3D Printed Capacitive Ink Sensors for Sustainable Electronics

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Abstract: *The current revolution of the Internet of Things (IoT) and smart homes largely depends on high-cost sensors and expensive circuit integration techniques. Also, the environmental effects of electronics manufacturing have mandated opting for sustainable, low-cost 3D-printed electronics. In this work, we present an effective conductive ink/paint to fabricate capacitive sensors. The proposed ink has been formed by experimenting with various materials in different compositions. The proposed capacitive ink for printing the sensors offers flexibility and creativity when designing the circuits. The conductive paint can be used in wearables because of its unique advantage of being very thin, water resistant, and versatile to all surfaces. The capacitive ink proposed exhibits high conductivity and has demonstrated improved switching capability over the traditional capacitive sensors.*

Keywords: 3D printing, printed electronics, sustainability, capacitive inks, conductive paints, carbon inks, charcoal.

1 Introduction

The demand for intelligent products, from personal wearables to intelligent household devices and IoT-enabled commercial applications, has increased exponentially, leading to a surge in the production of electronic devices. The impact of electronics products and the associated fabrication methodologies has been reviewed recently to evaluate their environmental effects [1]. In turn, the detrimental effects of electronics manufacturing have diverted much research toward finding low-cost manufacturing techniques and exploring energy-efficient and sustainable solutions.

Printed electronics have been at the center stage of Industry 4.0 because of the numerous advantages offered over conventional fabrication methods. The benefits of 3D printed electronics include low-cost production, flexible, compact, multifunctional, and sustainable design [2]. Additive manufacturing (AM) techniques have principally transformed the 3D printing market. AM has established 3D printing as an environment-friendly solution with no requirement for cutting, cooling, fixtures, and the majority of auxiliary resources required in traditional methods. AM even allows faster manufacturing of complex designs with the help of computer-aided design (CAD) methods. AM for Justin Time (JIT) supply chain has been investigated and has ushered a new dimension of using AM for more productive, and optimal development [3].

1.1 3D Printing and Sustainability

The environment impact assessment of AM used for 3D printing has been thoroughly reviewed in [1]. The impact assessment of 3D printing is done using Life cycle analysis (LCA) and Environmental Impact Assessment (EIA) methods. The environmental footprints, time to manufacture, and design complexity are different parameters considered in the review. Energy consumption is also essential for environmental impact assessment and has been done for different AM methods [3-5]. The conclusive study done in [1, 3-5] confirms the use of 3D printing as an environmentally friendly, sustainable, and low-cost solution to device manufacturing. The work in [6] has investigated the sustainability of 3D printing, both qualitatively and quantitatively. As a quality parameter, the socio-economic effects have been considered while the quantification of sustainability has been evaluated in terms of CO_2 emissions, cost incurred, and the energy consumed. The results achieved are encouraging. 3D printing can help reduce electronics manufacturing costs by 170-583 billion US dollars, a reduction in CO_2 emissions by 130.5-525.5 Metric tons (Mt), and save energy by 2.54-9.30 Exa Joules (EJ) by 2025. Huang et al. also predicted savings of the order 173 GigaJoules (GJ) / year with the adoption of 3D printing for aircraft component manufacturing [7].

Significant work has also been done to identify the benefits of 3D printing for reducing electronics manufacturing wastage[1-4]. Though 3D printing with AM has helped reduce material wastage, recycling has also been accepted as the best way to reduce wastage. Using recycled filaments in 3D printing is another important choice that must be adopted to make 3D printing sustainable[8] and reduce wastage.

A critical aspect of the sustainability of 3D printing has been raised in [9] concerning the choice of material used over the machine size and the usage frequency. In this work, a complete life cycle assessment has been done for six different materials- Fused deposition modeling (FDM) using Acrylonitrile butadiene styrene (ABS) plastic for commercial use and desktop printing, poly jet machine printing using polymer, Stereolithography (SLA) printing using polymer, inkjet printing of salt and FDM machine printing using Polyethylene terephthalate (PET) and Polylactide, (PLA) plastics. Most of the above materials considered are plastics and have significant ecological impacts such as fossil fuel depletion, detrimental to climate change, damage to human health, and ecosystem toxicity. The obvious conclusion has been to look for green printing materials.

