Applying Generative Systems to Product Design

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Abstract

Generative Design provides multiple benefits to the development of new products. First is the creation of intricate patterns that resemble natural systems, moving away from geometric shapes typical of mechanical design. Second is the automation of processes where computers perform complex and repetitive tasks that would be too hard or tedious for humans to do. The opportunities that automation provides is frequently considered the main benefit of generative design in the creation of new products, buildings and systems. In both of these approaches, the output that computers generate is driven primarily by a designer's vision that already has a general idea of how the result might look like. A new approach for generative design by software company Autodesk allows designers to define goals and criteria for functional CAD designs, and then having a program generate iterations of potential solutions. This process presents a radical shift where the computer is not just facilitating the ideas of the designer but rather designing itself. While designers still are in charge of the process, deciding which solutions are suitable for further refinement and implementation, the relationship between human and machine becomes collaborative.

This paper explores the concepts described above and it shares the Author's design explorations where both approaches for generative design are used in product design. Examples include products using Voronoi patterns and procedural networks where the physical appearance of the product is strikingly intricate and appealing, while the physical attributes of the product are not necessarily improved. Other examples illustrate the application of generative design structures created freely by the computer, following only set goals for supporting weight loads at given points. This process results in unique structures that are lightweight and strong but might also have a polarizing appearance for specific product applications. These examples will enable discussion on how designers will continue to integrate automation and generative systems into their process as technology continues to develop.

1. Introduction

Generative systems have been long used by various civilizations throughout history. Examples of geometric studies related to astronomy and the arts are found in ancient Greece. Islamic art is perhaps the best examples of how humans use geometry to understand the relationships between humans, nature and the divine [1]. The use of computers in the 1960's to generate complex geometries was the origin for generative art [2]. A couple of decades later its use expanded to in Architecture, Engineering and Construction (AEC) industry, leading to what is known today as generative design [3]. As digital computing has become prevalent in our society, automation is now a key component for generating complex solutions such as the ones in which generative design is based. Automation reduces the burden of performing repetitive tasks, allowing people to focus their energy and intellect into more meaningful activities that improve quality of life. The benefit of automation goes beyond just performing repetitive tasks, opening the door to achieving complex tasks that would be impossible for humans to perform by themselves.

Generative Design is a type of artificial intelligence that develops unique shape grammars based on three types of information: a set of rules for rules, a way for shapes to develop, and goals to be meet by the resulting shapes [4]. Goals can include factors such as mass, strength, or manufacturing processes. Generative design provides several benefits, including the development of shapes with unique geometries that are aligned to their context and improvement of mechanical performance [5].

Industrial design is embracing the principles of generative design, first focusing on the unique aesthetic style that comes from nature-inspired organic shapes. Designers have also been able to integrate automation into their process, which provides a streamlined workflow and intricate geometries with the potential of being efficient and resilient, providing advantages in mechanical performance and use of materials [6]. The integration of generative design can happen either as a tool that executes the vision that designers have for a given product, or as the creation of novel forms that meet goals set by design problems.

This paper provides insights of the workflows describes earlier, and uses design explorations developed by the Author, to illustrate the use of different types of generative design strategies in industrial design. These workflows are just a few of many ways of integrating generative design into creative processes for product development. As designers become more familiar with these workflows, generative design will consolidate itself as a key component of design process, that helps in developing solutions that are efficient, visually engaging, and better aligned with natural systems.

2. Generative systems from tools to collaborators

Designers benefit greatly from generative design and its ability to handle large and complex amounts of calculations. While designers need to understand the basic relations that systems need to have in order to create a particular pattern, they do not need to have full knowledge of how to perform these calculations in their entirety. By providing basic sets of rules and objectives, computers are able to turn them into algorithms that create 3D shape grammars [7]. There exists a wide variety of software programs that perform these tasks, and two of the most popular today for AEC and industrial design are Grasshopper and Dynamo. These programs work on brackets of information that generative complex calculations. Designers need to have the knowledge necessary to input commands to the program, and also to program them in with the right commands so that the results are successful. Once this is accomplished, the hard work occurs “under the hood” and the computer takes care of performing the tasks that have been assigned to it. The key element in all of these benefits is that generative design is a powerful tool, that complements and enhances the capabilities that designers have to create complex systems.

Generally speaking, generative design can be used in product development in two ways: one is as a tool that performs calculations in order to obtain a preconceived solution that the designer needs. In this case automation focuses as a tool that optimizes the creative process. The second way in which generative design can be used is by providing it with goals and parameters that a given solution needs to have, and letting computers generate solutions autonomously, without any preconceived notion of how a solution might look like.

