Digitally Fabricated Concrete: The future of manufacturing is already here

— Brad Bell, University of Texas at Arlington

It is hard to visit the pages of a blog or magazine these days and not come across the term *3D printing*. From fashion to food, and from design to defense, 3D printing has taken popular culture by storm and does not appear to be letting up any time soon. When President Obama namechecks it in his State of the Union address as one of the primary technologies that will lead to a renaissance of American manufacturing it is hard to miss that something must be happening.[i] But for all the uproar and the nearly ubiquitous nature of the 3D printing trend, many people are still trying to figure out what the technology actually is and what the real implications are to their lives and, in many cases, their livelihood.

Figures 1 and 2. Contour Crafting "24 Hour House" and a panel prototype being fabricated. Images: Dr. Berok Khoshnevis, professor, University of Southern California.

Three-dimensional printing is not a novel technology. The first machine to commercially utilize the technology was produced by 3D Systems Corporation of California in 1986. While the origins primarily came from the manufacturing industry, a wide range of disciplines immediately saw the potential of this new method for prototyping. This led to many different types of commercial and research applications that subsequently led to many different iterations of material and methodologies of fabrication. Initially the technology was termed rapid prototyping or layered manufacturing, both terms referring to these wide ranges of mediums and methodologies. But as the technology has become more popular, the term of 3D printing has taken over.

Regardless of the terminology, the process is almost entirely the same between mediums. At the most basic level 3D printing follows the same process of applying ink to paper, except instead of ink, a physical material is deposited in very thin layers that build-up until a solid object is produced. The primary function of the digital software is to take the object and produce a series of extremely thin slices or section cuts through the object that can then be transferred to the printed layer of material. In this way an object is printed slowly, layer-by-layer.[ii] Whether by powder and binder, plastics, metal or any other type of material, the process follows a similar method and has long been used as a prototyping medium. However, the maturation process with the technology has now facilitated some interesting new developments that have implications on the future trajectory of 3D printing and manufacturing.

Since 2007 3D printing sales have jumped 35,000%[iii] and it is estimated that by 2015 it could be a $3.7 billion industry.[iv] The rapid economic growth has touched almost every sector of the economy, with 20% of objects now printed as final output—with that number expected to rise to 50% by 2020[v]. The easiest method of assimilation into the precast industry is at the level of utilizing 3D printing in its current representational capacity to communicate design intention or detail and assembly sequencing. In this capacity, the 3D printed object serves as an invaluable tool that can be used from concept discussion to jobsite component implementation. The scaled 3D printed object quickly and effectively shows a range of design options and variations. Whether communicating to a client, an installer,

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Figure 3. Freeform Construction team at Loughborough Univeristy displays a composite wall prototype. Photo: Dr. Richard Buswell and Professor Simon Austin, Loughborough University.

an engineer, or designer, the capacity to accurately and quickly generate 3D printed objects is an effective tool in the design-to-manufacturing sequence. The affordable desktop ABS printers now make these types of applications a relatively easy entry point into rapid prototyping for almost any size company or firm.

Beyond the representational use of the technology, the limitation of 3D printing has traditionally been scale, especially when exploring larger manufacturing opportunities related to the building industry. However, this too is starting to change with substantial research and development investment from both academic and manufacturing sectors transcending the scale issue. Specifically as this pertains to the potential for 3D printing concrete, there are several interesting developments and two promising strategies. The first suggests the printing technology can increase in size to accommodate larger building components and be fit with the necessary rigging for concrete output. The second suggests a module-based concrete printing process that utilizes existing 3D printing technologies. This method requires a rethinking of material composition and component connection as parts begin to assemble together to make a larger part.

Large Composite Printing

The idea of linking a robotic armature to a large gantry to essentially 3D print with concrete is being explored by several different teams around the world. One obvious advantage to the concrete industry as a whole is the potential removal of formwork from the equation. Three-dimensional printing requires an unobstructed pathway for the deposition head to move when layering the concrete. Conventional use of formwork would obstruct the deposition head and the gantry movement. The opportunity to quickly deploy a large format concrete printer on a jobsite and start printing a structure would provide an economic advantage over many other forms of construction. The Contour Crafting: Robotic Construction System developed by Behrokh Khoshnevis, working in partnership with the University of Southern California, has developed one of the more advanced systems with future applications being lunar structures and the '24 hour house'[vi] **(Fig. 1, 2)**.

