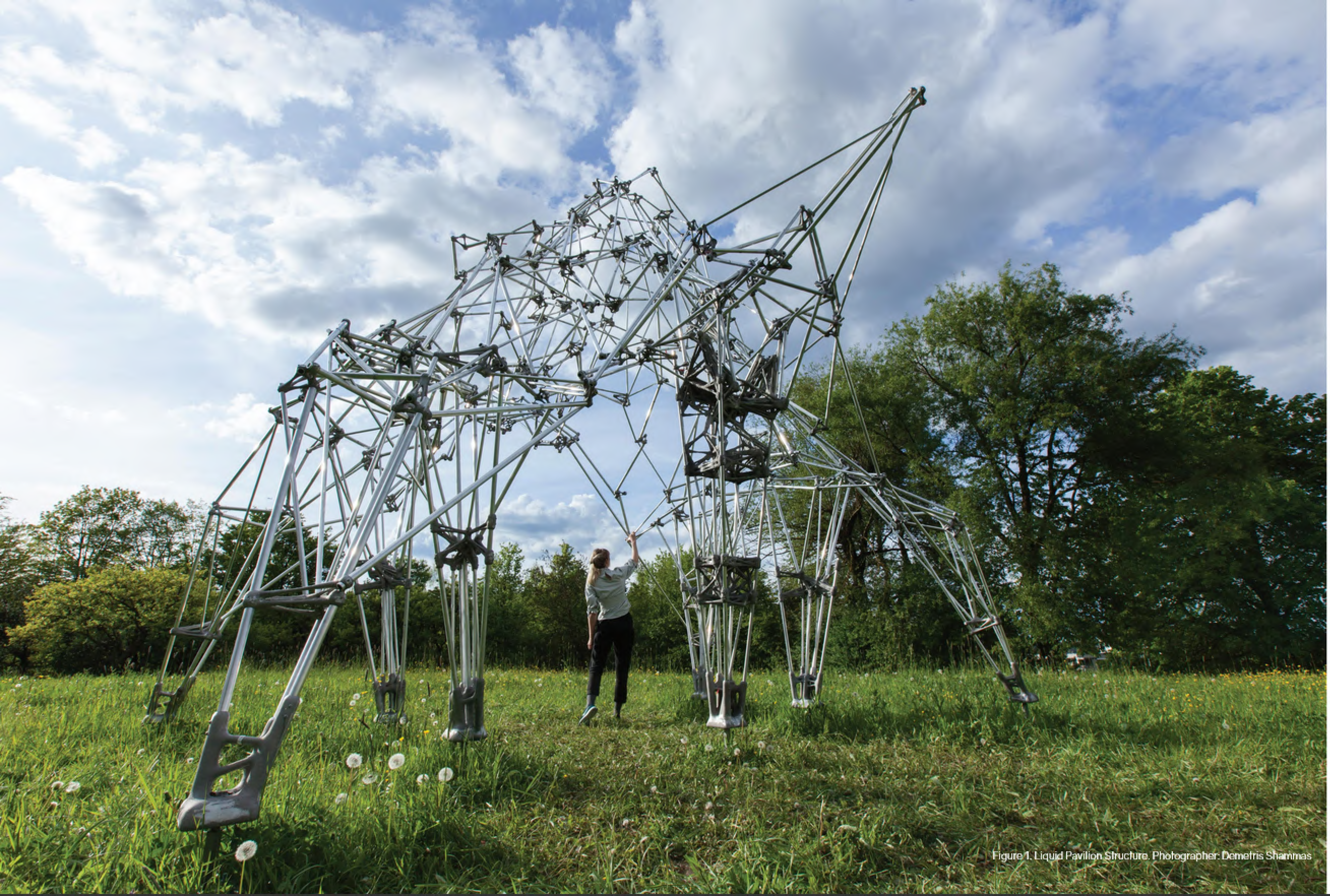

Figure 1. Liquid Pavilion Structure. Photographer: Demetris Shammas

Digital Metal

3D printing sand-mold to produce unimaginable and affordable cast metal parts in architecture

by Mania Aghaei Meibodi

Bespoke Metal Elements in Architecture

Cast metal has been widely used in architecture —for facades, bridges, beams, columns and connections. An historical example is the exposed cast-iron arches and columns in the Sainte-Geneviève Library France built by architect Henri Labrouste.

Cast metal can find application in architecture wherever strong parts with three-dimensional geometry are needed. Through casting molten metal can be shaped into any desired shape. Casting allows fabrication of intricate, integral elements with design features that cannot be obtained by other fabrication methods, such as undercuts, overhangs, internal structures and the three-dimensional differentiation in thickness of parts. However, the degree of geometric complexity achievable in a metal part is still constrained by our ability to fabricate the necessary mold, which is traditionally very labor and time intensive.

Today, advances in additive manufacturing of metal can bypass mold making and offer the ability to produce bespoke parts with complex geometry without molds. An example is the 3D printed steel node by Arup that was topologically optimized to reduce 75% of material (Galjaard et al. 2015). However, while today multiple technologies of metal 3D-printing exist, each have major shortcomings for the application in building industry, where usually a larger amount of bespoke large metal parts is needed within a short production time.

