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# 3D Printing of soft sensors for soft gripper applications

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## Abstract

Soft robotics is gaining more interest because of the increasing demands in the manufacturing line to handle various types of delicate parts. The progress in the development of soft robotics does not only rely on the technology in the fabrication of the soft gripper structures, it also depends significantly on the integration of electronics such as the soft sensors and circuits. 3D printing technology is an important manufacturing tool for soft robotics due to its ability to fabricate designs with complex geometry and multi-material printing capability. Herein, the recently developed soft electronics such as sensors and circuits that involved the use of 3D printing technology are focused upon. In this article, the various designs of soft sensors, their fabrication techniques, and the materials used will be introduced. Besides, the design considerations and requirements for soft electronics will be presented. Lastly, the potential applications and the future outlook of soft electronics for soft grippers will be discussed.

*Keywords: additive manufacturing; soft robotics; printed electronics; soft sensors*

## 1. Introduction

Geometry compliance is an essential feature of robots that operate in dynamic and unstructured environments [1]. One of the criteria that has been well accepted for such a geometry-compliant robot is the softness of its structure. Robots with soft structures allow the robots to change shape and manipulate freely with lesser geometric constraints. The same also applies to grippers that are used to manipulate objects with varying shapes. Soft grippers offer more control in manipulating objects as compared to their counterparts with rigid structures because they offer more grasping points on the objects, thus enhancing the stability during object manipulation. To date, there have been many types of soft grippers that have been developed [2-5]. One common feature of these soft grippers is that the skins of the grippers are mostly made up of soft materials that either allow for flexing or stretching. It has been reported that some of these soft grippers made of an elastomeric material such as silicone are capable of sustaining strain up to 100-500% [2]. Despite the advantages of soft grippers, there have been some design and fabrication challenges to achieving smart soft grippers that are integrated with sensors for haptic feedback control.

Sensing is one of the important aspects of robotics as it allows the robot to know or understand what is around its vicinity so that it can make necessary decisions based on the signals obtained from the sensors [1, 4-9]. However, the integration of sensors into soft structures remains an open problem. This is because most of the commercially available sensors do not meet the design and operational requirements for soft robotics. For instance, commercial strain sensors are designed to measure strain not more than 1% and they are usually packaged in non-stretchable polyimide substrate. The mismatch in the physical property of the commercial sensor and the soft robotics has resulted in difficulty in integrating the sensors into the soft gripper structure and poor sensing performance.

3D printing, or additive manufacturing, is a manufacturing technique that fabricates parts by adding the materials additively to the specific regions of parts. So far, 3D printing techniques have been demonstrated to be able to fabricate various types of materials ranging from metal, polymer, ceramic, biological materials, foods, and electronic materials. Compared to conventional manufacturing technology, 3D printing produces parts with much lesser time and materials and is capable of forming more complex parts [10]. 3D printing techniques also allow researchers and designers of soft grippers to have more flexibility in designing multifunctional structures that not only save space but also improve structural integrity.  More recently, researchers are exploring combining different materials within a single part using either a single printing technique or a hybrid 3D printing technique [11, 12]. Some of them even attempted to 3D print soft grippers with tunable rigidity with multiple materials, and separately, some have attempted printing sensors directly on gripper structures. However, only a few have demonstrated the fabrication of both printed sensors and soft gripper structures using 3D printing techniques.

In this review, we attempt to discuss the landscape of 3D printing of soft sensors for soft gripper applications. In particular, we will be discussing the design requirement and considerations of soft sensors, the different sensor designs that have been attempted, the type of printing technology that has been developed for the fabrication of soft sensors, and some of the potential applications of the 3D printed soft sensors.

## 2. Design requirement and consideration of soft sensors

Soft sensors often refer to sensing nodes or sensing arrays that are used together with a soft substrate that can be strained and retains its functionality when the substrate is deformed. They should be able to receive stimuli from the environment and output an electrical signal that can be used by the control system to make decisions. Soft sensors are often used in electronic skin or artificial skin for robotics, gripper, or prosthetics, therefore in most cases, the property of soft sensors tends to mimic the property of human skin. The design of the sensors largely depends on the type of sensing mechanisms and the required spatial resolution. All in all, the criteria for evaluating soft sensors such as the sensitivity, response time, and hysteresis, just to name a few, remain almost the same as the traditional sensors. Table 1 summarizes the fundamental requirements for designing functional soft sensors [13, 14].