With the 3D printing apparatus being mobile, this procedure more closely follows a cast-in-place procedure. Similar challenges found in more traditional site-cast concrete, such as variable site conditions, quality control, and structural limitations would still be present. However the rapid deployment and high degree of customization might provide unique opportunities in certain scenarios. There is so far very little applied evidence of this approach, however with funding from NASA and the number of companies who have recently gotten behind this method, it would seem positive for larger scale evidence based demonstrations to appear in the very near future.

The Freeform Construction team working out of Loughborough University in connection with Hyundai Engineering & Construction, Foster+Partners, and Burro Happold, are utilizing very similar technology but focusing on fully integrated panel construction of component parts.[vii] This approach more closely replicates precast panel techniques in that wall systems and architectural components are divided into a system of parts that can be manufactured off-site and then delivered and installed. The fully integrated panel has potential for not only increasing the efficiency in how building systems can be combined, but also the added advantage of mass-customization, making this a highly unique opportunity for each component to take on a varied geometry at no additional cost **(Fig. 3)**.

With the 3D printing technology essentially removing the need for formwork, there is a direct fabrication benefit that comes from this approach. In addition to the composite wall application, Freeform Construction team suggests the technology is also ideally suited for doubly curved cladding panels and complex structural components **(Fig. 4)**. These two issues directly correlate to almost all forms of digital manufacturing, which utilize a digital file to create the fabrication methodology. With the control of the fabrication process now being dictated by a computer file, complex geometries no longer present the same manufacturing challenges as they might have in the past.

In both examples from Contour Crafting and Freeform Construction team, the use of advanced material science to achieve a suitable mix in the concrete is integral to the successful implementation of the technology. To ensure that formwork is not needed, and that a direct printed form can be achieved, the mixture of concrete must be compositionally able to set up at a speed such that each successive layer can support the previous in a very

Figure 4. Doubly curved surface fabricated by the Freeform Construction team, Loughborough University. Photo: Dr. Richard Buswell and Professor Simon Austin, Loughborough University.

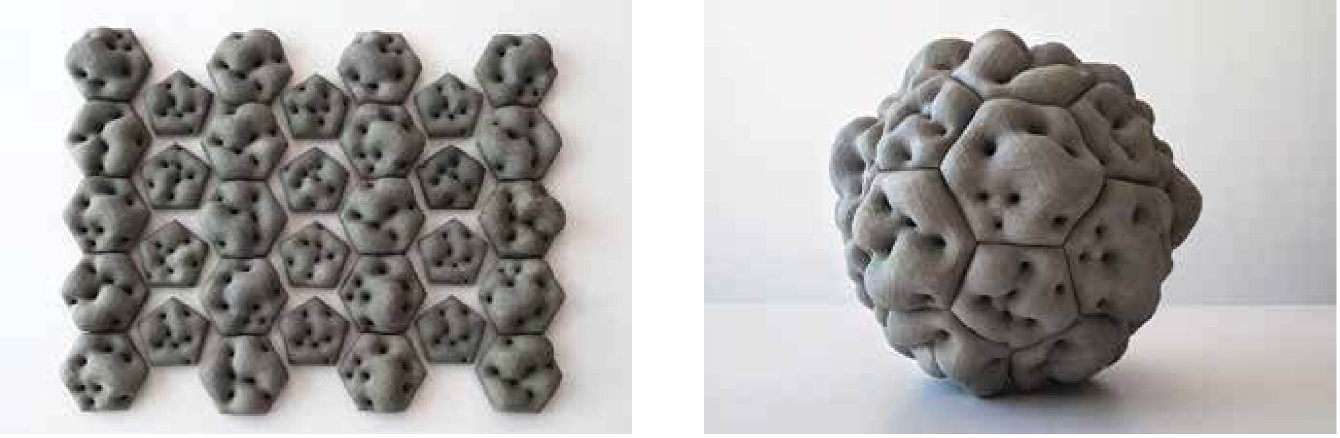


Figure 5 and 6. P_Ball Emerging Objects for Andrew Kudless. Images: Ron Rael + Virginia San Fratello, Emerging Objects.

short period of time.

