Constructive Design: Rule Discovery for 3D Printing Decomposed Large Objects

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Abstract. This paper presents a rule discovery process for designers that work with physically large 3D printed models. After a period of discovery, rules were formalized, then developed into operations and programmable functions used in a generative design system. Past examples of generative systems are built based on visual constraints leading to graphical outcomes. With the emergence of 3D printing, we introduce ideas for rule building based on physical constraints and outcomes. The decomposition rules are: curved surface slicing, freestanding attribute, interval patterning, edge mating, and pneumatic attribute. The freestanding attribute, the most novel rule, is based on Chilean anti-earthquake building techniques. This rule provides the greatest degree of structural stability to a model. We conclude with a discussion of results from the case study used to generate the set constructive rules. We believe this method of module generation, 3D Printing and assembles can support design prototyping and model manufacturing across scales.

Keywords: Decomposition, Large Objects, 3D Printing.

1 Introduction

We have experience many years of construction scale, additive manufacturing with success in machining development, however little advancement in computing [1]. Researchers have presented a variety of methods to 3D print buildings each mainly focused on print of large scale concrete structures. However, mass production of these machines is still far from becoming a reality and currently accessing a generic undersized 3D-printer is much easier. Therefore, the discovery process of rules for decomposing large scale complex objects is needed. It is our intent to explore which rules produce successful decomposing results. Decomposition rules enable 3D-printing of such objects by smaller pieces. Our research formalizes a set of rules for decomposing large objects for the 3D print manufacturing, exploiting current widely used machines. This advancements goal is to broaden the scope of 3D printed objects, as with novel techniques is would be possible to print cars, airplanes and buildings.

How to compute the decomposition of a large complex model into sub-pieces that fit in a generic 3D printing machine, preserving the model's structural and aesthetic soundness, is the question that leads this research. As an answer, we designed a complex form and subdivided it by pieces. This process allowed us to test different decomposition criteria, and to evaluate those criteria iteratively. We formalized such rules as a generative design system; in order to develop a generalizable method. We produced eight 3D-printed powder models that embody the evolution of the work.

Fig. 1. Assembly of final model

2 Related Work

Recent interest in creating large 3D printed objects in concrete by using digital fabrication can be found in Martin's work [7]. Garcia and Retsin have sought to increase the scale of printed objects by extruding plastic, printing large layers with the material. In both cases the printers do not have a bed, but rather work as independent devices, therefore the size does not depend of the device's size [4].

Past examples of large scale objects are the Larry Sass's exhibition at the Museum of Modern Art in New York, in 2008, 'Home Delivery, Fabricating the Modern Dwelling'. This house was produced by computing the subdivision of every constructive element in a board that could be assembled by interlocking.[1] Notwithstanding this example was built with lasercut plywood; the interlocking feature is highly well developed and constitutes an example for the presented system.

Prevost et al. have optimized internal mass of 3D printed objects by making those designs hollow in some areas and solid in others [8]. By these operations the researchers have tested the object's internal balance. In our research, as a secondary improvement, we follow the same idea and reinforce the structure by thickening specific zones. In other developments, using structural analysis, Telea and Jalba have developed a '*robust method for thin region detection based on distance'* [10]. This work revolves around the same idea that existent partitioning software use, as it will

[1] Museum of Modern Art | MoMA. (n.d.). Retrieved February 14, 2017, from https://www.moma.org/explore/multimedia/audios/80/450

be explained later. Umetani and Schmidt [10] have developed a framework for detecting weakness in 3D model for printing optimization, complementing Telea and Jalba's work. Zhou et al have analyzed the geometry of the objects to determine the worst case loads in the structure of the model [13]. This approach is of interest because it is focused on the object's geometry for determining the loads.

