Cartesian Concrete Spiel: A Syntax of 3D Printing

SASA ZIVKOVIC
Cornell University

LESLIE LOK
Cornell University

Don't write off Cartesian rules! Yet. The 3D printer, a Cartesian machine long understood as characterless, a device seemingly devoid of temperament that happily slices and spits out every geometry it is fed, a soul-less entity lacking any comprehensible rules or regulations is in fact highly distinctive. It is an apparatus with integrity, character, limitations, formal rigor, and a pinch of humor. [1]

Scaling up from desktop-size 3D printers to full-scale concrete printing uncovers a highly idiosyncratic set of tectonic possibilities deeply ingrained in the fabrication process that have yet to be consequentially explored spatially, formally, and functionally. Like an endless and repetitive pencil drawing, the printer relentlessly deposits material along a horizontal tool path, layer upon layer, again and again, until an object is built. Most printers operate with three axes, following a strict set of Cartesian coordinates to guide the printing nozzle to a point in space within the print bed. Spatially complex geometries are created through the act of corbelling, the incremental offset of stacked horizontal layers. When printing in concrete, the same rules apply as in small filament-based desktop 3D printers but gravity takes on an altogether different role in the process. Cantilevers have to be carefully constructed, new support material strategies have to be developed, and tool-paths have to be precisely manipulated – concurrently reconciling new means of making and architectural requirements at full scale. The paper gives a general overview of the state of concrete 3D printing, pointing out the many missed opportunities in how discourse is currently framed around this technology.

The manipulation of 3D printing rule-sets presents a tremendous opportunity: concrete printing requires the development of an entirely new architectural language which has to take into account the limitations of the process as well as its (per)formal advantages. Playing with the rules of the 3D printer reveals an inventory of new material possibilities, tectonic expressions, and formal strategies which are both familiar and novel. Complexity and shape emerge out of simple operations, and corbelling becomes a crucial strategy for design. All three projects presented in this paper – RRRolling Stones, Additive Architectural Elements, and Corbel Cabin – manipulate the process of 3D printing to generate new design languages at the scale of furniture, building components, and entire structures. The designs bend, adapt, exploit, twist, and turn common practices on their head – for the benefit of spaces, construction, performance, form, and building.

FIRST, MATERIAL MATTERS: MATERIAL STANDARDS IN CONCRETE 3D PRINTING

Concrete 3D printing has potential advantages in full scale building construction and design, but implementation and development of this technology in building industry (and academia) often follows obsolete models and ideas of 'traditional", non-printed architecture. While printing processes such as Contour Crafting developed at USC by Behrokh Khoshnevis[2] accomplish direct 3D printing with concrete, they often fundamentally fail to take full advantage of the 3D printer's ability to mass-customize complex geometry for no or little additional cost. Contour Crafting (CC) follow-up projects developed by building industry and universities alike (WinSun in China, Siam Cement Group in Thailand, Andrey Rudenko in the United States, University of Technology Eindhoven in the Netherlands, or the Singapore Centre for 3D Printing in Singapore, ApisCor in Russia, and many others) mostly rely on vertically extruded single-curvature surface shapes. Those forms generally do not necessitate 3D printing but can all be implemented more cheaply and efficiently by using existing precast construction methods. To take full advantage of the 3D printing process and its ability to mass-customize complex geometry[3], concrete printing needs to facilitate more drastic cantilevers than currently possible.

At a smaller scale, desktop 3D printing processes leverage a printing material (usually PLA or ABS) which has the inherent ability to rapidly cool and harden, providing structural stability during printing. The material therefore enables drastic cantilevers and allows for a high degree of geometric complexity. In PLA or ABS prints which exceed the material properties of the printing material, a PLA or ABS support material lattice system is used to create extreme cantilevers. Once the printing process is complete, the support material lattice is removed from the printed object. Concrete, however, does not rapidly cure and is very heavy, requiring a different support material strategy.

