Recent Advances on Capacitive Proximity Sensors: From Design and Materials to Creative Applications

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Abstract: Capacitive proximity sensors (CPSs) have recently been a focus of increased attention because of their widespread applications, simplicity of design, low cost, and low power consumption. This mini review article provides a comprehensive overview of various applications of CPSs, as well as current advancements in CPS construction approaches. We begin by outlining the major technologies utilized in proximity sensing, highlighting their characteristics and applications, and discussing their advantages and disadvantages, with a heavy emphasis on capacitive sensors. Evaluating various nanocomposites for proximity sensing and corresponding detecting approaches ranging from physical to chemical detection are emphasized. The matrix and active ingredients used in such sensors, as well as the measured ranges, will also be discussed. A good understanding of CPSs is not only essential for resolving issues, but is also one of the primary forces propelling CPS technology ahead. We aim to examine the impediments and possible solutions to the development of CPSs. Furthermore, we illustrate how nanocomposite fusion may be used to improve the detection range and accuracy of a CPS while also broadening the application scenarios. Finally, the impact of conductance on sensor performance and other variables that impact the sensitivity distribution of CPSs are presented.

Keywords: active materials; capacitive-based sensor; nanocomposites; proximity sensors

1. Introduction

Flexible electronics have recently experienced extensive applications in the Internet of Things (IoT), human–machine interfaces, robotics, safety protection, human motion tracking, and healthcare systems, among other applications. With the IoT increasingly making its way into thousands of homes, the area of flexible electronic wearable gadgets has also entered a new phase [1]. On the one hand, traditional ceramic/metallic sensors suffer from the limitations of fragile materials, limited size, high cost, and a limited detecting range. On the other hand, the fast advancement of visualization technology, as well as the enormous market for smart devices, has raised the bar for flexible and wearable sensors, requiring excellent performance, mass manufacturing, low weight, and flexibility, among other characteristics [2]. Additionally, flexible wearable technologies hold tremendous promise for health monitoring and nursing applications. Clearly, flexible sensors with great performance will be vital for the implementation of flexible wearable devices [3]. As such, flexible nanocomposites may open the gates for implantable and stretchy devices.

Numerous flexible and stretchy sensors have been created for a variety of applications using micro-electro-mechanical system (MEMS) technology. Strain sensors, for example, detect body motion [4], tactile sensors monitor three-axis item handling/manipulation [5], and proximity sensors assist in detecting objects within a certain range [6]. Among all these applications, proximity detection is a key task that aims to identify information...
about objects that are physically near another object without requiring physical contact. Numerous electronic platforms and industrial equipment need the use of proximity sensors. These sensors are critical components of systems ranging from human–machine interfaces to health care, smart homes, shipping industry, and soft robotics [7–10]. In addition to detecting external stimuli, proximity sensors are anticipated to detect instantaneous and continuous activities such as vibration, inertia, shear force, and normal force [11,12] to meet the requirements of smooth multifunctional interactions. These applications are highly demanded to be expanded in the near future.

To sense objects, a proximity sensor often measures change in either an electrostatic field or some form of electromagnetic field. Hence, they can be categorized into capacitive [13], electrostatic [14], magnetic [15], electromagnetic radiation (infrared) [16], and light (visual) sensors [17]. Another way to classify proximity sensors is to categorize them according to their operating principles as capacitive [18], piezoresistive [19], triboelectric [20], piezoelectric [21], and photo-detecting devices. In comparison to triboelectric and piezoelectric sensors, capacitive and piezoresistive sensors have received substantial research and many similarities in their mechanics are apparent [22]. Piezoelectric and triboelectric sensors, on the other hand, have the apparent benefits of not requiring an external power source and being more responsive to dynamic stimuli. The main characteristics of each proximity detection technique are summarized in Table 1.

| Sensing Technique | Detected Objects | Sensing Element | Operational Range | Standard Detective Circuit | Tangible Limitation |
|-------------------|------------------|----------------|-------------------|---------------------------|-------------------|
| Optical           | Non-conductive and conductive | Lighting resource | Frequency and condition dependent | Converter (V–I) | Lenses and object preparation needed |
| Ultrasonic        | Non-conductive and conductive | Sound producer | Frequency and condition dependent | Digital to analog converter or Sensor modules | Object dependent |
| Inductive         | Only Conductive   | Metal coil     | Coil size dependent | Impedance analyzer, LCR oscillator, | - |
| Capacitive        | Non-conductive and conductive | Conductive electrode fabrication/size dependent | Conductive electrode fabrication/size dependent | Charge amplifier, RC low pass filter, capacitance meter | - |

Inductive sensing can detect conductive and/or ferromagnetic objects, and the maximum scanning range is typically about equal to the sensing coil’s diameter. While both optical and ultrasonic techniques are capable of detecting non-conductive and conductive items, implementing a complicated light source or a sound wave actuator on fabric is challenging. Additionally, the detection range depends on the object’s surface polish and material quality. Because the capacitive proximity sensors detect both conductive and non-conductive objects, they are well-suited to identify humans and passive objects. Additionally, the capacitive technique is easy to set up and usually requires fewer components than other sensing systems. It is the most suited mechanism for printed implementation since it allows for the use of a simple conductive electrode of any shape as the sensing element. A basic sensing element of any shape is useful for creative applications since the sensor may be customized to any artistic shape required by the designer. Capacitive proximity sensors (CPSs) have been used in a variety of applications to date, including determining the aging of composite insulators [23], estimating the permittivity and thickness of dielectric plates and shells [24], measuring tire strain in automobiles [25], force sensing in biomedical applications [26], liquid level detection [27], and harvest yield monitoring [28].

