A Capacitive and Piezoresistive Hybrid Sensor for Long-Distance Proximity and Wide-Range Force Detection in Human–Robot Collaboration

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Safety is a core concern in human–robot collaboration (HRC), which highly relies on multi-information collected from its environment by various sensors. Current passive solution is to isolate the robot from human by fences or cages, which is invalid for a real collaborative robot, especially for the domestic and rehabilitation robots. Herein, a capacitive and piezoresistive hybrid sensor for long-distance proximity and wide-range force detection in HRC is reported. The sensor composes a pair of interdigital copper foil worked as the electrode for both coplanar capacitors and resistors, while a carbon black in polymer matrix works as the piezoresistive material. As-prepared hybrid sensor can detect the object approaching as far as 100 mm, while a contact force covers from 0 to 450 N. The maximum sensitivity is 0.65 mm$^{-1}$ for object proximity, and 17.73 N$^{-1}$ for contact force. Significantly, the proposed hybrid sensor is feasible and scalable integration for the electronic-skins (e-skins) with superior stability, mechanical flexibility and deformability, which can withstand large compression, bending and torsion in applications. Finally, the e-skins are used for safety control in two types of commercial robots, which exhibits the long-distance proximity and large-range force detection capabilities, illustrating its potential usage in complex, precise, and safe requirement conditions.

1. Introduction

The wide usage of robots has revolutionized in the intelligent manufacturing[1–7] as well as personalized domestic help,[8–11] impatient health care and surgery.[12–16] The applications in those fields are normally involved in human–robot collaboration (HRC), which rises a significantly important problem of human–robot safety. Nowadays, the passive solution in the industry, is to isolate robots from workers by fences or cages.[17–19] However, the method is invalid for the domestic robots and rehabilitation robots, even for collaborative robots. One of reasons behind this absence is lack of effective sensors at the interface of HRC for collecting multi-information, such as force/pressure,[20–24] temperature,[25–27] humidity,[28–30] and texture.[27,31,32] These perceptions can make the robots become awareness to the environment, thereby recognition of threats and feedback for motor controls.

In the last decade, electronic-skins (e-skins) with multimodal perceptions have been developed to enable the robot to interact with its environment more precisely, rapidly, and safely.[33–35] These e-skins are mainly based on one or two mechanisms, including capacitive, piezoresistive, piezoelectric, triboelectric, and electromagnetic.[36–42] The current strategies for developing multifunctional e-skins can be divided into two parts: one is directly integrating different functionalized sensors into a sensing network, the other is developing novel materials with the sensitivity for two and more types physical stimuli followed by decoupling algorithm. For the multifunctional sensing, a self-powered and highly sensitive triboelectric skin was reported to sense proximity and force via the triboelectrification effect. The compatible features enable the tribo-skin to perceive external stimuli and...
internal motions via self-generated electric signals. Pre-cracked silver nanowire-based fiber with helical microstructures were utilized as basic electrodes, which enabled both capacitive mode for pressure sensing and resistive mode for multidirectional strain sensing, independently. What is more, a 3D segregated conductive pathway of PEDOT:PSS in the stretchable latex film simultaneously perceived the location and temperature of the targeting object by integrating piezoresistive and capacitive sensing together with high performance. Nevertheless, both strategies are mainly confined to either the proximity or contact information, which is not sufficient for the robot control in HRC. Although the robot can feel external objects by optical elements such as fluorescent lamp, light emitting diode (LED), ferroelectric polarization, and ultrasonic, it may also result in unavoidable collisions of the sensor because of the low integration between proximity and contact performance. In this scenario, the robot itself is restricted in HRC, much less to the complex and elaborate actions with human.

Herein, we report a hybrid sensor combining the capacitative and piezoresistive mechanisms for proximity and contact force sensing. The proposed hybrid sensor contains five layers, in which the interdigital copper foil works as the electrode for both coplanar capacitors and resistors. The equivalent relative dielectric constant between two electrodes changes with the object approaching (0–100 mm) and contact force in a low range of 0–20 N, which leads to the change of capacitive output. Furthermore, the electrical resistivity of piezoresistive film will change with applied force in the large range (20–450 N), which leads to the change of resistive output. As a result, the maximum sensitivity is 0.65 mm/1 C0 for object proximity (ΔC/C0), and 17.73 N/1 C0 for contact force (ΔR/R0). Significantly, the proposed sensor is feasible and scalable for e-skins with superior stability, mechanical flexibility, and deformability, which can withstand large compression, bending, and torsion in the applications. Finally, the fabricated e-skins are proven to provide sensing feedback for safety control of robot arm in HRC, indicating the practical usage in robotics.

