Engineering 6 (2020) 590–592

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

News & Highlights

3D Printing Advances on Multiple Fronts

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Nearly four decades have passed since the concept of 3D printing went mainstream, with advocates hailing the technology as the "future of manufacturing." Now, as evidenced by orders of magnitude increases in print speed and size, and expanding biomedical applications, recent advances are bringing 3D printing closer to living up to its promise.

Today's most common version of 3D printing, also referred to as additive manufacturing, uses light to cure a liquid plastic resin, layer by layer, into a solid object. This process is about as slow as it sounds; handheld items often take the better part of an afternoon to manufacture. In addition, the interfaces between the layers tend to be weak, making finished objects structurally fragile. The result has been that rather than supplanting traditional manufacturing processes, 3D printing has been relegated to very specific uses. "3D printing, for the most part, has been primarily confined to prototyping due to a lack of speed, low throughput, and product instability," said Chad Mirkin, professor of engineering at Northwestern University in Evanston, IL, USA.

Significant improvements to the process began about five years ago when engineers at the University of North Carolina invented a novel 3D printing process called continuous liquid interface production (CLIP) that speeds up production time 100-fold compared to competing technologies [1]. The approach, since spun out into a company called Carbon (Redwood City, CA, USA), employs a semipermeable window that allows the infusion of oxygen into liquid resin to create a thin "dead zone" that resists curing. Above this zone, the light cures the resin into a solid. A robotic arm slowly pulls the growing solid out of the resin, allowing additional material to cure and adhere without a series of laminating interfaces, resulting in far more robust objects.

While CLIP's increased speed received much attention—the company has agreements in place to produce car parts, athletic shoe soles, and football helmets for Ford, Adidas, and Riddell, respectively [2]—its curing process releases considerable heat, which can cause printed parts to warp and crack. To dissipate this heat, printed objects are effectively limited in size to 25 cm × 25 cm × 41 cm.

"Carbon began to validate the argument that 3D printing could be used in manufacturing and they have done some really nice work in a variety of industries, but they have not found a way to print big objects fast," Mirkin said.

In late 2019, Mirkin's team reported the development of a new technology, called high-area rapid printing (HARP), in which a liquid coolant circulates beneath a vat of liquid resin [3]. The coolant, a fluorinated oil, pulls heat directly from growing objects as they are printed, allowing them to reach the size of a human adult in just a few hours (Fig. 1). Using light from multiple projectors, a process Mirkin calls "tiling," print sizes can reach about 1 m × 1 m × 4 m. In the future, additional projectors will enable HARP to make even larger items. "Tiling theoretically eliminates size restrictions," Mirkin said.

To commercialize HARP, Mirkin and colleagues launched the company Azul 3D (Skokie, IL, USA), which expects to begin selling printers before the end of 2021. Mirkin hopes HARP will shift the business model of 3D printing. "Almost all 3D printing companies must make a significant amount of revenue off their hardware because they simply do not use enough resin to make it a good business by selling it," he said. "With HARP, the company does not need to rely solely on the revenue made by selling hardware since they can also make money selling the resin needed to produce large quantities of parts. In this way, HARP lowers the barrier

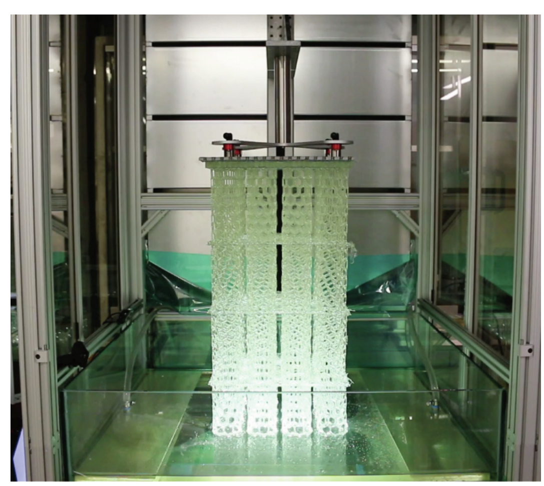

Fig. 1. A novel 3D printing technique called HARP uses a layer of liquid coolant circulating beneath a vat of liquid resin to remove heat from growing objects as they are printed, allowing them to reach the size of a human adult in just a few hours. At about 4 m tall and with a 0.76 m × 0.76 m print bed, this HARP printer can print a large, continuous structure or many, different small structures at once. Credit: Northwestern University (press release).

https://doi.org/10.1016/j.eng.2020.04.005

to entry as the initial hardware cost becomes almost inconsequential."

In another rapidly advancing area, 3D printing is showing its potential value in manipulating the miniscule. Swap out the "ink"—the plastics, polymers, and metal alloys—used in traditional 3D printers for living cells embedded in biological media, and the technology becomes an interesting tool for biomedical applications, potentially for making replacement tissues some day in the future. 3D bioprinting is already being used to fabricate simple tissues, such as skin, cartilage, and bits of heart muscle. As the technology improves, more complex organs, such as retinas, kidneys, and lungs, may follow [3]. Major challenges include packing in the wide variety of cell types comprising the organs and increasing the resolution enough to print the tiny blood vessels that deliver oxygen and remove waste.

"I doubt we are ever going to get there—with all the different cell types and the vasculature needed to keep them alive, organs are just too complicated," said Michael McAlpine, a professor of mechanical engineering at the University of Minnesota in Minneapolis, MN, USA. "The mistake has been trying to exactly replicate biology. Maybe with polymers and electronics, you can make a device that functions like a liver, but actually works better than what nature came up with."