The most common method is Powder bed fusion (such as SLM, EBM, and DMLS), in which each powder bed layer is selectively fused through energy, like laser or electron beam. This method is commonly used for manufacturing small, low volume, complex metallic parts (Bhavar, 2014). Major drawbacks of employing this technology for building industry are the small build volumes, long print times, limited metal material that can be printed, and high cost. Printing methods for larger dimension, such as robotic gas metal arc welding based additive manufacturing — where the stainless-steel rods are printed through welding layer by layer — are recently developed. However, this technique requires expensive postprocessing to reach a high-quality surface finishing and is still limited in the printable forms. In general, the available additive manufacturing methods for metal are too expensive for the application in architecture.

Digital Metal Research: Combining the Advantages of 3D Printing and Metal-Casting

To overcome these challenges, in my research at DBT, I employ AM to 3D print the sand-mold for metal casting rather than 3D printing the metal part directly. I do this to benefit from the geometric freedom offered by 3D printing and the flexibility of metal casting. When combining 3D-printed sand-molds with metal casting, we can efficiently create large bespoke elements without being limiting to specific metals or alloys—we can cast practically any kind of metal.

To fabricate sand-molds, Digital Metal research uses binder-jetting technology where a liquid agent is selectively dropped on thin layers of sand to bind it. For applications in architecture, binder-jetting technology offers a unique combination of geometric freedom, intricate detailing and large print-bed dimension. Molds can be printed at a precision in the range of a tenth of a millimeter and in dimension of up to 4x2x1 meters.

In Digital Metal research, 3D printing sand-mold and casting is used hand in hand with computational power. The increased computational power needed to calculate geomatrically complex and highly detailed forms

Figure 2. Cast metal in 3D-printed sand-molds

enables exploration of entirely new vocabulary of shapes for architecturally exposed metal structures. We can design and produce metal parts in a new and radically expressive aesthetic. Instead of using the cutting-edge technologies to mimic former details and concepts, in digital metal research this new paradigm is explored in a most radical and open manner.

This research entails development of computational methods to design and optimize bespoke metal elements which integrate the casting constraints. An important aspect is to facilitate the design of molds and casting system for any given shape. An attempt is to automatically integrate details such as the gating system that channels the molten metal to the mold cavity. Ideally, I would like to generate the required fabrication data for any geometry of part on a push of a button and send it directly to the 3D printer. The casting process itself can follow the traditional setup and can be done within a short period of time.

Two experimental projects: first architectural structures featuring new vocabulary of shapes for metal casts using 3D printed sand molds

To demonstrate and evaluate the proposed method in an architectural context, two 1:1 scale projects were designed and built together with the students of the Master of Advanced Studies in Digital Fabrication