2. Results and Discussion

To realize the proximity and contact force detection in a large range, a hybrid structure sensor is illustrated in Figure 1a. It contains five layers, a silicone elastomer sealing layer with a bump in the center, a piezoresistive composite film formed by carbon black fillers in the polydimethylsiloxane (PDMS) matrix, two interdigital copper foil electrodes, an air gap between the piezoresistive film and the electrode, and silicone elastomer substrate (Figure 1a). Specifically, two interdigital electrodes in-plane are employed to form a coplanar capacitor with its upper space (Figure 1a). Accordingly, the value of the coplanar capacitor is calculated by the Equation (1).

\[
C = \varepsilon_{\text{eff}}\varepsilon_0 w' + \varepsilon_{\text{eff}}\varepsilon_0 \left(1 + \ln(1 + 2\pi w' + \ln(1 + 2\pi w'))\right)
\]  

(1)

where w' is effective width of the electrode (Figure 1a and S1, Supporting Information). It has a relationship with its physical width (w) and half distance (a) between two adjacent fingers in Equation (2).

Figure 1. Design the hybrid sensor with capacitive and piezoresistive mode for proximity and contact force sensing. a) Design a hierarchical structure of hybrid sensor and the five layers are labeled, the electric field lines among the coplanar electrode are illustrated by dash lines. b) As object approaching, the hybrid sensor works at capacitive mode for proximity. c) As object contacting to the sensor at initial, the hybrid sensor still works at capacitive mode for tiny pressure. d) Under the considerable pressure, the hybrid sensor works at piezoresistive mode for large pressure. Simulated potential distribution near the electrode, e) at initial condition, f) at distance of 50 mm, g) at initial contact, and h) under considerable pressure, corresponding to (a-d). The inset scale bar in (h) is also valid in (e–g).
Therefore, the volume resistivity of the composite is calculated by

\[
\rho_v = \frac{2}{\pi} \ln \left[ \frac{1 + \frac{w}{a}}{1} \right] + \sqrt{\left(1 + \frac{w}{a}\right)^2 - 1}
\]  

(2)

In addition, \(\varepsilon_0\) is the dielectric constant of air, while \(\varepsilon_{\text{eff}}\) is the equivalent relative dielectric constant of the upper space above the coplanar electrodes (including air). Accordingly, \(\varepsilon_{\text{eff}}\) can be calculated by the Equation (3).

\[
e_{\text{eff}} = e_0 + \epsilon_1 q_1 + \epsilon_2 q_2 + \epsilon_3 q_3 = e_{\text{air}} + (\epsilon_{\text{PDMS}} - 1) q_1 + (\epsilon_{\text{piezo}} - \epsilon_1) q_2 + (\epsilon_{\text{air}} - \epsilon_2) q_3
\]  

(3)

where \(q_i\) is the filling coefficient of single layer dielectric layer calculated as Equation (4).

\[
q_i = \frac{1}{2} \frac{K(k'_i)K(k_0)}{K(k_0)} (i = 1, 2, 3)
\]  

(4)

For the given structure herein, the physical sizes of \(l, w, a\) are fixed, but the effective sizes are changed with external approaching object or contact force. As a result, the \(e_{\text{eff}}\) of upper space above the coplanar electrode is changed. For the proximity prospection, the electric field around the coplanar electrode have been changed as the object approaching, thereby changing the \(e_{\text{eff}}\). The above formulas are also applicable to calculate the capacitance as the object approaching. During the process, the \(e_{\text{eff}}\) changes according to the Equation (3), leading to the change of capacitance by taking the \(e_{\text{eff}}\) into Equation (1). As a result, the device can index the characteristics of approaching object based on the capacitive mechanism. Upon a small contact force (i.e., 0–20 N), the sensor works at the normal capacitive mode. For the given structure, the piezoresistive film begins to contact the coplanar electrode owing to a large deformation when the applied force is above a critical value. In this scenario, the operating model of the sensor has been changed to resistive model owing to the conduction of piezoresistive film between two electrodes. As illustrated in Figure S1d, Supporting Information, an equivalent resistance between the piezoresistive film and a pair of electrodes is formed once contacting, which contains a bulk resistance of the piezoresistive film and the interface equivalent resistances between the piezoresistive film and the electrode. Further improving the force, the piezoresistive film will contact two and more pairs electrodes (Figure S1e, Supporting Information). Therefore, more bulk and interface resistances can be formed in the equivalent resistance. For the piezoresistive composite film, we assume the conductivity of PDMS is approximate to 0, compared with the good conductivity of carbon black. Therefore, the volume resistivity of the composite is calculated by Equation (5).\(^{[3]}\)

\[
\rho_m = \frac{1}{\phi_c} \left(1 - \phi_c\right) t
\]  

