provided by the capacitive technology in order to develop interactive control strategies.

The capacitive-based sensor technology described in this paper was characterized and tested to accurately analyse the performance of the sensor technologies for augmented proximity detection in an HRC scenario. The main concept described in this paper was patented on January 2020 (deposit number: WO2020012440A1), where in this specific case, the emitting capacitive element was a wearable bracelet worn by a human operator, whereas the reading sensor was integrated onto a robotic anthropomorphic arm.

A. Capacitive Technologies and Physics

Our technology relies on the interaction between electrical fields generated by two active units, both built following a coplanar plate configuration (Fig. 1 A). According to this configuration, capacitive sensors – contrary to a parallel plates configuration (Fig. 1 B) – are made-up by two co-planar electrodes among which an electrical field is induced due to their different potential. One electrode is active, stimulated in the AC domain, whereas the second one is grounded.

The extracted sensing measurement is represented by the variable capacitance of the reading sensor, which exploits the intensity of the electrical field induced between the plates.
The electrical field generated by the electrodes of the reading sensor is distorted when an object approaches its electrical propagation domain. Consequently, a variation in the density of charge on the grounded electrode is recorded, leading to a variation in the capacitance of the reading sensor itself. Since the electrical field can be distorted by both conductive or non-conductive objects, the reading sensor can also be used to detect heterogeneous materials, as mentioned in [24]. Fig. 2 shows how the electrical field generated by the reading sensor is distorted by a passive (Fig. 2 A, B and C - left) and active (Fig. 2 A, B and C - right) emitting unit approaching the electrical propagation domain in a simulated finite element model (FEM) environment implemented in COMSOL Multiphysics 5.3a (COMSOL Inc., Stockholm, Sweden). When no physical interactions occur, the electrical field generated by the reading sensor goes from the electrode with the higher voltage to the grounded one (Fig. 2 B). On the other hand, when the emitting unit enters the propagation domain of the reading sensors, its propagation lines are interrupted and distorted, causing a reduced density of charge on the reading sensor (Fig. 2 C). However, the sensor performance in proximity detection is severely influenced by the physical nature of the detected object (e.g. iron, skin, plastic, glass). Therefore, the response of the reading sensor needs to be properly calibrated and adapted to the specific material in order to deterministically compute the distance of proximal objects.

As previously anticipated, capacitive sensors can also exploit a different technology based on parallel plates (Fig. 1 B). Although they can offer a good resolution, parallel plates capacitive sensors are mainly employed to provide pressure or pre-contact information due to a low sensitivity range; in addition, such technology can only detect conductive and grounded objects.

Due to these limitations, and also assuming the need to interact with non-conductive objects in the case of HRC applications, our capacitive-based technology uses a coplanar architecture, thereby exploiting the beneficial effects of active emitting units (connected to the objects to detect) to improve the sensitivity range of the reading sensor.

In order to increase the maximum detectable distance of coplanar capacitor-based sensors, an electro-mechanical design can be performed on either the detected object or on the electro-mechanical features of the sensors. Assuming the need to maintain embedded sensors with compact areas to cover any small and non-regular surface with a high 2D resolution, this paper focuses on the design of a combined small-size capacitive-based sensor technology and in particular on the combination with external active elements (i.e. emitting units), which can be used to improve the sensitivity range of a capacitive-based reading sensing module.

**B. System Design and Fabrication Process**

First, several sensor geometries were tested and, for each one, the physical parameters of the electrodes (i.e. dimension, distance and pitch) were interchanged in order to optimize the sensor performance. A FEM was implemented and tested in COMSOL Multiphysics 5.3a. The outcomes confirmed the results of the state-of-the-art, as demonstrated in [14], in which the authors stated: “concentric rectangular spiral electrode offers higher performances from an electrical point of view”.