*Table 1. Design considerations and requirements for soft sensors*

| **Design considerations** | **Design requirements** |
|---|---|
| 1. Stretchability and compliancy | It should be as stretchable as human skin (55%) and capable of being mechanically compliant to the surface it will be placed on. It is recommended that the sensor should have a stretchability of up to 75%. |
| 2. Material’s elasticity | The elastic modulus of human skin ranges between 25 and 250 kPa, therefore it is recommended that the soft sensor should have elastic stiffness that matches the human skin, also it should not exceed 1MPa. |
| 3. Detection of different loading conditions | A good soft sensor should be able to detect various types of sensations including pressure, shear, lateral deformation, vibration, etc. |
| 4. Spatial resolution | The sensor should have a low footprint to allow for higher spatial resolution for the detection of loading conditions. |
| 5. Sensing performance | The sensor should exhibit linear response with high sensitivity and small hysteresis and creep. Here, creep refers to no change in the sensor’s output with time, temperature, humidity, and other environmental factors) |
| 6. Response time | The sensor should be quick to respond to a sudden change in the stimuli. It is recommended that the response time should be reasonably short (eg. <1s) |
| 7. Repeatability | The sensor output should be reversible, predictable, and not susceptible to drift to allow for accurate measurement over a long duration |
| 8. Durability | The sensor should be able to output signal reliably within its operating window without exhibiting a sign of fatigue |
| 9. Cost | The design of the sensor should not incur too much manufacturing cost such as the cost involving the intermediate steps, and the mold and stencil fabrication. |

## 3. Types of soft sensors design

In general, sensors are added to the grippers to allow them to feel the objects while manipulating the objects. In most cases, the type of mechanical parameters that are used for touch sensing includes pressure, strain, and force. All this information is used by the grippers to provide information such as the shape, the weight, and the position of the objects for better handling.

Soft sensors are usually classified based on their sensing mechanisms. Generally, there are various types of sensing mechanisms such as resistive, capacitive, piezoelectric, magnetic, and optical-based sensors. Each of these sensors may require unique materials and sensors designed to achieve good sensing capability. Table 2 summarizes the different sensing mechanisms and the material and designs for each type of sensor.

*Table 2. Overview of various sensing mechanisms, their working principles, and their corresponding materials and sensor designs.[10, 14]*

| **Types of soft sensors** | **Working principles** | **Advantages and Disadvantages** | **Materials and Designs** |
|---|---|---|---|
| Resistive sensor | Detect long term deformation by monitoring the change in resistance | *Advantage*: Low cost, simple readout circuit<br>*Disadvantage*: High power consumption | • Vertically embedded liquid metal strain gauge [15]<br>• Conductive traces made of multi-walled carbon nanotube/polymer composite [16]<br>• Gallium-based liquid metal [2, 4, 17] |
| Capacitive sensor | Detect long term deformation by monitoring the change in the electric field | *Advantage*: Reliable and sensitive response<br>*Disadvantage*: Prone drift due to material degradation | • Parallel plate conductor separated with a microstructured elastomeric layer [18] |
| Piezoelectric sensor | Detect short term deformation by monitoring the change in voltage | *Advantage*: Highly sensitive to short change in deformation<br>*Disadvantage*: some piezoelectric materials are not suitable for static measurement | • Piezoelectric polymer polyvinylidene fluoride (PVDF) [19] |
| Triboelectric sensor | Detect movement due to vibration by monitoring the voltage between 2 dissimilar materials caused by friction | *Advantage*: Suitable for dynamic measurement<br>*Disadvantage*: not suitable for static measurement | • Embedded copper wire coated with silicone [20] |
| Magnetic sensor | Detect displacement by monitoring the change in the magnetic field | *Advantage*: Simple design<br>*Disadvantage*: Interaction with ferromagnetic material can affect detection | • Inductive coil made of liquid metal [21]<br>• A combination of permanent magnet and Hall effect sensor [22] |
| Optical sensor | Detect deformation of optic fiber due to bending and stretching by monitoring the change in wavelength or change in light intensity | *Advantage*: Highly repeatable over long use and fast measurement<br>*Disadvantage:* Performance affected by lighting conditions, high power consumption, limited stretchable fiber option, expensive equipment | • Silicone rod [23]<br>• Fiber grating sensor [24]<br>• Highly stretchable polymer optical fiber with spirally twined design [25, 26] |