Graphene has been identified as a substantial green material for sustainable 3D printing [10]. Nevertheless, analysis of the materials used depends on the application intended and the additive process technology used. In their work, Jandyal et al. [11] have done a detailed review with reference to the process used for 3D printing and the potential materials used evaluating their relative benefits and limitations. The analysis is further mapped to the application intended. So, the material choice strongly depends on the process used and the application considered. A novel silicone 3D printing approach using transdisciplinary Integrated tools has been proposed, which ranges over many applications and is a significant step towards sustainable development [12].

Conductive bio inks using biomaterials have been recently developed to make 3D printing sustainable and environment friendly. In their work, Pakkanen et al. [13] have considered and compared different biodegradable/recycled filament materials for 3D printing compatible with FDM. This imposes a limit on the life cycle of the material and restricts its usage for short-span applications. Hydrogels are another choice of insoluble polymers catching fast as high-resolution 3D printing materials, especially for biomedical devices. Polymers blended with biomolecules are also a good choice, offering flexibility, versatility, and low cost, but choice depends on the application [14].

In general, a conductive ink is used for printed circuits. The conductive ink offers minimal space for circuit design, using optimized hardware components and flexibility to be painted in any desired form/manner on any insulated surface [13,15].

1.2 History of the Research- Capacitive Sensors

The noncontact working principle of capacitive sensing in conductive ink has made it an attractive choice for numerous applications, but its sensitivity to electromagnetic interferences was a challenge.

Brasseur [16] proposed a carrier frequency system with a radiometric evaluation algorithm and a frequency hopping strategy that guaranteed capacitive sensors' safe operation. Since then, capacitive sensors have been studied for use in sophisticated applications such as robotics [17], human-computer applications [18] on platforms like Arduino and Raspberry Pi [19], and touch pads [20]. Various capacitive ink materials have been explored for these applications [15-20].

Initially, electrically conducting polymers had been explored for printing circuits [21-22]. Nanofibers have been demonstrated to exhibit properties of electrical bi-stability and non-volatility, making them potential candidates as low-cost, fast-response chemical sensors [23]. The use of cotton fabric as a substrate on which highly sensitive thin copper electrodes are mounted too has been demonstrated for flexible electronics applications [24]. Microfluidic droplets have also been explored for manufacturing capacitive sensors [25], but the design may be restricted in dimensions. Simple conductive thermoplastic materials that can sense capacitance were widely accepted for 3D printing but were limited in strength [26] paving way for thermoplastic composites.

Metal Ink liquid, due to its adhesive and electrical properties, was another alternative explored for forming circuits [27]. The use of conductive colloidal ink for the realization of radio-frequency identification (RFID) tags on flexible substrates using micro-fabrication techniques has been demonstrated by Dang et al. [28]. They further progressed their research to synthesize conductive ink composed of silver nanoparticles to make conductive patterns [29]. Krishna et al. [30] proposed using silver-containing inks in printed electronics, which were a much better alternative in terms of cost to gold and platinum-based alloys. However, silver is still an expensive metal, which made printing circuits with silver-based capacitive inks a less preferred alternative. To reduce the cost, Razwan et al. [31] synthesized a silver precursor ink by a simple and environment-friendly method based on chemical reduction. The silver precursor ink finds printing applications in a variety of sensors and Micro-electromechanical systems (MEMs). A simple dry writing pencil-like device composed of silver nanoparticles was used to construct hybrid layered nanostructures [33]. This moisture-resistant material could be used to draw electrical circuits on paper, and it was a step toward paper electronics. However, the use of silver still made it an expensive choice.

Graphite-based conductive paint sensors have been demonstrated in the fabrication of RC circuits as simple, low-cost implementation [33]. Thompson [34] demonstrated electrical capacitors using pencil graphite. Instead, use of carbon derivatives as graphene-based inks [13] or carbon nanofibers (CNFs) has demonstrated a low sheet resistance and excellent conduction of current even under stress conditions [35].