Our geometry, in fact, has the advantage of the superposition property of the electrical field propagation, which becomes clearly significant once the single sensor is surrounded by a 2D array of several sensor units. Taking advantage of these properties, our capacitive sensor unit, for both the master reading sensor and the slave emitting unit(s), was built on a bio-inspired geometry based on a honeycomb structure. An exploded rendering of the single sensor unit is shown on the left in Fig. 3; the same figure also shows the image of a real fabricated sensor on the right of Fig. 3.
The multi-layer compliant sensor is based on a multi-element structure composed of a conductive layer (area: 2.092 mm², Fig. 3 B) lying on an insulate polyimide film (i.e. Kapton® layer, L: 68 mm and W: 69 mm, Fig. 3 C) with an overall thickness of 300 μm. The two layers are then embedded into a polymeric insulating matrix (thickness: 3 mm for the upper and 7 mm for the lower parts, respectively; Fig. 3 A and D) designed to operate as a shock absorber to reduce the energy transferred during the contact [12], as well as for mechanical and electrical protection. In addition, since the sensitivity direction of the sensor is radial due to the propagation of the electrical field, an additional layer (a shield, Fig. 3 E), was introduced in order to force the electrical field propagation vertically to the surface on the upper side. The effectiveness of the shielding was optimized by exploiting its electrical absorption proprieties, as:

\[ A = 3,34 \sqrt{f_e \mu_r \sigma_r} \]  

where \( t \) is the thickness of the shielding layer, \( f_e \) is the frequency of the induced electrical field, and \( \mu_r \) and \( \sigma_r \) are the electrical relative permeability (H/m) and relative conductivity (S/m), respectively. Since the thickness of the shielding layer strongly affects the stiffness of the sensor, a Nedler-Mead optimization model [25] was computed, assuming the maximum thickness acceptable for the shielding layer equal to 1 mm. Therefore, considering key-control variables, i.e.: i) thickness, ii) ratio between electrodes, and iii) shielding layer dimension, the model was used for optimizing a specific cost function, i.e., the electrical field norm, on the bottom side of the sensor. The design of the shielding layer, and consequently the mechanical compliance of the single sensor unit, can be customized according to the sensing application. For example, with regard to the HRC, it is essential to reduce the impact between the robot and the human being during a fully inelastic contact, in accordance with ISO/TS 15066:2016 [8].

A hexagonal honeycomb-inspired shape was chosen for electrical and mechanical reasons. This choice is also supported by other sensorized technologies that adopted a polygonal shape in order to offer an optimal response to external mechanical stress. This structure for example was used by the “robotic skin cells” developed by the ICS group of TUM [26], where a single hexagonal unit integrates pressure, temperature and magneto-inertial sensors, and by the ‘aka’ skin [27] of the iCub robot, where triangular-shaped units are used to provide pressure information. Capacitive sensing elements can therefore be used for a simultaneous measurement of proximity, contact pressure and forces applied to any non-regular surface.

C. Electronic Circuit Model

The electronic circuit developed for the single sensor unit and for the multi-unit combined technology characterization, illustrated in Fig 4, was designed following a well-assessed signal conditioning scheme, by embedding data collection, conversion, amplification and filtering modules. An external generator provides a 1.5 Vpp sinusoidal signal at 60 kHz-0° used to power, through the virtual short-circuit of U1, one electrode of the reading sensor (Fig 4 A-0), while the second electrode is grounded. At the same time, the same sinusoidal signal of 1.5 Vpp at 60 kHz-0° was directly connected to a phase-locked loop (PLL) to power one electrode of the emitting unit (Fig 4 A-2), whereas the second electrode is grounded as well. The system was conceived to be portable and compact in size, and a 1.5 Vpp reference voltage was selected to be compatible with an embeddable and commercial silver oxide coin battery. Signal frequency is set to optimize sensor performances until the maximum analog input voltage of the ADC is reached (±10 V). The counter-phase is forced in order to maximize the interaction effects of both the reading sensor and emitting unit. A PLL electric circuit was thus developed (Fig 4 A-2). This circuit ensures a specific phase shift of the input signal, and also a permanent oscillation through a voltage-controlled oscillator (VCO), containing a Schmidt trigger comparator circuit.

