The Resolution of Architecture in the Digital Age

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Abstract. The resolution of architecture is a measure of the spatial density of information inherent in a building. This paper demonstrates how the confluence of advances in computational design and additive manufacturing has recently led to a paradigm shift in potential architectural resolution. Buildings can now be designed and fabricated with elements at the threshold of human perception. This resolution can be used to replicate existing architectural styles ever more efficiently and accurately. Yet as with the introduction of other new technologies, architects must now explore the latent potentials and determine what kind of new architectures become conceivable. Specifically, what architectures can adequately express this enormous resolution and the unlimited geometric complexity within reach? With the project *Digital Grotesque*, we present the first human-scale, enclosed structure that truly exploits these opportunities. Algorithms are used to articulate and orchestrate the geometry from the macro scale down to 1mm small details. The structure is enriched with local information at a previously unseen resolution. A unique language of form is developed that transcends rationality and celebrates spatial expression: a digital exuberance.

Keywords: high resolution, additive manufacturing, 3d printing, digital fabrication, computational design, subdivision, mesh.

1 Transformative Technologies

New materials and fabrication methods have historically led to radical changes in architectural design. They have indeed been the primary drivers in its evolution. The introduction of new methods and materials is usually followed by phases of intense experimentation, during which architects explored the new potentials – often without preconceptions - and tried to determine how these can best be applied. Past examples of transformative technologies include:

- Advances in cast iron and plate glass technologies in the late 19th century initially lead to the construction of vast crystal palaces, exhibition halls, and pavilions.

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- The advent of steel and later concrete and rebar had a broad architectural impact. They enabled new cast free-form geometries, facilitated construction of high-rise buildings, and allowed for open floor plans.
- The introduction of composite materials in the 1960's instigated experimentation with modular, pre-fabricated housing components.
- Advances in mathematics and computation led to complex and highly performative truss structures such as towers and bridges.

Some of these explorations did not prove viable. The cast-iron buildings with their exposed structures, for instance, were not sufficiently fire-resistant, and thus the typology quickly fell out of favor. Yet in many cases, the results of these experiments were eventually assimilated into standard architectural practice. In the process of assimilation, certain explorations may have forfeited their initial radicalness, yet they significantly altered the trajectory of the architectural canon.

In recent years, there have arguably been not one but two important and related technological advances in architecture. The first of these developments is in the field of computational design, in which computers have advanced from mere drawing aids to generative design tools. The second development concerns CNC fabrication, where early two-dimensional subtractive methods are being complemented by ever more powerful additive methods. Taken together, we believe these two technologies herald a paradigm shift for architectural design: the concept of resolution will become a key characteristic of architecture.

We briefly outline the path of computational design and CNC fabrication technologies over the past decades. We demonstrate how in their current state their intersection enables a newfound, almost infinitesimal resolution. We then present a first project, *Digital Grotesque*, which materializes this revolution in resolution.

2 Background: From Design to Production

The development of computational design and CNC fabrication in architecture can be broadly divided into two phases. In the first phase, newly developed CAD software allowed architects to bring architecture into the computer. In the second phase, architects increasingly explored methods to bring this architecture back out of the computer, primarily through CNC fabrication.

2.1 Into the Computer: A Productivity Enhancing Drawing Tool

The late 1980's saw the advent of CAD software. These programs, conceptually foreshadowed by the Ivan Sutherland's Sketchpad program in 1963 [1], were initially embraced by engineering firms and then gradually adopted in architectural offices. Through the use of these programs, the computer began to function as a digital drawing machine. Buildings could be designed and visualized in the computer – first in planar views and eventually in three dimensions.

The architect's design methodology remained similar to manual drafting, with the pen replaced by a mouse. Yet the incorporation of features such copy and paste, semantic models, and file management – just to name a few - led to significant productivity gains. These gains were realized despite the fact that CAD software's output was initially limited to paper prints of plans and construction drawings, without a direct link to fabrication tools.

2.2 Out of the Computer: A Tool for Construction

The late 1990's saw the extension of architectural CAD software into the third dimension. Certain architects began to appropriate software packages that were initially developed for film animation, while others explored packages that were destined for the aeronautics industry. The former software included elaborate geometric features, yet mostly lacked possibilities to get the data out of the computer. The latter software, by contrast, had could readily export data for fabrication, yet had fewer features on the design new forms.