The use of carbon derivatives for capacitive ink ignited the research for low-cost 3D printing capacitive ink, which could offer applications from robotics to smart wearables, health solutions, and aesthetic electronic switching solutions. Any part of the conventional circuits can practically be replaced with conductive paint and integrated to get the desired results. This will help reduce costs and give a lot more flexibility in designing circuits. Any surface painted with conductive ink/paint can act as a capacitive sensor. The paint will make the surface conductive, so connecting it to a source of charge can turn it into a capacitive sensor. With the help of microcontrollers and processing devices, a simple painted surface can be programmed to perform several applications by touching it or hovering hands over it. So, the painted surface can work as a proximity sensor. Printed capacitive sensors offer numerous advantages over the current technologies, which include:

- Touch sensors can be designed and printed in various shapes and sizes, allowing flexibility and attractive designs.
- The sensors are more versatile and durable as they do not have any moving mechanical parts in them, thus saving from the gradual wear and tear of the sensor.
- The design is more robust as it is not dependent on surface features like notch, hole or duck.
- The sensors have no gaps between them, so they are protected from dust and humidity.
- The implementation price is drastically reduced because no extra cost of wiring inside or through the walls is necessary.
- The 3D printed capacitive sensors offer easy and inexpensive modification.
- They can detect hands from a significant distance if required.
- They pave a path to innovative automation and housing solutions at very affordable prices.
- They have low power consumption.
- They can work from distances even as long as 30 cm.

The proposed work in this paper has been motivated to revolutionize the applications of printed electronics using low-cost materials. In this work, commonly available materials have been experimented with, to determine their properties as capacitive ink.

2 Methodology

To explore the potential of capacitive inks based on low-cost carbon derivatives available in abundance, we conducted a series of experiments on different materials- Aluminum foil, unburnt charcoal, activated wood charcoal, and Lead graphite (thick and thin). The methodology proposed for testing and validation has been presented in Figure 1.

1. A capacitive sensor is set up and used as a proximity detection circuit. The circuit has a fixed resistance and two types of capacitance connected in parallel: fixed (C_0) and variable (C_T). The fixed capacitance (C_0) is due to it behaving as a parallel plate capacitor with the surface on which it is printed, and the variable capacitor (C_T) is formed with the conductive paint surface as a positively charged plate and the hand behaving as the negatively charged plate of the parallel plate capacitor. In the case when two plates of the parallel plate capacitor have different areas, the plate that has the lower area is chosen for calculating the capacitance given by the formula,

$$C = \varepsilon \frac{A}{d} \tag{1}$$

The Atmega 328P microcontroller continuously polls the capacitive sensor and keeps track of the resultant time constant of the formed RC circuit. The resultant time constant is then sent to the relaxing oscillator, which generates an oscillating frequency and sends it to the two timers in the Arduino.

