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Editorial

To Print, or Not to Print, That Is the Question

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This month I'd like to provide some brief thoughts on the role of three-dimensional (3D) printing in modern sensor science. 3D printing describes a number of different fabrication methods that allow the production of geometric structures from a digital model. Although originally proposed in the 1940s[1] and put into practice in the 1980s,[2] the field of 3D printing (or additive manufacturing) has evolved tremendously over the last 15 years, with a plethora of low-cost and open-source printers now being used by hobbyists, academic researchers, or in manufacturing applications. As envisioned by the inventor of stereolithography, Charles Hull, 3D printing tools have had their most obvious impact in prototyping, allowing geometrically sophisticated structures to be fabricated on short time scales. This has meant that 3D printing has become a valuable tool in the on-demand production and prototyping of precision devices and parts used by the experimental scientist.

While 3D printing techniques are readily accessible, cost-effective, and flexible, they are not without their drawbacks. First, although many plastics and metals can be 3D printed, the printable material or "ink" is constrained by the printing method itself. Indeed, the difficulties in controlling the rheological properties of plastics, glasses, or metals means that printing bespoke materials can be immensely challenging. Second, contemporary sensor, actuator, or fluidic components are small, with minimum dimensions commonly on the micron or even submicron scale. This poses a significant challenge for most 3D printers, since minimum feature sizes rarely drop below 100 μm. There are exceptions. Nanoscribe's Photonic Professional printers, for example, leverage two-photon polymerization (2PP) to fabricate structures with dimensions below 200 nm. While 2PP can be used to make sophisticated components for optical sensing, fabrication times can be excessively long (often days!) and build-volumes very small.[3]

As recently discussed by Cheng and colleagues in this journal,[4] 3D printing has been widely used to fabricate structures for molecular sensing. These include optical and plasmonic structures, mechanical components, and fluidic components for molecular assays. While almost all of these systems have been shown to function as intended, it is often unclear to me why 3D printing is advantageous or beneficial. Indeed, is it really enough to show that a device can be made using 3D printing if it can be made via a more conventional and scalable route? I would almost always say "no". Perhaps, a better question to ask is "when does 3D printing a sensor or analytical device make most sense?" There is no comprehensive answer to this question, but a few scenarios spring to mind.

First, if 3D printing allows us to make a structure or component that is difficult or impossible to make using any other fabrication method, then clearly this is desirable. A great example in this regard was shown a few years ago by Lee and co-workers, who used stereolithography to create a helical microchannel device in which pathogenic bacteria could be separated and detected.[5] To do this, the authors used antibody-functionalized magnetic nanoparticle clusters (MNCs) to capture bacteria, with the complexed MNCs being separated from free MNCs via Dean drag and lift forces generated in a curved channel. Since 3D printing allowed the fabrication of a helical microchannel with a constant radius of curvature (basically a hollow spring), the authors were able to fix the Dean number and thus control the associated drag force (which mediates the separation), unlike a "classical" 2D microfluidic device, where a spiral channel would have a variable radius of curvature and thus a variable Dean number. Making such a device using any other fabrication would be at best costly and exceptionally time-intensive. So, the take home message is that 3D printing is always advantageous if you want to make truly three-dimensional optical or fluidic structures.

Second, 3D printing can be of huge utility when performing experiments in low resource settings, where access to instrumentation and supply chains is limited or nonexistent. The most obvious example in this regard would be point-of-care testing in the developing world. Since most 3D printers are portable or at the very least "transportable", diagnostic sensors could in theory be made in a standardized manner in any location. Although there are few, if any, fully developed 3D printed diagnostic systems, numerous examples of 3D-printed components for sample pretreatment/manipulation, molecular separations, biomarker detection, and signal readout have been reported.[6] Indeed, it should not be forgotten that 3D printing has played a small but significant role in the global response to the ongoing COVID-19 pandemic, with 3D-printed nasopharyngeal collection swabs and lateral flow tests being noteworthy contributors to the detection and isolation of infected individuals in both the developed and developing world.[7]

Finally, and in a more speculative and exciting vein, 3D printing is perfectly suited to the in situ fabrication of functional sensors and diagnostics on and inside the human

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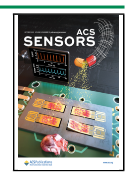

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body. The opportunities in this regard are vast. Soft and compliant biomedical sensors could made at the point-of-application and used to monitor therapeutic interventions, wound healing, and bodily functions. A beautiful example of such a sensor was recently presented by McAlpine and co-workers, who printed a hydrogel motion sensor on a porcine lung to continuously monitor respiration-induced deformations.[8] This is just the start, and it is likely that fully autonomous operation of similar sensors could be achieved through integration of the printed sensor with soft control and power electronics.

So, despite the opportunities that 3D printing offers in the field of sensor science, it is a little surprising that in my role as Associate Editor, I have yet to handle many papers that leverage 3D-printing in making new sensors. That said, I expect this situation to change very soon, with ongoing advances in 3D printing technologies opening up new and creative avenues for our sensor community.

Andrew deMello, Associate Editor orcid.org/0000-0003-1943-1356

AUTHOR INFORMATION

Complete contact information is available at:
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Notes

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