Scaling-up 3D printing processes requires specialized equipment. In 2016, a large-scale open-source 3-axis gantry 3D printer named Daedalus[4] was designed and fabricated at the Cornell Robotic Construction Laboratory (RCL). Based on smaller scale open-source machines such as the RepRap and the Prusa Mendel 3D printers, the 8 x 8 x 16 feet lightweight steel frame gantry utilizes adapted Marlin firmware to run Silkworm-generated G-code from Rhino Grasshopper. Methodologically, the printing process follows

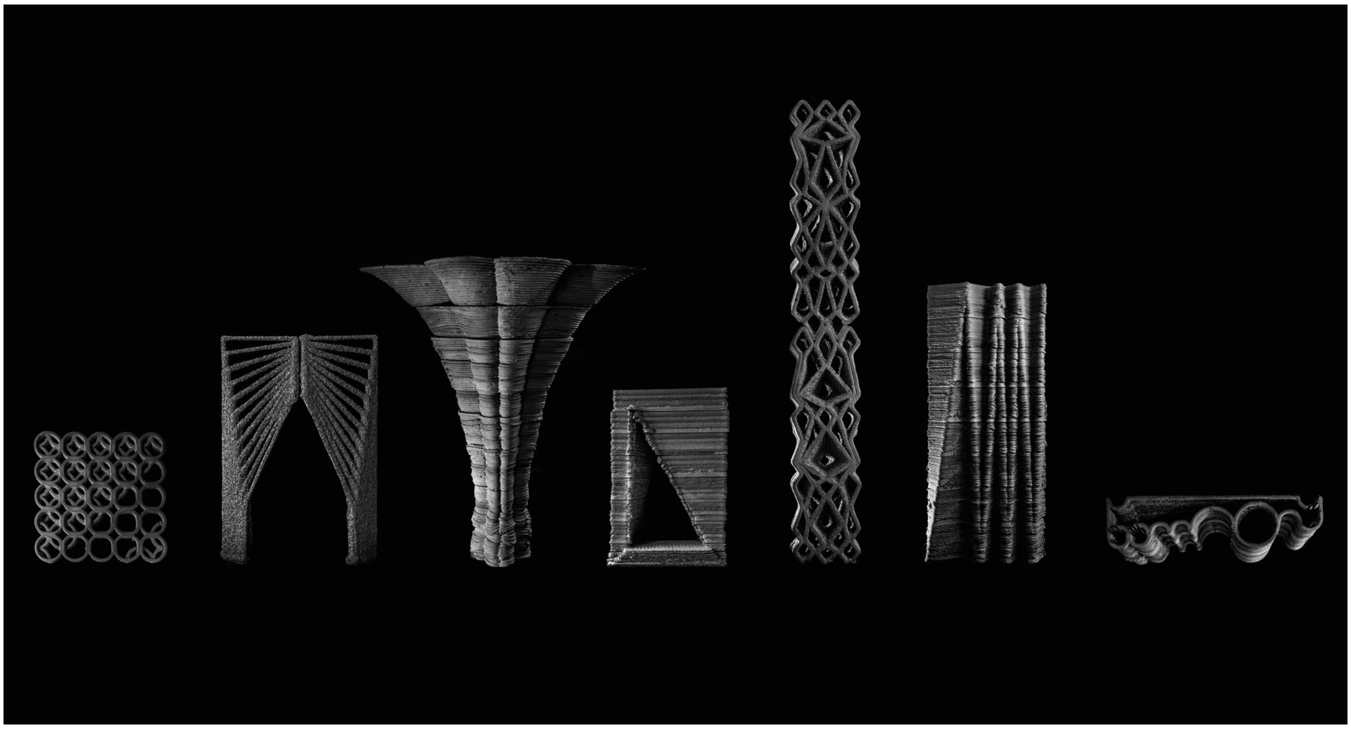

Figure 1: Additive Architectural Elements - A New Robotic Brutalism Project. Photography: HANNAH (2017)

a well-established line of precedents in concrete 3D printing[5,6]. While the highly economical Daedalus fabrication platform offers a certain degree of automation, the machine heavily relies on a set of human helpers to mix concrete, apply gravel, and adjust flow parameters during the printing process. Rather than automating the full system, Daedalus embraces a “collaboration” between analog humans and digital machines.