(5)

where \(\rho_m\), \(\phi_c\), \(\phi\), and \(t\) are the resistivity of polymer matrix, percolation threshold of piezoresistive composite, filling concentration of carbon black, and seepage coefficient of the composite, respectively.

Figure 1a illustrates an initial condition of the device without external object approaching. The dash lines index the electric field lines distribution between the coplanar electrodes (Figure 1a bottom). Figure 1e depicts the potential distribution outside the electrode simulated via COMSOL by placing a copper sphere (diameter of 20 mm) without charge at an infinite distance. In the simulation (Figure 1e), one of coplanar electrode is charged with 1 V and other is grounded. Meanwhile, the volume of outside sensor is much larger than that of the sensor itself. If there is no object outside the sensor, all the electric field lines symmetrically distribute between two electrodes. The relative uniform color indicates a uniform distribution of electric field with electrical potential of \(\approx0.5\) V outside the sensor. Following, the copper sphere is approaching from 100 to 10 mm (Figure 1b), leading to gradual change of potential and distribution of the electric field above the coplanar electrode (Figure 1f copper sphere at 50 mm), thereby change of \(e_{\text{eff}}\) and then the value of capacitor. The high potential points are continuously compressed to the near field area of the coplanar electrode as object approaching (Figure 1f), which guarantees the capability for proximity detection. In this scenario, the capacitive mode is response for the proximity detection.

Once the object contacts with the bump, the contact force will induce the deformation of the structures above the coplanar electrode (Figure 1c), the electric field lines are mainly restrained within the PDMS cover and air gap above the electrode (Figure 1g). The deformation, including the compression of piezoresistive film, PDMS cover and air gap, will lead to change of \(e_{\text{eff}}\) as well as the capacitance. At this stage, the device still works at capacitive mode for these tiny pressures (Figure 1c). Further improving the force size, the large deformation of the piezoresistive film will result in its contact to the coplanar electrode (Figure 1d). In this scenario, the operating model has been changed to resistive model owing to the conduction of piezoresistive film between two electrodes (Figure 1d,h). Above all, the proposed sensor structure can detect the proximity of external object as well as contact force by hybrid capacitive-resistive modes.