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|---|---|---|---|
| Pneumatic pressure sensor | Detect the change in volume of the enclosed chamber by monitoring the change in pressure | *Advantage:* Do not need to integrate the sensor within the structure.<br>*Disadvantage:* Prone to leakage | • Gripper structure with enclosed pneumatic chamber [5, 13, 27, 28] |

As most sensors require the use of conductors, the main challenge of integrating the sensor into the soft structure is the limited stretchability of the conductive materials. Conventional sensors are usually made of rigid conductive materials such as silver, copper, and gold that have high stiffness and poor elongation property. Despite this, various efforts have been made to incorporate stretchability to the structure of the substrate, such as buckled film, serpentine circuit, and kirigami that minimize the stress when the thin film conductive structure is stretched [29-33].

Another way to achieve the stretchability of the conductor is by using liquid metal such as eutectic Gallium-Indium (EGaIn) [2, 4, 17]. The material is found to have good electrical property and is very resistant to breakage under high elongation. Usually, the sensing structure is formed by creating a microchannel within the stretchable encapsulation to form the conductive pattern. However, the fabrication of such sensors is very tedious as it involves multiple steps such as molding, pouring and curing of the resin, injection of liquid metal, and sealing of microchannel.

Alternatively, a pneumatic pressure sensing method can be used for soft gripper [5, 13, 27, 28]. The soft gripper should contain a pneumatic chamber and the structure can be made of an elastomeric material such as silicone to allow for better shape compliance. The state of the gripper can be deduced from the pressure change as a result of the change in volume of the enclosed pneumatic chamber. This sensing method is advantageous because the integration of the pressure sensor is rather simple. The only disadvantage of such sensing mechanism is that it does not have touch sensing capability and it is prone to leakage.

## 4. 3D printing of soft sensors

Fabrication of soft sensors by using 3D printing techniques allows for better design flexibility, higher compatibility with a wide range of substrate materials, more choices for functional inks, and easier integration with multi-material printing capability [11, 34, 35]. To date, there have been many attempts to use 3D printing for fabricating soft sensors. The 3D printing techniques that have been used for these works include the material-extrusion technique, material-jetting technique, and vat-polymerization technique. The following section discusses the working principle of the 3D printing techniques and their pros and cons as fabrication tools for printing soft sensors.

Table 3. Various 3D printing techniques for the fabrication of soft sensors

| **Types of 3D printing techniques** | **Working principle** | **Advantages** | **Disadvantages** | **Examples [Ref.]** |
|---|---|---|---|---|
| **Material-extrusion techniques [36]**<br>-Fused filament fabrication (FFF)<br>-Direct ink writing (DIW) | Material is extruded through a nozzle and the extruded filament forms the patterned layers. | -Able to form free-standing sensors<br>-Easy to achieve multi-material design<br>-easy to integrate the sensor into the structure | -Poor electrical property because composite materials are used<br>-Low extrudability at high particle loading<br>-Usually low printing resolution due to the large nozzle size | • Piezoresistive sensor [37]<br>• Capacitive touch sensor [38] |
| **Material jetting techniques**<br>-Inkjet printing (IJP) [39]<br>-Aerosol jet printing (AJP) [40-42] | Material is jetted through a nozzle in droplet form and forms a patterned layer after being deposited on the substrate. | -High printing resolution<br>-Easy to achieve multi-material design | -Usually, only form thin-film conductor when solvent-based ink is used<br>-Low electrical property when resin-based composite ink is used<br>-Requires a substrate for the case of AJP | • Soft capacitive pressure sensor [43]<br>• Soft strain sensor [44]<br>• Force sensor[45] |

| | | | | |
|---|---|---|---|---|
| **Vat polymerization techniques** | Raw material in the form of photocurable resin is placed in a vat and parts are formed by using a light source. | -High printing resolution | -Difficult to achieve multi-material design<br>-Conductive material is achieved by the addition of conductive material into the photocurable resin, thus the electrical conductivity is not high | - Soft hydrogel pH sensor [46] |