Utilizing a gravity-fed hopper-auger nozzle system, the concrete mixture is designed to work with readily available off-the-shelf materials and admixtures. The mixture has an open time of approximately 1 hour and can be extruded at a maximum layer height of 10 mm and to an overall print height of up to 200 mm before allowing time for the concrete to set. The concrete mixture includes locally available aggregates and portland cement compounds. One batch contains 11.5 kg portland cement, 19.5 kg fine sand, 25.2 kg Mortar Mix Type S, 110 g Thermo-Lube, 35 g Superplasticizer #5, 10 g Nylon fibers, and 11.5 kg of water. When analyzed for its compressive strength, at around 62 N/mm^2, it is about three times stronger than regular grade concrete.

To address the critical issue of complex curvature creation and support material in concrete 3D printing, the research teams at HANNAH and the Cornell Robotic Construction Laboratory (RCL) developed a method which enables cantilevers by implementing a recyclable gravel aggregate as support material. The gravel aggregate has an approximate top size of 10 mm and is added to provide support for the concrete during the 3D printing process. With the gravel as support material, steep cantilevers up to 60 degrees can be achieved during the printing process. Gravel is manually added during the concrete printing process and ensures the stability of the prints. The following three case study projects all take advantage of the gravel support material method while mass-customizing complex geometries through 3D printing. The projects aim to overcome the limiting paradigms of linear extrusion that thus far dominate concrete 3D printing research and enable new formal expression. Changing the rules towards incremental layer corbelling makes for a very different printing game!

CASE STUDY 1: ADDITIVE ARCHITECTURAL ELEMENTS

Tectonic Expressions and Rules Sets in Concrete 3D Printing: The Additive Architectural Elements project aims to reveal the 3D printer’s own and highly idiosyncratic architectural tectonics and narratives. Choosing common-place prototypical architectural motifs (such as floors, columns, doors, windows, walls, and ceilings), strategies were developed as to how the layering of concrete, the relentless three-dimensional drawing of extruded lines of material, and the act of corbelling can suggest new strategies for building. The critical question is: what is the architecture of 3D printed concrete?

The manipulation of 3D printing rule-sets constitutes a tremendous opportunity: concrete printing requires the development of an entirely new architectural language which has to take into account the limitations of the process as well as its (per)formal advantages. Exploring the rules of the 3D printer reveals an inventory of new material possibilities, tectonic expressions, and formal strategies which are both