3D bioprinting has found more immediate applications, though, including in drug discovery and consumer product testing [4]. Among McAlpine's many projects is a 3D printed device for spinal cord regeneration [5] and electronic tattoos embedded with sensors that monitor patients' physiological and biochemical markers [6].

While 3D bioprinting principally focuses on the very small, at the other end of the size spectrum, innovators in Texas are using very large-scale 3D printing to build houses (Fig. 2). Developed by the Austin, Texas-based construction technology firm Icon, a 3D printer called the Vulcan II can print the walls of a 37 m^2, two-bedroom home in about 24 h. The Vulcan II was specifically designed for remote, rural use, where traditional construction is near impossible due to limited resources, unpredictable weather, and unreliable power sources. The 3.5 m tall, 1725 kg machine continuously deposits a 2.5 cm tall, 5 cm wide line of a malleable form of concrete called "lavacrete" in stacked rows that harden into walls (Fig. 3) [7].

Icon is currently printing dozens of homes in a 51 acre (1 acre = 4046.873 m^2) development for homeless people in Northeast Austin and about 50 homes for families in the small, rural town of Tabasco, Mexico [7]. While the Vulcan II cuts down on the labor involved in building a home, construction is not a one-step process; workers still have to lay down the foundation and install

Fig. 2. The Icon (Austin, TX, USA) Vulcan II 3D printer deposits a 2.5 cm × 5 cm line of a concrete-based material called "lavacrete" to build the walls of 37 m^2 houses, like this completed one, in about 24 h. Credit: Icon (press release).

Fig. 3. Icon's Vulcan II 3D printer, at the far end of the three structures, was used to create the walls of three 37 m^2 homes with different floor plans on a single foundation in Austin, TX, USA. Credit: Icon, with permission.

the roof. Aside from the time-saving aspect of 3D printing homes, the ability to print smoothly curving and sloping walls may allow for more freedom in their design relative to other low-cost housing.

In another large-scale application, the Los Angeles-based company Relativity Space, Inc. (Relativity) has developed a 3D printer called Stargate (Fig. 4) to build less earthbound objects: 30 m tall rocket ships. Relativity plans to 3D print the entirety of its first line of rockets, called the Terran-1, save for the electronics, cables, and a handful of moving parts [8]. By comparison, SpaceX, Blue Origin, and others are also using 3D printing, but just for select parts [8]. Relativity has contracts to launch payloads for a handful of satellite operators and an agreement to use two test facilities at the National Aeronautics and Space Administration's John C. Stennis Space Center in Hancock County, MS, USA. The company also has secured the right to launch its Terran-1 rockets—the first of which is expected to fly some time in 2021—from Launch Complex-16 at the Cape Canaveral Air Force Station in Florida [9].

While rockets typically consist of thousands of individual parts, Relativity designs parts that incorporate several pieces that would traditionally be manufactured separately and later assembled. As a result, their rockets will have about 100 times fewer parts than comparable rockets. Fewer parts means fewer interfaces and fewer chances for something to go wrong. Also, while most manufacturers have to retool their facilities to fabricate each additional piece of hardware, Relativity just needs to run a new program in the printer's software to create the next part. Making

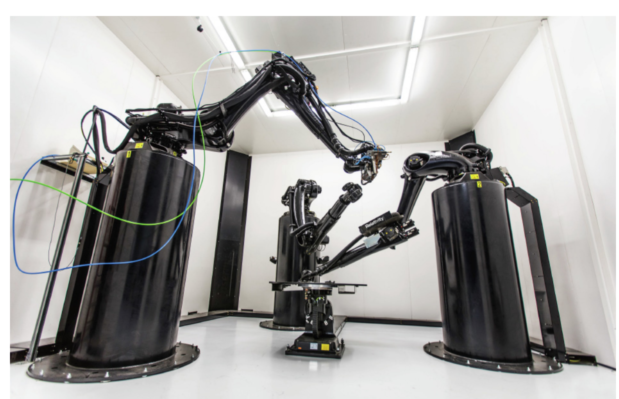

Fig. 4. The Relativity Space (Los Angeles, CA, USA) Stargate 3D printer uses directed energy deposition to create enormous metal objects, such as a rocket's fuel tanks and engine. Standing 9 m tall, the printer has three massive robotic arms. One arm uses a powerful laser to melt metal wire, which is deposited layer by layer to build up parts for the rocket. The other two arms hold tools for finishing the printed components. Credit: Relativity Space, Inc., Wikimedia Commons (CC BY-SA 4.0).

design changes is also easier and less costly than in traditional rocket manufacturing [10].

"Traditionally the space industry is risk averse, preferring confidence in launch success over novel concepts," said Ian Christensen, director of Private Sector Programs for Secure World Foundation, a Broomfield, Colorado-based organization focused on promoting peaceful and sustainable uses of outer space. "How the market will respond to something so fully novel as a 3D-printed rocket is an open question."

Just because the reality of 3D printing has begun to match its promise does not exclude much more ambitious goals. Not content with just building rockets to launch satellites into orbit, Relativity has its sights set on shipping its printer to Mars to print rockets on the red planet that can send soil samples back to Earth [10]. "This sample-return concept is theoretically interesting, but it will almost certainly require integration into government space exploration and planetary science programs, which are slow moving," Christensen said. "The policy and institutional challenges may be as significant as the technical challenges."

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