By the early 2000's, this link between design and fabrication in software became more firmly established. Computers were increasingly used to directly control fabrication tools. These tools include laser cutters, CNC mills, stamping machines and bending machines. At an architectural scale, these tools are often used to fabricate facade components and paneling. The advent of visual programming languages embedded in CAD programs has facilitated this type of design with parametric elements. Ideally the sequence from design to fabrication is completed entirely within the computer, without the need for paper drawings.

Mass Customization – with Constraints. The confluence of advancements in computational design and CNC fabrication technologies enabled a new degree of customization. Standardization of components is no longer mandated by economies of scale, thus components can be highly individualized.

Yet these CNC methods involve substantial design restrictions. Two-dimensional forms can be fabricated with relative ease, yet true three-dimensional geometries with complex topologies can only be realized with much additional computation and often adaptation. Unless the fabrication constraints are already incorporated into the design process, one effectively needs to model two distinct processes: the design itself, and then the generation fabrication data.

As a result, despite the use of CNC technology, current buildings usually have a lower resolution in the third dimension than in previous times when manual labor was affordable and available. This contrast becomes apparent when one compares the richness of information in a façade of a renaissance building with a contemporary building. For example, contemporary free-form façades are usually triangulated and produced as two-dimensional CNC fabricated panels. Multi-axis milling of panels is a complicated alternative that has its own geometric constraints and requires the development of complex milling strategies.

3 A New Era: Synthesizing Architecture

The most recent developments in information technology foretell a new era for computer-aided architecture. On both the computational design and the fabrication side, parallel concepts have evolved based on the idea of particle elements. Countless abstract geometrical elements can be computationally composed to form the architecture of entire buildings. Countless particles of material can be solidified by 3D printers into massive building components. The field of architectural synthesis is open.

3.1 Design Side: Modeling Particles

Central to this idea of synthesis is the concept of an architectural resolution. In two dimensions, resolution implies how much information per surface can be contained in an image or plan. This can be measured, for instance, by the pixels per square inch multiplied by the amount of information contained in each pixel. Analogously, in three dimensions, and object's resolution is defined by the number of points or cells per volume, and by their capacity for information.

At an architectural scale, current computational capacity allows for a density of elements that exceeds the threshold of human visibility. Therefore these elements are no longer read as single units, but instead viewed as a synthesized form. Geometry can now be described in an enormous granularity, comprising many gigabytes of data, without the need for any compression as provided by repetition, modularization, or self-similarity.

There are multiple strategies for generating a high-resolution architecture. At a broad level, computational geometry can either be described by mathematical formulas, or it can be synthesized out of discrete spatial elements. In the former method, which includes splines and NURBS, geometries are broken down into individual elements when they are displayed or turned into fabrication code.

In the latter method, geometry is defined from the outset by individual spatial elements with coordinates. These are interlinked or grouped together in structures as a mesh or as a voxel space. In this discrete approach, architectural synthesis is closely related to various discrete analysis models in engineering.[1] These types of analyses can be integrated in real-time into the architectural design process.

3.2 Fabrication Side: Materializing Particles

Architectural construction can be termed an additive process, as components need to be joined together to create a structure or building. The components, such as bricks, tiles, wooden beams, and panels, are often standardized and prefabricated. With the rise of CNC fabrication, this need for standardization was overcome, and components could be customized. The effect can be compared to the introduction of digital printing in pressrooms: without the need for printing plates, variable motives can be

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[1] Examples of such engineering tools include force distribution and energy flow simulations.

produced with each impression. The traditional CNC fabrication methods still require prefabricated elements as a base for customization. Milling, bending, and laser-cutting all manipulate semi-finished materials.

Additive manufacturing introduces a new printing revolution in design. First attempts at printing spatial objects were made in the early 1970's. The term "3D-Printing" appeared in 1995 in relation to the experiments of Jim Bredt and Tim Anderson at MIT as they printed binder onto a powder bed [2].

3D printing differs from other CNC methods in that it additively combines material, instead of subtractively removing it (e.g. milling, laser-cutters, hole punchers) or deforming it (e.g. CNC tube bending, metal bending). It also introduces a new scale in computer-controlled fabrication: materialization occurs at a fraction of a millimeter.

The most prominent technologies in additive manufacturing can be differentiated by the state of their raw material (granular, liquid, laminates, extruded), the components involved in the production process (with or without binder) and the mechanism of solidification (binder, laser, light or heat).

