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The Synergistic Role of Additive Manufacturing and Artificial Intelligence for the Design of New Advanced Intelligent Systems

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Intelligent materials and devices are considered the key to fulfill the strict and challenging requirements given by a large set of applications in numerous fields. The synergistic interplay of additive manufacturing (AM) technologies, specifically 4D-printing, and artificial intelligence (AI), have widened the design space and accelerated the design phase. 4D-printing, intended as the combination of 3D-printing with a fourth dimension (i.e., time), ensures the fabrication of complex topologies with materials that can be selectively triggered to change specific features (e.g., shape, color), whereas the use of smart inks or embedded sensors can bring additional functionalities (e.g., repairing, sensing, actuating) to fulfill the requirements of the targeted application. AI is the tool allowing scientists to train machines for developing human-like capabilities to discern, predict, and represent the statistically significant behavior of a phenomenon. If applied to the design of smart structures, it can be a powerful and efficient tool capable of reducing the time-to-manufacturing, improving the traditional design approach. In this perspective, a viewpoint is provided on how the synergistic use of AI and AM can advance the design of intelligent systems, with successful applications ranging from the robotics to the bioengineering sectors.

1. Introduction

Intelligent systems are, by definition, setups that are able to adapt their features and functions for a specific set of applications. Systems intended to be "intelligent," or "smart," usually have a specific arrangement of active and passive structural components. The first class is the key of a setup and includes all those parts of a device made of materials that are activated upon a triggering stimulus (e.g., pH, heat) against nonreactive components. Smart systems, in a broader sense, also include those made of materials able to perform living-like functions, such as healing, sensing, and actuating.[1]

Designing intelligent systems has pushed scientists to develop new strategies in terms of behavior enhancement and property predictability in relation to each specific application. For instance, any device intended for the biomedical sector has to comply with the challenging needs of dimensions and biocompatibility to prevent any mechanical and biological issue to living tissues. In contrast, applications for industrial robotics require high adaptability and reliability for manipulating objects and, in case of collaborative robotic operations, to ensure operator safety. While previous design approaches have included mathematical techniques like linear elastic topology optimization or level-set topology,[2] multiphysics finite-element models (FEMs) have widened the design space, giving scientists new tools to design, simulate, and predict the behavioral capabilities of complex structures, also by introducing material and geometric nonlinearities and solving multiple physics problems in parallel. Remarkable examples are the optimization of structures included in geometrical and material nonlinear environments,[3] studies on failure mechanisms difficult to observe experimentally,[4] or the development of compliant mechanisms for mechatronic and medical applications that exploit nonlinear deformations.[5] However, the traditional path of a device from the in silico design to manufacturing has two main limitations. From the design standpoint, FEMs represent a powerful tool that can handle parametric models by sweeping parameters across specific ranges of values. Yet, they cannot smartly cover the large number of design parameter combinations without an expensive computational cost.[6] This scenario is also complemented by the traditional fabrication technologies that narrow the topologies

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manufacturable due to the intrinsic mechanical and control limitations of the machine tools. A step forward in this direction has been brought by the advent of advanced manufacturing technologies and in particular additive manufacturing (AM). The latter, often called, through a metonymy, 3D printing (3DP), has given scientists the opportunity to make, through a layer-by-layer fabrication approach, structures with complex geometries, widely expanding the design possibilities in terms of achievable topologies with an extremely reduced amount of time. Recent progress in materials science has expanded the range of processing materials, including those with specific physical–chemical properties, which can be triggered by an external stimulus, thus enhancing macro-/microfeature variations (e.g., color/shape changing) or functional activities (e.g., structure healing) over time, defined as the fourth dimension.[7] A further step ahead is given by artificial intelligence (AI), a tool allowing scientists to train machines for developing human-like capabilities to discern, predict, and represent the statistically significant behavior of a phenomenon. When applied to the design of smart structures, it can be a powerful and efficient instrument to enlarge the design space and decrease the time to manufacturing, improving the traditional design approach.

In this Perspective, we provide our viewpoint on the synergistic use of AI and AM and how it could define a new era in the design of advanced intelligent systems. Through different case studies, spanning from robotics to materials design and bioengineering, we show the diverse applications of AI and AM and the various levels of integration in mechanical systems design.

Specifically, we first discuss recent advances in AM, from 3DP to 4D printing (i.e., 3DP and 4DP) and beyond (including the time dimension and multiples functionalities provided by smart inks).[8–10] We then discuss the recent progress in AI, in particular, regarding the field of materials design, from optimal design topologies[11] to image-based methods to detect manufacturing-induced defects[12,13] or to assess object printability[14] and perform structural health monitoring through embedded sensors.[15] We finally leverage different case studies to show how the synergistic use of AI and AM will advance the design of intelligent systems, from robotics to bioengineering sectors, also providing an outlook for its application in the near future.

