Propelling the widespread adoption of large-scale 3D printing

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Standfirst

3D printing can be used to automate the manufacturing of building elements for large-scale structures such as skyscrapers, aircraft, rockets and space bases without human intervention. However, challenges in materials, processes, printers and software control must first be overcome for large-scale 3D printing to be adopted for widespread applications.

[H1] Introduction

Large structures, such as buildings, account for a high proportion of global material and energy consumption, and their manufacturing is traditionally highly wasteful. Three-dimensional (3D) printing – or additive manufacturing – is a sustainable [1] and disruptive technology that is revolutionizing various industries such as construction or aeronautics. 3D printing involves the creation of digital designs (which are eco-friendly and easy to convert into 3D objects and iterate on [2]) followed by rapid and intelligent additive processing (which doesn't require a mold and exploits many degrees of freedom). This process maximizes material savings through design optimization and reduces resource waste by eliminating the need for templates and/or molds. However, traditional 3D printing is mostly limited to micrometer- to meter-scale fabrication and faces some unresolved issues such as the inability to achieve multifunctional printing, which hampers the automated manufacturing of large complex structures such as buildings, aircraft and rockets.

Since 2010, large-scale 3D printing (LS3DP) has emerged as a solution to overcome these limitations. LS3DP has already been successfully utilized in some landmark construction projects such as the Shanghai Putuo Bridge (the first 3D-printed polymer bridge in China, with a total printed length of 15.3 m) [3]; the Chengdu Bridge (currently the longest 3D-printed polymer bridge in the world, with a total length of 66.8 m and a printed length of 21.6 m); the SCG S&T Building (the first 3D-printed habitable and deliverable two-story building in China, with a height of 6 m) [4]; the Comac C919 aircraft (with a 3D printed wing rib of 3 m); and the Terran 1 rocket (which is 33.5 m high and for which 85% of the body was printed).