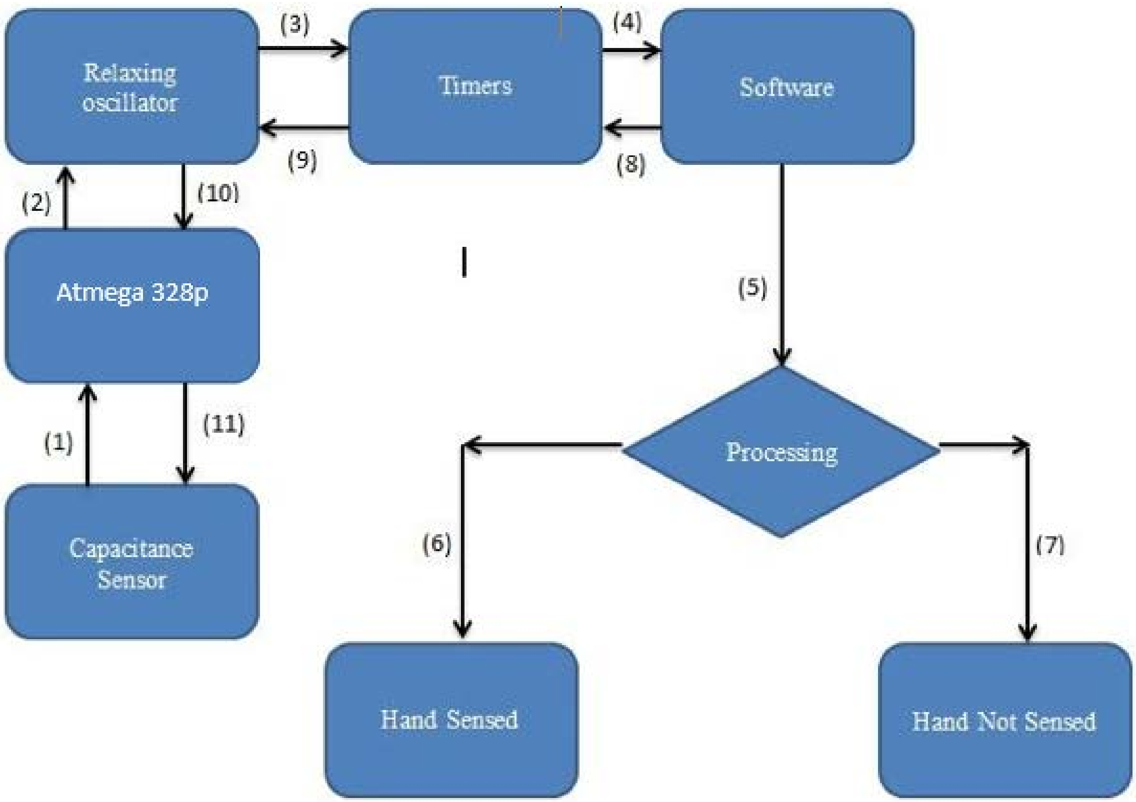

Figure 1 Flowchart for the Proposed Methodology.

2. The Timers then time the circuit to charge the RC circuits to a fixed threshold voltage (V_{th}), which is set by giving a supply voltage to one of the operational amplifiers given to the non-inverting terminal present in the relaxing oscillator. Usually, it is taken as $\frac{2}{3}V_{max.}$ So,

$$V_{th} = \frac{2}{3}V_{max} \tag{2}$$

3. The timers then send the processed time (t_1) to the software, which compares this time with the time (t_0) stored initially (in absence of an extra capacitor, C_T or when no object is in the proximity of the capacitive sensor).
4. Two cases appear now and are denoted in the flowchart by the decision making.
    1. If the time $t_1 > t_0$

       The flow chart follows the path (6), and it is concluded that the hand is sensed.
    2. If the time $t_1 = t_0$

The flow chart follows the path (7), and it is concluded that the hand is not sensed.

2.1 Design Specifications

2.1.1 The specifications/constraints for the Conductive Paint are:

1. Application Method: The paint should be applied in even layers for best results. The paint can be applied through standard printing or a simple paintbrush.
2. Power Sources: The paint works on low DC voltages. The ideal voltage supply should be less than 12V.
3. Substrates: The paint has a water base and can be used on surfaces /substrates like paper, plastics, and metals.

4. Drying Tips: The paint takes 3 to 5 minutes to dry at room temperature. The drying time can be reduced by placing a low-power heat source near the paint.
5. Resistance: The resistance of the patch of conductive paint is directly proportional to the ratio of length/ width (l/w) ratio of the paint patch.

2.1.2 Specifications of the Capacitive Switch

The specifications required for conductive ink to act as a capacitive switch in electronics circuit applications have been explored and presented in Table 1.

Table 1 Design Specifications of Capacitive Sensor [36]

S.No.	Property	Meaning	Range
1	Switching distance (Sn)	It was measured at room temperature, with a thickness of 1mm and a supplied power of 5V.	0-4 cm(adjustable)
2	Switching Frequency	It indicates the number of times a switch can be used per second for error-free results	10Hz
3	Max output current	Maximum permissible output current	200mA in DC
4	Min output current	Minimum permissible output current	10mA in DC
5	Voltage drop (sensor ON)	Voltage across sensor	<1.8V in DC
6	Temperature limits (deg. Celsius)	Temperature range	- 10 to 70

2.2 Comparison between Carbon Inks and Silver Inks

For manufacturing purposes, there are two main types of inks, carbon inks, and silver inks, which are compared below in Table 2.

Table 2 Comparison of Silver and Carbon-based inks

S. No.	Inks	Applications	Key Features	Product Features	Application Method	Surface Resistance
1	Carbon Inks	Membrane Switch Flex Circuit Additive circuits.	They are used for screen printing traces and resistance pads, Lower cost	Excellent metal adhesion.	Screen print, dip, or coat	< 30 Ω/ sq/mil
2	Silver Inks	Reliable membrane switches Best for touchscreen For substrates with difficult adhesion	Better conductivity, Heat resistance for reliable applications	It can be printed as thin base layers.	Screen print or thin layers (spray)	< 0.010 Ω/sq/mil

The comparison presented in Table 2 shows that silver inks offer thin wiring and better conductivity, but the cost is a crucial disadvantage. Additionally,

1. Various chemical methods are used to manufacture silver inks. First, silver nanoparticles are prepared, which are then processed into silver inks.
2. Carbon inks are beneficial as they have high conductivity.
3. Carbon ink is less costly than silver or any other type of ink.