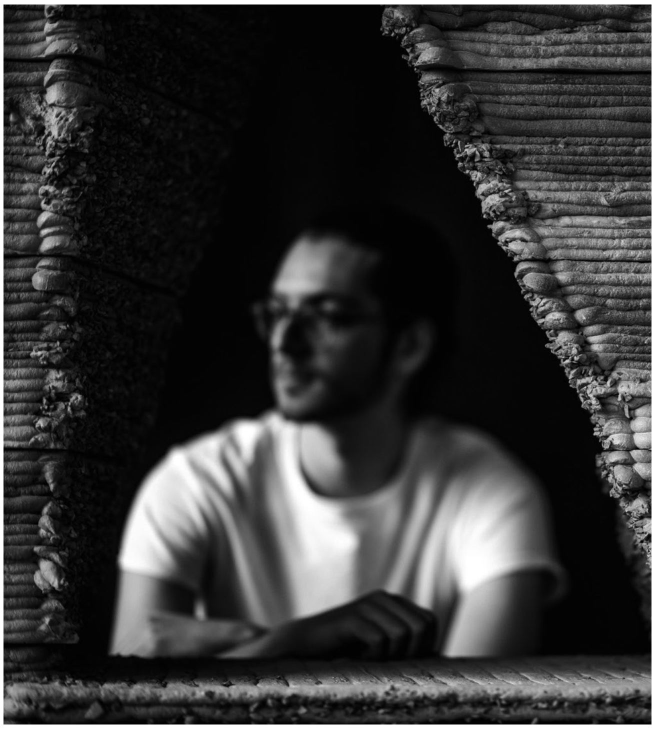

Figure 2: Window Detail of Additive Architectural Elements - A New Robotic Brutalism Project. Photography: HANNAH (2017)

familiar and novel. Complexity and shape emerge out of simple operations, and corbelling becomes a crucial strategy for design.

In a 3D printed structure, all common architectural motifs and building components must be re-thought to fit the logic of layered construction. For example, a concrete printer cannot print in midair; therefore, the otherwise rather simple task of creating a rectilinear window opening in a wall becomes a de-facto impossibility. Rather than drastically altering the process (stopping the machine to insert a beam), shortcomings become opportunities for design: as the printer can incrementally cantilever, one logical consequence for the window is to become a triangular corbelled arch. Suddenly, seemingly advanced technology relies on “obsolete” or archaic structural strategies such as corbelling. Other methods deployed in the manipulation of structural form in the Additive Architectural Elements are the modification of printing direction (printing upside-down or printing in section) to overcome printer deficiencies, g-code manipulation for smart material deposit, or alterations of geometries for structural reasons related to the fabrication process.

In a series of seven full scale 3D printed concrete prototypes, forty-nine 3D printed PLA models, and seven proto-architectures 3D printed from PLA, the Additive Architectural Elements – A New Robotic Brutalism project explores the architecture of 3D printed concrete within Mushroom Columns, Force Columns, Smart Poche Walls, Ceilings, Floornaments, Doornaments, and Corb. Windows. Changing the rules of printing alters the architectural possibilities for each of the elements:

Mushroom Column: The Mushroom Column takes advantage of concrete’s ability to readily cantilever over support material when printed upside down, resulting in structural assemblies that seamlessly transition from vertical to horizontal orientations. The exterior surface of the Mushroom Column is smooth and striated, whereas the interior of the column is raw and faceted due to the residual gravel formwork left by the fabrication process. Undulations in plan produce a rich variety of elevations and sectional conditions. Eventually, the Mushroom Column delaminates at the top and culminates in a fine structural lattice, fostering new roof-to-column relationships.

Ceiling: 3D printing facilitates the integration of building systems and furniture. The Ceiling element is an expressive play on ducts for ventilation and reflectors for lighting, a type of performative poche which is highly over-articulated and forms a lush ornamental Ceiling. In 3D printing, the functional integration of building systems becomes a spatial opportunity. Rather than a hidden performative necessity, structural elements such as ceilings can be modified to accommodate varying additional functions, following the printer’s inherent economic logics of mass-customization.

Floornament: In the printing process, ornamentation can occur vertically or horizontally. The Floornament can be structurally and algorithmically optimized to produce rigid structural lattice ceiling assemblies. As object of pleasure, the ornamented floor is visually stimulating and references a rich history of floor finishes in architecture. In 3D printing, intricate patterns come at no additional cost: in fact, the less material is used, the quicker and cheaper the part becomes. As the machine is indifferent, 3D printed floors can be complexly ornamented.

Forced Column: The Forced Column element explores the 3D printer’s ability to deposit material where structurally necessary. In areas of high structural load, the concrete grid can densify whereas in areas of lesser structural load the column might become more transparent. The exhibited column study is obviously diagrammatic: however, structural optimization solvers can easily generate performative alter-egos of the Forced Column where concrete is deposited along the lines of principal stress. In the Forced Column, excessive structural expression can take on many forms and architectural articulations.