Based on the above analysis, the value of \(e_{\text{eff}}\) is a core factor for the capacitive mode and determines the output of hybrid sensor for proximity and small force detection. Although the value of \(e_{\text{eff}}\) is difficult to be solved by analytical method, the finite element analysis (FEA) by COMSOL software will give the numerical solutions. First of all, we carried out COMSOL simulations to determine the structure parameters of the proposed sensor (Figure 2a). The basic capacitance (\(C_0\)) and resistance (\(R_0\)) as well as their relative changes (\(\Delta C/C_0\) and \(\Delta R/R_0\)) were taken as optimized targets. Both the basic value and relative change are critically important for the signal process circuit. Figure 2a illustrates the optimized parameters of the sensor, including the side length, height of sensor unit, number of electrode pairs, electrode spacing, thickness of air gap, and piezoresistive film. Figure 2b plots an increase of \(C_0\) as increasing number of electrode pairs, but a decrease of \(\Delta C/C_0\). Analogously, the \(R_0\) and \(\Delta R/R_0\) show the opposite trend (Figure 2c) compared with those in capacitance (Figure 2b). Therefore, there is a trade-off for optimized number of electrode pair. Thus, four pairs are confirmed in the sensor, in which \(C_0\) and \(\Delta C/C_0\) are larger than 1.0 pF and 20%, while \(R_0\) and \(\Delta R/R_0\) are larger than 1 k\(\Omega\) and 85%. Those parameters are large enough for detection and benefit for the signal process circuit fabrication too. Figure 2d plots a nearly linear increase of \(C_0\) as increase of side length from 7.5 to 20 mm, while...
a total opposite trend is revealed for the \( \Delta C/C_0 \). The similar trend is also found in contact process (Figure S2, Supporting Information). As a result, the side length is defined at 12.5 mm near the crossing point (Figure 2d), in which the \( C_0 \) is larger than 2 pF and \( \Delta C/C_0 \) is greater than 10%. After determining the number of electrode pairs and its side length, the distance between each electrode also has a significant influence on the \( C_0 \) and \( \Delta C/C_0 \) (Figure 2e). The \( C_0 \) decreases by a half as the electrode gap increasing from 0.05 to 0.25 mm, while the \( \Delta C/C_0 \) possesses an opposite tendency in the same range (Figure 2e). Herein, we choose the crossing point of the two curves, which is 0.1 mm for the electrode gap, in which the \( C_0 \) is \( \approx 3.75 \) pF and \( \Delta C/C_0 \) is about 4.5% (Figure 2e). Figure 2f shows the influence of thickness of air gap (\( T_{\text{air}} \)) on the \( C_0 \) and \( \Delta C/C_0 \). It plots an exponential attenuate of \( C_0 \) as enlarging the air gap, while a fluctuation curve of \( \Delta C/C_0 \) around 5.5% is revealed (Figure 2f). Considering the initial value and its variation as well as manufacturing accuracy, the air gap is set at
An enlarged sensor unit displays the layered architecture of the e-skin, we design a 5 × 5 sensor array as an e-skins (Figure 3a). An enlarged sensor unit displays the layered architecture of the five layers (Figure 3b). The size of piezoresistive film is 12.5 × 12.5 × 1 mm³, while the air gap has the same dimension. The bump has a circular section with diameter of 4 mm, leading to the effective contact area of ≈12.5 mm². To realize the designing structure, a mold-casting method following by assembling is employed to fabricate the sensor unit and its array (Figure 3c), which is benefit for the feasible and scalable preparation of e-skins. Among the components, the piezoresistive film is the core part, which determines the sensor performance in the piezoresistive mode. Herein, the synthetic process of the piezoresistive film is illustrated in Figure S4, Supporting Information. It is composed of carbon black in PDMS matrix with different mass ratios, which can be fabricated up to 4 in in diameter (Figure S5a, Supporting Information). The cross-sectional scanning electron microscope (SEM) image (Figure S5b, Supporting Information) shows 1 mm in thickness and a very dense film without shrinkage pores or bubbles, which is benefit for continuous deformations and signals. The surface SEM image exhibits a corrugate surface morphology (Figure S5c, Supporting Information). Above all, the corrugate structure is benefit for large change of the interface resistance once contacting to the coplanar electrode. Figure S5e, Supporting Information, plots the resistivity of the piezoresistive film with respect to mass ratios of carbon black, which exhibits a typical percolation behavior as before with the threshold at 2.5 wt%. The Young’s modulus of the piezoresistive films were accumulated in Figure S5e, Supporting Information (red symbol and curve), showing gradual increase as the mass ratios increase. Furthermore, the electromechanical performances of the piezoresistive film with the carbon black ratio of 2.5 wt% were measured by a two-terminal device configuration. The typical current–voltage curves are accumulated in Figure S5f,g, Supporting Information, with applied forces in the large range of 0.1–450 N. The 450 N is considered as the maximum force that each component of the e-skins needs to withstand according to the standard of ISO15066. Generally, the current gradually increases as the force in the range of 0.1–140 N (Figure S5f, Supporting Information), while decreases as the force in the range of 140–450 N (Figure S5g, Supporting Information). The composite film exhibits a positive piezoresistive effect in

| Electrode pairs | Side length [mm] | Electrode spacing [mm] | Tair [mm] | Tpiezo [mm] | Height [mm] | Diameter of bump [mm] |
|-----------------|-----------------|------------------------|----------|------------|-----------|----------------------|
| 4               | 12.5            | 0.1                    | 1.0      | 1.0        | 3.7       | 4                    |

Table 1. Optimized feature size of the proposal hybrid sensor.