Overall, it is concluded that various materials can prepare conductive paints, but the choice has to be determined based on the application requirements.

To understand the working of conductive inks, consider the diagram shown in Figure 2 which details the working of a capacitive ink sensor.

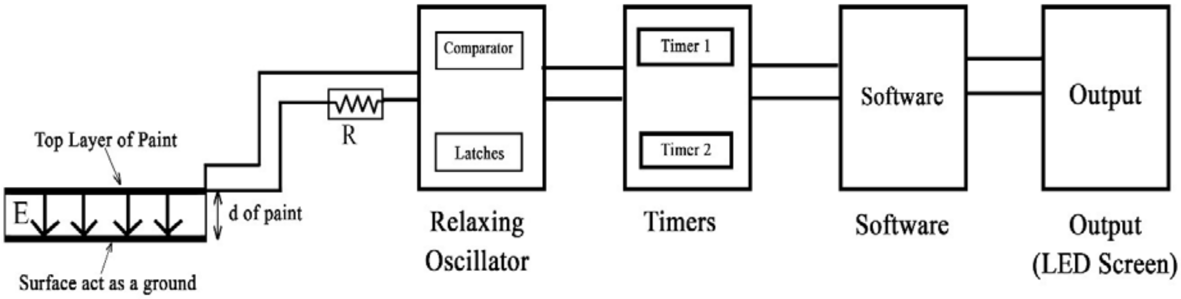

Figure 2 Working of Capacitive Inks for Electronics Applications.

The plates of the capacitor are equally charged but are of opposite polarity. This develops an electric field between the two plates of the capacitor, as given by equations (1) and (2). The fringing effect is ignored as the density of the electric field lines around the corners/edges is less when compared to the density of electric field lines between the plates. Also, the field strength depends on the electric field line density. So, the capacitive switch amounts to working as a proximity detector.

The principle of capacitive sensing helps detect the presence of any conducting or non-conducting object near the capacitive sensor whose dielectric is not the same as that of air.

The thin layer of conductive paint will act as the positive plate of the capacitor. Two types of capacitances are generated as described below:

1. Capacitance C_0 (In the absence of any object in the proximity of the capacitive switch)
   This is the fixed capacitance between the surface on which the sensor is printed and the top layer of paint. Capacitance C_0 is not affected by the presence of any object near the capacitive sensor.
2. Capacitance C_T (When there is an object in the proximity of the capacitive sensor)
   This is a variable capacitor generated between the surface of the conductive paint and the hand of the human.
   Here, the conductive paint surface acts as the positively charged plate, and the hand acts as the negatively charged plate. The capacitance generated increases as the hand moves toward the sensor as the distance between the two plates (d) decreases, and C is inversely proportional to the distance (d), as we know from (1).
   The painted patch has fixed resistance determined by the formula

$$R = \rho \frac{L}{A} \tag{3}$$

Where ρ is the resistivity of the conductive paint, L is the length of the rectangular patch, and A is the area of the thickness of the rectangular patch.

To measure the capacitance, two cases have been considered:

Case 1:When no object is present in the proximity of the capacitive sensor

In this case, the equivalent capacitance of the conductive paint capacitive sensor is equal to the C_0. No variable capacitance is generated because of the proximity of any object towards the sensor.

$$C_{equivalent} = C_0 \tag{4}$$

Case 2: When an object is present in the proximity of the capacitive sensor.

In this case, in addition to the above-mentioned fixed capacitance C_0, we also have a variable capacitor C_T because the hand behaves as the negatively charged parallel plate while the conductive paint serves as the positively charged plate. The two capacitors, C_0 and C_T, are connected in parallel to each other, hence the equivalent capacitance becomes equal to

$$C_{\text{equivalent}} = C_0 + C_T \tag{5}$$

The overall capacitance increases in presence of hand coming near the conductive paint. Due to the presence of both resistance and capacitance, the conductive ink patch acts as an RC circuit. If both the Resistance and Capacitance for the painted circuit are known, the RC time constant can be easily calculated as

$$\tau = RC_{\text{equivalent}} \tag{6}$$

The time constant in the two cases is as follows

1. When no object is present in the proximity of the capacitive sensor

$$\tau = RC_{\text{equivalent}}$$
$$\tau = RC_0 \tag{7}$$

2. When an object is present in the proximity of the capacitive sensor

$$\tau = RC_{\text{equivalent}}$$
$$\tau = R(C_0 + C_T) \tag{8}$$

As shown in Figure 2, RC circuit acts as a mechanical switch. The relaxing circuit continuously polls the capacitive touch sensor to detect any changes in the equivalent capacitance of the circuit. Any change in the equivalent capacitance of the circuit represents an intrusion in the proximity of the capacitive sensor. For example, when the switch is touched, the frequency of the relaxing oscillator changes.