CPSs, in comparison to other proximity sensors, have a number of advantageous qualities, including affordable construction cost, low energy consumption, broad monitoring range, excellent dynamic response, and a flexible and changeable structural design [29].
Additionally, CPSs may respond more strongly to static stimuli, and their mechanisms and production methods are relatively straightforward [30]. CPSs have gained considerable attention among researchers in the past few years, as Figure 1 suggests.

The numbers in Figure 1 were obtained after a thorough exploration of search engines such as the Elsevier Online Library, Google Scholar, Web of Science, IEEE digital, and a few publications such as Wiley, Taylor & Francis, etc. We searched through peer-reviewed journals, technical bulletins, textbooks, and dissertations. The following keywords were used to compile the databases through an iterative process of research: “proximity sensors”, “piezoelectric and triboelectric sensors”, “displacement sensing”, “proximity detection”, and “occupancy-based control in HVAC”. This research aims to provide standard terminology and taxonomy that will serve as a unifying framework for all engineering disciplines involved in the design and construction of capacitive proximity sensors.

Given the importance and numerous applications of CPSs, there is a lack of a thorough review study to highlight the recent progress and publications. Ref. [31], which is the closest match to the present study, was published in 2019 and many investigations have been performed since then, necessitating the need for a fresh review article. Ever since, a substantial body of research has been conducted on this topic, necessitating a need for an up-to-date review paper examining the most current state-of-the-art procedures. Nonetheless, extensive research on the variations of materials and technologies used for CPSs and their applications under various criteria has not been adequately addressed. The majority of previous literature is focused on closed-form mathematical modeling of CPSs, ignoring the materials employed in the production process. We want to bridge this gap by addressing current advancements in the manufacturing of CPSs. An overview of modeling approaches with their strengths and weaknesses, categorization of construction methods, design parameters, and constraints imposed by different applications are among some of the highlights of this review article. This study is rather different from previous publications as it addresses these issues and incorporates more recent publications and it provides a detailed picture of many factors related to proximity sensors. The evaluated articles are examined from various angles to illuminate their limitations across several aspects. This article will also assist in highlighting the present state of research on CPSs and any research gaps that have yet to be discovered.

2. Capacitive Sensing: Principals and Applications

A capacitive sensor functions similarly to a standard capacitor. A metal plate on the detecting face of the sensor is electrically coupled to an oscillator circuit, while the target to be detected serves as the second plate of the capacitor. In contrast to inductive sensors, which generate a magnetic field, capacitive sensors generate an electrostatic field. External capacitance between the internal sensor plate and target plate contributes to the oscillator
Capacitive sensing follows the principle of an interaction between a material under test and the probing electric field. A sensor-electrode-generated electric field penetrates a sensed object, causing electric displacement inside the tested material to counteract the applied field. The displacement pitch modifies the stored charge between those electrodes, thereby altering the inter-electrode capacitive field, which is used to infer the material properties, such as permittivity, conductivity, and their distributions, and ultimately to derive system variables such as temperature and humidity. As such, a CPS is usually made up of two electrically conducting electrodes that are connected through a potential difference to produce an alternating electrostatic field. When a targeting object moves near to the sensor, this field is disrupted, and the change in capacitance indicates the item’s vicinity (self-capacitance if one electrode is utilized, as seen in Figure 3 on the right, or mutual capacitance if two electrodes are used, as shown in the left side of Figure 2). Thus, CPTs are capable of detecting the existence of any solid, metallic, or nonmetallic object by altering the capacitance of the sensor [32]. It is worth noting that different sensor combinations, geometries, and designs have been customized to meet various application requirements.

![Schematic of a capacitive proximity sensor.](image)

**Figure 2.** Schematic of a capacitive proximity sensor.

Generally, a driving electrode is used to provide an electrical stimulation, whereas a sensing electrode is used to collect data. Typically, the frequency of the electrical stimulus, and hence the produced alternating electric field, are restricted. For example, the Agilent 4294A precision impedance analyzer operates between 35 and 105 MHz. Therefore, the relative permittivity and conductivity are only characterized in this frequency range [33].