2. 4DP: Tools for Fabricating Intelligent Systems

From its first appearance in a TED Talk in 2013,[16] 4DP was defined as "3DP + transformation capability." This definition was later modified into "3DP+time" with the fourth dimension being time.[17] Today, broadly speaking, the concept of 4DP is connected to the change in the shape, property, and functionality of a 3D-printed structure with time upon exposure to external stimuli, which can be either physical (temperature, electromagnetic fields, humidity, UV light, mechanical loads) or chemical (pH, chemical reaction). These smart constructs are able to perform specific tasks (e.g., drug delivery, actuating mechanisms through multistable topologies) by changing shapes or enabling dynamic properties (e.g., pore size variation upon dynamic physical–chemical conditions).[18] Such particular properties make 4D-printed parts highly attractive in a large number of fields, from mechanics to biomedicine.[19] Remarkable examples are represented by the design of bioinspired mechanisms that aim at replicating propulsions of living organisms such as the 2 mm wingspan flapping wing mechanism developed by Soreni-Harari et al.[20] or the corkscrew locomotion of microrobots actuated by magnetic fields, and triggered by light sources, used for drug delivery applications (**Figure 1**A).[21,22]

4D-printed parts may also be used in robotics for a wide range of applications including actuators, grippers, sensors, or deployable structures. For instance, Shao et al. recently published the design and fabrication of a 4D-printed gripper made of a composite that combines silver nanowires with a shape memory polymer, able to be electrically controlled. This system composed of five locally deformable petals allows the operator to efficiently grasp cargos also at low temperatures (Figure 1A).[23] Other interesting studies concern, instead, multistable structures that perform rapid actuations when triggered by external heat without electric inputs (Figure 1B).[24,25] Tissue engineering is also another interesting field of application: smart materials and composites have been designed to replace tissues with complex topologies to easily adapt to the host tissue using specific stimuli (e.g., light, pH), activate a controlled release of drugs or particles to reduce inflammations, or treat pathologies or tumors.[21]

A different approach has been given by the advent of meta(bio) materials, a new class of constructs that are able to mimic the functionalities of natural tissues by exploiting specific topological designs. These structures, often fabricated in large scale via AM, are thus able to adapt to each different target (e.g., tissues of patients) and be low-cost solutions that are totally free of being target/patient specific.[26] These ambitious goals can be achieved by operating both at the macro- and the microscale, creating topologies that can easily perform, for instance, load-bearing tasks in prosthetics[27] (also using folding structures, as shown in Figure 1D[28]) or antimicrobial activities.[29,30]

Thanks to the rapid growth in materials research, today, 4DP also includes, in a broader sense, the principles of 3DP to fabricate complex topologies with active (or smart) inks.[8–10] The versatility of smart inks enables 4DP of soft devices with shape-change ability when triggered by an external stimulus. In this context, the involvement of AI can open new venues for shape-programming ability, allowing the fabrication of wearable devices that can adapt to body motions or implants that can adapt to anatomical location, overcoming the limitation of traditional trial-and-error approaches and topology optimization.[2,31]

2.1. Beyond 4DP: Enabling Multiple Functionalities

4DP has also been considered the key to mimic the characteristic features of living organisms like sensing and self-repairing, both desirable for structural applications (e.g., in the aerospace and bioengineering sectors). Self-healing has always been a long-sought characteristic of natural systems: plants and animals can seal and heal wounds, and bone has the capacity of self-repair.[32] Inspired by living materials, researchers have developed synthetic self-healing polymers capable of repairing fractures at the microscale, also recovering the mechanical strength at the macroscale.[33] The healing capability is generally activated by extrinsic or intrinsic factors, via different