In order to detect and interpret changes in frequency, a measurement circuit is introduced into the system. The system consists of both hardware and software and with its help, it is concluded whether the switch has been touched or not.

The charging and discharging time of the RC circuit formed because of the conductive paint is analyzed below. The input voltage waveform is a square pulse of maximum voltage 5V, as shown in Figure 3a

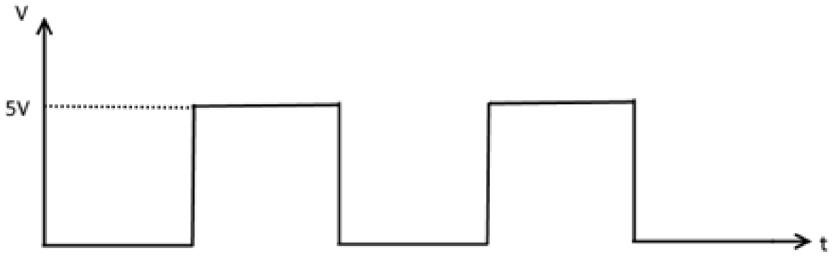

Figure 3a Input voltage waveform

A threshold voltage V_{th} is decided and fixed in the software. For the analysis, we have fixed it to 4V. The time the RC circuit takes to reach this Threshold voltage V_{th} is noted down.

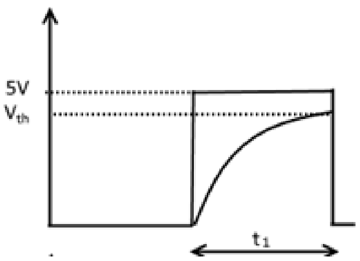

Figure. 3b Charging time in the Case 1

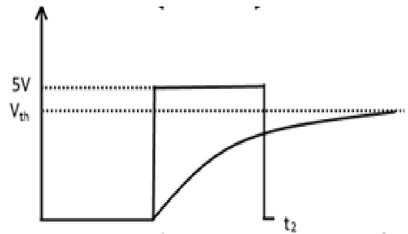

Figure. 3c Charging time in the Case 2

For the two cases discussed above:
Case 1: The time constant obtained in this case, as shown above, is $\tau = RC_{0.}$
Therefore, the time it takes to reach the threshold voltage at the input-defined pin of Arduino is given by, the voltage across the capacitor as

$$\mathrm{Vth} = Vmax(1 - e^{\frac{-t}{\tau}}) \tag{9}$$

Let the time taken to reach threshold voltage be $t_{1.}$
Case 2: When there is an object in the proximity of the capacitive sensor
Let the time taken to reach threshold voltage be t_2
Now, the software continuously compares the time to reach threshold voltage(t_2) with the base reference time to reach threshold voltage(t_1).

1. If $t_2 = t_1$, no object is present near the capacitive sensor.
2. If $t_2 > t_1$, the object is present near the capacitive sensor.

The efficiency of the capacitive switch is dependent on various factors like switch size, material, placement, and conditional environment.

2.2.1 Touch Sensor Size

It is known that the capacitance is directly proportional to the area of the plate of the parallel plate capacitor. Therefore, the more area there is, the more capacitance there is.

Care must be taken while placing two capacitive sensors adjacent to each other so that no false triggers are generated, as when the hand is placed vertically above the target sensor, the nearby sensor also forms a capacitive relationship with the hand. An excellent alternative to providing sufficient insulation from the hand is the introduction of a ground trace/plate printed adjacent to the near sensor, because of which a larger base capacitance is generated; thus, the capacitance introduced because of the hand will have less effect on the percentage shift of the oscillator or the time to reach the threshold voltage as shown in Figure 4. This can be advanced by increasing the area of ground trace. The greater the area of the ground trace, the more capacitance C_{F2} will be attenuated.