Table 1. Non-exhaustive overview of additive manufacturing technologies based on Pham [3]

State of material	Solidification	Material	Technology
Liquid	Light	Liquid Polymer	Stereolithography
		Resin	Digital light processing
	Heat	Molten Material	Fused deposition modeling
Discrete Particles	Laser	Metal	Sintering
	Binder	Sand, Plaster	Powder bed and inkjet head 3d printing
Solid Sheets	Laminate	Paper	Laminated object manufacturing

In each of these methods, the material used is loose in its initial state, and is selectively hardened into a solid in layers. Millions of small neutral elements are combines into a whole.

In this process, resolution implies how much information can be embedded in a single volume. The limiting factor in additive manufacturing is usually the layer height. In its simplest form, this information contains only the binary state of fixed or not, while some systems even allow further information such as color information or multiple material ratios to be embedded.

3.3 Implications for Architectural Design

Additive manufacturing technology nullifies many of the restrictions that were imposed by subtractive CNC methods. Yet the possibilities extend far beyond a mere lifting of restrictions. Rather, the potentials of additive manufacturing may profoundly alter architectural design processes as a whole. We identify five major implications for architectural design:

1. **Design in three dimensions**: As there is a WYSIWYG equivalency between design and fabrication, it is no longer necessary for architects to produce two-dimensional plans, details, or construction drawings. The design never leaves 3D space. Even connection details such as nuts and bolts can be modeled in 3D – including the gap between them – and directly printed.
2. **Fabrication without adaptation**: As there are no geometric restrictions and any topology is feasible, forms do not require any post-processing or adaptation for production. Forms can generally produced without a loss in information.
3. **Fusion of structure and surface**: Printed forms can function structurally, yet can simultaneously exhibit complex surface attributes. A structural ornamentation becomes feasible.
4. **Unlimited differentiation within an element:** As the material is synthesized out of countless particles, its local attributes can be highly differentiated. Thus a form can locally be thicker or thinner, hollow or massive, and some printers even allow a mix of material properties. With most additive techniques, there is neither a significant time cost nor a material cost involved in printing highly complex forms. Simplicity is no longer economically imperative – there is no cost for complexity.
5. **Unlimited individuality among elements:** As with traditional CNC fabrication methods, additive manufacturing does not impose a cost on individuality. Uniformization is no longer an imperative as there are no economies of scale on the production side.

4 Printing Exuberance: The Digital Grotesque

Given the leap in resolution that these technologies have enabled, we seek to manifest this potential in a built architecture. We seek to show how the combination of computational design and additive manufacturing can lead to a non-standardized, highly differentiated and specially complex architecture that is defined at the scale of millimeters.

The Digital Grotesque project is the first inhabitable room that is entirely 3D printed. The combination of a computational design approach with additive manufacturing technology allows the articulation of a form in an unseen richness of detail, and it enables its rational production. The complete enclosing structure of a three-meter high space is printed in sandstone in an accuracy of a tenth of a millimeter.

4.1 Mesh Refinement

Architecture that fully exploits the full resolution of current information technology can no longer be specified, controlled or designed manually. Instead, on a higher level of abstraction, algorithmic procedures must be defined to explore the solution space in an adequate manner.

In the Digital Grotesque project, every detail of the architecture is generated through customized algorithms, without any manual intervention. The form is articulated uniquely through abstract symbolic rules. A simple input form is recursively refined and enriched, culminating in a geometric mesh of 300 million individually specified facets. The geometry is evolved primarily by means of a subdivision scheme [3]. This process, performed over 11 iterations, is controlled by a set of locally differentiated replacement rules of a mesh-grammar [4]. Each facet of the input geometry is divided into sub-facets. The position of the new vertices is calculated through rules that incorporate the previous state of the geometry.

A single process thus generates many scales of architecture, from the overall form with its broad curvature, to local surface development, down to minute textures. The process can enrich both the form's topography and topology. Despite the recursive nature of the approach, there is no self-similarity at any scale.

The data describing the resulting geometry comprises circa 15 gigabyte of file-size without any redundancies. A voxel-based algorithm transforms the mesh into a volumetric model [5] in the resolution of over 8 billion voxels. This algorithm allows control over the thickness and local massiveness in accordance with structural considerations of weight and stability. It also permits the segmentation into printable components and provides an accurate detailing of the connections in three dimensions.