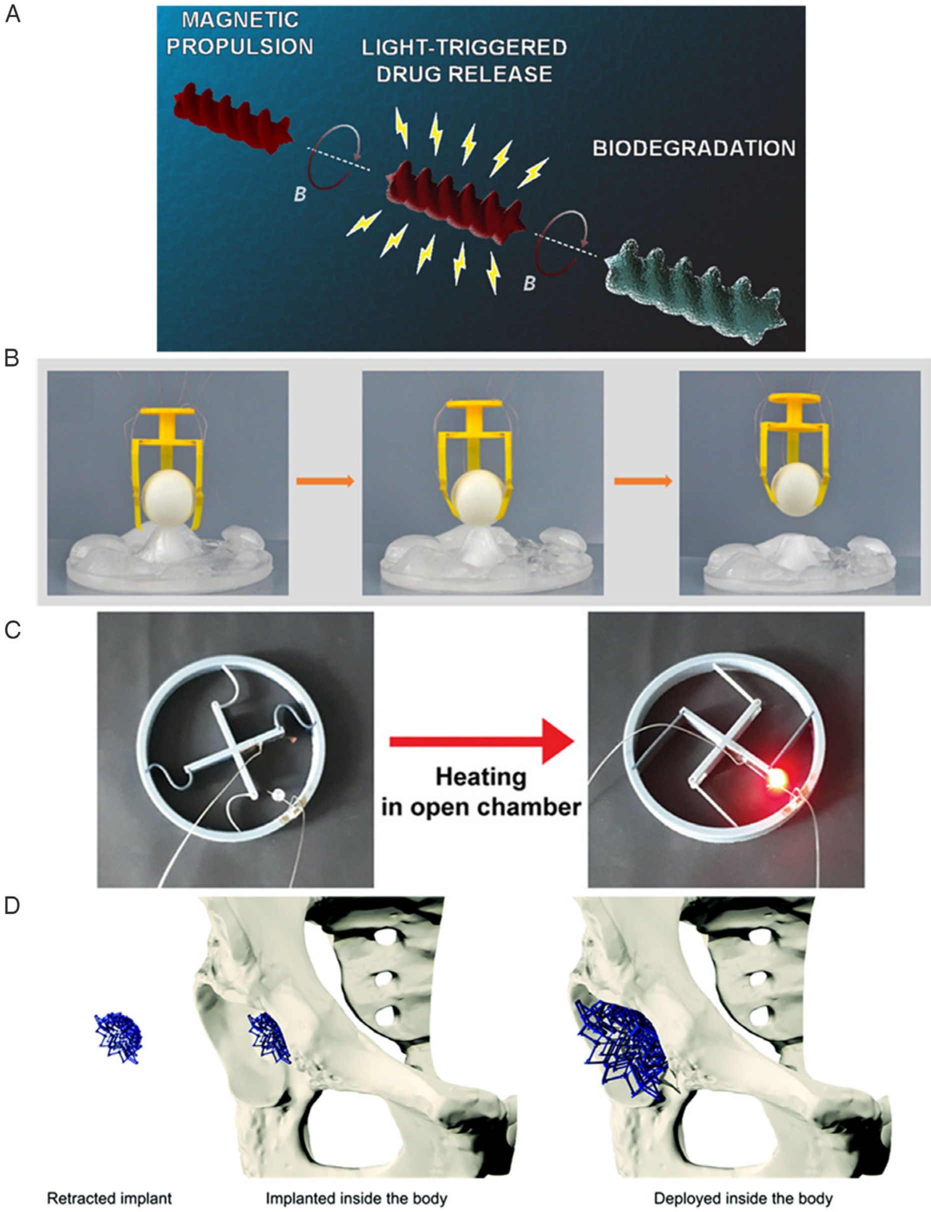

Figure 1. A) Applications of 4DP. Helicoidal microrobot actuated by magnetic fields for drug delivery triggered by light sources. Reprinted with permission.[22] Copyright 2018, American Chemical Society. B) Soft gripper locally deformable when triggered by electricity. Reprinted with permission.[23] Copyright 2020, Elsevier. C) Multistable actuator triggered by external heat. Reprinted with permission.[24] Copyright 2018, John Wiley and Sons. D) Multistable unfolding structure used for load-bearing prosthetics. Reprinted with permission.[28] The Royal Society of Chemistry.

mechanisms (e.g., encapsulated curing agents released upon fractures, intrinsic dynamic bonds, etc.).[34] Recent progress in AM has expanded the range of printable polymers, also including self-healing elastomers.[10,35] However, AM of such polymers is not a straightforward process due to their structural and rheological complexity and the limited quantities produced at lab scale. In addition, the synthesis of a material with intrinsic healing capacity and an optimal combination of mechanical properties (i.e., stiffness, strength, and toughness) remains a key challenge. This limits the exploitation of the full potential of self-healing polymers in structural applications.