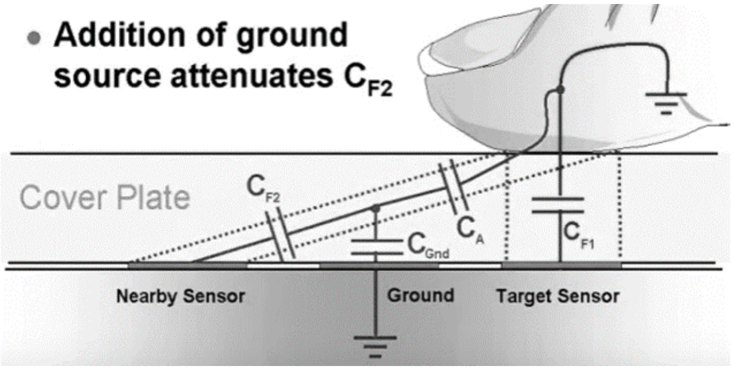

Figure 4 Preventing the false trigger

2.2.2 The Behavior of the Sensor under Moisture

Water has an extremely high permittivity of around 75, and therefore, water droplets on the sensor touch surface have the potential of being triggered as false hand detection.

For this, a press and detection algorithm can be introduced in the microcontroller; this helps to define a specific window of time in which press and release must occur; anything too fast or slow is considered to be false detection. The Design considerations used have been presented in Table 3.

Table 3 Design considerations for Conductive paint

S.No.	Condition	Observation	Result
1	Touch Sensor Size	Directly proportional to the area	More will be the area, More will be the capacitance
2	Adjacent Touch Sensors	The value of capacitance is inversely proportional to the diagonal depth	False triggering of the nearby sensor when the trigger is for the target sensor.
3	Adjacent Touch Sensors (Alternate Method)	Providing sufficient insulation by the introduction of ground trace	A larger base capacitance is generated.
4	The behavior of sensors under moisture	Water has high permittivity, thus high capacitance	Press and detection algorithms can be introduced
5	Design of paint inside the sensor	Relative capacitance depends on the area of the paint	Hashed-painted sensors provide better results

The results summarized in Table 3 clearly establish increase of capacitance in presence of moisture.

3 Results and Discussions

Considering all these observations, the materials to be tested were formed and experimentally tested.

ALUMINIUM FOIL

Initially, testing was done using an aluminum foil. It has a very low resistance.

Disadvantage:

- Not durable.
- Rough surface

UNBURNT CHARCOAL

Then, normal unburnt charcoal was used to make the paint. Hot water was used here. Elmer's glue and acrylic paint were also used.

Disadvantage:

- Resistance (200 kΩ) was quite large.
- Pieces were still larger than required and insoluble.

ACTIVATED WOOD CHARCOAL

As unburnt charcoal was not able to give the desired results, activated wood charcoal was used to make paint with sodium silicate water as the emulsifying agent.

Disadvantage:

- Its resistance was large (50 kΩ).
- Charcoal pieces were insoluble.

GRAPHITE-THICK

As charcoal was giving a high resistance, we switched on to graphite. Initially, thick leads were crushed to make the powder. It was then blended with water, Elmer's glue, and black acrylic paint. The paint was more soluble than charcoal powder.

Disadvantage:

- The paint was more soluble than developed by charcoal, but still some insoluble particles were present.
- Resistance (35-40 Ω) was more than required.
- It couldn't be used in household applications as dust was shed by the paint.

Figure 5 Mixing of different materials used

GRAPHITE-THIN

Thin leads of graphite were crushed to make the paint using water, Elmer's glue, and black acrylic paint.

Disadvantage:

- Resistance (15-20 Ω) was less than the previous methods used but still not as much conductive as required.
- It couldn't be used in household applications as dust was shed by the paint.

Figure 6 Different types of substances tested for making conductive paint

STONE CHARCOAL

Finally, the paint was made using stone charcoal. The resistance was quite low for stone charcoal. Adding water, Elmer's glue, and black acrylic paint made it conductive. Its conductivity increased when vinegar was added instead of water.

The materials formed were tested using the circuit, as shown in Figure 7a, and its schematics are shown in Figure 7b.