1 mm. Furthermore, the thickness of piezoresistive film (Tpiezo) was optimized in the range of 0.2–2.0 mm. Figure 2g shows a little variation for both C0 and ΔC/C0 values, which indicates they are insensitive to the thickness of the piezoresistive film. For the convenience to fabrication, we also set 1 mm for the piezoresistive film. In this condition, the maximum deflection of the sensor itself is calculated to be 30 μm without external force (Figure S3, Supporting Information), which is far less than the thickness of air gap and does guarantee no contact to the coplanar electrodes without external force or with a little force. That means the change of sensitive mechanism from capacitive to piezoresistive upon the external force can occur if the applied force is large enough. Table 1 illustrates the optimized feature size of the hybrid sensor by theories and simulations.

For the real applications of hybrid sensor in the robotic perception, we design a 5 × 5 sensor array as an e-skins (Figure 3a). The composite film exhibits a positive piezoresistive effect in the piezoresistive mode. Herein, the synthetic process of the piezoresistive film is illustrated in Figure S4, Supporting Information. It is composed of carbon black in PDMS matrix with different mass ratios, which can be fabricated up to 4 in in diameter (Figure S5a, Supporting Information). The cross-sectional scanning electron microscope (SEM) image (Figure S5b, Supporting Information) shows 1 mm in thickness and a very dense film without shrinkage pores or bubbles, which is benefit for continuous deformations and signals. The surface SEM image exhibits a corrugate surface morphology (Figure S5c, Supporting Information). Above all, the corrugate structure is benefit for large change of the interface resistance once contacting to the coplanar electrode. Figure S5e, Supporting Information, plots the resistivity of the piezoresistive film with respect to mass ratios of carbon black, which exhibits a typical percolation behavior as before with the threshold at 2.5 wt%. The Young’s modulus of the piezoresistive films were accumulated in Figure S5e, Supporting Information (red symbol and curve), showing gradual increase as the mass ratios increase. Furthermore, the electromechanical performances of the piezoresistive film with the carbon black ratio of 2.5 wt% were measured by a two-terminal device configuration. The typical current–voltage curves are accumulated in Figure S5f,g, Supporting Information, with applied forces in the large range of 0.1–450 N. The 450 N is considered as the maximum force that each component of the e-skins needs to withstand according to the standard of ISO15066. Generally, the current gradually increases as the force in the range of 0.1–140 N (Figure S5f, Supporting Information), while decreases as the force in the range of 140–450 N (Figure S5g, Supporting Information). The composite film exhibits a positive piezoresistive effect in

![Figure 3. Preparation of hybrid sensor ant its array. a) Schematic illustration of the hybrid sensor array, represented as e-skin. b) Enlarged view and structural component of the sensor unit. c) Process of preparation of hybrid sensor via mold-casting following assembling. d) Digital pictures as-prepared hybrid sensor unit. e) Digital picture of as-prepared e-skin. Scale bar in (e) is 12.5 mm.](image-url)
the small force, while shows a negative piezoresistive effect in the large force. The behaviors could be explained by gradual formation of conductive path upon the low-force regimes and destroyed upon the high-force regimes. After determining the piezoresistive film, the hybrid sensor was assembly fabricated, as shown in Figure 3d. The dimension of the sensor is 15 × 15 × 3.7 mm³ (Figure 3d), which is one unit in 5 × 5 array for e-skins. The final dimension of e-skins is 130 × 130 × 3.7 mm³ (Figure 3e), which is used in the HRC further.

Finally, the performance of the hybrid sensor is detailed and results are accumulated in Figure 4. The capacitance exhibits a linear decrease as object (e.g., human hand) approaching the sensor from 100 to 20 mm, while sharply reduces within 20 mm (Figure 4a). This is a good result both for the researches and applications. The change of capacitance as the object approaching can be explained by the edge effect of coplanar capacitor. The coupling of electric field between object and sensor electrodes (Figure 1a) has a significant influence on the capacitance. The capacitance change (ΔC/C₀) with respect to proximity distance is plotted inset in Figure 4a, which derives two segment linear scopes at least (100–20 and 5–0 mm) with sensitivity of 0.10 and 0.65 mm⁻¹. The long distance of object results in weak influence of electric field of sensor, leading to a small sensitivity, and vice versa. We also notice the fluctuation of capacitance as the object at large distance (e.g., 100–80 mm). Nevertheless, it can be linearly fitted (Figure 4a inset) thereby can detect the object approaching in above range. Figure S6, Supporting Information, plots the capacitance with respect to the proximity distance and applied force. The distance below 0 represents there is a contact force on the sensor. The applied force causes structure deformation, which induces the dramatic change of electric field lines inside sensor and increases the capacitance significantly. Obviously, the capacitance under the contact force is quite larger than that during the approaching process (Figure S6, Supporting Information). Meanwhile, the trend of the capacitance change (ΔC) is totally opposite in the two processes. As a result, the sensor output can be judged from either object approaching or contacting by combining the capacitance and its change.