4.2 Printing Stone Out of Sand

Despite its enormous potential, additive fabrication in architecture is currently used for rapid prototyping of scaled models. Most of the technologies still have limited production dimensions, high costs, and non-optimal material properties.

With the Digital Grotesque project, the authors explore the first application of additive manufacturing at an architectural scale. The authors choose sand-printing technology as the sole manufacturing process. Currently, sand-printing is mostly used to produce forms for iron casting. It uses a mixture of silicate as a base material together with a resin-based binder. Still unexploited for architectural applications, this technology offers several advantages over other 3D printing alternatives: It allows printing at architectural dimensions (current maximum size: 4.0 x 2.0 x 1.0 meters) with both a high precision (ca. 0.15mm) and a relatively low material price. Printed artifacts have similar physical properties to sandstone, and can be employed as such. The technology is also significantly faster than competing approaches: the entire Digital Grotesque room (circa 3.5 x 5.0 x 3.2 meters) can be printed within a few days.

5 Conclusion

The Digital Grotesque project presents an architecture that has only become possible through parallel developments in additive manufacturing and computational design.

On a rational side, these technologies allow for a high degree of differentiation in architecture: single building components can individually adapted to maximize their functionality in respect to their local conditions, and likewise entire architectures can be highly distinct according to their context and environment.

As a fictive narrative space, the Digital Grotesque project is less concerned with functionality than with the expressive formal potentials of these technologies. It examines new spatial experiences and sensations that these technologies enable. As such, the Digital Grotesque is a lavish, exhilarating space, full of details at the threshold of perception, waiting to be discovered. It is a manifestation of exuberance.

A Paradigm Shift. For architecture, the technologies used in the Digital Grotesque project imply a turning point. Design is less likely to be justified by costs. Design is also less likely to be determined by its constructability, as all geometries are now within reach. The defeat of the fabrication constraints that were imposed by subtractive CNC methods implies that these constraints can no longer serve as justification for simple forms. Ornament and formal expression are no longer a luxury – they are now legitimized.

With additive manufacturing's ease of fabrication, the development work for architects shifts its focus from the production to the design phase. Architects can achieve a new level of control at the scale of millimeters, and they must now find content for the new resolution. In a 1971 lecture to students, Louis Kahn stated:

> *You say to brick, "What do you want, brick?" Brick says to you, "I like an arch." If you say to brick, "Arches are expensive, and I can use a concrete lintel over an opening. What do you think of that brick?" Brick says, "I like an arch."* [7]

The question today is: What would a sand-corn like to be?

6 Outlook

Many promising further advances in additive manufacturing have recently been introduced that are waiting to be explored. One of these is a printing process that incorporates multiple materials, and allows these to be mixed freely. This makes it possible to control attributes such as local transparency, elasticity, and stability.

Another future research direction is the hybridization of the generative processes to produce not only formal geometries, but to allow for the automated incorporation of infrastructure systems such as electricity, HVAC, and water.

For sand-printing in particular, future research could better explore structural performance, and could investigate material properties regarding insulation, fire resistance, and ability to withstand moisture.

The Digital Grotesque project is composed of printed modules with up to a cubic meter of volume – as measured by the bounding box. Current fabrication technology already allows single modules of up to 8 cubic meters, with larger machines in development. Given adequate tools to transport and assemble such modules, it would be easy to increase the scale of the final structure, and transition from printing a room to printing a house appears feasible. A new exuberant architecture is within reach!