Smart Poche Wall: Similar to the Forced Column element, the Smart Poche Wall explores a manipulation of concrete density to optimize for structural performance. The printer has the ability to deposit material where structurally necessary

Figure 3: RRRolling Stones arranged as one long bench in Socrates Sculpture Park, Photography: Zachary Tyler Newton (2018).

without any extra effort or economic disadvantages. Walls can alter in thickness or mass and respond to the structural load within the wall. Smart Poche Wall explores various infill strategies resulting from this density-shift in vertical wall assemblies and furthermore investigates potential architectural articulations of such strategies.

Corb. Window: The Corb. Window element investigates the archaic strategy of corbelling, an incremental stepped cantilever structure. 3D printing encourages the gradual cantilever and offset of stacked layers: rather than creating a rectilinear opening, triangulated corbelling becomes a natural strategy to create windows in solid wall assemblies. The 3D printed opening is therefore inherently triangular. The corbelled gravel surface becomes an expressive feature in the Corb. Window element and can be customized for views and solar shading. The articulation of window sills and shading elements is derived from toolpath manipulation and calibration of incremental step-over parameters between layers.

Doornament: The potential for excessive ornamentation is explored in the Doornament. Points of entry which demarcate important and sometimes symbolic thresholds into a house or building have historically been heavily ornamented for representative reasons. 3D printing holds the potential for a re-vitalization of ornamentation as an architectural strategy at the scale of an element or the entire building. In concrete 3D printing, the creation of ornamentation follows a series of particular material and fabrication parameters. The full scale Doornament concrete prototype plays with a precise de-lamination of layers to create screen-like moments of transparency.

Together, the Additive Architectural Elements form a material-derived series of speculative investigations that challenge predominant tectonic articulations and simplifications of 3D printed architecture.

CASE STUDY 2: RRROLLING STONES

Mass-customization and Self-similarity in Concrete 3D Printing: “RRRolling across the meadows of Socrates Sculpture Park are twenty-five unique 3D printed concrete follies. The Stones are both smooth and jagge(re)d, each turn reveals new curvature and seating profiles that adapt to different body types and sizes. Leveraging movement architecturally and as folly itself, park visitors discover new seating configurations with each turn. Responding to scales within the park landscape, the RRRolling Stones form a long continuous bench object, aggregate into smaller benches, or disperse entirely to form different size seating groups or solitary compositions. The seats are constructed using a large-scale 3D printer at the Cornell Robotic Construction Laboratory (RCL). 3D printing with concrete enables the creation of 25 affordable and

Figure 4: Corbel Cabin in Ithaca, NY. Photography: Yuxin Chen (2017)

self-similar, but ultimately entirely individual seats. Despite appearances, this is not a cookie-cutter design! While sectional profiles reference archetypes of chairs, seats, and lounge chairs, the layered fabrication process becomes materially ingrained in the tectonics of the seats."

Besides an efficient use of material, no waste, and the elimination of formwork, concrete 3D printing allows for the mass-customization of seating furniture at no additional fabrication cost or effort. The fabrication method is highly affordable because the printing material is readily available in any home improvement store. The concrete used in the fabrication process is durable and can withstand a range of weather conditions. Printed from the ground up in layers, the striations make for a comfortable textured seating surface. During the printing process, the interior of the seats is supported with a gravel bed that enables the printing of cantilevers and ruled surfaces, giving the seats their distinct appearance. The RRRolling Stones project demonstrates the feasibility and ease of mass-customization inherent to concrete 3D printing. Applied to the scale of architecture, mass-customized 3D printing will change the rules and economies of design. No longer bound to the relentless paradigm of standardization, 3D printing opens possibly for design freedom, customization, and individuality.