![Schematic of two basic CPT sensors.](image)

**Figure 3.** Schematic of two basic CPT sensors [31]: (a) mutual capacitance sensor, and (b) self-capacitance sensor.
Table 2 shows a few applications for the capacitive sensors implemented in previous literature. The capacitance of the circuit changes as the sensible object moves away from the electrodes. While capacitive displacement sensing may be used to measure distance, displacement, and position, the detection range is limited by the size and dielectric constant of the detected object. Additionally, by putting multiple electrodes in a regular pattern, one can discern the object’s position, movement direction, and certain interaction intents expressed by the movement trajectories of a human body. Numerous applications for this sensing mode have been suggested, including electrical capacitance tomography [34], capacitive voltage sensors [35], capacitive humidity sensors [36], and capacitive gas sensors [37]. For example, electrical capacitance tomography is largely utilized for non-invasive imaging, with capacitance measurements used to determine the dielectric permittivity distribution inside inaccessible domains [34]. Additionally, based on the underlying features of the electrodes and certain transformation associations between the electrode distortion and the observed physical variables, it is easy to infer the force, acceleration, or actions of the subject human as the muscle moves from the displacements. The capacitance changes generated by electrode deformation are used to determine acceleration [35], angles [36], force [37], displacement [38], and muscle action for interaction [39].

Table 2. Some of the practical applications associated with capacitive sensors.

| Reference | Application                      |
|-----------|----------------------------------|
| [34]      | Electrical capacitance tomography |
| [35]      | Capacitive voltage sensors       |
| [36]      | Capacitive humidity sensors      |
| [37]      | Capacitive gas sensors           |
| [38]      | Displacement detection           |
| [39]      | Muscle action for interaction    |

In Refs. [40–43], CPSs are offered as a viable cost-effective and nondestructive alternative to optical sensors for a broad variety of applications involving the examination of geometrical and physical properties. Their sensitivity, on the other hand, is affected by moisture and temperature. Additionally, parasitic capacitance and noise from external disturbances may affect the response of capacitive sensors, necessitating proper shielding of the device and design of the readout circuits. Capacitive proximity-sensing methods have been extensively used for the nondestructive evaluation of materials with poor conductivity [44].

Capacitive sensing methods have also been utilized to monitor the structure healthy state of a concrete slab retrofitted with composites by detecting the local fluctuation in the dielectric characteristics of the materials under test [45]. The proximity capacitive approach was used by El-Dakhakhn et al. [46] to identify empty cells in grouted masonry buildings. A concentric coplanar capacitive sensor was designed for quantitative material property assessment of multilayered dielectrics [47], and the suggested approach for detecting water incursion in random constructions was experimentally confirmed. Additionally, the outer insulating layer of electric wires is often made of a low-conductivity substance. Capacitive sensing methods have been used to characterize the insulation qualities of cables. Chen et al. [48] developed a capacitive probe for determining the permittivity of wire insulation, and tests established the possibility of determining the state of wiring insulation deterioration using quantitative capacitive approaches. The introduction of proximity-coupled interdigital sensors to detect insulation degradation in power system cables confirms that the proximity capacitive approach is sensitive to the existence of holes and water trees in a power line cable [49]. Sheldon et al. [50] designed an interdigital capacitive sensor to detect aircraft wire aging damage and experimentally confirmed the capacitance fluctuation caused by aviation fluid immersion. Figure 4 shows a few CPSs used in traditional applications, as well as creative industries.
Figure 4. Application of proximity sensors proposed by Refs. [12,15,19,24,47]: (a) solid-shell curvy model, (b) 3D-printed thermoplastic polyurethane (TPU)/PVA model, (c) 3D printing a shell model before wiring, (d) signal of relative capacitance as measured by a choker sensor while the phrase “melody” is repeated four times, (e) recording pulse signal when a fiber-sensor is attached to the wrist, (f) optical images demonstrating the resulting flexible conductive films, (g) PAM (white) and PAM-FGO (black) fragments in optical photos of the healed specimens, (h) the PAM-FGO film-based proximity sensors allow for remote monitoring of human movements, (i) image of a graphene electrode-based wearable capacitive touch sensor, (j) optoelectronic characteristics of capacitive sensor, and (k) bendability and wearability of the proposed sensor.
3. Design, Materials, and Fabrication of CPSs

The most often used electrode configurations for capacitive sensing are planar parallel plate electrodes and co-planar electrodes (also called capacitive proximity sensors). Capacitive proximity sensors operate on the basis of the fringing electric field effect. In comparison to the traditional parallel plate capacitor, capacitive proximity sensors have several advantages, including one-sided access (the other side can be open to the environment), easy control of signal strength via dimension changes, multiple physical implications in the same structure (magnetic, acoustic, and electric), and a broad frequency range of operation. As a result, they are extensively employed in a variety of sectors, including humidity sensing, monitoring material qualities, chemical sensing, biosensing, and sensing of electrical insulating properties [51,52].

According to research, the electrode designs and parameters have a significant effect on capacitive sensor performance metrics such as signal intensity, diameter, sensitivity, and signal-to-noise ratio, which all impact the detecting capabilities of capacitive proximity sensors. Numerous improvements have been made to the performance of capacitive proximity sensors [53,54]. Various sensor designs were explored, including square-shaped, maze, spiral, and comb patterns. It was found that complex sensor patterns may increase the effective electrode area, hence increasing sensor signal and sensitivity [55]. Rivadeneyra et al. [56] designed a serpentine structure that combines meandering and interdigitated electrodes to increase signal strength and sensitivity. For humidity measurement, a capacitive sensor with an interdigital electrode arrangement and an enhanced height was built [57]. In comparison to the conventional interdigital electrode sensor, the suggested sensor demonstrated increased sensitivity because of the confinement of horizontal electric field lines in the polyimide sensing layer. Syaifudin et al. [58,59] investigated the effect of electrode configuration on capacitive proximity-sensor performance and discovered that the optimal number of negative electrodes between two adjacent positive electrodes can increase chemical detection sensitivity. A few petal-like electrode devices were constructed for water detection in an automated windshield system [60].