*4.1 Potential of 3D printed soft sensors for smart gripper applications*

Traditionally, the integration of sensors and grippers is done with a series of manufacturing processes. Generally, grippers are uniquely designed for specific applications, thus posing a great challenge in integrating the sensors as the placement of sensors has to be deliberated on a case-by-case basis. With 3D printing, the sensors can be easily redesigned for each gripper design at a much lower cost. This section attempts to discuss some of the works that demonstrated the fabrication of fully 3D printed smart soft sensors for smart gripper applications.

| **Types of sensors** | **Printing methods** | **Materials** | **Descriptions** | **Ref.** |
|---|---|---|---|---|
| Capacitive touch sensor | FFF | - Flexible filament<br>- Conductive filament | The gripper incorporates 3D cellular structure for light-weighting purposes. The fingertip of the gripper contains a parallel plate capacitive sensor that is fabricated with conductive filament using a multi-nozzle FFF printer. The gripper is capable of detecting the gripping force when handling objects of different shapes and sizes. | [47] |
| Resistive-based sensors | 3D IJP | - TangoPlus<br>- TangoBlackPlus (conductive) | A fully 3D printed soft pneumatic gripper with resistive element embedded within the soft gripper structure for contact and curvature sensing purposes.<br>However, the performance of the sensor is limited by the scarce choice of the conductive material. | [48] |
| Resistive and capacitive sensors | IJP | - Paper substrate<br>- Silver nanoparticle ink | The smart gripper structure is made up of an elastomeric body embedded with a paper-based capacitive sensor for proximity and curvature sensing. The sensor is fabricated by depositing silver nanoparticle ink to form a pair of interdigitated electrodes on a paper substrate. | [49] |
| Multidirectional resistive-based tactile sensor | FFF | - PDMS<br>- Conductive filament with carbon nanotube filler | The sensing element is made of a core-shell filament with a core made of conductive filament with carbon nanotube filler and a shell made of PDMS. The touch sensor is a scaffold-based sensor with the core-shell sensing element embedded within it to achieve multidirectional sensing | [50] |
| Triboelectric sensor | Indirect 3D printing | - Silver nanowire<br>- Ecoflex 00-30 | A 3D printed mold with micro-pyramid structures is designed and fabricated for the active layer of the triboelectric sensor. The triboelectric sensor is manually inserted into the gripper during the manufacturing process. The tribo-skin can be used as a force sensor as well as an energy harvester. | [51] |

In a nutshell, we can see that there are not many works that have demonstrated the fabrication of gripper and sensor structures together with 3D printing technique. The main hindrance to adopting such multi-material 3D printing technology for the fabrication of the smart gripper could be attributed to the lack of suitable conductive materials that are compatible with the printing techniques and the lack of standardized design and fabrication protocol for manufacturing such multifunctional structures. Nonetheless, these works have demonstrated the potential of 3D printing for realizing integrated smart grippers for enhanced structural reliability and integrity.