In Fig 4 A-0, a C/V converter (ADA4610-1ARZ, Analog Devices, Massachusetts, USA) is used to amplify and convert the variable capacitance into a voltage signal. In Fig 4 A-1, the voltage signal is amplified through an IN-AMP (U2) with an adjustable gain set by to Rg. U2 provides a reduction of the bias voltage thanks to \( V_{off}(t) \). The signal is then filtered using an LPF (U3) and then half-rectified through the usage of a diode (D).

To ensure a reliable and straightforward characterization, electrical components reported in Fig 4-A 1 were digitally replaced in LabVIEW programming language (National Instruments, Texas, USA), where, an analysis of the power
spectral density of the signal \( V_0(t) \) was performed in order to define the cut-off frequency of the low pass filter (62kHz). Moreover, since the PLL electric circuit had been extensively tested in the laboratory, the PLL was also replaced with a dual signal generator used to power simultaneously both sensors in the counter-phase. The emitting unit, represented in Fig 4 A-2, in fact, generates an opposite electric field with respect to the excitation signal of the reading sensor and its induced electrical field. The signal was then acquired using an NI DAQmx 6363 (National Instrument, Texas, USA) with a sampling rate of 300 kHz (according to the Nyquist criterion). It is worth mentioning that application-oriented developments of the electronics will integrate the PLL circuit within the emitting unit scheme.

D. Experimental Tests: Sensor Technology Characterization

Tests were performed in order to describe the main features i.e. sensitivity, accuracy, precision, time of response, and resolution) of the single capacitive sensor (i.e. reading sensor) and of the combined sensor technology. In each test, pre-defined distances between the electronic capacitive-based units were tested assuming air as the dielectric between the reading sensor and the emitting unit (i.e. the object to detect). The experimental setup and hardware components (as mentioned in Section II.C) are reported in Fig 5 A. The reading sensor and the emitting unit employed in the physical experimental tests have a 2D dimension of 68 mm (L) and 69 mm (W), with an overall thickness of 10 mm, including the external polymeric insulating matrix (see Fig. 3).

The first set of tests (Test#1) was performed to derive the curve of response of the reading sensor, while interacting with a passive emitting unit (Fig 5 B - left). The reading sensor was powered with a 1.5 Vpp sinusoidal signal at 60kHz-0°, whereas the emitting unit was simply connected to the ground.

Starting by a 3 mm relative distance (minimum distance achievable due to the thickness of the polyimide upper part, Fig. 3 A), the two capacitive units were tested increasing the inter-element gap with a constant incremental step (\( \Delta z \)) of 30 mm (15 measurements, i.e. from 3 to 423(H) mm). The maximum distance has been chosen taking in consideration the common requirements and achieved results in HRC applications, where about 400 mm distance can be considered adequate for the robot to perform a demanded task avoiding potential obstacles within the shared workspace [3], [17].

For each measuring step, the output signal from the reading sensor was acquired: 10 thousand samples were collected, filtered and processed to derive significant statistical parameters for an appropriate sensor characterization, i.e. mean value (\( \mu \)) and standard deviation (\( \sigma \)), in order to evaluate the sensor features in terms of resolution and accuracy. The acquisition and post-processing (Section II.C) of the raw data were performed through algorithms developed in NI LabVIEW programming language. The sensor curve of response obtained was then compared with the one achieved by performing the same tests in a FEM simulation environment with COMSOL Multiphysics 5.3a.

A second set of tests (Test#2) was then performed with the reading sensor interacting with an active emitting unit (Fig 5 C - left): the emitting unit was powered at 1.5 Vpp at 60kHz-180°. Assuming an increased sensitivity of the combined active technology, results were then compared with those achieved in Test#1, where the emitting unit was passive.

The main objective of these two sets of tests was to assess the contribution of an active emitting unit (which can be integrated with the object to be detected) interacting, in counter-phase, with a coplanar-based active capacitive sensor (i.e. the reading sensor), in terms of how this enhances the sensitivity range for high-range proximity detection. In addition, the contribution of a relative orientation between the two sensing units was preliminary tested by rotating the emitting unit from 30 to 90 degrees (with a 30° incremental step) around the z-axis to investigate how orientation affects the reading sensor measurements. Due to the symmetry of the electric field propagation, independent rotations around x-axis and z-axis are assumed to influence sensor measurements in a comparable manner, whereas rotations around y-axis does not affect the sensor measurements, as the two elements are maintained parallel.