Contour Crafting relies upon pumping concrete to the deposition head much the same way a traditional pumping mechanism would work, however the connection of the head to the robotic arm on the XYZ gantry makes this a highly customizable outcome in terms of geometry and a very fast and efficient way of controlling the distribution of the concrete. The flow of the concrete comes out in wider swaths and can be tooled or shaped by a processing tool working in coordination with the deposition head.

The Freeform Construction process, by contrast, uses a smaller build deposition size of 6mm high by 9mm wide and provides a dual print capability where one printhead provides the build layer while the other is capable of depositing a support layer that can be removed after completion.[viii] The introduction of the ability of dual printing furthers the capacity to explore a wider range of non-Euclidian geometries that might require preliminary support while the concrete is curing or being put into position. In both cases it is possible to achieve large build areas as a result of how the adaptation of the printing technology to larger format deposition heads, larger gantry systems, and site and factory modifications have facilitated construction and manufacturing capacity. These approaches will be one facet of the Rapid Manufacturing movement that will change the way we think of building in the very near future.

Smaller-Scale, Component-Based Printing

In contrast to the larger scale build techniques, the company Emergent Objects[ix], located in Oakland, Calif., and working with UC Berkeley, has initiated an alternate direction to the implementation of 3D printed concrete. Led by Ron Rael and Virginia San Fratello, Emergent Objects has opted to utilize existing 3D printing technology, but work more extensively with what they have described as a *digital materiality*[x] **(Fig. 5, 6)**. What this approach facilitates is the ability to work with the material science of concrete composition and leverage 3D printing technologies to pursue innovative and new geometric outcomes.

A deposition head on a 3D printer capable of working with a powder base material, in this case Portland cement, works with a 35-pico liter printhead. This essentially means that the binding agent deposited through the printhead works as aggregate and places layers on the Portland/sand mixture at 0.001 thickness to slowly build up the object. While this seems slow and possibly tedious, the benefit is the strength and resolution of the outcome. With Emerging Objects' approach, they are able to obtain a very competitive 4700 psi in compressive strength and, at the same time, provide unparalleled object definition. Because this process is transferable to almost any powder-based substance, Emerging Objects is capable of 3D printing in concrete, wood, paper, nylon, acrylic, and most recently salt. While this process is initially limited to build sizes and technologies of some of the current 3D printers, Rael and San Fratello have noted that there is no limitation to adapting their approach and material intelligence to larger formats. As this becomes available it may provide the capacity to achieve superior resolution, coupled with increased surface strength, giving the Emerging Objects approach an advantage long-term.

Broadening the Spectrum

Three-dimensional printing represents one aspect of how concrete component fabrication is changing the way the architecture, engineering and construction (AEC) and manufacturing industries are evolving. Within the broader spectrum of digital manufacturing methods impacting the precast and prestressed industry, there are several other outliers that show potential for transforming the industry. Much of this work is concentrated on the area of digitally fabricated formwork. This work possesses some of the lowest-hanging fruit for the industry in how already known factors of working with the casting process provides an easier on-ramp for technology transfer and workforce training. Areas of advanced structural integration, coupled with progress on new material possibilities like developments in Glass Fiber Reinforced Concrete (GFRC), suggest there are still areas open for exploration.

Because most of the digitally fabricated formwork explorations tend to follow component-based assembly system logic, the most compelling area for research lies in how parametric software will allow for more varied and yet integrated outcomes. The work of Dave Pigram's research group at University of Technology, Sydney (UTS)/ Supermanoeuvre[xi] **(Figs. 7, 8)** as well as TOPOCAST Lab[xii] at the University of Texas at Arlington **(Figs. 9,10)**, are exploring how performance-based software can inform the fabrication process. From structural to acoustic and solar mitigation, parametric design tools are helping to define more

Figure 7 and 8. Pre-Vault by University of Technology, Sydney and Aarhus School of Architecture. Photos: Dave Pigrim, University of Technology, Sydney/Supermanoeuvre, Ole Egholm Pedersen & Niels Martin Larsen, Aarhus School of Architecture.

articulated formwork capable of not only being aesthetically compelling, but also producing parts with highly specialized performance outcomes.