To enhance the flexibility and wearability of CPSs, flexible electrodes and dielectric layers made of polymer elastomers such as polyethylene terephthalate (PET) [61], polydimethylsiloxane (PDMS) [62], polyvinyl alcohol (PVA) [63], polyimide (PI) [64], polyvinylidene fluoride (PVDF), and Eco-flex [65] are frequently used [66]. Pressure sensitivity of these flexible substrates still needs improvement. As a result, a straightforward approach for introducing conductive fillers into the dielectric layer of polymer elastomers has been widely researched [67]. Due to the percolation threshold hypothesis [68], the inclusion of a conductive filler may raise the dielectric constant under applied pressure, resulting in a change in capacitance [69]. Additionally, the sensor’s noncontact detection mode enables it to recognize and monitor the form and location of an item without a physical touch and interaction with the surrounding environment, highlighting the sensor’s particular capabilities. Zhang et al. [70] produced a stretchy dual-mode sensor array capable of detecting a 4% relative capacitance fluctuation at a noncontact distance of 10 cm. Sarwar et al. [71] described a transparent touch sensor developed on a hydrogel electrode with a maximum capacitance corresponding difference of 15% in absolute value. Due to the structure and material properties of the classic film- or resin-based capacitive sensors, their low air permeability is incompatible with sweat evaporation for wearable electronic application, thus impeding long-term deployment of such devices for wearable electronics. As a result, flexible capacitive sensors with a high degree of breathability are still required to increase comfort and durability.

Textile-based capacitive sensors have been claimed to increase the permeability of flexible capacitive sensors owing to their low weight, flexibility, deformability, comfort, and softness [72,73]. By depositing PDMS on the surface of the conductive fiber as a dielectric layer and vertically stacking the two PDMS-coated fibers, Lee et al. [74] created a highly sensitive CPS. Chen et al. [75] electrospun the nylon dielectric constant and electrode to create a CPS that can detect human joint motion with high accuracy. As a result,
textile-based CPSs are favored for achieving durability, flexibility, multifunctional sensing capabilities, and comfort all at the same time, making them an important research topic in the field of flexible and wearable CPSs.

Nonetheless, the construction process of some CPSs is barely documented, particularly for fabric-based CPSs with multifunctional sensing. Table 3 summarizes some of the studies that report the construction processes of their proposed sensors in a detailed manner.

Table 3. Summary description of few CPS studies with manufacturing details, CDC (capacitance-to-digital converter), PCB (printed circuit board), and LCR (inductance, capacitance, resistance).

| Reference | Application | Shape/Size | Measuring Range | Shielding | Error or Resolution | Method of Measurement |
|-----------|-------------|------------|-----------------|-----------|---------------------|-----------------------|
| [44]      | Inductive and capacitive sensors integration | 20 mm × 5 mm | 10 mm | × | - | Resonance |
| [45]      | Ultrasonic and capacitive integration Two arrays of 16 × 16 electrodes | 60 mm × 30 mm × 0.1 mm | 200 mm | ✓ | 30 mm | CDC:AD7143 |
| [63]      | Woven-polyester fabric, printed on a standard Temperature and capacitive sensor combined | 5 mm × 100 mm Rectangle | 170 mm | ✓ | - | 200 kHz charging circuit |
| [64]      | Symmetrical distribution of electrodes—circular shape | 180 mm × 180 mm × 3 mm Spiral | 80 mm | × | 0.5 mm | CDC:MTCH112 |
| [67]      | Moving target detection CPS | 7 mm × 3 mm × 0.1 mm Rectangle | 17 mm | ✓ | - | CDC:AD7746 |
| [73]      | Equally distributed sensors (120°) | 310 mm × 190 mm | 60 mm | ✓ | 5 mm | LPF, C/V circuit |
| [76]      | 45 mm × 45 mm Circular | 55 mm | ✓ | 0.3–4.6% | LCR meter |
| [47]      | 85 mm × 40 mm Single | 336 mm | ✓ | 3.3 mm | Neural Network |

In this context, a 3D honeycomb, which consists of a supporting yarn layer and two independent mesh-knitted textiles, has been suggested because of its great wearing comfort and compression, making it a viable material for flexible CPSs [76]. In this context, Ref. [77] described the construction of a bimodal fabric-based CPS using a practical and affordable manufacturing process. The suggested sensor was made out of a 3D honeycomb fabric dielectric surface (weight: 220 g/m², thickness: 3 mm) and bottom and top conductive Ni-plated woven electrodes, giving it a high sensitivity for noncontact detection with a detection distance of 10 cm and a maximum relative capacitance change of 15%. Furthermore, at the short distance range (≤3 cm), a maximum sensitivity of 0.022 cm⁻¹ is obtained. When a hand is hovered at various distances, the capacitance fluctuations are consistently maintained, proving the proposed sensor’s stable noncontact detecting response. Furthermore, when the finger is hung above the sensor array unit, the capacitance change rate of the corresponding sensor unit is 9%. This demonstrates that the proposed fabric-based sensor array can precisely detect the finger and provides outstanding noncontact spatial response.