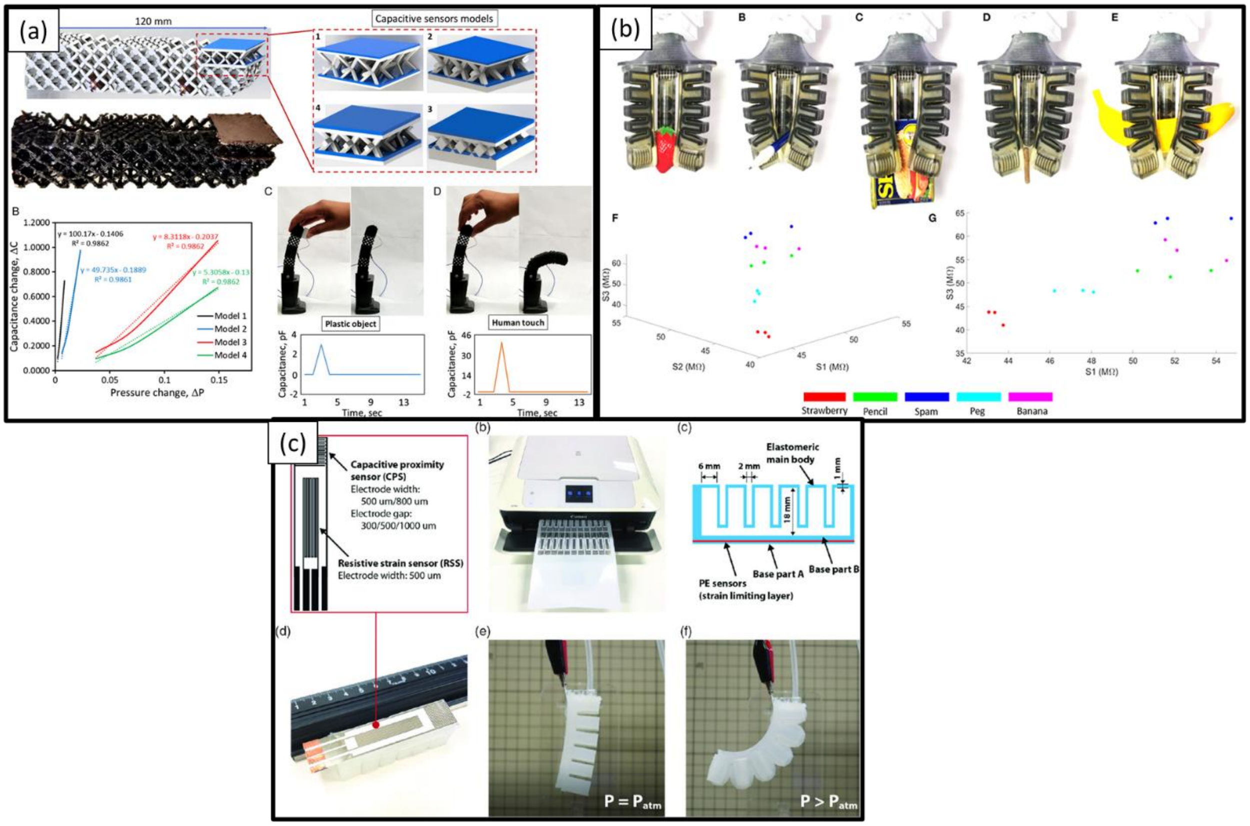

**Figure 1** (a) 3D printed cellular structure integrated with a parallel plate capacitive sensor that is fabricated with conductive filament using a multi-nozzle FFF printer. Reprinted with permission from [47]. Copyright (2019) John Wiley & Sons, Inc. (b) A fully 3D printed soft pneumatic gripper with resistive element embedded within the soft gripper structure for contact and curvature sensing purposes, Reprinted with permission from [48]. Copyright (2019) Frontiers Media S.A. (c) The smart gripper structure is made up of an elastomeric body embedded with a paper-based capacitive sensor for proximity and curvature sensing, Reprinted with permission from [49]. Copyright (2020) John Wiley & Sons, Inc.

## 5. Conclusions

Remarkable advances in the development of soft electronics and their applications in soft grippers have led to progress in materiel science and manufacturing engineering. Especially, the development of 3D printing that allows for highly customizable and flexible electronic structural designs has been shown beneficial and advantageous for the fabrication of soft grippers with integrated sensing nodes for haptic feedback. Recent studies on soft grippers with soft sensors for haptic feedback have demonstrated their advantages when handling delicate objects. Despite this, there are several challenges to overcome, including the limited material options, the printing resolution, and the performance and reliability of the 3D printed sensor. Nevertheless, 3D printed soft electronics will continue to improve with the innovative effort by the research community from various fields such as material science and manufacturing technology.

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