Conclusion

William Gibson, father of the cyberpunk science fiction genre wrote, “The future is already here—it’s just not evenly distributed.”[xiii] In many ways 3D printing suggests a future for manufacturing, design, and DIY culture that is already upon us. When taken with the broader spectrum of digital manufacturing, it is clear that the industrial paradigm is shifting. However, the fact remains that it is not so evenly distributed. No technology is uniformly adopted or implemented. production—it is safe to say the future of concrete component-based fabrication is already here.

Endnotes

i. http://www.whitehouse.gov/the-press-office/2013/02/12/remarks-president-state-union-address “Our first priority is making America a magnet for new jobs and manufacturing…There are things we can do, right now, to accelerate this trend. Last year, we created our first manufacturing innovation institute in Youngstown, Ohio. A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything. There’s no reason this can’t happen in other towns.”

ii. For more information on the history and process of 3D printing and Rapid prototyping please see “Computer-Aided Manufacturing in Architecture” by Nick Callicott. Chapter 19: Solid Freeform Fabrication. Architectural Press, Oxford, 2001.

iii. *Bloomberg News*, Max Raskin & Ilan Kolet, October 23, 2012.

iv. Reuters Roll Call, Ben Deighton, March 6, 2013.

v. *The Economist*, “3D Printing: The Printed World,” February 10, 2011

vi. http://www.contourcrafting.org & http://www.craft-usc.com.

vii. http://www.buildfreeform.com.

viii. Xavier De Kestelier of Foster + Partners and Richard Buswell of Loughborough University provide an in-depth analysis of their methods in “A Digital Design Environment for Large-Scale Rapid Manufacturing” ACADIA 09: reform. Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) Chicago, pp. 201-208.

ix. http://www.emergingobjects.com.

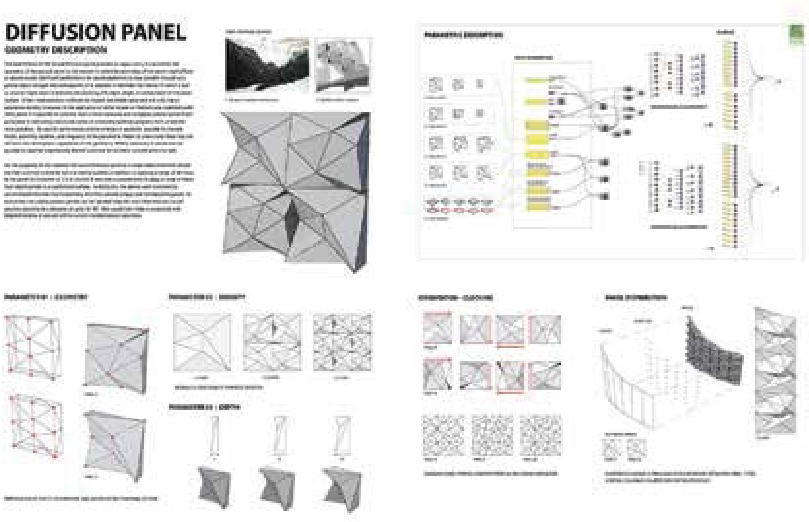
x. Digital materiality as a term was originally introduced by Fabio Gramazio and Matthia Kohler, 2008. *Digital Materiality in Architecture*, Lars Muller Publisher.

xi. http://supermanoeuvre.com/pre-vault/.

xii. http://www.topocastlab.com .

xiii. *The Economist*, December 4, 2003.

For more information on these or other projects, visit www.pci.org/ascent.



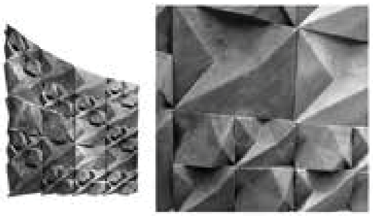


Figure 9 and 10. Parametric precast sound diffusion panels by TOPOCAST Lab at University of Texas at Arlington. Photos: Brad Bell, University of Texas at Arlington.