# 3D Printed Integrated Sensors

Subjects: Engineering, Manufacturing

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The integration of 3D printed sensors into hosting structures has become a growing area of research due to simplified assembly procedures, reduced system complexity, and lower fabrication cost. Embedding 3D printed sensors into structures or bonding the sensors on surfaces are the two techniques for the integration of sensors.

Keywords: 3D printing ; embedded sensor ; additive manufacturing ; sensor integration ; 3D printed electronics

## 1. Introduction

Integrated sensors are microelectronic systems incorporated in a host material or structure and able to sense their exposed stimuli to produce an electrical output. Integrated sensors have been used in biology [1][2], energy [3], civil and mechanical structures [4], aerospace [5], and additive manufacturing [6] applications. Temperature, pressure, humidity, and motion are among the physical properties that can be detected by integrated sensors. Wang et al. sought to integrate the technology of structural health monitoring diagnostics for microelectronic systems [1]. Preventative measures were taken to reduce the risk of sensor failure and damage when integrated into the composite system. Various integration methods were tested, and low-cost pressure sensors were manufactured. Petrie et al. investigated the effects of inserting sensors in silicon carbide (SiC) ceramics for monitoring the nuclear energy production process [3]. Sensor embedment was done by infiltrating cavities within SiC structures for nuclear reactor system monitoring. Parameters such as strain and fuel temperature were monitored for encapsulated material integrity and power operation productivity.

Classifications of integrated sensors are based on their specific functions and implementation of the structure in the field of application. The types of integrated sensors studied are embedded or surface-bonded sensors. Embedded sensors are a network of technology that are directly incorporated into a material and can be integrated though direct embedment or by inserting into voids within the host material [7]. Shifts in stress concentration, crack development, and increased matrix stiffness are some issues that can be encountered when embedding sensors. Nevertheless, since the sensors are shielded from the outside environment, which reduces the risk of sensor damage and enhances durability. Surface bonded sensors are attached to the host structure surface using an adhesive [8]. Careful surface preparation must be done to effectively secure the sensor, and the bonding layer should be scaled accordingly. Sensing performance and the transducer ability to produce a signal through the bonding layer can be a setback for surface-bonded sensors. However, practical access to sensors suggests feasible sensor maintenance when experiencing failure.

Additive manufacturing (AM), also referred to as 3D printing or rapid prototyping, is the process where the material is deposited or joined in a layer-by-layer fashion to produce a three-dimensional part or object based on a digital model [9]. This type of technology has rapidly grown in popularity throughout the years due to its many benefits over conventional manufacturing methods. In comparison to traditional techniques such as computer numerical control (CNC) machining, injection molding, plastic forming, and plastic joining, AM technology has many advantages. These benefits include but are not limited to manufacturing cost, speed, part quality, and reliability [9][10][11]. AM costs are much lower than conventional technology in small volume manufacturing which requires expensive investments in mold development. It ensures fast prototyping and manufacturing, reduced time to market, and efficiency. This technique ensures innovation for customization, personalization, and the use of design imagination. AM technology keeps innovating and changing to increase its advantages and benefits over other manufacturing technologies [12][13][14][15].

The essential part of embedded/integrated sensing is that it cannot function without proper connections of functional materials (sensing part) with electrically conductive materials (communication part). In traditional manufacturing methods, multiple steps are required to complete the production of a single sensor and integrate it into the structure. Compared to traditional methods, AM technology is highly advantageous because with multi-material printing, a fully functional sensor can be fabricated within a single step in multi material printing [16]. The degree of freedom available when designing a sensor is incomparable to any other conventional technology [17]. Because of the unique set of advantages of AM methods, instead of competing with other traditional methods (computer numerical control (CNC) machines, hot pressing, and molding approaches), it is more likely that AM will complement other fabrication methods. Currently, there are different AM methods to combine functional material with conductive parts to enable sensing functionality. Hybrid AM method combines AM-printed parts with non-AM structures such as regular wiring, printed circuit boards, or entire sensors [18].