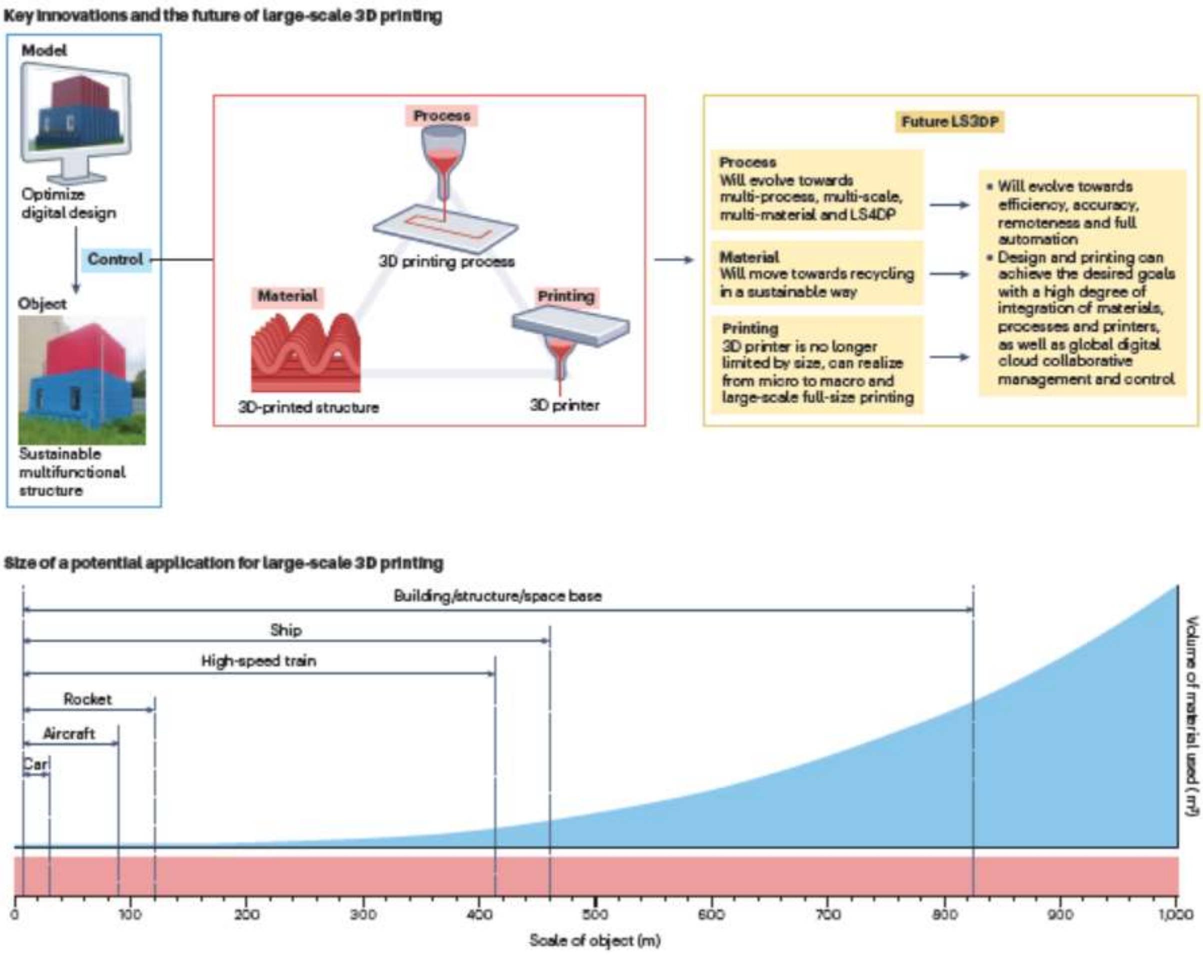

Fig. 1 | Overview and future of large-scale 3D printing. The widespread adoption of large-scale 3D printing (LS3DP) depends on innovations in processes, materials, printers and software control. LS3DP has the potential to be used for the automated manufacturing of giant complex structures such as buildings, rockets and even space bases. LS4DP, large-scale 4D printing.

However, the adoption of LS3DP is still somewhat limited as its large scale gives rise to new challenges, notably to a necessary compromise between accuracy and efficiency. The necessity to print thicker layers to minimize the printing time negatively impacts the shape, accuracy, quality and performance of the printed structures. LS3DP would therefore greatly benefit from improvements in materials, processes, printers and software control to facilitate its widespread adoption.

[H1] Developing appropriate materials and processes

Materials currently used, either in conventional 3D printing or in LS3DP, are adapted from those available in traditional manufacturing. For example, 3D-printed buildings typically use cement-based materials, polymers, metallic materials and wood-based materials. Components for 3D-printed aircraft and rockets are metallic materials or alloys, polymers, ceramics and composites. However, to achieve different scales and functionalities, the range of printable materials must be expanded [5], either by using new additives, modifying existing materials or automating preparation production lines to make them suitable for LS3DP. In addition, new material preparation processes to transform nonprintable materials into printable materials must be developed, for example by using additive manufacturing as a digital material synthesis method. Briefly, this strategy involves creating a synthetic material using the 3D printing equipment directly. This route consists of accurately designing the chemical composition and physical properties of the materials to be synthesized from the microscopic scale, creating high-precision microscopic and macroscopic 3D models of the materials to be synthesized, and converting them into printable programs. This approach is expected to create functionally graded materials, smart materials, engineered living materials, or even metamaterials that are not possible with conventional manufacturing or in nature.

In addition, as 3D printing is a layer-by-layer additive process, several problems that are typical in traditional 3D printing (such as weak bonding between printed layers, material defects [1] and various anisotropies [2]) can no longer be overlooked for large-scale printed structures. Therefore, strategies to alleviate these limitations need to be developed. Examples include the simultaneous printing of materials with different tensile strengths, the synchronization of printing and structure reinforcement, the enhancement of the structure through print path design, and the modification of the materials through physicochemical processing.

There is also a need to develop more advanced processes such as large-scale 4D printing (LS4DP). LS4DP – where the 4th dimension refers to time-dependent transformations - can be used to develop controllable multifunctional structures using materials that possess the ability to sense, evolve, learn, adapt, assemble, retain memory and heal. LS4DP requires controllable and programmable responsive and/or smart materials that respond to external stimuli (or programmed control that triggers a shift in the printed structures) and that can be studied using mechanistic models to accurately predict and control the desired changes. LS4DP must also overcome new challenges inherent to the size of the printed structure, such as its inability to effectively return to its original state after multiple cyclic changes. Nonetheless, this technology offers potential applications for high-performance structural engineering where shape, properties and function are self-altering.

[H1] Creating integrated and multifunctional structures

Most small-scale and conventional-scale 3D printing is limited to single-material, single-process printing, which makes the manufacturing of products with multiple features and functionalities difficult. For example, we can print the fuselage of a large aircraft and the walls of a building, but we cannot simultaneously print the aircraft's functional parts and necessary electronic components, or integrate pipes and cables into the building's walls. Therefore, LS3DP should ideally be multiscale (covering the macro, meso, micro and nano scales), multimaterial (integrating rigid to flexible materials) and multiprocess (combining multiple processes such as traditional 3D printing or subtractive manufacturing or switching between them) to enable fully integrated and autonomous manufacturing. Potential applications of this technology would be self-maintaining vehicles and artificial ecosystems in space, as well as climate-adaptive, low-energy, low-carbon and fully interactive smart buildings.