In order to assess the influence of the sensor dimension for the capacitive-based response, another set of tests (Test#3) was performed in a FEM simulation environment (COMSOL Multiphysics 5.3a), due to the consistency of results previously obtained with Test#1 (Fig 5 D - left). To this purpose, three different sizes were simulated, scaling down the initial 2D dimension of the sensors (L: 68 mm and W: 69 mm) to 1:2 (L: 34 mm and W: 34.5 mm), and to 1:3 (L: 22.5 mm and W: 23 mm). Each size was simulated with the emitting unit both in an active and passive configuration, following the same protocol described in Test#1, where the reading

| TABLE II
| Sensor Technology Characterization - Active Reading Sensor Interacting With a Passive Emitting Unit |
| --- |
| Features | Simulated | Experimental |
| Sensitivity range (mm) | [0 - 243] | [0 - 243] |
| Accuracy (V) | 0 | 0.0016 |
| Precision | 100% | 92% |
| Time of response (ms) | N/A | 3.4 |
| Dynamic range (V) | [0 - 0.6916] | [0 - 0.5911] |
| Resolution (V) | 0.002 | 0.0027 |

| TABLE III
| Sensor Technology Characterization - Active Reading Sensor Interacting With an Active Emitting Unit |
| --- |
| Features | Simulated | Experimental |
| Sensitivity range (mm) | [0 - 423] | [0 - 423] |
| Accuracy (V) | 0 | 0.0016 |
| Precision | 100% | 94% |
| Time of response (ms) | N/A | 3.4 |
| Dynamic range (V) | [0 - 0.7081] | [0 - 0.7607] |
| Resolution (V) | 0.002 | 0.0027 |
Fig. 5. A) Experimental setup and components; B) reading sensor interacting with a passive emitting unit (left) and results (right); C) reading sensor interacting with an active emitting unit (left) and results (right); D) simulation of different size (left) and curve of responses achieved (right); and E) reading sensor interacting with 6 different human beings (left) and results (right) – Data in the graphs are reported on a logarithmic scale for X and Y-axis, such as the signal sensitivity limit (black trace line).
sensor was powered with a 1.5 Vpp at 60 kHz-0°. Again, when active, the emitting unit was powered with a 1.5 Vpp at 60 kHz-180°.

A final experimental test (Test#4) aimed at defining i) the reading sensor unit curve of response, while interacting with a human hand, and ii) its response variability between different human subjects, both female and male, was performed by placing each hand at incremental proximity distances with the active reading unit (from 3 to 423 mm, 15 measurements) (Fig 5 E - left).

### III. RESULTS

Simulations, implemented in COMSOL Multiphysics 5.3a, were performed, where the reading sensor interacted with a passive emitting unit at different distances. The same conditions were applied in a real scenario with the sensors shown in Fig. 3 and the results were compared (Test#1). Fig 5 B - right compares the curve of response of the reading sensor both in simulated and real scenarios. The maximum error between the curves is 10.05% at a 3 mm relative distance and decreases as the distance increases (average error: 0.81% and minimum error: 0.56%). The higher errors at smaller distances are probably due to environmental conditions, such as humidity and temperature, which were not considered in the FEM simulations. In addition, both sensor curves of response presented a logarithmic behaviour in line with the state-of-the-art [14].

When the reading sensor interacts with a passive emitting unit, and under the hypothesis of electrically stimulating the reading sensor as described in Section II.D (i.e. 1.5 Vpp at 60kHz-0°), the maximum detectable range achieved is from 3 mm (contact) to 243 mm. Above 243 mm, the sensor response presents comparable values with the electric noise (i.e. sensor response comparable with sensor baseline ± standard deviation: ± 0.0022±0.0006). This value increases with the conductivity of the external detected object interacting with the reading sensor. Depending on the performance required, sensitivity can also be enhanced by increasing the voltage of the electrical signal to the reading sensor. Table II summarizes the properties of the proposed technology, with the reading sensor interacting with a passive emitting unit (i.e. grounded) in real and simulated environments.

