Sensor-Based Additive Manufacturing Technologies

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Abstract: Additive manufacturing is the term that uses the CAD data to build components layer by layer; it is also termed layered manufacturing or 3D printing. The major advantage of additive manufacturing is the capability of building components without the use of molds or tools. Five major categories of AM processes include Powder Bed Fusion (PBF), Direct Energy Deposition (DED), Material Jetting (MJ), Binder Jetting (BJ), and Sheet Lamination (SL). The sensor may be defined as a device that responds to a physical stimulus and transmits a resulting impulse. Sensor technology has been widely adopted in advanced manufacturing, aerospace, biomedical and robotic applications. Commonly used sensors are temperature sensors, strain sensors, biosensors, environmental sensors, and wearable sensors, etc. Additive manufacturing technologies can fabricate sensors and microfluidic devices with less labor. This paper focuses on various sensors developed by additive manufacturing processes, and their practical application for the particular purpose is reviewed.

Keywords: additive manufacturing (AM); 3D printed sensors; fused deposition modeling (FDM); challenges of additive manufacturing.

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1. Sensor Classification

1.1. Physical sensors.

These can detect changes in physical quantities and transform them into electrical signals that can be used [1]. Tactile, temperature, particle, gas concentration, and radiofrequency sensing are all applications for physical sensors.

1.2. Chemical sensors.

To detect chemical reactions, chemical sensors use electrochemical and optical methods [1]. Chemical sensors printed in 3D are commonly used to detect liquid concentrations, gas concentrations, and pH variations. However, recent studies show that nanomaterials are more often used due to high surface area and high reactive sites [2-11].
1.3. Biosensors.

The majority of biosensors are used in biological science. Biosensors are primarily used in medical science, food manufacturing, and marine applications. For selective analysis, biosensors use biochemical, molecular recognition properties [12].

2. Additive Manufacturing Technologies for Sensor Fabrication.

Stereolithography, Polyjet, Fused Deposition Modeling, Selective Laser Melting, Selective Laser Sintering, 3D Printing, and 3D Inkjet/Extrusion are examples of sensor fabrication technologies. Fused Deposition Modeling is the most commonly used of these technologies due to its low material cost.

2.1. Fused Deposition Modeling (FDM).

FDM technology is the most dependable and cost-effective form of fabrication. The FDM process uses the content efficiently, resulting in less waste. FDM can be used for a variety of thermoplastic polymers [13]. Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polycarbonates (PC), Polyetheretherketone (PEEK), and Polyetherimide (PEI) are some of the most commonly utilized products.

FDM is a hot-melt extrusion process that usually uses a filament feedstock with a diameter of 1.75 mm to 3 mm. A drive gear mechanism feeds the filament to the printer. At the heated liquefier, the filament is melted, and the material is deposited layer by layer according to the CAD results. The diameter of the FDM nozzle is 0.4 mm, while the diameter of extruded threaded ranges from 0.1 to 0.4 mm. FDM's mean working temperature varies from 250 to 500 ŒC. During the printing process, the print head will travel in an X-Y direction to finish printing a single sheet, then the platform will be lowered in a vertical Z-direction to print the next layer, and so on until the entire object has been printed.
3. Applications of 3D Printing in Biomedical Diagnostics

3.1. Sample pretreatment

It is necessary for diagnostics to reduce the process's complexity and increase the sample's sensitivity [14]. The microfluidic system depicted in Figure 2A has cell flow near the inner wall of the tube, which separates platelets and blood cells from plasma.

![Figure 2. (A) Microfluidic device to separate platelets and blood cells from plasma; (B) Microfluidic device to separate magnetic nanoclusters coupled to bacteria E. coli; (C) Microfluidic channel to separate platelets from blood cells; (D) Trapezoidal filter with a microfluidic channel [14].](image)

The microfluidic system used to isolate pathogenic bacteria E. coli from milk samples is shown in Figure 2B. The theory is based on the separation of free magnetic nanoclusters from bacteria-bound nanoclusters during the flow of magnetic nanoclusters through microfluidic channels. The microfluidic channel in Fig 2C separates platelets from blood cells with 100% purity, using a syringe to pass the blood sample to the device manually. The trapezoidal filter with a microfluidic channel shown in Fig 2D was used to isolate the magnetic nanoparticles from the blood sample.