[H1] Overcoming size limitations

Developing printing equipment that is compatible with various processes and materials is crucial to print large structures with different scales, shapes and functions. There are two approaches for LS3DP printers-based construction. The first is prefabricated 3D printing, in which the large structure is divided into appropriately sized components, which are printed and then assembled with reliable connectors. The second is overall 3D printing, in which the large structure is divided into layers of appropriate thickness, and then the large structure is printed layer by layer. However, for LS3DP printers to be applicable to either approach, they must be flexible and have a scalable print range. Therefore, there is a need to develop new printers such as modular-guideway-adaptive scaled-up 3D printers, 3D printers with printing and synchronization support to realize suspended horizontal structures, mobile 3D printers or factories, and teams of 3D printing mobile robots to enable unlimited printing in the horizontal direction. In the vertical direction, developing self-climbing 3D printers, climbing 3D printers that can attach to printed structures, crawling 3D printing robots that can traverse printed layers, and nature-inspired swarms of unmanned 3D printing robots [6] could help achieve unbounded printing.

[H1] Improving printing accuracy and efficiency

To efficiently and accurately control printing, guarantee the safety of the printing process and ensure that the final printed structure meets the desired goals and functions, developing quantitative print control equations and relations matching the desired goals to the printing processes, materials and printers is essential. During the process, it is also necessary to incorporate a materials printability database to control the printing. Finally, LS3DP needs to enable the printing of materials only where they are needed for the structure or function [7], the printing of the right type of material (with an optimal scale) in the right place, and the printing of unique structures for unique functions [1], thus proactively securing high performance and versatility for the printed structure.

[H1] Adapting LS3DP to extreme environments

Automated LS3DP may also serve pressing needs in extreme environments that present high risks to human operators, such as underground or post-disaster sites, disused nuclear facilities or underwater. In addition, LS3DP is well-suited for the construction of space bases for space exploration [8], which require remote, unmanned and in situ construction. However, various challenges still need to be overcome before these applications can be realized. Notably, to build the structures in situ, there is a need to develop automated equipment to overview the engineering surveys, gather the necessary natural resources and prepare and print the materials. For the latter, one solution would be using lightweight 3D printing robots that can be remotely controlled.

[H1] Considering sustainability

We must also consider the sustainable use of materials throughout the whole life cycle, which include material design, raw material production and extraction, preparation of the printable material, transportation and conveying, product printing and manufacturing, product use, maintenance and repair, recycling and reuse. Wherein, beyond the development of new materials, the preparation of printable materials requires the conversion of the endless huge amounts of waste from life and production (industrial, construction, domestic and agricultural solid waste) into printable materials, realizing the transformation of waste from consumption to recycling and maximizing the use of resources. Computationally optimized digital designs (leading to, for example, topology optimization from the micro- to macrostructural scale) and highly optimized structures can be used to reduce the use of materials and maximize material resource savings [7]. Concurrently designing and printing at the micro- and macroscale can lead to highly efficient, multifunctional structures [9] that demonstrate better performance - in terms of, for example, energy savings and reduced CO_2 emissions [7] - than structures obtained with traditional methods [10]. Such efficient structures include topological, cellular and biomimetic structures, which are more environmentally friendly, lightweight, and high-performing (due to the combination of various characteristics such as high strength-to-weight ratio, high heat resistance and high reliability [1]).

[H1] Outlook

Through progresses in materials, processes, printers and software control, LS3DP is expected to break through the size limitations encountered with traditional 3D printing to realize the fully automated and unmanned construction of arbitrarily-shaped large structural bodies (Fig. 1). This approach is also poised to enable integrated manufacturing by simultaneously printing internal multifunctional components and wires. Such a system would be safer, more efficient, smarter and greener, providing the printed structures with previously unattainable functions and performances and greatly reducing the consumption of global resources. We also envision that combining large-scale 3D printing and artificial intelligence will facilitate decentralized manufacturing. This next-generation LS3DP would provide remote collaborative management and printing through a reliable and fault-tolerant 3D printing digital twin controlled through the cloud. Through this global cloud platform, consumers could not only communicate with 3D printing service providers but also design and build customized products, process 3D printing models, transfer processed files to cloud terminals, set parameters and control printing remotely.

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Author contributions

Z.Z., Y.H., X.C., J.L. and Longlong Zhang researched data for the article. Z.Z., W.D.C. and V.M. contributed substantially to discussion of the content. All authors wrote the article. Z.Z., W.D.C., Y.Z., J.X., Y.Y., K.Z., Lulu Zhang and V.M. reviewed and edited the manuscript before submission.

Competing interests

The authors declare no competing interests.