This method allows for specific combination of parts and complements other classic assembly techniques. Another method is conductor infusion that can print channels in otherwise non-conductive sensing materials by AM methods with a subsequent infusion of conductive inks [19][20][21][22]. In this method, the infusion of conductive materials in dielectric materials is possible by using dissolvable support material to form networks of channels. This method allows complicated electrical wiring to be printed since the channels are formed in full freeform fabrication [17]. The most complex and advantageous method to integrate sensors is multi-material printing that combines conductive and non-conductive materials [16][23]. Freedom of design, straightforward fabrication, and co-printing conductors, i.e., conductive materials printed in the same cycles as the dielectric materials, are the most desirable and positive sides of AM technology [17].

## 2. Sensing Mechanism and Type

### 2.1. Transducing

Sensors are made up of the sensing component, a transducing mechanism, and an apparatus to interpret output data [24]. There are various types of sensing mechanisms based on physical or chemical principles. To distinguish which sensing element is suitable for a specific application, the characteristics of various transduction methods are discussed in the following section.

#### 2.1.1. Piezoresistivity

Piezoresistive devices interpret variations of electrical resistivity within electromechanical systems while they are subjected to mechanical strain [25]. Piezoresistive mechanisms incorporate electrodes that can be embedded or attached to the device. The structural mechanical, and electrical behavior of sensor materials, those of which should be electrically conductive, directly affects the performance of the piezoresistive response because of possible discrepancies in signal strength and accurate sensor readings. Wang et al. tackles common piezoresistive obstacles, such as signal sensitivity, by successfully 3D printing stretchable and porous sensing elements [26]. The electrode printing ink was comprised of plastic urethane and silver flakes while the sensing layer employed conductive carbon black nanoparticles and sacrificial sodium chloride particles for porosity.

**Table 1.** Fabrication, mechanism, and applications of 3D printed integrated sensors.

| Methods | Printed Materials | Mechanism | Applications | Ref. |
| --- | --- | --- | --- | --- |
| FFF | Thermoplastic elastomer | Capacitive | Force sensor | [27] |
| | TPU/PLA/Carbon black | Capacitive, Resistive | Mechanical and tactile sensing | [17] |
| | Polyphenylsulfone/Polycarbonate | Capacitive | Biomedical sensing, human interface devices, material sensing | [28] |
| | PA12/Magnetic particle | Magnetic | Magnetic sensor application | [29] |
| DIW | Sensor: TPU/Carbon black, Electrode: TPU/Ag | Piezoresistive | Skin-attachable electronics, human–machine interfaces, and electronic skins | [26] |
| | Silver with sacrificial ink | Inductive/capacitive | Food deterioration | [30] |
| | Graphene/PDMS and PTFE/PDMS | Electrical resistive | Smart textile | [31] |
| | Urethane Triacrylate/Methacrylic acid | Inductive/capacitive | Neuro-robotics and neuro-prosthetics | [32] |
| | Clay slurry | Capacitive | Relative humidity sensing | [33] |
| LPBF | Type K thermocouple | Seebeck effect | Temperature sensing | [34] |
| | SS 316L powder (Conductive material) | Magnetic | Structural health monitoring | [35] |
| SLM | SUS 316L, Inconel 718C | Thermal | Self-cognitive ability of metals | [36] |
| SLA | PDMS | Electrochemical | Biologically active molecule sensing | [37] |
| | Optical fiber | Pulse-calling | Particle analysis | [38] |
| DLP | Elastomer | Piezoresistive | Tactile sensor | [37] |
| SP-RF0900 | Resistive | Robotic manipulation | [39] | |
| Resin | Capacitive | Particulate matter sensing | [40] | |