After performing the sensor characterization in the operating conditions of Test#1, a second test was performed to characterize, in a simulated and real scenario, the curve of response of the reading sensor interacting with an active emitting unit stimulated by a sinusoidal signal in counter-phase, as described in Section II.D (Test#2). For the sake of completeness, Fig 5 C - right shows the reading sensor behaviour while interacting with both a passive and active emitting unit. Due to the generation of an electrical field in counter-phase by the emitting unit, with the one generated by the reading sensor, as expected, the performance of the sensor technology increases when combined with an active emitting unit. In this case, the reading sensor sensitivity was almost 1.7 times higher than the sensitivity achieved while interacting with a passive element, both in the real and simulated environment. Table III summarizes the properties of the capacitive-based sensor technology, while interacting with an active emitting unit.

In addition, as expected, the relative orientation between the units affected the sensing performance. Relative orientation of 30, 60 and 90 degrees around the z-axis, tested as a feasibility study, reduced the maximum sensitivity range of the sensing technology by 35%, 41% and 49%, respectively.

In order to investigate the scalability of the proposed technologies, different sensor sizes were then compared (Test#3). One of the key points of the presented capacitive technology, in fact, is its easy adaptation to the features required (i.e. sensitivity, resolution, etc.). Fig 5 D – right shows the curve of response achieved by modifying, in a simulation framework, the size of both elements. As expected, the dimension of the sensor affects the overall sensitivity range (increases with the dimension) and resolution (decreases with the dimension). Interacting with a passive emitting unit, in fact, the reading sensor with the smallest area has the most limited sensitivity range (i.e. up to 153 mm). Whereas, interacting with the active emitting unit, the three tested dimensions showed a sensitivity range that reached a 423 mm distance (limited by the maximum distance evaluated). Although, at this distance, the sensor with the smallest area showed the smallest delta.

| Technology       | Area (cm²) | Perception information | Max. sensitivity range (mm) | Limitations                                                                 | Ref.s |
|------------------|------------|------------------------|-----------------------------|-----------------------------------------------------------------------------|-------|
| Optical          | -          | Global (+++)           | Meters scale                | Affected by ambient illumination and necessity of a line-of-sight detection   | [3-5] |
| VIA              | -          | Local                  | 0                           | Contact (no proximity detection)                                            | [9]   |
| Piezoresistive   | 105 (divided in 24 units) | Local                  | 0                           | Contact (no proximity detection)                                            | [12]  |
| Capacitive (coplanar plates) | 589       | Global (+++)           | 400 (human’s hand) and 605 (metal object) | Complex integration due to sensor dimensions and no directional response | [14]  |
| Inductive        | 3          | Global (+)             | 20                          | Affected by object’s material and geometry                                  | [18]  |

Presented technology [15.64-46.92] Global (+++) 303 (human’s hand) and 423 (with active emitting unit) Shielding needed -
variation \( (3.8E^{-3}) \), the sensor with the biggest area showed a higher variation of \( 6.6E^{-3} \).

A final test was then performed to validate the robustness of the sensor using a human’s hand as the external interacting object. This test was repeated with several users in order to investigate variability among human subjects (Test#4). Due to the lack of studies regarding the variability of the electrical parameters of the skin, Test#4 was directly performed in a real scenario. Fig 5 E - right shows the curve of response of the sensor while interacting with six different human subjects (1-3-5 males and 2-4-6 females). Although anthropomorphic differences (e.g. the male hand is statistically 1.3 times bigger than the female hand [28]), the results showed a good behaviour in terms of variability. Fig 5 E - right highlights how these differences become negligible when the relative distance between the reading sensor and the human’s hand increases, moving monotonically from a maximum error (sensor variability between different subject) of 28.28% at a 3 mm relative distance to 0.09% once the relative distance between the subject and the reading sensor reached 60 mm.