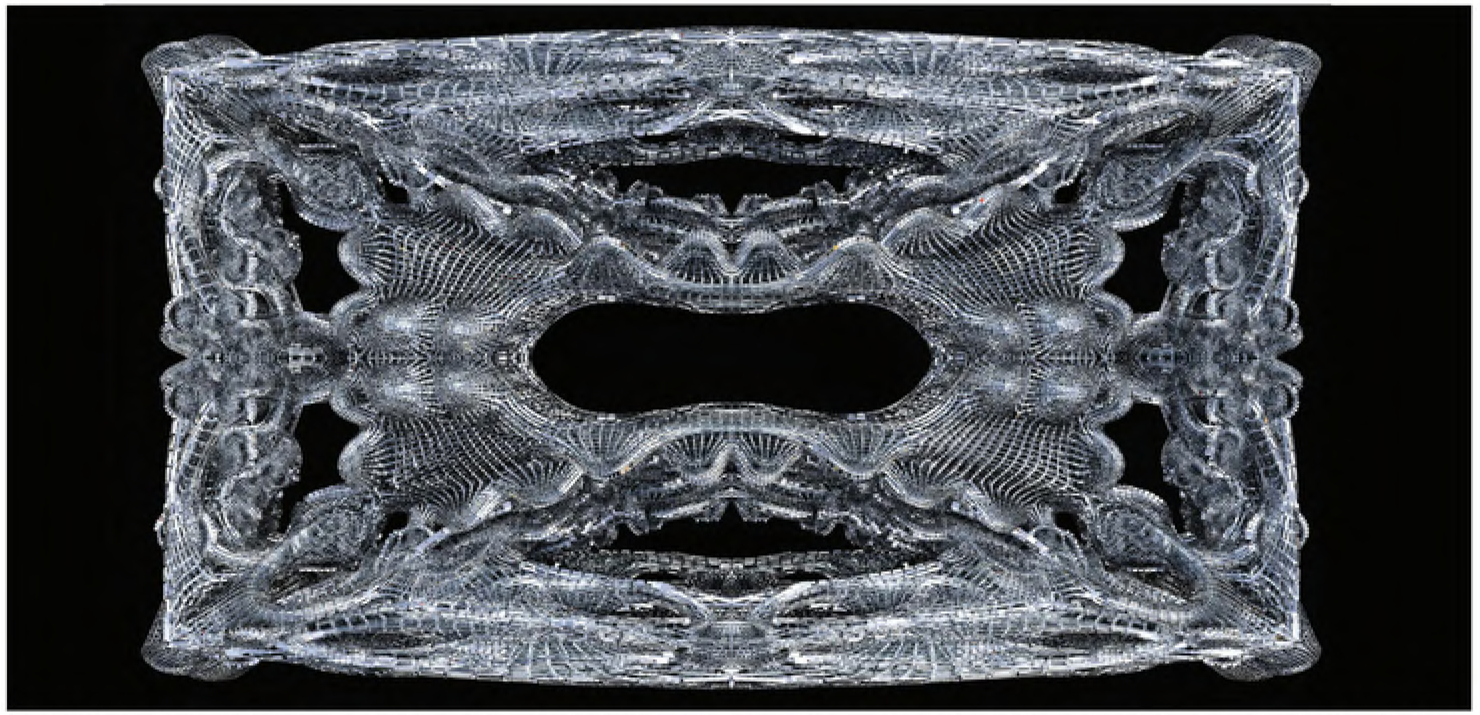

Figure 3. Design for a cast facade-panel by Mania Aghaei Meibodi. Computation is used to explore new vocabulary and aesthetic of cast metal part in digital age.

(MAS DFAB) at ETH Zurich. These projects highlight possible application of the proposed fabrication method for structural metal nodes and three dimensionally articulated façade elements. The metal connection in combination with standard tubular profiles enable the construction of large freeform spaceframe structure. The facade elements allow precise control of transparency and shading properties though porous 3D structures.

In 2017, "Liquid Pavilion", a five-meter-high space-frame structure was designed and built from 182 non-repetitive lightweight joints in combination with off-shelf metal profiles. All nodes were digitally designed and digitally fabricated using 3D-printed molds, reducing the overall fabrication time and effort.
The constraints of metal casting were encoded in the algorithm that generates the geometry of the nodes and their molds, which then ensured cast-ability, dimensional-accuracy and good surface finishes. AM allowed integration of a gating system for the liquid metal into the mold, thus considerably reducing tolerances and fabrication time. As a result, the fabrication of all nodes took less than two weeks, which is considerably faster than casting with the traditional process of mold-making or the direct 3D metal printing. With commercially available metal printers, large connections would even have to be split into smaller parts to fit into the printing box.

In 2018, a six-meter-high and four-meter-wide "Deep Facade" was designed and constructed from 26 three-dimensionally articulated panels up to the size of 2 sqm, that were also cast using 3D-printed sand molds. A modified differential-growth algorithm was used to generate the ornamented structure that expresses the liquidity and strength of metal as a building material. Here we used an open cast principle, which helped us to reduce the size of the necessary printed sand-molds.

Figure 4. A 3D printed sand mold (left) and an aluminum cast joint (right), the MAS DFAB at ETH Zurich 2017. Photographer: Ma Xije

Outlook: A promising approach for bespoke metal parts in architecture

The discussed digital fabrication approaches for bespoke metal parts are targeting very different applications in architecture and it is important to strategically decide when to use what. Powder-bed metal printing is best in producing highly precise, lightweight small metal parts in low volume / lot size. Casting metal in 3D printed molds has enormous advantages when high volume custom parts or parts with a larger dimension are needed.
Here, the indirect use of 3D printing is much faster, cheaper and feasible than direct 3D printing and is well qualified for architectural applications. In another word production of large and geometrically complex structural parts are becoming affordable.

An important aspect for future research is to facilitate the design of molds for any given shape, and to automatically orient parts in an optimal way, integrate details such as the feeding of the metal and minimize the necessary post-production. Such specific molding strategies can dramatically reduce the required amount of post-processing. To further increase the degree of automation of the discussed process, unpacking and post-processing, which are currently done manually could be in future automated by robots.

Figure 5. Liquid Pavilion, designed and built by the students of MAS DFAB at ETH Zurich 2017. Photographer: Demetris Shammas

Figure 6. Deep Facade, designed and built by the students of the MAS DFAB at ETH Zurich 2018. Photographer: Jelana Ruangjun (Jel)

Linking the ancient fabrication method of casting to state-of-the-art 3D printing opens the door for revival of cast metal in architecture. It will allow us to structurally optimize metal components and reduce the amount of material. Coupling this fabrication approach with computational design, we can unlock an entirely new vocabulary of shapes for architecturally exposed metal structures, previously unavailable with traditional mold making systems.

> *"We can design and produce parts in a new and radically expressive aesthetic."*

Mania Aghaei Meibodi is senior researcher at Digital Building Technologies (dbt) research group, ETH Zurich and cofounder architect at meonia. Her research focuses on hybrid approaches in using computation and digital fabrication to explore new architectural form and materialize complexity at a building-scale with ultra-high resolution.

Industrial Collaborators of Deep Façade and Liquid Pavilion:
DGS Druckguss-Systeme AG, Aluminium-Laufen AG Liesberg, Aluminium-Verband Schweiz, Christenguss AG, ExOne Gmbh

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