When the object contacts with sensor surface, the contact force will generate the compression deformation of sensor structure above the coplanar electrode, leading to an increase of

![Figure 4](https://www.advancedsciencenews.com/)<br><br>Figure 4. Performance of the hybrid sensor for long-distance proximity and wide-range force detection. a) The plot of capacitance with respect to the proximity distance. b) The plot of capacitance with the initial contact force in the range of 2–20 N. c) The plot of resistance as the applied force in the range of 20–450 N. d) Response and recovery time for capacitive sensor with contact force of 2 N. e) The continuous response of capacitance under the forces of 1, 2 and 3 N. f) The stability in the capacitive working modes tested up to 1.2 × 10⁴ s. g) Response and recovery time for resistive sensor with contact force of 50 N. The black curves in (d,g) are the applied force step. h) The continuous response of resistance under the forces of 20 N, 50 N, and 100 N. i) The stability in the resistive working modes tested up to 6.0 × 10⁴ s.
between the signal change from 10% to 90% of its capacitance in return (Figure 4b). Because of the viscoelastic feature of PDMS, the sensor has a dull response to the tiny force (0–2 N). The capacitance has an obvious change as applied force larger than 2 N. Further increasing forces leads to fast increase of capacitance with a maximum slope of 17.73 N \(^{-1}\) (Figure 4b inset), respectively. Following, the capacitance becomes saturated at 220 pF with the force between 15 and 20 N, which is about 35 times compared with the initial capacitance. According to the simulation results, the down bent piezoresistive film will contact to the coplanar electrode under 20 N, which induces the transformation of mechanism of sensor from capacitive to resistive mode. The sensitive mechanism conversion has been observed during the experiments. Figure 4c depicts an exponential decay of resistance output of the sensor as the applied force in the range of 20–450 N. The resistance decreases by \(\approx 17\) times from 1.2 to 0.07 M\(\Omega\) in the same range of applied forces (Figure 4c). The rate of resistance variation (\(\Delta R/R_0\)) can be fitted by segment scops, resulting in the maximum slope of 0.65 N \(^{-1}\) (Figure 4c inset). Finally, the range of the sensor can cover 0–450 N by combining the capacitive and piezoresistive modes.

The responsivity of the sensor is measured in both capacitive and piezoresistive modes with contact forces of 2 and 50 N, respectively. Figure 4d,g plots sensor outputs with respect to applied force pluses (black curves). The response and recovery times are calculated to be about 70 and 100 ms for capacitive sensor (red curve in Figure 4d), while they are about 120 and 150 ms for resistive sensor (blue curve in Figure 4g), respectively. Herein, the response and recovery time are defined as the time between the signal change from 10% to 90% of its final value within one step.\(^{[86]}\) It shows a little time-delay response at force of 2 N (Figure 4d), while boosts at force of 50 N (Figure 4g). The delay can be attributed to the viscoelastic feature of both PDMS and piezoresistive films. In addition, the applied force does not have the ideal rectangular pulse shape (black curves in Figure 4d,g), which also causes a delay response. As a result, abovementioned two factors are response for the relative longer response and recovery time. Although the data are slower than those of inorganic sensitive materials,\(^{[57–61]}\) they keep in the similar range to those reported results before for the flexible sensors based on the PDMS composites.\(^{[62–66]}\) Furthermore, the continuous responses of capacitance under the force of 1, 2, and 3 N are plotted in Figure 4e, while the responses of resistance under 20, 50, and 100 N are plotted in Figure 4f. The stable and repeatable response under the all applied forces indicates our sensor has a practicable usage in a large range for force sensing. Finally, the stability of sensor in capacitive and resistive working modes was tested up to 1.2 \(\times\) 10\(^5\) and 6.0 \(\times\) 10\(^5\) s (Figure 4f,i), respectively. Both curves exhibit a very stable cycle in a long turn operation. Specifically, we compare capacitance change at the initial 800 s and last 800 s of the test (Figure 4f inset). The force pulse (loading and unloading cycle) generated from the setup during the test is plotted in black curve, while the response is plotted in red/blue curve (Figure 4f, i, inset). Since the force is applied by the displacement of head of force gauge, there is different loading/unloading time in Figure S7, Supporting Information. Meanwhile, the final forces are 20 and 450 N for the capacitive and piezoresistive modes, respectively. As a result, it shows a better following response for the capacitive mode (Figure S7a, Supporting Information) compared with that in the resistive mode (Figure S7b, Supporting Information). In addition, the response curve indicates the quite good stability and durability of the sensor (Figure 4f). Analogously, the resistive mode also shows the similar stability and durability (Figure 4i). The quite good stability of the sensor both in the capacitive and piezoresistive modes are significantly important for the practice usage in future.