A further trend toward multifunctionality is to harness the conductivity properties of nanoparticles, such as carbon nanotubes (CNTs) or graphene, to add self-sensing features.[36] Nanoparticles have been increasingly studied for their exceptional mechanical properties, mainly due to their characteristic nanosize. However, translating their unique nanoscale properties into large-scale systems is extremely complicated. An alternative to properly exploit their potential is to change perspective and embed them into larger-scale materials, taking advantage of their conductive properties. Lately, such nanoparticles have been integrated into the printing process, leading to novel conductive inks,[37] with tunable conductive properties, which are used to manufacture electronic components[9] or selectively controllable smart devices via an electroactivated shape memory effect.[38] Through printing, the ink can cost effectively build microfluidic devices and a wide range of other electronic devices, including flexible electronics, with high resolution and strong metallic conductivity.[39]

The emerging trend to print a wide palette of functional and smart inks, including electronic and biological inks, has made patient-specific wearable devices accessible to a wide range of people and enables smart biomedical implants for applications such as health monitoring and regenerative biomedicines.[8] Yet, 4D-printed multifunctional wearables and implantable devices are still in the early stages of development. Current limitations involve ink formulation and compatibility with traditional inks[40] but also mismatch issues with the target surface or surrounding tissue.

3. AI for Designing Intelligent Systems and Materials

AI and its subsets, machine learning (ML) and deep learning (DL), are imbuing the field of intelligent materials and systems design. AI, in a broader sense, is intended as a wide set of computational techniques that mimic human intelligence, thus having the ability to perceive, reason, and act like human beings.[41] ML, instead, can learn on its own from given sets of data, fed as input, to predict future outputs. AI, and in particular ML, has the ability to reach unexploited regions of the design space, thus widely expanding its boundaries.[42] From an alternative route to solve optimization problems[11] to the designing of high-performing materials without exploring the entire design space,[43] and yet to discover of unprecedented set of mechanical properties, ML is proving to be a powerful and versatile tool of the materials researcher's equipment. A recent example is given by a