3.2. Microfluidic flow devices.

Microfluidic flow devices are compact fluidic instruments that can monitor the handling of extremely small samples and assay reagents. AM methods can be used to fabricate microfluidic systems more efficiently and at a lower cost. Figure 3A shows a microfluidic device for calculating the viscosity of a blood sample that is less costly than industrial viscometers [14]. The microfluidic system in Figure 3B has two key functions. The detection chamber will detect the developed luminescence after the adenosine triphosphate sample is mixed with the luminescence reagent mixture. A 3D printed microfluidic chip to detect cancer biomarker proteins is shown in Figure 3C. The proposed design will reduce the assay time to
30 minutes. The microfluidic device in Figure 3D is used to monitor the flow of samples and assay reagents manually.

Figure 3. (A) 3D Printed syringe for blood viscosity measurement; (B) 3D Printed microfluidic device for quantification of adenosine triphosphate; (C) 3D Printed microfluidic chip to detect prostate-specific antigen (PFA) and platelet factor-4 (PF-4); (D) 3D Printed microfluidic unit that controls the flow of assay reagents and samples [14].

Chemical flow analysis, hematological analysis, electrochemiluminescence DNA tests, and salivary cortisol detection may all benefit from 3D printed microfluidic flow instruments.

4. Engineering Applications of 3D Printed Sensors

4.1. Strain sensor.

Mohammad Reza Khosravani et al., in their publication, discussed 3D printed strain sensors and tactile sensors. Tensile and compressive strains are converted into useful electrical signals using this device. These sensors were created using a stretchable conductive material and a flexible conductive material [15]. The direct ink writing (DIW) method, similar to the FDM technique, is commonly used for fabricating strain sensors. The strain sensor explained by Mohammad Reza Khosravani et al. [15] was created by embedding silicone elastomer and piezoresistive inks. These sensors have excellent stretchability and can withstand mechanical strains of up to 800%, and they have a gauge factor of 3.8±0.6, which is comparable to traditional strain gauges.

4.2. Acceleration sensor.

The acceleration sensor is made by printing on polyethylene terephthalate, which gives the sensor more flexibility [15]. The structural substance is a silver paste, and the sacrificial substrate is polyvinyl alcohol. In their publication, Mohammad Reza Khosravani et al. described the details of the six-sided gaming die, which includes a microprocessor and an
accelerometer, which was 3D printed. The die will be able to sense motion and recognize top surfaces using gravity.

4.3. Pressure sensor.

Mohammad Reza Khosravani et al. [15] discussed pressure sensors that can detect changes in pressure and load. It's a beam-based structure made with the FDM method. Changing the diameter of the various printed components allows for differential pressure measurement. Changes in friction, bending, and the fabricated sensors can also detect twisting moments.

4.4. Particle sensor.

Particle sensors are used to determine the content of particles in the atmosphere since they can detect particulates found in the air. Environmental factors can influence the sensors' precision. Mohammad Reza Khosravani et al. [15] discussed particle sensors in which 3D printing technology is used to build microchannels. The output of the sensor was calculated by delivering particles to the flow channels using a Quartz Crystal Microbalance (QCB) sensor attached to the microchannels.

5. Applications of AM Technologies

Carmen M. Gonzalez-Henriquez et al., in their publication, showed how AM technologies are used in a variety of industries, including automobile, electronics, aerospace, sports, jewelry, mold making, and architecture [16]. AM technologies have recently become very common in biomedical and medical diagnostics, dentistry, and surgical instruments. AM innovations have shown the ability to create completely personalized goods at a lower cost. The various application areas of AM technologies explained by Samad M. E. Sepasgozar et al. [17] are illustrated in Figure 4.

![Figure 4. Applications of AM Technologies [17].](https://biointerfaceresearch.com/)

6. Challenges of Additive Manufacturing

6.1. Safety.

Waste disposal, material handling risks, and radiation exposure are all risk factors associated with AM technologies. All operators are required to complete safety training.

6.2. Technical knowledge.

This relates to the AM sector's specific expertise. The ASTM established standards that covered test methods, AM materials, health and safety precautions, AM science and
innovation, and industrial applications of AM. Prior training is required for all operators who wish to use the AM equipment.

6.3. **Data security.**

Software packages for creating stereolithography files and generating tool path commands are embedded in AM technologies [18]. All AM machines can accept STL files, but tool path commands differ from machine to machine, and only the manufacturers of AM machines are aware of this.

6.4. **Post-processing challenges.**

Separating a component from its base plate and surface finish and deburring are both post-processing issues. In addition, the method for removing the supports can influence the final product's dimensional accuracy.

6.5. **Sustainability.**

During the processing of the metal powder, the unused metal powder is recycled. Due to the formation of agglomerated powder during the laser melting process, this job is a little difficult.