One example of an existent digital tool that can subdivide large complex models is Autodesk's 3DPrintTech Software (www.apps.autodesk.com: Nov 2015). This tool determines how to split an object into as few boxes as possible that can fit inside a generic 3D-printer machine. However, 3DPrintTech does not take into account fragile sections of the model; it makes straight cuts, and the modules do not interlock. Linjie Luo et al. present "Chopper" software that partitions using a search algorithm, developing such system one step further from 3DPrintTech [6]. The algorithm finds fragile areas of the model and starts splitting from there. This is a remarkable tool; yet, it slices the shapes with straight cuts only, producing disjointed rebuilt models. A newly paper published by Song et al. have presented the development of an algorithm that subdivides 3D models in cubes, as a voxelization, and afterwards the algorithm interleaves the blocks [9]. We had access to this paper after the development of the research presented in this paper. Song et al. research project makes a wonderful progress in developing the interlocking system based in the "Chopper" idea. Unlike these projects that work with full filled volume models, our approach works with shallow shapes because this method uses significantly less material. The “Choper” cannot successfully subdivide the geometry presented in this paper. Our research project is also based on the work of Linjie Luo et al. and takes one step forward their development by finding a method to increase the stability of the structure [6].

In addition, the “embodied problems” that 3D printing produces, have been scarcely addressed in previous research. By these problems we refer to the factors that emerge when assembling the object from which the sub-pieces were computed from. Often, the assembly process is obstructed because is not possible to operate with our hands over the model, to hold de pieces together or to scaffold a side of the object. For our research process we considered these issues and addressed them with design.

Fig. 2. In this image is possible to observe which pieces present the freestanding attribute that will be described in detail in the following section

3 Overview

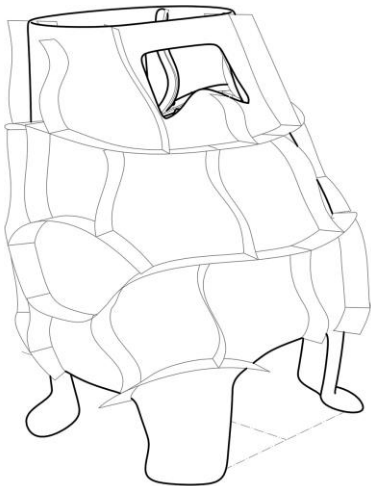

Fig. 3. Final model shape and planar outline of decomposition pattern

Our main research question consists of: How can one compute the subdivision of a large complex model into parts or modules that fit in a generic 3D-printing machine, preserving the model's structural strength and improving its aesthetic soundness? When computing the subdivision, the following question emerges: How to start subdividing the model? As previous work have demonstrated, salient and special parts of the model are required to be whole pieces and therefore such zones stand as a starting point for splitting. What shape should the modules have in order to achieve a more stable assembly? How can gravity be used, addressing compression stress to favor the structure, and minimizing shear stress in the connection zones?

This research project uses a hollow shape, emulating a chair at a fourth of its scale, constituting the "chair volume." The chair volume conserves the finishing elements of a common chair such as the legs and a handle. The hypothesis tested is: parts with curved edges, freestanding attributes, and interlocking assembly are structurally and aesthetically sound. As was stated before, the aim of the research is to find a system, a method, to compute the decomposition of large complex objects into pieces, modules that fit in a generic 3D printer, enabling the 3D-printing of such objects. Current 3D-printers are underexploited, limited to producing only small objects. Current methods to subdivide large objects are a valuable advance; however, these methods are often based in graphical results.

Powder 3D-printing machines can produce elaborated shapes. Consequently, the module's geometry is designed exploiting the machine's capability to handle complexity when depositing layers of powder. We, as designers, decide and evaluate every step of the iterative process, by finding the required rules and then applying them recursively. Our approach and selected tools focus on the geometrical shape, in order to control structural behavior and formal expression first, and generate decomposition criteria that is generalizable.

In another line of inquiry, related to Continuous Designing, in terms of open source design / production system, if this and other methods promote and make accessible the printing of large functional objects by pieces, perhaps 3D-printing will become massive, enabling many people to produce objects by their own means. If numerous people gain these skills, reaching a reality in which many people are makers, these types of enterprises could contribute to creating a 'distributed mode of actions and responses' [12]. Consequently, the following question arises: How is it possible to make this method accessible and simple to apply? Our system relates to open source/production system by enabling designers to understand how to decompose complex geometries to be 3D printed by pieces. Instead of generating a tool that would limit the variety of models that could be subdivided, we focused on designing principles that can be adapted by a designer to almost any geometry. Generic 3D modeling software can be used to produce this decomposition. Our ambition is that this method can be done using any 3D-modeling software, including free and open source software; therefore making it accessible for a large public.