| Methods | Printed Materials | Mechanism | Applications | Ref. |
|---|---|---|---|---|
| DED | Ti-6AL-4V | Magnetic | Eddy current test | [41] |
| | Stainless Steel/Zirconia | Resistive | Structural health monitoring | [42] |
| Inkjet | Tin oxide | Electrical resistive | Gas sensing | [43] |
| | ZnO | Resistive | Gas sensing | [44] |
| | Acrylic rubber | Resistive | Robotic gripper | [45] |
| FDM | TPU/graphite ink | Capacitive | Robotics | [46] |
| | PLA/wax filament | Nucleotide sequence | Dengue virus detection | [47] |
| | BTO/MWCNT/PVDF | Piezoelectric | Energy storage | [48] |
| | BTO/PVDF | Piezoelectric | Pressure sensing | [49] |

#### 2.1.2. Capacitance

The capacitive sensor consists of two parallel electrode plates and a dielectric material sandwiched in between [27]. The distance between the capacitor plates is directly influenced by the exerted force on the sensor, and the capacitance can be measured by also considering the plates' overlying area. Qiu et al. fabricated integrated sensing capacitors to fabricate tissues and organs for surgery preparation through 3D printing technique [2]. The capacitance capability exhibited by their 3D printed sensors was accomplished through printing with polyacrylamide hydrogels for the plates and a silicone elastomer as the dielectric material, where the elastomer experienced deformation when compressed. Due to deformation, the tactile sensor produced a capacitance change directly related to the applied pressure that simulated organ/tissue handling during surgical procedures.

#### 2.1.3. Piezoelectricity

The piezoelectric effect translates applied mechanical energy into a voltage or generation of electric current [50]. Piezoelectricity is amongst the most efficient transduction methods, in terms of output voltage and high sensitivity [51]. The piezoelectric transducer is comprised of two electrodes that contain a piezoelectric material sandwiched in between; piezoelectric materials can be Lead zirconate titanate (PZT), Barium Titanate (BT) or Polyvinylidene fluoride (PVDF). Cui et al. prepared PZT colloidal particles for implementation into photo-sensitive ink to produce 3D-printed complex architectures [52]. The usage of 3D-printing enabled the ability to print convoluted geometries while maintaining a strong piezoelectric efficiency and therefore, functionalization of an additive manufactured part. Complete manufacturing of the piezoelectric devices follows the order, 3D printing fabrication, electrode formation, and poling. 3D printing makes it possible to merge the first two steps and make the poling process easier [9].

#### 2.1.4. Magnetic Sensing

Magnetic sensors detect the presence of a magnetic field and provide actionable data regarding an object's positioning, speed, rotation, and direction of movement. 3D printing technology presents a promising manufacturing technique to fabricate functional magnetic sensor devices of complex geometries with multiple materials and scales [53]. Only a few pieces of research in his field are available till now [29][41]. Christian Huber and his group mixed permanent magnetic filaments with pure polyamide (PA12) filaments and 3D-printed polymer-bonded magnets with a variable magnetic compound fraction distribution to obtain a required external field of the manufactured magnets [29]. Credi et al. proposed two different techniques for 3D printing high-sensitivity magnetically responsive cantilever beams and verified their feasibility as magnetic sensors [54].

### 2.2. Wired

3D Printing sensor technology can be considered as (a) embedding an existing sensor into a printed structure or (b) printing the entire sensor [46]. Electronic functionality has been added to additively manufactured parts by embedding wiring, printed circuit boards, or entire sensors. Integrated wired sensors can be obtained by joining a non-conductive material with conductive inks through previously printed channels or using multi-material printing of conductive and non-conductive materials [17].

Embedded sensors can be easily fabricated by manufacturing the non-conductive part first and then adding the electronic component. Shemelya et al. successfully fabricated capacitive sensors using fused deposition modeling and embedded wiring and were able to manufacture a fully encapsulated sensor [55]. To achieve this, the AM process was interrupted various times to fully embed all electronic components. In order to 3D print a joint-angle sensor, the fabrication process had to be halted once the cavity for the wiring harness has been printed to add this mentioned component to the part before printing is resumed. However, since the printing process must be interrupted multiple times during sensor fabrication, the procedure has to be organized and registered to maintain accuracy during the prints.