7. **Studies on Sensor Applications**

| Author | Year | Type of sensor | Applications |
|--------|------|----------------|--------------|
| Mohammad Vaezi [19] | 2012 | Capacitive Pressure Sensor | To measure gas or liquid pressures in jet engines |
| R Shashanka et al. [20] | 2013 | Silver Nanoparticle/Carbon Paste Electrode (AgNps/CPE) sensor | To detect uric acid in the presence of dopamine at physiological pH. |
| Kenry et al. [21] | 2016 | Polyurethane dispersed stretchable strain sensor | The stretchable strain sensors are attached to different facial and body parts and can detect and monitor skin strains and muscle movements during facial expressions and daily activities. |
| Dirk Lehnhus et al. [22] | 2016 | Fibre Optical Sensor | Structural Health Monitoring. |
| M.T. Rahman et al. [23] | 2016 | Capacitive touch sensor | Measurement of capacitance in touch as well as in untouched state. |
| Arkadeep Kumar et al. [24] | 2017 | Microfluidic Sensor | Used for actuation of soft robotic grippers. |
| JuYoun Kwon et al. [25] | 2017 | Potentiometric Sensor | To monitor sodium levels in real-time. |
| John O’Donnell et al. [26] | 2017 | Screen printed glucose and lactate biosensor | Utilized in cell toxicity studies. |
| Sepehr Nesaei et al. [27] | 2018 | Glucose biosensor | Used in diabetes management. |
| Yanglong Lu et al. [28] | 2018 | Physical Based Compressive Sensor (PBCS) | To measure the temperature distribution of manufacturing processes. |
| Jinke Chang et al. [29] | 2018 | Flexile strain sensor/piezoresistive sensor | To sense the change of resistance at different hand positions. |
| Rafiq Ahmad et al. [30] | 2018 | Radiation Sensor | Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT). |
| R Shashanka et al. [31] | 2018 | Linear Sweep Voltammetry (LSV) Sensor | To determine the phenomenon of pitting corrosion in stainless steel. |
| Yan Li et al. [32] | 2019 | Graphene aerogel based flexible sensor | Used in finger motion manipulation auxiliary apparatus. |
| D. Wolozny et al. [33] | 2019 | 3O-C12 living biosensor | To diagnose lung infections. |
| R Shashanka et al. [34] | 2020 | Cyclic Voltammetry Sensor | Electro generation and deposition of Copper oxide (CuO) nanoparticles. |
| Xiaofan Ruan et al. [35] | 2020 | Portable microfluidic device sensor | Used in continuous monitoring of human microdialysate. |
| Author                  | Year | Type of sensor                        | Applications                                                                 |
|------------------------|------|---------------------------------------|-----------------------------------------------------------------------------|
| Mahshid Padash et al.  | 2020 | Iontophoretic biosensor               | Used in alcohol monitoring systems.                                         |
| Jose Munoz et al. [37] | 2020 | Graphene/ PLA biosensor               | Used for the analysis of glucose in blood plasma using chronoamperometry.    |
| Fernando Otero et al.  | 2020 | Sweat glucose sensor                  | To measure glucose level, humidity, pH, and temperature.                    |
| Moe Elbadawi et al.    | 2021 | Calorimetric Sensor                   | Used to monitor glucose and Cholesterol levels                              |
| Jyoti et al. [40]      | 2021 | 3D printed nanocarbon electrode sensor (3DnCE) | To detect chlorophenols and nitrophenols in aqueous solutions              |
| David T. Bird et al.   | 2021 | Gastric Resident Electronics (GRE) device | Used in personalized diagnostics and treatment of soldiers                  |
| Priya Kishor Dave et al.| 2021 | Electrochemical MERS-CoV Sensor      | Used to detect MERS-CoV based on a competitive assay                        |
| Thanyarat Chaibun et al.| 2021 | Electrochemical biosensor coupled with rolling circle amplification (RCA) | Highly sensitive and specific detection of SARS-CoV-2                     |
| Fahad Alam et al.      | 2021 | Smart Contact Lenses (CLs)            | To detect and continuously monitor the glucose concentrations in tears of diabetic patients. |

8. Conclusions

3D printing has many advantages over traditional methods, particularly when it comes to commercial goods. 3D printed sensors have shown increased sensitivity and compatibility with a wide range of personalized items. Fused Deposition Modeling is one of the most promising methods for producing low-cost, high-productivity sensors. With extreme dimensional precision, the FDM process can create critical geometries and cavities. As opposed to traditional methods, 3D printing is most useful in biomedical diagnostics because the testing time is steadily reduced. The use of sensor-based technology can easily measure mechanical parameters such as force, velocity, acceleration, strain, and bending moments, which can help engineers solve critical problems in less time.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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