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Dimensions of Smart Additive Manufacturing

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Additive manufacturing (AM) has matured in parallel with advances in computation. This is not a coincidence as taking advantage of the structural freedom afforded by AM requires detailed calculations and an ability to design and process complex structures in three dimensions. However, the ability to program AM systems is not the only way in which computation, and more recently machine learning, have impacted AM as a field. In fact, recent years have seen a number of innovations in AM that have endowed the process with varying degrees of 'intelligence' in distinct ways. While many of these are connected, several of these approaches to smart AM are wholly distinct in that they advance different aspects of the state-of-the-art. Our goal in this editorial is to highlight three such dimensions of intelligence in AM and connect them to articles in this special issue of *Advanced Intelligent Systems* that discuss innovations along these dimensions. These dimensions include advances in the materials and structures produced by AM to make them smarter or more functional, advances in processing to produce better and more reliable products, and advances in using AM as an ecosystem that is more agile and capable than traditional manufacturing (**Figure 1**).

Dimension 1: Data-Driven Approaches for Multifunctional Smart Material Designs

Advances in AM have enabled the fabrication of multimaterial, multiscale, and multifunctional structures. Machine learning and optimization algorithms have extended the structures created by AM with specific functions and desired properties of interest. This is especially useful when it comes to exploring the vast design space offered by AM. Several methods of integrating data-driven tools in various materials design problems in AM are reviewed by Tian et al. (article number 2100014). Specifically, they mention several methods such as genetic algorithms, artificial neural networks, topology optimization, high-throughput simulations, among others that can be utilized to design materials to be additively manufactured. Smart engineered multifunctional structures and designs with controlled deformation, self-repair, and sensing characteristics are highlighted by Ji et al. (article number 2000271). Chen et al. reviewed the 3D-printing of smart electroactive materials that form the backbone of printable devices with a wide variety of applications throughout biology, engineering, and chemistry (article number 2100019). They further expand on the use of machine learning methods to aid in the development, design, and manufacturing of electrically conductive materials. These articles delineate the use of AM systems and data-driven approaches to create smart, multifunctional materials and structures.

Dimension 2: Data-Driven Approaches for Advances in AM Processing

While AM has made large strides in the past decades, challenges still remain when it comes to optimizing the process. In addition to materials design problems, data-driven approaches have been applied to the process parameters of AM for improved resolution and detection of defects. For instance, Zhou et al. created a data-driven mask image planning method based on subpixel shifting in a split second by tuning the process in both temporal and spatial domains to improve printing resolution (article number 2100079). Their experimental results show that the data-driven based mask image calibration and planning techniques can drastically improve the printed part quality without compromising the process efficiency. Nassar et al. have explored using multimaterial fused deposition modeling 3D-printing methods as a method of embedding electrical interconnects from a copper-based conductive polymer composite (article number 2100102). The authors systematically explored the effects of printing conditions and orientations on resolution and conductivity of the printed part. Seifi et al. discussed the presence of process-induced internal defects such as pores and microcracks on the structural durability of parts created by AM. They developed a nondestructive evaluation method of fatigue performance from the process of laser-based AM processes, specifically with a focus on in-situ monitoring of the thermal history (article number 2000268). These show examples of the impact data-driven methods can have on improving AM processing.

Dimension 3: Additive Manufacturing in a Smart Ecosystem

While AM is but one facet of modern manufacturing, it has the unique feature that it is massively decentralized. As such, AM presents a unique opportunity for building an ecosystem in which knowledge and materials are widely shared and

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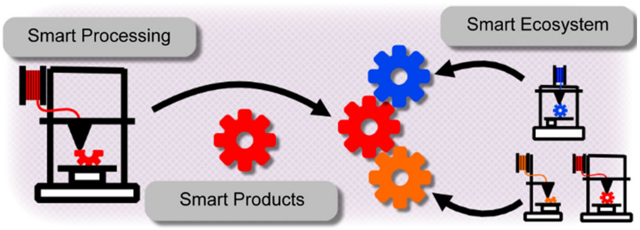

Figure 1. Schematic showing three dimensions of intelligence in additive manufacturing.

co-developed. In many ways, this community has already evolved through online communities and shared repositories of digital designs. There are many ways that this community, and the ecosystem in which it operates, can advance in ways that enhance the capabilities of AM and its broader role in society. Sustainability is one arena that has recently received attention and Li and Yeo write about how sustainability can be designed into AM (article number 2100069). AM has some obvious advantages in the context of sustainability such as shorter supply chains, but there are challenges when facing the economies of scale presented by centralized manufacturing. Li and Yeo argue that these obstacles can in part be overcome through shared bodies of knowledge related to life cycle analysis, design optimization for sustainability, and recycling. One additional virtue of AM is that systems can be retasked at a moment's notice to adapt to changing circumstances or needs. Raeymaekers et al. write about how this versatility could be used to make AM a resilient backbone of production for disaster scenarios (article number 2100121). Such a "rideshare-like" model has the potential for leveraging decentralized manufacturing to dynamically meet manufacturing needs of individuals or small companies. These examples highlight some of the advances that are possible with the collective action of the AM community.

While these three dimensions of AM represent areas of high present research interest, they are by no means the only ways in which AM is advancing. Indeed, the natural partnership of AM and the advancing fields of machine learning, computation, and widespread connectivity are only in its infancy. We hope that this special issue will draw attention to the diversity of ways in which AM can be enriched through this partnership.

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