Generative design approach guides this research project: understanding design as a process capable of being interpreted in a system of rules that can be used to produce new designs. An open iterative process leads to the final result, going back and forth when applying the proposed features and avoiding the constraints of a sequential process. Visual expression and tactile information acquire predominance for making decisions. The stance of our research is to focus on visual, structural and material information for the discovery of constructive rules.

4 Rule Discovery

4.1 Process

Our goal is the discovery of *constructive rules* for a generative design system to be used for decomposing a shape into smaller elements/modules ready for 3D Printing and manual assembly. Unlike traditional decomposition systems that work with visually based rules, constructive rule generation is governed by laws based on structure, resistance, and how we think-manufacture objects with our hands. We present our method of rule discovery through geometric modeling and 3D printing in five-steps. The ultimate goal is shape preservation after the components have been assembled. Here, our constructive rules were discovered through iterative modeling, 3D printing as a way of observing assembly behavior and redesign to manage errors. Any variation in the physical model from the virtual model is defined as an error. A selection of five key models is shown in Fig. 3. The final model is an abstract hollow shape composed by light pieces. This model was an easy to assembly set of contoured sub-shapes with three dimensional freestanding properties.

Fig. 4. Sample of models used to discover modulation operations

4.2 Step 1: Curved surface slicing

A previous method to decompose a shape into smaller puzzle pieces, with joineries decomposed in large curved shapes [14]. In this case a tiling pattern was created by dividing the initial shape evenly horizontal and vertical (fig 3a). Our current approach uses spline curves for the initial decomposition of shapes into tiles as a way to assume fitting, reduce assembly errors, and reinforce the structure. (fig 3b). Spline curves create a unique connection between tiled elements, distributing some of the\structural loading across neighboring modules. As the shape is decomposed it is relevant to maintain its structural properties as a whole. Spline curves engage geometrically and structurally the total of the final shape. Unique parts aid in organizing the direction and sequence of the assembly. In this case, the model is assembled from bottom to top and therefore the modules must follow that sequence.

Fig. 5. Prior study, the decomposition of an initial shape using straight cuts. Current study using spline curves to decompose the initial shape.

4.3 Step 2: Freestanding Attribute

Adobe anti-earthquake construction techniques are the source of the most original application of our method for 3D-printing large objects by pieces; the freestanding attribute. Adobe walls must be designed to be freestanding, in order to resist earthquakes. In order to satisfy this condition, walls must be shaped as “L”, "X" or “T” figures in plan. These figures resist horizontal structural efforts in every direction. Fig. 10 is part of the book "Basic Construction Course" written by Prof. Euclides Guzman [5]. This book is used to teach architecture undergrads construction and structural resistance in Chile. Chile is one of the most seismic countries in the world, and adobe construction techniques have proven to be a successful measure to preserve these fragile buildings.

The model of the presented research project was decomposed checking that most of the modules have 3D-dimensionality. The pieces were defined using curved slicing for the edges and seeking to be spatially curved in more than one direction, similarly to adobe walls. This rule builds on previous rule. Thus, by incorporating the concept of decomposing a shape into pieces that have freestanding attribute, the final artifact gains a greater structural resistance.

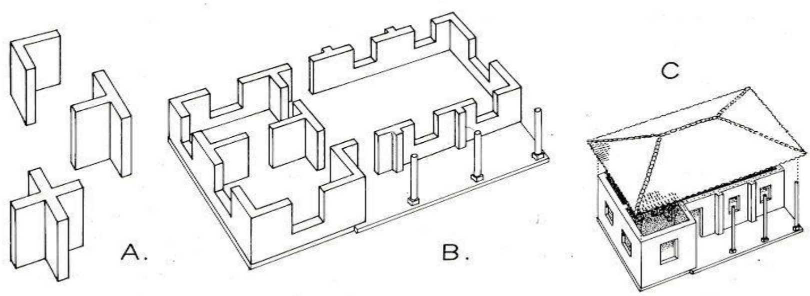

Fig. 6. Chilean adobe anti-earthquake construction techniques. Image from "Basic Construction Course" by Prof. Euclides Guzman [5]