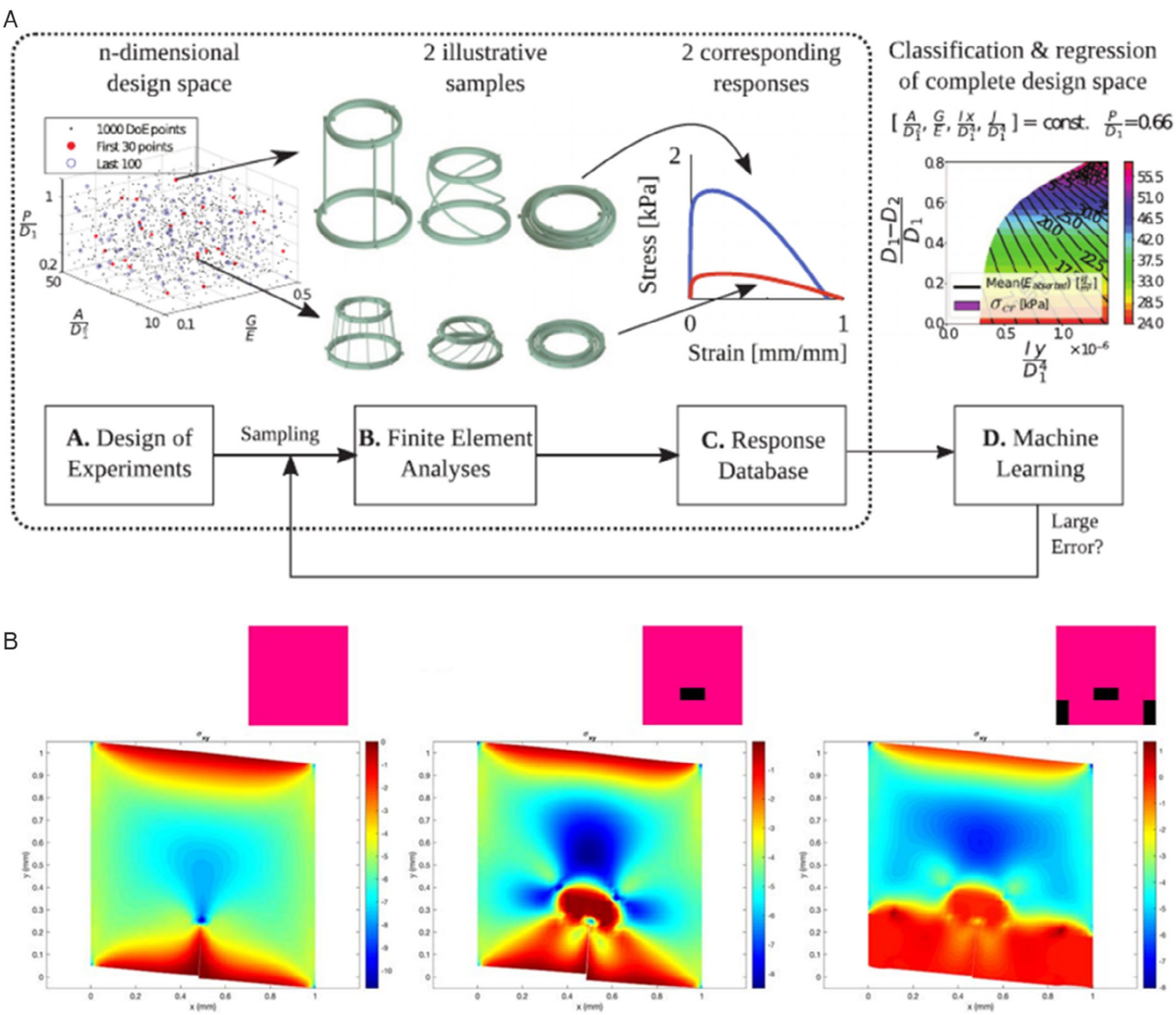

Figure 2. Applications of AI for designing optimized materials and structures. A) Data-driven design of a supercompressible metamaterial. Reproduced under the terms and conditions of the CC BY license.[44] Copyright 2019, The Authors. Published by Wiley-VCH. B) Optimization process to design a tough nanocomposite material using a genetic algorithm. Simulation results for three selected architectures with increasing toughness. Reprinted with permission.[46] Copyright 2019, IOP Publishing Ltd.

new supercompressible yet strong material, designed through a computational data-driven approach, without conducting any experimental tests (**Figure** 2A).[44] A related but different approach was presented in two recent works, whose authors used AI to optimize the crack resistance of a nanocomposite material exploiting also genetic algorithms. The ML simulations were also validated using FEM modeling (Figure 2B) and experimental campaigns on selected promising 3D-printed architectures.[45,46]

The use of ML with 4DP is expected to further accelerate the materials design and discovery process. ML is involved in 4DP at multiple levels: besides the role played in the discovery of new materials, ML can be incorporated into AM to address common issues in manufacturing.[12,13] One of the most relevant applications, for instance, is the evaluation of the best fabrication parameters to improve the process, balancing the quality of the workpieces and processing time, or to assess an object printability (**Figure** 3B).[14] A recent example of such an approach has been published by Lee et al.,[47] who correlated the printability and mechanical properties of collagen-based inks using an ML approach to achieve high-fidelity constructs. Although AM has revolutionized component and material fabrication by enabling the design of complex multimaterials architectures and breaking down the limitations given by conventional manufacturing techniques, it is still a fabrication approach that cannot be scaled up to the industrial field because of several issues (e.g., precision, repeatability). Here, both open-loop and closed-loop AI methods can come into play: the former use sensory data, previously acquired via different imaging techniques, to get a 3D representation of the printing process and a map of the shape-morphing distribution; the latter, instead, integrates sensory data as part of the printing process, to detect imperfections and modulate printing parameters in real time.[8,12] Additional opportunities are currently opening for integrating AI into 4DP, enabling the fabrication of multifunctional and stimuli–responsive (adaptive) materials, surgical robots, and smart devices via AI-assisted fabrication technologies. 4DP functional inks and devices represent an attractive route to intertwine several material functionalities in 3D. Nevertheless, the computer controls the entire process, as the intelligence behind is not yet integrated into the 3D printer, nor into the materials. Recent progress in AI-powered 4DP will provide a step change in the 4DP of multifunctional materials and devices through in situ 4DP, the latter being more adaptive than ex situ printing. In situ AI-powered 4DP will acquire the capability to sense, adapt, and predict the printing state (e.g., learning from historical sensory data to predict possible future states), thus enabling the efficient 4D bioprinting of organs, also in collaboration with robotic platforms.[8]

4. AM and AI: An Outlook Toward a Synergistic Integration

AI-empowered AM approaches will bring new and challenging perspectives in smart manufacturing, although the main challenge is to completely integrate them, ensuring they are working as a whole. In the future, we expect that the synergistic contributions of AM and AI will give life to "5D printing", in which AI will assume the role of the fifth dimension (Figure 3A). A manufacturing approach, which is controlled by AI and leverages smart materials, will ensure the online correction of the printing