Sensors can also be fabricated by fusing a conductive material through channels fabricated in a non-conductive printed part. This approach for embedded sensors is challenging to implement because the fusion of materials makes it challenging to insert and remove supports in small spaces. With this method, the inks used can (a) remain liquid after infusion, (b) be infused as a liquid and then solidified via curing or evaporation of solvents, or (c) be infused as a solid via a carrier that evaporates after the process [56]. Chizari et al. developed highly conductive CNT/PLA nanocomposites to fabricate liquid sensors via 3D printing [56]. Here, the material was extruded out of a nozzle, allowing for tunable scaffold thickness affecting the relative resistance change inversely. The evaporation of solvent during the printing process raised issues of deformation, leading to filament overlap, and hence, more sensitive sensors. Utilizing the freedom that AM offers, Chizari et al. increased the number of printed layers, resulting in lower sensitivity. Mu et al. embedded silver nanoparticle ink via direct ink write into another 3D printed part for the use of flex sensors, leading to 9% yield strain, and low resistance change after cyclic loading and unloading [57]. TGA/DSC was conducted to ensure that the volatile solvent had been removed completely. This method of embedding sensors born of ink solvent removal was successful due to its use of limited supports and verification method. Mu et al. fabricated a flexible sensor, fabricating a ring that varies resistance based on the bent position of the finger.

Fusion of materials via multi-material printing to fabricate sensors has the design freedom and is a straight-forward fabrication. Sensors fabricated using this method are primarily manufactured using ink or paste-based 3D printing technology such as direct ink write (DIW). Nassar et al. demonstrated the feasibility of this method by 3D printing a silver palladium paste and Glassbend Flexi material to fabricate a bendable smart sensing structure [23]. In comparison to the previous techniques, multi-material printing allows for the sensor to be manufactured in one single print without the need of interrupting or pausing the fabrication at the mid-print stage.

The challenge with wired embedded sensors, for all these methods, is that the sensors do have to be connected via a physical wire to a power source and to the component that will be outing the data provided by the sensor to have a fully functional sensor. Therefore, a new technology has emerged, allowing for wireless sensors to be fabricated via AM technology.

### 2.3. Wireless

Embedded printed components serve as efficient wireless sensors for accurate sensing, computation, and communication. These sensors shine in their capacity to monitor a wide range of physical and environmental variables, including pressure, temperature, motion, and others [58]. Wu et al., fabricated a passive wireless inductor-capacitor (LC) tank sensor using inkjet AM technology to create the coils channel and pad structures, which were later filled with liquid metal paint to create electrically conductive structures. This wireless LC tank sensor was used to measure the shift in resonance frequency which showed difference of 4.3% when the milk was stored at room temperature for 36 h [30].

Farooqui et al. pioneered the creation of 3D-printed disposable wireless sensors that incorporate microelectronics for extensive environmental monitoring. As a proof of concept, they demonstrated wireless temperature, humidity, and H2S level sensing [59]. Additionally, researchers have explored 3D-printed wireless implantable sensors. Herbert et al. developed a wireless, stretchable implantable biosystem via 3D printing for real-time monitoring of cerebral aneurysm hemodynamics, achieving wireless monitoring up to 6 cm through biological tissue [60]. Kalhori et al. designed and 3D printed a compact LC location sensor with enhanced wireless detection capabilities, enabling readouts from a distance of 10 cm [61]. Parker et al. created a customizable wireless implantable neural probe using 3D printing technology [62]. Furthermore, there have been reports on 3D-printed soft capacitive strain sensors integrated with wireless vascular stents, providing a biocompatible, battery-free, and wireless monitoring system [63][64].

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