4.4 Step 3: Interval Patterning

A third method is used to increase the strength of connections between modules is by staggering the link between rows, or the creation of a brick bonding patterning (fig 5). This is an obvious system of tile assembly (brick bonding), however the challenge is computing such a pattern in particular at the bottom and top of the shape. The brick pattern prevents the shape from vertical separation. The challenge in interval patterning is computing seam location, seam variation and alignment.

Fig. 7. Interval patterning

4.5 Step 4: Edge Mating

A fourth attempt at modeling, printing and assembly of modules resulted in parts that assembled out of plane. Applying convex and concave features at the edges of each module provided a seat and sustained assembly after many courses of modules. The challenge here was sorting of profile edges between modules. Spline curve edge of each module provided a starting point for profile generation (Fig 6). A convex, concave was a hard coded profile applied to spline curves *sP-X*.

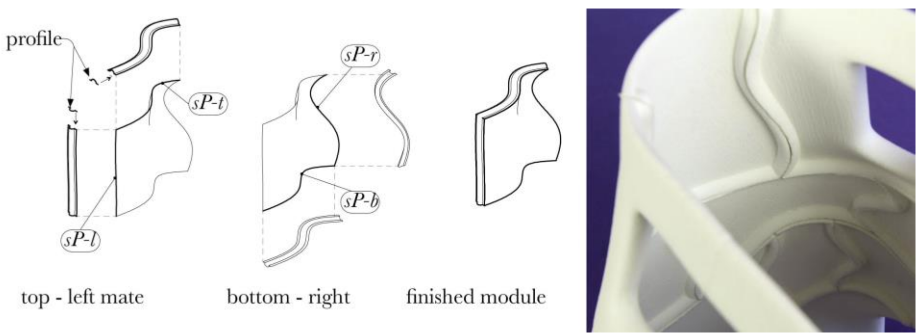

Fig. 8. Finished mating geometry and reduction in weight through pneumatic modeling

4.1 Step 5: Pneumatics

Finally, we developed a system to perforate each of the modules, making them lighter and generating an aesthetic effect. We were inspired by topological mass optimization, in which the surplus mass is removed, leaving the parts of the volume that respond to structural effort. We followed the principle of skeletal pneumatics, which in biological terms, refers to hollow bone structures found in birds. The perforations were made using 3D splines, and following grid geometry.

4.2 Assembly

The assembly strategy consisted of defining a series of rings, starting from the lower part of the model and ascending to its top. Each of the rings edges were defined by splines, in the same way that each of the models was in the curved slicing step. The spline curved edges facilitated the fit between neighboring rings. Models were assembled manually using a small amount of tacky white glue. The five operations used to form each element resulted in an easy to assemble artifact.

Fig. 9. Assembly process

5 Results

How to decompose large complex models into parts that can be printed with a generic 3D-printing machine is the question that leads the development of the discovery process and the produced models. In the presented research project we developed a method in an iterative process of discovery and formalization of rules that can be used to decompose a shape into modules. Overall, there was a significant structural stability increase in the final 3D-printed model. In parallel, there was the development of an aesthetics that reflects the process that was taken to produce the geometry of the model. In our opinion this weighted aesthetics produces attractive objects.

The implementation of the *curved surface slicing* rule proved to provide increased efficacy for the assembly process. It was possible to observe that the pieces were more solidly joined together. The discovery process derived significant insight about how to decompose a complex geometry into pieces. At the final stage we used a model with straight cuts as a control model for the *curved surface slicing* feature. The comparison between these models allowed us to observe the improvements achieved by our method. In further steps the structural resistance of the decomposed and not decomposed models can be compared in order to test their structural resistance. Nevertheless, it is possible to observe in the physical model that both present similar conditions.