To reveal the practice usage of the e-skins, the basic performance is inspected at a home-made signal process setup (Figure S8, Supporting Information) for object approaching and contact force tests. The initial capacitance of each unit is about 70.19 pF once connecting to the setup. Figure 5a plots a capacitance mapping (bottom) of sensor array when a stainless steel made letter “H” is approaching at distance of 100, 40, and 0 mm (Figure 5a, middle), respectively. The shape of “H” becomes clearer in the mapping as decrease of distance, indicating a good proximity sensing ability of the e-skins. In addition, the same size star-like blocks fabricated with stainless steel, teflon, and silicon, respectively, are put at the same distance of 5 mm, which results in different values of 67.36, 69.38, 68.62 pF in the capacitance mapping with the relative change (\(\Delta C/C_0\)) of 4.27%, 1.39%, and 2.47%, respectively (Figure 5b, bottom). It exhibits an ability of identification of the approaching objects with different conductivities at the same approaching distance. For the contact tests, the capacitance increases with the applied force of 5, 10, and 15 N, which results in increased capacitance of 105.13, 135.87, and 182.93 pF in the mapping with the relative change of 6.19%, 37.24%, and 84.78% (Figure 5k), respectively. In addition, the capacitor values (Figure 5c) increase by 1–2 orders compared with those in the proximity tests (Figure 5a). Further increasing applied force to 150, 300, and 450 N, the resistance decreased to 893.5, 289.4, and 18.6 k\(\Omega\) in the mapping with the relative change of 36.27%, 77.74%, and 98.57% (Figure 5d), respectively. All the mappings (Figure 5a-d) show a clear spatial resolution both in proximity and contact models.

Furthermore, the e-skins (Figure 5e) are attached to the surface of robots for the proximity and contact force sensing and safety control, which shows an ability of stopping as object approaching and backing as object contact occur (Movie S1, Supporting Information). Figure 5f-h shows snapshots of a robot arm (EFORT) attitude during drilling hole, in which the attached e-skin (Figure 5f) can detect the human body approaching (Figure 5g) and backing from the body to avoid collision (Figure 5h), thereby making a safe operating condition for both human and robot. Analogously, the e-skin is applied in ELITE collaborative robot (EC63), which can detect human finger and palm approaching and contacting forces (Movie S1, Supporting Information). The robot can gradually decelerate and stop as human palm approaching, and back at variation of speeds and distances while tiny or large contact forces are applied on the e-skin, respectively (Movie S1, Supporting Information). The motion control behaviors based on the e-skin are highly significant for HRC to make the collaboration more effective, precise and safe in the future. Figure 5i-l shows snapshots of robot with palm approaching, tiny force contact at fingertip, large force at palm, and different approaching position, respectively. Finally, Both the static and dynamic tests prove the capability of sensor array for detecting the external object.
approaching as well as a large range of external force contact, which will be usage in the collaborative robots, safety management in human–machine interaction, and intelligent perception.

3. Conclusion

In summary, we propose a capacitive and piezoresistive hybrid sensor, which can realize long-distance proximity and wide-range force detection. The change of equivalent relative dielectric constant during the object approaching and applied tiny force is a core factor for the sensing of coplanar capacitor. The change of sensing mechanism from the capacitive mode to piezoresistive mode will extend the sensitive range of applied force to 450 N. In addition, the high stability for both proximity and contact force sensing guarantees practical usage in robots. Finally, the e-skins are used for safety control in HRC in two type commercial robots, which exhibits capabilities of detection of long-distance proximity and large-range force, illustrating their potentials for complex, precise, and safe requirement.