In another study, the authors described a hierarchically porous silver nanowire-bacterial cellulose fiber that can be used to sense both the pressure and closeness of human fingers [15]. The conductive fiber was made by continuous wet spinning at a speed of 20 m/min, and it had a diameter of 52 cm, an electrical conductivity of $1.3 \times 10^4$ s/cm, a tensile strength of 198 MPa, and an elongation strain of 3% at break. To create the fiber sensor element, which is thinner than a human hair, the fibers were coaxially coated with a 10 cm thick poly(dimethyl siloxane) dielectric elastomer. The capacitance variations between the conductive cores in response to closeness were monitored using two fiber-based sensors that were arranged diagonally. The suggested sensor was found to be very sensitive to objects up to 29 cm away. In addition, the fiber may be simply sewed into
clothes as pleasant and stylish heartbeat and voice-pulse sensors. A fiber sensor array may be used to play music and correctly identify the closeness of an item without the need for a touchpad. A two-by-two array was also shown for detecting faraway objects in two- and three-dimensional space.

A recent study looked at the usage of a noninvasive omnidirectional CPS developed in-house as a possible option for human–machine interaction applications [78]. The performance of the proposed sensor was compared to that of infrared, time-of-flight, and ultrasonic sensors, all of which are routinely employed in comparable applications. The suggested sensor is based on a heterodyning approach employed in theremin, which consists of two digital oscillators, one of which is coupled to a sensing (conductive) plate (primary/sensing). If a grounded item enters the detecting range, the oscillator’s total capacitance rises, affecting the frequency of the produced square wave. In our tests, we employed a $10 \times 10 \text{cm}^2$ thin copper PCB square as a sensor plate. The detecting plate is linked to the main oscillator, which has a fixed $10 \text{k}\Omega$ resistor in the feedback line. Any grounded item put within the sensing range will add capacitance to this oscillator, causing it to shift frequency by some amount. A measuring system is built to verify the performance, as shown in Figure 5. The camera is used to compute the displacement of the user’s hand from the sensor module in this arrangement. They concluded that the sensing mechanism may be extended to all directions surrounding the detecting element by using an omnidirectional CPSs, such as the one described in their study. In addition, the suggested capacitive sensor’s range (4–11 cm) is greater than that of comparable capacitive sensing technologies. The power usage was further decreased to 5 mW by duty-cycling the power supply while still allowing 50 readings per second to be acquired.

Figure 5. Measurement setup proposed by Ref. [78] for CPSs.

To advance contactless measurement, some research has been conducted on incorporating the proximity-sensing function of nanofillers into applications for other kinds of sensors, such as touch, pressure, and strain sensors, which are gaining growing popularity in wearable electronics [79–88]. Table 4 summarizes the key characteristics of modern CPSs coated on a variety of flexible polymeric substrates using nanostructured particles/fillers. As previously stated, only a few flexible nanocomposite polymeric CPSs with a broad detection range exist.
Table 4. Summary description of a few CPS studies with manufacturing details. A summary of the fundamental properties of flexible capacitance-type proximity sensors enhanced with nanomaterials. PET stands for polyethylene terephthalate that is ultrathin FPCB is for flexible printed circuit board. CNC stands for cellulose nanocrystals. GO is for graphene oxide, PDMS stands for polydimethylsiloxane, AgNWs stands for silver nanowires, CMC stands for carbon microcoils, MWCNT stands for multiwall carbon nanotube, and ms stands for millisecond.