7 Illustrations

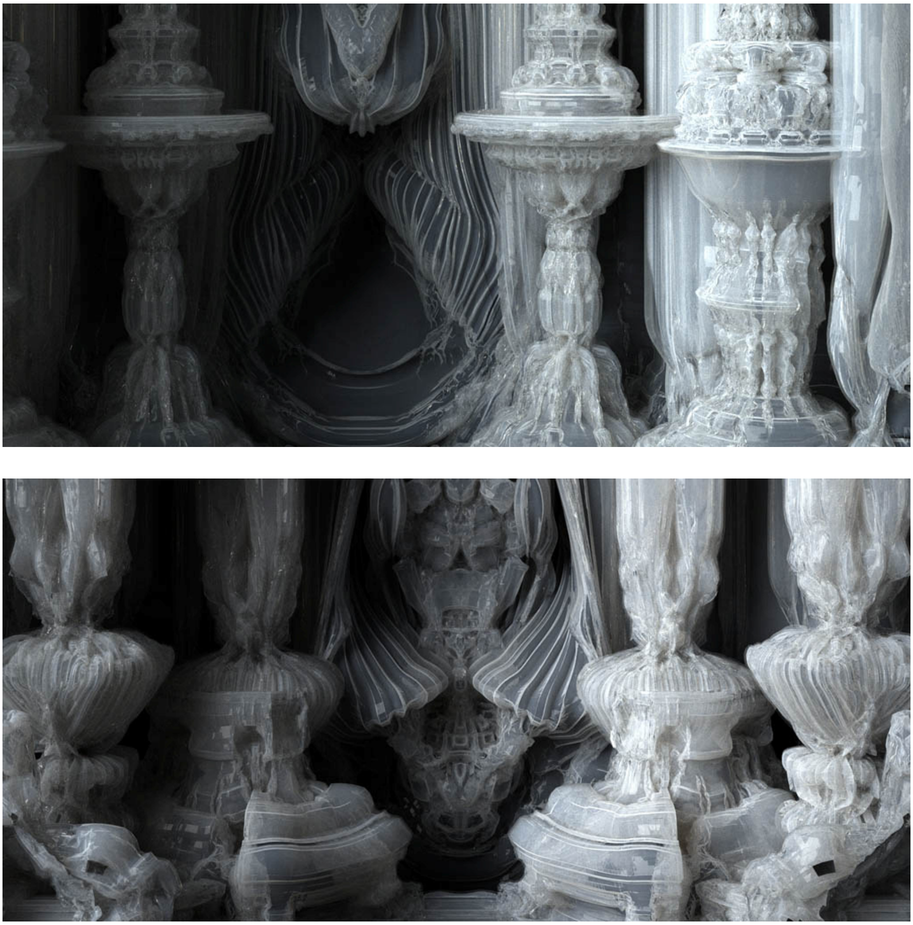

Fig. 1. Visualization of the Digital Grotesque segments, each consisting of a mesh with circa 40 million faces

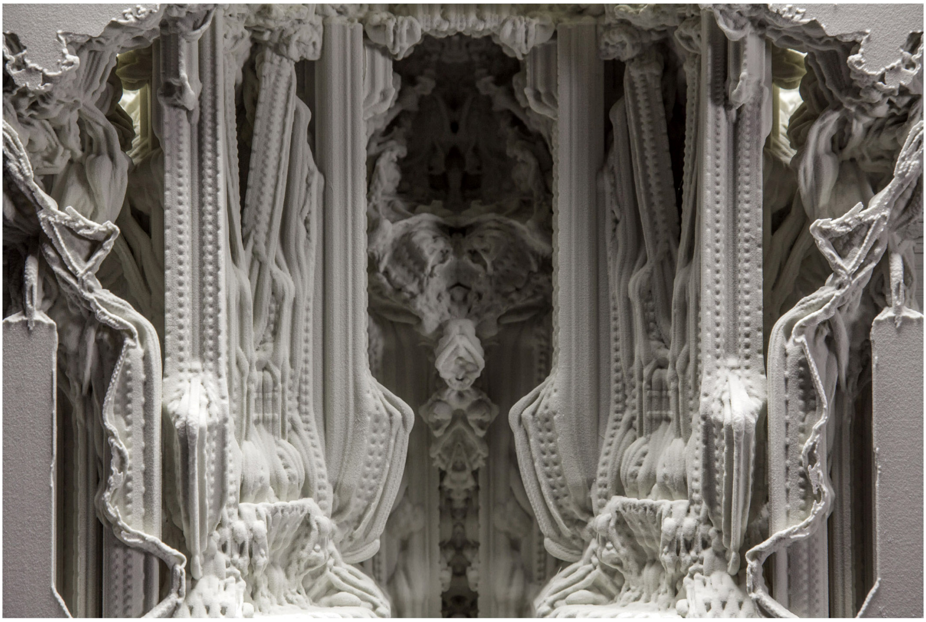

Fig. 2. Excerpt of 1:10 scale model of Digital Grotesque interior. Sandstone print.

Fig. 3. Work-in-progress: one of forty full-scale Digital Grotesque wall components. Circa 120 x 80 x 60 cm, 300kg, hollow sandstone print, untreated surface.

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