IV. DISCUSSION AND CONCLUSION

This work described the electrical and mechanical development of a capacitive integrated system for high-range proximity and contact detection. The system is made up of a reading sensor unit, embeddable onto any non-regular surface, which interacts with an emitting unit with a tested maximum detectable distance up to 423 mm and a compact 2D dimension of 68 mm (L) and 69 mm (W). Moreover, as already pointed out, if combined with an active emitting unit, even reading sensors with reduced dimensions (W: 22.5 mm and L: 23 mm) were able to sense the entire tested workspace, reaching a maximum detectable distance of 423 mm. This preliminary and promising results, achieved through FEM simulations, will lead us in the future to realize and test in a real environment, reading sensors with an increasingly compact size. Moreover, the presented technology was mainly simulated and tested with both the capacitive sensor units parallel, even if in non-structured environments a relative orientation between reading sensor and emitting unit might occur. However, the intrinsic flexibility and modularity of the presented technology allow for a full coverage of the robots’ external surfaces, thus mitigating the possible effect of a relative orientation between emitting and reading units. Further tests will be performed considering complex rotations of the two capacitive sensor units.

Although the system can be used both for pressure and proximity detection, the main innovation lies in its high-range proximity detection. To the best of our knowledge, this feature is currently particularly limited given that sensors with a very compact dimension have a sensitivity range of only a few centimetres (usually 20 to 30 mm) and are used to provide pre-contact information. Table IV compares the performance of our capacitive technology with the current state-of-the-art. As summarized, our technology provides a comparable performance (i.e. 76% of the maximum sensitivity range when interacting with a human’s hand) to the gold standard solution proposed by Ye et al. where the sensor interacts with an iron bullet [14]. Moreover our solution guarantees a more compact dimension as the biggest reading sensor tested has an area of 46.92 cm², i.e. 12 times smaller in terms of sensing area. In addition, our system is also modular, which means that the single sensor unit can be arranged in an array of compliant elements to cover any non-regular surface; this can also improve the system performance thanks to the superposition effect of the electrical field propagation.

Given its modularity, our technology can be designed by adapting both the physical parameters of the sensor (i.e. sensor dimension, material) and the electrical parameters of the electric signal (i.e. amplitude and phase) to the performance required. Our system can therefore overcome the main drawback of embedded sensor technologies, which can only give local or pre-contact information due to a limited sensitivity range. Thanks to the high ranging detectable distance, our system not only provides local information, but can also detect and re-map obstacles by reducing the gap between the environmental and embedded sensor technologies.

Finally, regarding the electromagnetic compatibility, since the system is working at low frequencies (60 kHz), and according to ICNIRP guidelines [29], the electrical fields induced by the proposed technology are not dangerous even in the case of long-term exposures.

V. FUTURE WORKS AND ROBOTIC APPLICATIONS

The capacitive technology developed in this work could have a potentially high impact thanks to the: i) low-cost (5-10€ per unit), ii) compliant and modular structure, and iii) high sensitivity in force/pressure and proximity detection.

The authors are focused on integrating this technology into robotic applications, such as multiple object grasping, HRC, companion robots, localization and so on. The capacitive technology, in fact, can be integrated into a robotic gripper and anthropomorphic manipulator for both industrial and medical applications.

A further development of our system will be required in order to use the patented technology to detect either conductive or non-conductive materials by adapting the sensor curve of response to the material detected. This will then improve the computation of the relative distance between the obstacle and sensitive elements.

Finally, the emitting unit can come in different shapes, for instance, as a bracelet worn by the human operator. The emitting unit could include dedicated electronics (embedding the PLL circuit in order to guarantee the counter-phase of the electrical fields) and other sensors, such as IMUs or accelerometers, to provide redundant information regarding the position of the human being within the collaborative scenario. Emitting units, together with other sensor technologies, can also be integrated into suits worn by the human operator to monitor physiological parameters and to calculate the relative distance from external moving machines in order to study ergonomic and behaviour states, always with safety as the key priority.
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