| Reference | Active Materials and Substrate | Response Time (1 pF) | Shape/Size | Sensitivity $\frac{\Delta C}{c_0}$ mm $^{-1}$ | Operational Range | Error or Resolution | Other Features |
|-----------|-------------------------------|---------------------|------------|---------------------------------|------------------|-------------------|----------------|
| [15]      | AgNW–BC/PDMS fibers           | <75 ms              | 53 µm Diameter 10 µm | 0.19 (Skin) | 30 cm | 1 mm | Proximity and Pressure, bacterial cellulose coated with PDMS, Wet spinning for compressibility |
| [16]      | CNC-mGO-epoxy GO (conducting particles) | -                   | 1 x 2 cm$^2$ 0.16 mm | 7.8 (Skin) 0.0 (Copper and plastic rod) | 0.6 cm | 0.6 mm | Durability of the touch sensor (100 cycles at the distance of 0.02 cm), Excellent stability and repeatability, Average recovery time (3 s) |
| [10,82]   | PET-PDMS-AgNWs AgNWs (electrodes) | <40 ms              | 7.5 x 2.5 cm$^2$ 1 mm Thickness | 0.06-0.12 (Skin) | 9 cm [10] 14 cm [82] | 4.8 mm | All pressure sensing Reversibility (up to 100 kPa) [92] and (50% strain) [10], Stability (2 h), Bending stability (310 cycles and $r_1 = 3$ cm) [10] |
| [24]      | Graphene, acrylic PET, PET (mesh-structured), Graphene (electrodes), Acrylic polymer (dielectric layer) | <60 ms              | 6 x 4 cm$^2$ 8 x 8 Channels 0.03 mm | 0.66 (Iron) 0.10 (Skin) 7 cm (Skin) | 5 mm | | Touch sensing Searchability~9–16% (r_b = 0.15 cm) |
| [33]      | AgNW-PDMS AgNWs (electrodes) PDMS (dielectric layer) | <40 ms              | 800 x 2500 µm$^2$ 3 µm Thickness | 0.16 (Skin) | 15 cm | 5 mm | Durability (200 cycles in 100 kPa), All pressure sensing Reversibility |
| [63]      | PCB                           | -                   | 0.7 x 0.3 cm$^2$ 16 x 16 sensor array | 0.18 (Steel) | 8 cm | 1% output frequency | switched-charge amplifier and sampling/filtering for noise rejection, |
| [67]      | CMC-MWCNT-silicone CMC (elastomer composite sheet) | -                   | 3.3 x 3.3 cm$^2$ FPCB electrode 0.6 mm | 0.10 (Copper) | 6 cm | 2 mm | Inductive and capacitive sensing modes, Repeatability and reversibility (5 cycles), Durability (3000 cycles for 150 kPa), Maximum detection 1.5% |
| [74]      | PDMS Copper Electrodes        | -                   | 600 x 600 µm$^2$ 16 x 16 capacitor array | 0.5 (Plastics, PVC, Acrylic, HDPE) | 17 cm | 0.5 mm | Dual-mode functioning custom circuit board, many possible variations of the electrode configuration |
| [78]      | -                             | <16 ms              | -            | 76% less conductive ink via loop design, Microchip MTCH112 to simplify the circuit |
| [81]      | Fabinks TC-C4001, Polyester woven | <30 ms              | 0.4 x 0.4 cm 30 µm | 0.79 (Skin) | 0.1–40 cm | 0.5 mm | Energy efficient using duty-cycling power supply, boot-up self-adjustment mechanism via digital potentiometer, Wide variety of applications |
| [75]      | Micro-Electro-Mechanical      | -                   | sensors size 500 x 50 µm$^2$ electrode width of 10 µm | 0.8 (Skin) | 10–10,000 µm 0.48 fF/µm | | Conductor or nonconductor measuring, batch fabricated via Micro-Electro-Mechanical, Micro sensor size, Capable of measuring permittivity |
| [87]      | PET-PDMS CP coating           | <100 ms             | 10 x 10 cm$^2$ 5 grid lines Effective line width 3.3 mm | 0.5 (Skin) | 13 cm | | High flexibility (2 cm), Transparent (90%), Can detect several stimuli, Pressure touch, Minimal noise |
| [88]      | TPU-CNT                       | <30 ms              | 6 x 2 cm$^2$ 0.5 mm | 0.3 (Brass, Skin) | 2–22 cm | 0.3 mm | Excellent detection range, Reasonable flexibility and durability |
In Refs. [19,79], a new form of conductive flexible film is developed using self-healing polyazomethine (PAM) and functionalized graphene oxide (FGO) as conductive fillers. PAM-FGO conductive films were made by using imine bonds to crosslink the PAM polymer chains with the FGO. With a skin-like elongation of 200 percent and elastic moduli of 0.75 MPa, the conductive films produced demonstrated excellent flexibility. Furthermore, the papered conductive films showed an excellent intrinsic self-healing capability that benefited from dynamic covalent interactions, with an important role in enhancing mechanical properties and electrical conductivity as high as 95 percent, respectively, after healing the fractured sample for 24 h at 25 °C. Importantly, strain sensors based on the PAM-FGO conductive film showed ultrahigh sensing sensitivity, with GF up to 641, and could detect large-scale human movements and delicate physical signals with accuracy. Because of its ultrasensitive capabilities, proximity sensors based on the organic film field-effect transistor architecture could record human movements from a distance of up to 1 m. This research can pave the way for the creation of multifunctional soft materials. Sensors based on the FGO-PAM film have a wide range of applications in wearable electronics, health diagnostics, human–machine interface, and security protection.

Ref. [80] describes the dispenser printing of a CPS on a woven cloth made entirely of polyester. Three electrode designs, spiral, filled, and loop, are reviewed and contrasted to determine a trade-off between ink consumption and maximum detection distance. To facilitate operation, a simple detecting circuit based on a proximity sensor chip is constructed. Three patterns with identical exterior dimensions were used to investigate the effect of sensing electrode design on performance. A commercially available CPS integrated circuit (IC), the Microchip MTCH112, is chosen to obtain the proximity sensor functionality. The MTCH112 supports a maximum input capacitance of 41 pF and may be set to offer two independent CPSs channels or one sensor channel plus an active guard electrode to mitigate the effects of external electrical noise. The linearity (maximum detection distance correlation coefficient with the proximity sensor width) of the sensing circuit is determined to be 0.8 after testing printed CPS with varied diameters ranging from 1 cm to 40 cm. A broad detection range indicates that the proximity sensor is capable of interacting with humans in big-scale creative applications.