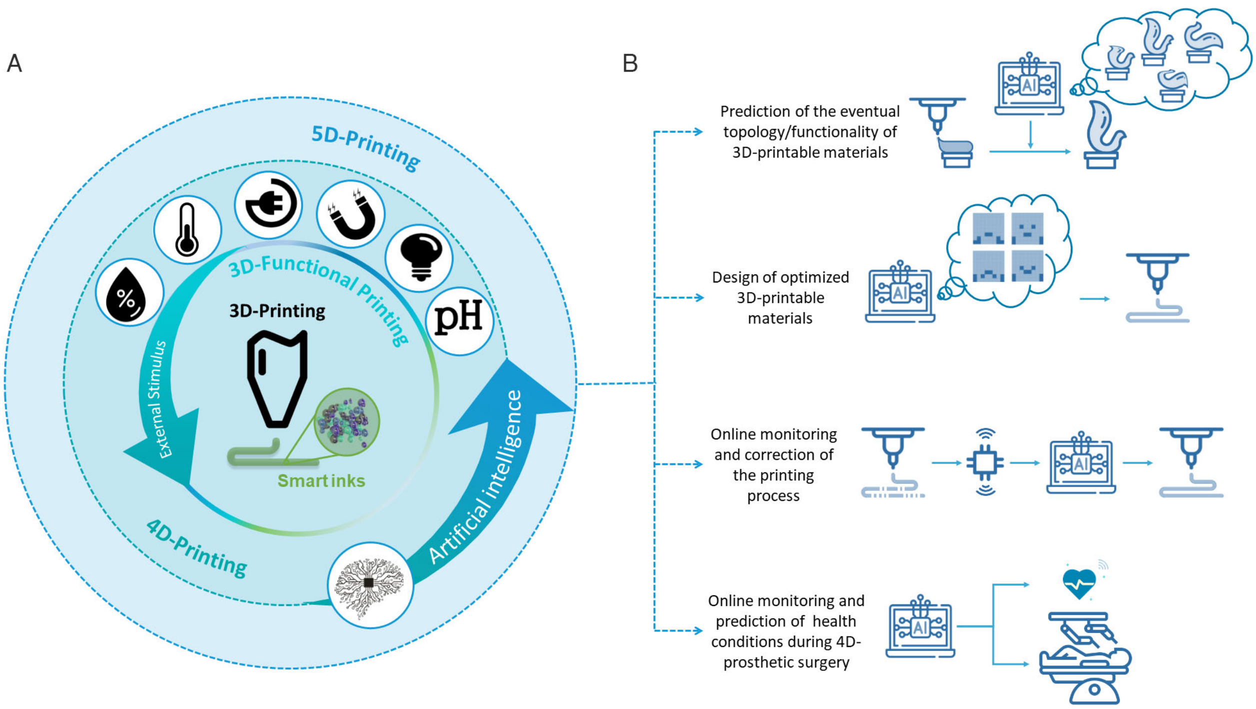

Figure 3. A) From 3D-functional printing to 5D printing, across 4DP: the evolution of AM techniques to fabricate functional constructs able to selectively respond to external stimuli and provide multiple functionalities. B) Envisaged applications of the synergy between AI and AM. This figure was designed using icons made by LAFS, deemakdaksina, Freepik, Eucalyp, SBTS2018 from www.flaticon.com.

process and the intelligent fabrication of components with multiple functions, dramatically shortening the assembly operations and the associated energy costs, with enormous benefits for the environment (Figure 3B). Looking ahead, for instance, we envision products made from ecofriendly and biocompatible living materials (e.g., chitin from fisheries or cellulose from plants): for instance, gloves lined with chemical-sensing hydrogels or protective bandages and patches that may detect signs of infection or disease or new prosthetic devices with complex shapes. Moreover, by leveraging microstructure-driven properties, as in the case of metamaterials, it will be possible to use AM and AI to design and trigger selective sets of features, optimal for specific functions (e.g., drug delivery based on shape mutation,[48,49] optical/optoelectronic properties triggered by changeable textures[50]), or activate new properties, currently not found in nature,[51] thus opening up new opportunities for the design of soft robots and intelligent systems with functionalities encoded in the material itself (Figure 3B). Concerning other potential applications, we picture an extensive use of 5D printing in the robotics field. For instance, AI could support surgery, by monitoring and online predicting health parameters at each step of the procedure and managing, in parallel, the simultaneous fabrication of functionalized constructs (e.g., self-healing prosthesis) to replace damaged structures in vivo (Figure 3B). As for industrial applications, production lines could be reorganized, improving the working role of the operators and making them supervisors of the process in view of a collaborative and integrated approach between humans and machines.