CASE STUDY 3: CORBEL CABIN

Building A 3D Printed Building: Corbel Cabin questions common expectations around concrete 3D printing (printing is easy and automated) and explores the architectural opportunities of digital-analogue construction hybrids. Adding to current discourse in concrete 3D printing, the project develops a ground-up methodology from tool to construction process to building, which involves explorations of large-scale fabrication equipment design, software adaptation, material experimentation, construction methodology development, implementation of tolerances, and logistics of on-site construction.

Corbel Cabin is a building case study at full scale which questions common notions of "high-tech" and "low-tech" techniques in building practices. Utilized construction methodologies mediate between the precise control of digital tools, the volatility of material behavior in concrete, and the idiosyncratic layered printing process. The cabin has a footprint of 10 x 10 feet and lifts off the ground on 3D printed legs which adjust to the terrain. The legs are arranged in an interlocking pattern to provide lateral stability. The concrete structure is characterized by three programmatic areas, a table, a storage seat element, and a 6.5m tall working fireplace. Architectural manifestations of corbelling are explored throughout the structure by geometrical manipulation of 3D printed sacrificial concrete formwork modules. For example, below the structure, the corbelled support legs create a

Figure 5: Interlocking floor detail of Corbel Cabin in Ithaca, NY. Photography: Yuxin Chen (2017)

cavernous space reminiscent of Upstate New York Geology. Along the chimney, slight undulations reinforce the motif of corbelling and create a more slender vertical elevation.

The 3D printed components function as sacrificial zero-waste formwork for the main structural system, a cast-in-place concrete structure with custom rebar cages. As the construction site is remote, the printed formwork was designed in small sectional modules to be transported and assembled manually without the use of any heavy machinery. Throughout the project, the imprecisions and volatility of the concrete material properties inform joinery details and assembly strategy tolerances. Both the design and manual on-site assembly leverage deviation in tolerance to articulate reveal details.

The cabin's architectural qualities lie in the reciprocal relationships which emerge from the oscillation between digital and analogue processes of construction. The structure is a play on machine precision contrasted by material imperfection and subsequent tolerance deviations during fabrication. The concrete has texture, is alive, and liquid. Similar to board form concrete casting, local conditions during the construction process are inextricably engrained in the printed structure. Corbel Cabin is a techno-archaic, ruin-esque, massive-primitive, and nearly anachronistic structure, which emerges from the re-calibration and combination of machine, material, and people-informed construction processes. Contributing to disciplinary self-reflection by developing a comprehensive and ground-up methodology from tool to construction process to building, Corbel Cabin suggests alternate modes of design research at full scale.

ENDNOTES

1. Zivkovic, Sasa, and Leslie Lok. "Beyond the Ecology of Concrete Sausages." (2016). *ACSA 2016 International Conference: Cross-Americas: Probing Disglobal Networks* [Proceedings of the 2016 International Conference of the Association of Collegiate Schools of Architecture (ACSA)] Santiago de Chile, Chile, 29 June - 1 July, 2016
2. Khoshnevis, Behrokh. "Automated construction by contour crafting—related robotics and information technologies." *Automation in Construction* 13.1 (2004): 5-19.
3. Lipson, Hod, and Melba Kurman. *Fabricated: The New World of 3D Printing.* John Wiley & Sons, 2013.
4. Zivkovic, Sasa, and Christopher Battaglia. "Open Source Factory: Democratizing Large-Scale Fabrication Systems." (2017). *ACADIA 2017: DISCIPLINES & DISRUPTION [Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture* (ACADIA)] Cambridge, MA, 2-4 November, 2017, pp. 660- 669
5. Bos, Freek, Rob Wolfs, Zeeshan Ahmed, and Theo Salet. 2016. "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing." *Virtual and Physical Prototyping* 11, no. 3, pp. 209-225
6. Gosselin, Clément, Romain Duballet, Ph Roux, Nadja Gaudillière, Justin Dirrenberger, and Ph Morel. 2016. "Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders." *Materials & Design* 100. 102-109