Using an extremely transparent material, Ref. [81] investigated the continuous response of pressure and proximity sensing. The sensor functions by detecting the capacitance change between two transparent silver nanowire electrodes. A sandwich construction was used to construct the capacitive sensor. The substrate was a polyethylene terephthalate (PET) sheet with parallel electrode stripes printed on it. Two of these PET substrates were connected together using an elastic polydimethylsiloxane dielectric layer with orthogonal top and bottom electrode stripes (row-and-column electrodes). Throughout their tests, the authors encountered a constant issue: the development of ghost points for multi-point object recognition, which occur from virtual intersections in places other than the actual locations of the items. To examine the sensor’s reaction performance, the capacitance fluctuations as a finger approached and moved away for four cycles was depicted; the device demonstrated excellent reversibility and stability with a rapid response, allowing for accurate proximity detection.

Refs. [74,82] describe a modular dual-mode capacitive sensor for robot applications that combines touch and proximity-sensing capabilities into a single platform. The sensor is composed of a PDMS (polydimethylsiloxane) mechanical framework and a mesh of numerous copper electrode strips. The suggested sensor is capable of switching between tactile and proximity sensing modes or vice versa by simply rearranging the electrode connections. Through simulation of numerous two-dimensional models, the capacitance shift produced by an approaching item was calculated. For proximity measurement, we evaluated a variety of materials ranging from conducting metals to a human hand. The built sensor was capable of detecting a human hand up to 170 mm distant. Additionally, the authors successfully showed the viability of the
suggested sensor operating in dual modes in real time by using a custom-designed PCB, and a data-collecting pad.

Ref. [83] demonstrated an electronic skin equipped with CPSs. They incorporated carbon nanotube forests, which serve as the sensing element, into a transparent and flexible artificial skin through a simple and inexpensive manufacturing technique. The electronic skin exhibited a high capacitance and sensitivity, allowing for easy detection of proximity using specialized laboratory equipment and commercially accessible on-chip circuits. At room temperature, the capacitance between the electronic skin and two CNT forest sensing devices was continually monitored. They plotted capacitance against the vertical distance between the grounded electrode and the electronic skin, as seen in Figure 6. The maximum vertical gap considered in this study is 10 mm.

![Figure 6. Measured capacitance versus the vertical gap of the proposed CPS in Ref. [83].](image)

In reference [24,84], a CPS with excellent sensing capabilities in both contact and non-contact modes is described. This is made possible by the use of graphene and a thin device architecture. The resultant graphene-based three-dimensional sensor is directly attached to deformable human body parts such as the palms and forearms and demonstrated high stretchability (15%) and reasonable sensing performance in noncontact modes (22 dB SNR at a 7 cm distance). They demonstrated a three-dimensional mapping graph of relative capacitance changes across three distinct distances between the item and sensor in this setting (0.5, 1, and 1.5 cm). The depicted surfaces represent the results of the mapping of relative capacitance changes from the $8 \times 8$ capacitive sensor array. Their findings are shown in Figure 7.

![Figure 7. 3D representation of capacitance changes for three shapes: cone, ring, and sphere [24].](image)

Ref. [85] describes a flexible CPS with great transmittance and sensitivity. An interdigital capacitance (IDC) structure is developed using a polydimethylsiloxane (PDMS) sensing layer to cover indium tin oxide (ITO) electrodes interdigitated on a polyethylene-terephthalate (PET) substrate. They studied the pressure and proximity sensing capabilities
A dual-mode array sensor based on carbon micro-coils (CMC) on a soft dielectric elastomer surface layer is presented in [86]. It uses variations in inductance to determine the distance to an item. Numerous tests on dielectric substrates, electrode structures, and target objects are carried out by varying the electrical impedance created by CMC when excited with an alternating current at a dominating excitation frequency of 90+ kHz. The authors proved the performance of their 10 × 10 proximity tactile sensor, which is able to detect a 30 mg droplet at a maximum distance of 15 cm from the metal object.

In Refs. [47,87], the crackling templating approach was used to fabricate a flexible CPS panel. The metal-mesh electrode was pixelated into interlocking diamond patterns on flexible PET using a mask created by laser-printing toner. The dielectric material was a thin (30 m) PDMS layer. Although their suggested sensor is versatile and innovative, they do not discuss the specific properties of proximity sensing.