Finally, although 5D printing methodology is a really promising route for smart manufacturing in the Industry 4.0 era, many challenges still need to be addressed for achieving a complete versatility of the approach. In our opinion, the most relevant issue concerns the full scalability of the process. While FEMs and AI-driven optimizations will be continuously refined to achieve high levels of precision in predicting the behavior of a material/device, the main bottleneck relies on the current limits possessed by fabrication technologies in terms of repeatability, resolution, and precision when addressing miniaturized components. Moreover, although smart materials can be used in combination with micro-/nanoparticles for selective and efficient functionalization, experimented in controlled environments, the application in real unstructured scenarios may lead to deviations of the expected behavior, which could be difficult to simulate and predict. In view of this, the role of AI will be fundamental to access and analyze data not only from/for the printing process, but also from experimental datasets that will improve the learning process for real-case scenarios.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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[1] I. Must, E. Sinibaldi, B. Mazzolai, *Nat. Commun.* **2019**, *10*, 1.
[2] K. Maute, A. Tkachuk, J. Wu, H. Jerry Qi, Z. Ding, M. L. Dunn, *J. Mech. Des.* **2015**, *137*, 111402.
[3] M. Milazzo, P. G. G. Muyshondt, J. Carstensen, J. J. J. Dirckx, S. Danti, M. J. Buehler, *J. Mech. Behav. Biomed. Mater.* **2020**, *103*, 103541.
[4] E. A. P. Liberati, C. G. Nogueira, E. D. Leonel, A. Chateauneuf, *Eng. Fail. Anal.* **2014**, *46*, 247.
[5] Y. Sun, D. Zhang, Y. Liu, T. C. Lueth, *IEEE Trans. Med. Robot. Bionics* **2020**, *2*, 364.
[6] C. M. Hamel, D. J. Roach, K. N. Long, F. Demoly, M. L. Dunn, H. J. Qi, *Smart Mater. Struct.* **2019**, *28*, 65005.
[7] S. Tibbits, *The Emergence of "4D Printing,"* TED Talk. [Online], **2013**.
[8] Z. Zhu, D. W. H. Ng, H. S. Park, M. C. McAlpine, *3D-Printed Multifunctional Materials Enabled by Artificial-Intelligence-Assisted Fabrication Technologies*, Nature Publishing Group, **2020**.
[9] D. Espalin, D. W. Muse, E. MacDonald, R. B. Wicker, *Int. J. Adv. Manuf. Technol.* **2014**, *72*, 963.
[10] K. Yu, A. Xin, H. Du, Y. Li, Q. Wang, *NPG Asia Mater.* **2019**, *11*, 1.
[11] G. X. Gu, C. T. Chen, M. J. Buehler, *Extreme Mech. Lett.* **2018**, *18*, 19.
[12] Z. Jin, Z. Zhang, K. Demir, G. X. Gu, *Machine Learning for Advanced Additive Manufacturing*, Vol. 3, Elsevier, Cell Press, Cambridge, MA **2020**, pp. 1541–1556.
[13] Z. Jin, Z. Zhang, G. X. Gu, *Adv. Intell. Syst.* **2020**, *2*, 1900130.
[14] T. Lu, in *Proc. IEEE Int. Conf. Ind. Technol.* Howard Plaza Hotel in Taipei, Taiwan May **2016**, p. 922.
[15] Y. Wang, Y. Lin, R. Y. Zhong, X. Xu, *Int. J. Prod. Res.* **2019**, *57*, 3975.
[16] S. Tibbits, *The Emergence of "4D Printing" | TED Talk*, **2013**.
[17] S. Tibbits, *Archit. Des.* **2014**, *84*, 116.
[18] A. P. Piedade, *J. Funct. Biomater.* **2019**, *10*, 9.
[19] P. Morouço, B. Azimi, M. Milazzo, F. Mokhtari, C. Fernandes, D. Reis, S. Danti, *Appl. Sci.* **2020**, *10*, 9143.
[20] M. Soreni-Harari, R. St. Pierre, C. McCue, K. Moreno, S. Bergbreiter, *Soft Robot.* **2020**, *7*, 59.
[21] G. Adam, A. Benouhiba, K. Rabenorosoa, C. Clévy, D. J. Cappelleri, *Adv. Intell. Syst.* **2021**, 2000216.
[22] U. Bozuyuk, O. Yasa, I. C. Yasa, H. Ceylan, S. Kizilel, M. Sitti, *ACS Nano* **2018**, *12*, 9617.
[23] L.-H. Shao, B. Zhao, Q. Zhang, Y. Xing, K. Zhang, *Extrem. Mech. Lett.* **2020**, *39*, 100793.
[24] H. Y. Jeong, E. Lee, S. Ha, N. Kim, Y. C. Jun, *Adv. Mater. Technol.* **2019**, *4*, 1800495.
[25] A. Zolfagharian, A. Kaynak, A. Kouzani, *Mater. Des.* **2020**, *188*, 108411.
[26] A. A. Zadpoor, *Biomater. Sci.* **2020**, *8*, 18.
[27] H. M. A. Kolken, S. Janbaz, S. M. A. Leeflang, K. Lietaert, H. H. Weinans, A. A. Zadpoor, *Mater. Horiz.* **2018**, *5*, 28.
[28] F. S. L. Bobbert, S. Janbaz, A. A. Zadpoor, *J. Mater. Chem. B* **2018**, *6*, 3449.
[29] M. Milazzo, G. Gallone, E. Marcello, M. D. Mariniello, L. Bruschini, I. Roy, S. Danti, *J. Funct. Biomater.* **2020**, *11*.
[30] M. Ganjian, K. Modaresifar, M. R. O. Ligeon, L. B. Kunkels, N. Tümer, L. Angeloni, C. W. Hagen, L. G. Otten, P.-L. Hagedoorn, I. Apachitei, L. E. Fratila-Apachitei, A. A. Zadpoor, *Adv. Mater. Interfaces* **2019**, *6*, 1900640.