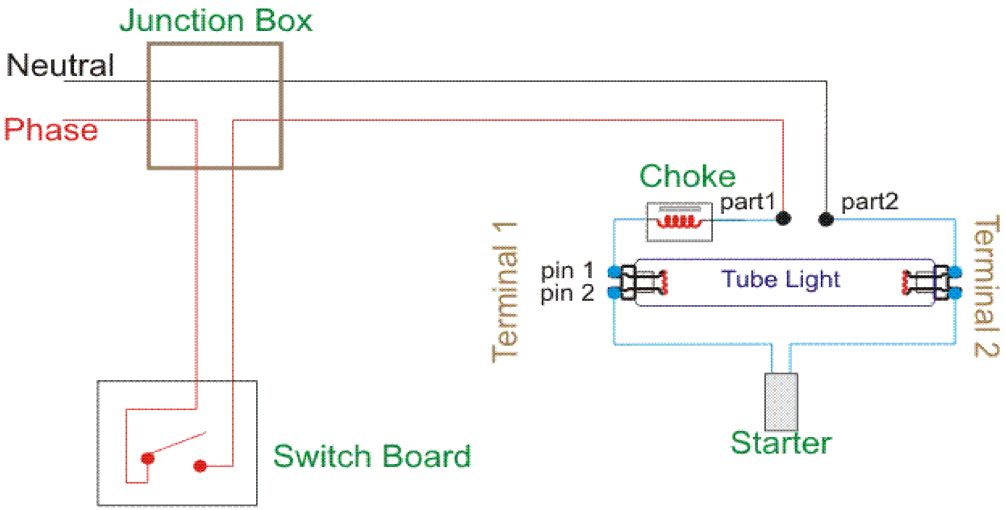

Figure 7a Circuit used for Testing

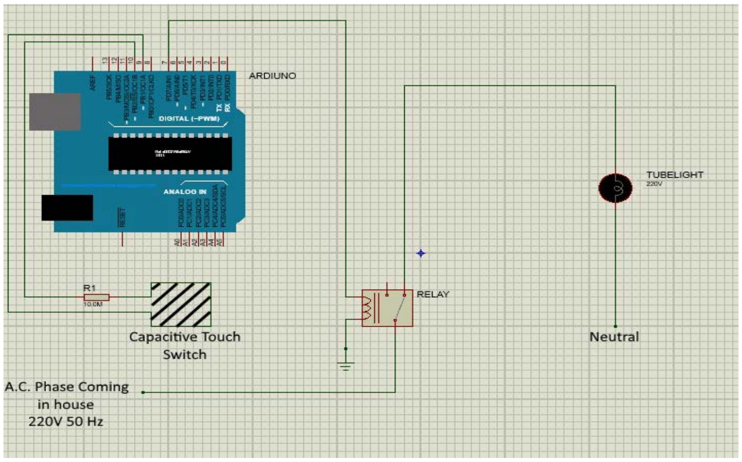

Figure 7b Schematic of the Circuit used for testing

A simple test has been performed using aluminum foil (as capacitive touch sensor) in the setup of Figure 7b. The resultant circuit is shown in Figure 8a and 8b. As seen in Figure 8a, when no hand is brought near the aluminum foil, which here serves as a conductive surface, no light glows because of the absence of capacitance. However, in Figure 8b, as the hand is brought closer, light glows due to the capacitance built between the human hand and conductive surface, allowing RC charging of current. The same experiment was conducted for six different materials considered- aluminum foil, unburnt charcoal, activated charcoal, thick graphite lead, thin graphite lead, and stone charcoal.

Figure 8a No light glows in the absence of a hand**.**

Figure 8b Light glows in the presence of a hand**.**

Results of stone charcoal material were the best when used as conductive ink and have been tabulated in Table 4.

Table 4 Properties of Stone charcoal conductive paint for Flexible electronics

S.No	Property	Specifications
1	Surface resistivity	70 ohm/sq m at 1mm thickness
2	Base	Vinegar
3	Solubility	Partially soluble in water
4	Switching distance	25 cms
5	Current Range	Ten mA to 200 mA
6	Voltage drop(sensor ON)	<1.8 V

The resistivity and voltage drop are comparable to that of a good conductor making it a good choice for 3D printed electronic sensors.

4 Conclusion

After experimenting with different materials, it can be established that the capacitive touch sensor we developed can be used at a higher level for more sophisticated applications. It is an important contribution to electronic devices, be it smart wearables, health monitoring devices, educational toys, etc. Cracks in buildings and low-cost bands can be detected using this paint for interactive applications. Paint can also be used in a lot of household devices. All these applications verify the use of capacitive inks is providing a new approach and way to interact with the way we interact with electronics at this stage and opens a world of low-cost, affordable 3D printed devices.

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