A polymer-based sensor with a nanostructure composite sensing element has been constructed for use in healthcare and automotive applications [88,89]. A probing station was used to apply distances ranging from 2 to 20 cm. To determine the maximum change in capacitance, the samples were saturated with 6 V direct current to eliminate the tunneling effect. Additionally, a 25 mV alternating current swiping signal was used to determine the film’s capacitance at various frequencies. The CPS has a detection range of 12 cm and a precision of 0.3 percent/mm. Tunneling and fringing effects are studied to explain substantial capacitance shifts as sensing mechanisms. Percolation threshold investigation of various TPU/CNT concentrations revealed that nanocomposites containing 2% carbon nanotubes had outstanding sensing capabilities, achieving maximum detection accuracy with the least amount of noise. In this context, Figure 9 summarizes the platform setup, the sensor construction, and the results associated with some of the references studied so far. A modeling of capacitive proximity sensors using the Laplace’s equation has been analytically solved and proven to be a fast and reliable technique to obtain the capacitance of a CPS [90].
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Figure 9. Measurement setup and the results proposed by Refs. [15,79,81,88]: (a) touchless piano being played optically with a human finger hovering 40 mm above the keyboard, (b) schematic representation of sensor sensing, (c) increase in relative capacitance with response to an approaching object, (d) performance comparison of the proposed setup with previous works, (e) printed proximity sensors on fabric with filled design, (f) printed proximity sensors on fabric with spiral design, (g) printed proximity sensors on fabric with loop design, (h) maximum detection distance as a function of the proximity sensor width, (i) capacitance change simulation via COMSOL, (j) sandwich structure of CPS with the AgNWs stripes serving as the row and column electrodes, placed orthogonally on the top and bottom PET substrates, (k) capacitance variation as a function of vertical distance from the intersection, (l) contour graphics depicting the estimated capacitance change profile of a center pixel and its four closest neighbors with varying degrees of sensitivity, (m) proximity sensing depiction of two metal bars, the intersections of which are denoted by dashed black boxes, (n) relative capacitance change vs. response time during four cycles, (o) a schematic representation of a TPU/carbon nanotube proximity sensor configuration, (p) noise minimization using semi-planner 45° probes, and (q) mutual capacitance becomes apparent when an item is moved near to the sensor. Shunting the initial electric lines results in a highly strong and distributed fringing field between the object, film, and probes, resulting in a dramatic decrease in capacitance. (r) Comparing the maximum sensitivity of various weight percentages of carbon nanotubes (CNTs).

4. Opportunities and Challenges

Although CPSs have grown in popularity over the past decade because of their attractive features, several issues have remained persistent. The following issues can be further explored to forward the progress of CPSs:
As the literature survey suggests, the integration of CNTs into TPU have the potential to outperform other flexible CPS designs. However, fabricating a flexible nanocomposite tailored to desired performance and functionality is not addressed primarily because of the lack of basic understanding of microstructure formation from the molecular level to higher scales. Integrating CNTs into polymer composites often involves time/cost-inefficient processes that lead to inhomogeneous dispersion of CNTs, weak interfacial bonding between polymer and CNT, and damage to the sidewalls of CNTs that alter their intrinsic properties. Therefore, there is a need for a transformative strategy in the processing and manufacturing of CNT-based polymer nanocomposite flexible capacitive sensors to overcome these limitations. However, there are few reported applications of incorporation of CNTs in TPU-based nanocomposites for proximity sensing.

Meanwhile, because the detection range of CPSs is highly dependent on the size of the electrodes, they must have a particular size to allow for a good detection at a significant distance. In the absence of sufficient contact distance, the sensors’ use may be restricted. Typical methods for boosting the detection range include expanding the electrode size and optimizing the interface circuit’s performance, although these measures have only a marginal impact. Additionally, a sensor array system requires a compromise between resolution and detection range. Recent research provides intriguing examples, such as combining it with another detection approach, such as ultrasonic and inductance sensors, or fusing several detection techniques (e.g., CMUT). This method may provide high-quality sensing and a wide detection range. In the meantime, a quicker reaction time of the capacitance measuring circuit is required to fulfill the demand for real-time performance, since the working electrodes must flip numerous times throughout the measurement period.

Last but not least, CPSs are sensitive to their surroundings (changes in ambient variables, such as temperature, humidity, or illumination; or changes in the presence or location of interior items), which may impair sensor-data accuracy. Post-processing raw sensor data, rather than the converted discrete distance, may effectively decrease sensor-data variability and noise caused by deployment-specific environmental variables. As a result, significant effort will be required to address these critical concerns and challenges. Regarding future study, the authors believe that the combination of object distance characteristics with machine/deep learning methodologies is one of the most promising and leading research topics.

5. Conclusions

In this study, the current level of knowledge about the role of CPSs operating in the displacement sensing mode is summarized. CPSs are simple, inexpensive, and very energy efficient, and may be installed under any nonconductive shielding. It is necessary to describe and categorize these applications as has been done in this review article by addressing the most pertinent literature on the approaches to CPS applications. Another objective of this article is to further stimulate academics and developers to explore broader application possibilities. It is possible to expand the investigation of CPSs in the areas of object detection and human interaction in the future. Particularly since they do not compromise user privacy and require touch, the application of capacitive displacement sensing in intelligent devices cannot be overlooked and has considerable future potential. Meanwhile, capacitive technology continues to confront a number of obstacles, including production constraints, a limited detection distance, imprecise measurement precision, and interference from the environment, necessitating more discoveries and developments.

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