[31] P. Fernandes, J. M. Guedes, H. Rodrigues, *Comput. Struct.* **1999**, *73*, 583.
[32] M. J. Harrington, O. Speck, T. Speck, S. Wagner, R. Weinkamer, *Self-Healing Mater.* **2015**, 307.
[33] X. Kuang, K. Chen, C. K. Dunn, J. Wu, V. C. F. Li, H. J. Qi, *ACS Appl. Mater. Interfaces* **2018**, *10*, 7381.
[34] V. K. Thakur, M. R. Kessler, *Polymer* **2015**, *69*, 369.
[35] L. Ritzen, V. Montano, S. J. Garcia, *3D Printing of a Self-Healing Thermoplastic Polyurethane Through FDM: From Polymer Slab to Mechanical Assessment*, Vol. *13*, **2021**, 305.
[36] K. Park, D. Scaccabarozzi, C. Sbarufatti, A. Jimenez-Suarez, A. Ureña, S. Ryu, F. Libonati, *Carbon* **2020**, *166*, 193.
[37] G. Gonzalez, A. Chiappone, I. Roppolo, E. Fantino, V. Bertana, F. Perrucci, L. Scaltrito, F. Pirri, M. Sangermano, *Polymer* **2017**, *109*, 246.
[38] A. Cortés, A. Cosola, M. Sangermano, M. Campo, S. G. Prolongo, C. Fabrizio Pirri, A. Jiménez-Suárez, A. Chiappone, A. Cortés, M. Campo, S. González, A. Jiménez-Suárez, A. Cosola, M. Sangermano, C. F. Pirri, A. Chiappone, *Adv. Funct. Mater.* **2021**, *31*, 2106774.
[39] M. A. Skylar-Scott, S. Gunasekaran, J. A. Lewis, *Proc. Natl. Acad. Sci. U.S.A.* **2016**, *113*, 6137.
[40] Y. L. Kong, M. K. Gupta, B. N. Johnson, M. C. McAlpine, *3D Printed Bionic Nanodevices*, **2016**, 330.
[41] P. H. Winston, *Artificial Intelligence*, Addison-Wesley Publishing, Reading, MA **1992**.
[42] M. Schwabacher, The use of artificial intelligence to improve the numerical optimization of complex engineering designs, Rutgers The State University of New Jersey-New Brunswick, **1996**.
[43] C. Yang, Y. Kim, S. Ryu, G. X. Gu, *Mater. Des.* **2020**, *189*, 108509.
[44] M. A. Bessa, P. Glowacki, M. Houlder, *Adv. Mater.* **2019**, *31*, 1904845.
[45] G. X. Gu, C. T. Chen, D. J. Richmond, M. J. Buehler, *Mater. Horiz.* **2018**, *5*, 939.
[46] C.-H. Yu, Z. Qin, M. J. Buehler, *Nano Future* **2019**, *3*, 035001.
[47] J. Lee, S. J. Oh, S. H. An, W.-D. Kim, S.-H. Kim, *Biofabrication* **2020**, *12*, 35018.
[48] X. Zhao, J. Kim, C. A. Cezar, N. Huebsch, K. Lee, K. Bouhadir, D. J. Mooney, *Proc. Natl. Acad. Sci.* **2011**, *108*, 67.
[49] T. van Manen, S. Janbaz, K. M. B. Jansen, A. A. Zadpoor, *Commun. Mater.* **2021**, *2*, 1.
[50] N. Zhou, Y. Bekenstein, C. N. Eisler, D. Zhang, A. M. Schwartzberg, P. Yang, A. Paul Alivisatos, J. A. Lewis, *Sci. Adv.* **2019**, *5*, eaav8141.
[51] S. Chibani, F.-X. Coudert, *APL Mater.* **2020**, *8*, 80701.

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