4. Experimental Section

**Mechanical and Electronic Simulations:** The finite element method was used in structural mechanical analysis to calculate the deformation of the sensor. Also, the above method was used in static electric field and direct current simulations to get the potential distribution. The simulations were
performed using the commercial software COMSOL Multiphysics (COMSOL Multiphysics 5.5, COMSOL Inc. 2019).

Materials: Carbon black (Ketjenblack EC-600JD) was purchased from Lion Corporation (Tokyo, Japan). Nano-SiO$_2$ was purchased from Yuanjiang Chemical Co., Ltd. (Shanghai, China). Polydimethylsiloxane (PDMS, Sylgard-184) was purchased from Dow Corning (Midland, MI). Comb-shape FPC electrodes were ordered from Ruida Express Co., Ltd. (Shenzhen, China). Teflon molds were ordered from Jizhi Technology Co., Ltd. (Qiqihar, China).

Preparation of Piezoresistive Films: The PDMS was mixed with n-heptane (0.75 mL n-heptane was added to 1 g PDMS, regarded as mixed solution A) and ultrasonically vibrated for 1 h. The carbon black and nano-SiO$_2$ were mixed with n-heptane (the volume ratio of carbon black to n-heptane was 1:3), and then the mixed solution B was ultrasonically vibrated for 1 h. The above solution A and B were mixed to obtain mixed solution, and the ultrasonic vibration was carried out for 5 h. The ratio of mixed solution A and B is determined by the proportion of raw materials in two solutions, respectively. Then the mixed solution was put into a vacuum drying oven for 6 h to completely volatilize n-heptane. After adding the curing agent to the mixed solution, we poured it into the Teflon mold. Then we put the mold in vacuum for 1 h to remove bubbles and scrape it to the specified thickness. Finally, the molds were put into the oven to cure at 80°C for 6 h to get piezoresistive film. The diagram of the corresponding fabrication process is shown in Figure S4, Supporting Information.

Fabrication of Device: Flexible substrates, sealing layer, and bump were fabricated by PDMS with specific Teflon molds. The Comb-shape FPC electrodes were adhered to the flexible substrate by RTV room temperature cured silicone rubber. The bump, sealing layer, piezoresistive film, and flexible substrate were bonded together by surface plasma treatment.

Characterization of Piezoresistive Film: Optical images were obtained using Digital Single Lens Reflex (DS600, Nikon). SEM images were taken with FESEM (S8010, HITACHI). The surface morphologies of the piezoresistive films were characterized by contact-mode AFM (Dimension ICON, Bruker). The mechanical test was carried out with a measurement system containing a motorized test stand connected with a force gauge (ESM1500G, Mark-10). We used the interdigital coplanar electrodes with the dimension of 12.5 × 12.5 mm$^2$, which is the same as that used in the sensor. The force was applied by the commercial equipment (ESM1500G, Mark-10) with a force gauge. The electrical measurements of piezoresistive films were characterized by a semiconductor parameter analyzer (Keitley 4200 A-SCS, Tektronix Inc.) with different sizes of force up to 450 N (2.88 MPa).

Measurements: Optical images were obtained using Digital Single Lens Reflex (DS600, Nikon). The mechanical test was carried out with a measurement system containing a motorized test stand connected with a force gauge (ESM1500G, Mark-10). For the measurement, the object was fixed on the motorized test stand and electrically grounded. The proximity distance was realized via the movement of the motorized test stand. The contact force on the sensor can be read out from the force gauge in real time. The pressure was calculated via the force divided by contact area (i.e., ≈12.5 mm$^2$ for one bump in our experiment) (Figure S5, Supporting Information). The electrical properties of hybrid sensor units were characterized by the LCR digital electric bridge (HG2810B, Huigao Electronic Co., Ltd.). The sensor array was connected to a home-made signal process setup to collect static electrical signals. The dynamic properties were tested on a collaborative robot (EC63, Suzhou Elite Robot Co., Ltd.) and EFOR robot Co., Ltd. (61771156, 52122513), National Science Foundation of Heilongjiang Province (YQ2021E022), Applied Technology and Development Plan of Heilongjiang Province (GA19C008), Millions Major Projects of Engineering Science and Technology in Heilongjiang Province (2019XZ1203), the Fundamental Research Funds for the Central Universities (HIT.BRET.2021010).

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
Research data are not shared.

Keywords
electronic-skins, human–robot collaboration, hybrid sensors, long-distance proximities, wide-range force detection

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Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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