The *freestanding attribute* rule provided structural autonomy to the model, fostering the production of self-supporting objects. The freestanding attribute increased model strength against gravity. The *interval patterning* made the assembly process more efficient. As a result of the implementation of this feature, we were able to easily assemble pieces in weak places, such as on the legs of the model. *Edge mating* rule increased the contact surface between pieces. Correspondingly, the mass projections form a secondary structural network composed by nerves inside the models, which could also be manipulated in further research. Finally the *pneumatics* feature reduced the weight of the pieces and improved aesthetics final object. This step also improved the assembly process in an unexpected way; the previous model to the final one, did not have perforations and because of the weight of the modules the pieces did not join accurately. After the pneumatics rule was performed, the link between neighboring modules improved significantly. Further, the discovered rules present an interesting and particular aesthetics that express the criteria and process behind the design.

Fig. 10. Detail of the structural nerves network inside the models

The validity of our proposal lies in the fact that we generated a sufficiently complex first model to be subdivided and rebuilt. Decomposing the geometry of the model into valid modules presented a difficult challenge. In addition, powder 3D-printing is one of the most fragile 3D-printing technologies, and therefore our process faced the difficulty of providing structural soundness through the design. The reliability of the process lies in the extensive series of models that we produced to test and iterate our ideas. The final model was decomposed applying the discovered rules, and with this process we increased its strength, stability and aesthetics. The model that we produced to test our process is sufficiently complex to validate the idea that the discovered rules are applicable to other designs.

6 Discussion

From the rule discovery process we identified and formalized rules and produced a generative design system for decomposing a complex shape into modules for 3D Printing and manual assembly. The formalization of these rules implies that the hidden potential of currently under used 3D printers can be exploited for 3D-printing large objects by pieces. Consequently, our project contributes to the enterprise of automating the production of large 3D pieces, as the rules can be used as parameters of a manufacturing sequence. In addition, our method is a generative design system that is generalizable to a wide range of objects. As stated in the overview, our goal is to present principles or steps to be adapted by designers for decomposing almost any complex geometry, in order to contribute to open-source design/ production systems.

Previous decomposition rule systems did not include the majority of the construction rules presented on this paper. In our prior experience we subdivided complex shapes with a continuous grid, without curved surface sliced edges, freestanding attribute or interval patterning. In those cases the joints between neighboring modules received a considerable load, producing a high level of shear stress. The new method solved those problems and introduced further advancements. The transfer of the *freestanding attribute* from adobe anti-earthquake construction techniques is to the extent of our knowledge, an idea without precedents. It is relevant to emphasize the importance of rescuing principles, derived from obsolete construction systems, to be used within the processes of digital manufacture.

One limitation of the proposed study is that we only explored five rules for the development of our generative design system, when in fact there might be several other techniques that are significant and useful. For example, it is possible to observe that the thickness and mass of the modules is an important factor to structure the 3D-printed model. Therefore, the mass of each piece can be designed with higher detail. Further, due to time constraints, we produced the presented eight models and determined that a real life model size will be part of following studies. Additive technologies present the challenge of structure and scale, addressed by this paper in a discovery process. Weak instances of the model were discarded by visual and tactile inspection, evaluating the two main factors of additive printing; structure and scale. Our models are a quarter of its real scale, allowing us to carry out these analyses. Nevertheless, we 3D printed pieces in one to one scale to evaluate their strength. Real scale pieces conserve strength characteristics. In further studies, structural and scale improvements will be measured with quantifiable methods.

Finally, in the future our proposed method can be used for 3D-printing buildings. Parts designed with the rules presented in this paper function as pre-fabricated construction elements to be assembled into an architectural object. In further research steps we intend to print real life scale model, and develop a script following the method. Different materials provide different constrains. It is of interest to test our generative design system with other materials such as concrete, ABS and PLA. Notwithstanding the impossibility knowing a priori, it is possible to speculate that concrete would behave similarly to powder, and that plastic would present a new elasticity component to be handled by the design. Nevertheless, working with the constraints of powder 3D-printing challenged our techniques even more, proving our rules useful and significant for digital fabrication practice in general.

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