This process elevates the role of the computer from just a tool that performs tasks to an active participant in the creative process. The computer is now more than a tool for the designer; it is a collaborator that provides solutions that would had been unimaginable otherwise. Generative design becomes a source of creativity that is evocative and adaptive [8]. Its evocative character is based in its ability to evoke new thinking and to display new ways of solving problems. Its adaptive character is shown in its ability to generate solutions in a wide variety of applications.

3. Generative methods in product design

The are several types of generative systems, all of which provide varied workflows and resulting shapes. Generative art is an excellent starting point to analyze and understand how generative systems and grammars work, and the shapes that they produce. There are five main categories of generative systems: Shape Grammars, L-Systems, Cellular Automata, Swarm Intelligence, and Generic Algorithms [9,10]. Each one of these categories contain variations within as designers and artists experiment with algorithms and geometries in novel ways. In this paper, three types of generative systems will be analyzed and described: Voronoi patterns, procedural networks, and generative structures' software. These three systems have been selected for the interesting way in which shapes are created as well as because of how they complement the traditional process that industrial designers use to develop new products. The goal of this analysis is to encourage designers to integrate generative systems into their current workflow, or to expand their current use with new approaches. For each of these methods described within, examples of products designed by the Author will be used to illustrate how design process and CAD software can be used.

3.1. Voronoi patterns

Voronoi patters are some of the most common generative systems used in product design. They are subdivisions applied to a plane or surface that sit at the same distance from a specific point [11]. Voronoi patters are quite popular in industrial design as they can be created with just a few, straight-forward parameters: area to be covered by the pattern, distance between cells, and point of origin, called seed. There are several online applications that automatically generate Voronoi patterns and several CAD programs also include this tool either as a native feature or as an add-on extension. Voronoi patterns are visually engaging, with the cells distributed in a fluid order. They are commonly compared to the interior mesh of bones, and in general they highlight organic, intricate nature that generative design is associated with. A key characteristic of Voronoi patterns is that they are based on pre-existing designs. There is no need to learn complex algorithms in order to generate shapes. This setup provides designers with ample control of the design process, which takes a solid body and cores it out with the Voronoi pattern, similar to how a filter is applied to a 2D image (See Figure 1).

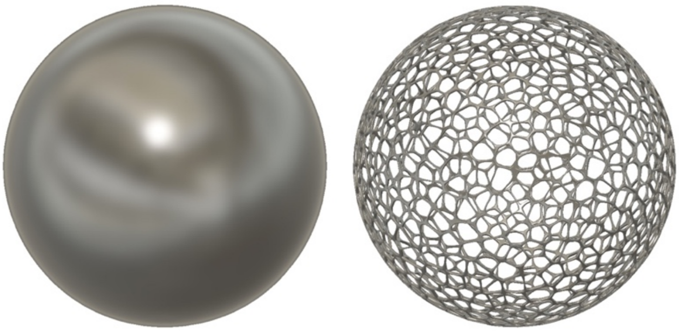

Figure 1. *Comparison of a solid body and its Voronoi-based version.*

Along with their visual appeal, Voronoi patterns can generate forms that are stronger and lighter than their solid versions. By turning solid surfaces into meshes, the geometry of the bodies is filled with more edges, which provides more strength and stability. The mesh at the same time removes surface area, which depending on the manufacturing process, can reduce the amount of material needed substantially. When 3D printing the bodies shown in Figure 1, the Voronoi version would use 40% less material than the solid version. A potential trade-off is that many shapes that would be fabricated with traditional manufacturing processes would not be able to be created if they have a Voronoi version, due to the more complex geometry. For many Voronoi-based shapes, particularly if they are non-linear, the only fabrication method possible will be additive manufacturing, which could increase fabrication time and cost.

An example of a Voronoi pattern in product design is an electric bass guitar (See Figure 2). The bass guitar was originally designed as a solid shape. After the shape was completed, the main body of the instrument was divided into sections. The outer sections were turned into a Voronoi mesh using an online shape creator called Voronator.com. The sections closer to the electronic components remained solid, in order to not affect the functionality of the base as well as to provide enough solid material for the bass to sound well and avoid any feedback. A similar exercise of keeping solid sections was applied to areas that connected with the neck of the bass guitar. The result is an instrument with a strong visual aesthetic and that is significantly lighter than its solid version.

Figure 2. *Electric bass guitar with Voronoi body.*

The same workflow was used to create the stool in Figure 3, which combines solid sections with Voronoi-meshes. This allowed for more control of the shape of the piece, making sure that there was a good flow and proportions all around the object. The inferior sections of the stool were meshed out with a Voronoi pattern in order to create a more interesting design. The top section of the stool remained solid, in order to make the piece more comfortable to sit on, avoiding unnecessary pressure points that could touch against the body. In this case, using the Voronoi mesh in the inferior parts of the stool adds mystery to the overall design, creating curiosity in the user, without compromising the performance and the perception of strength and stability than a seating object must deliver.

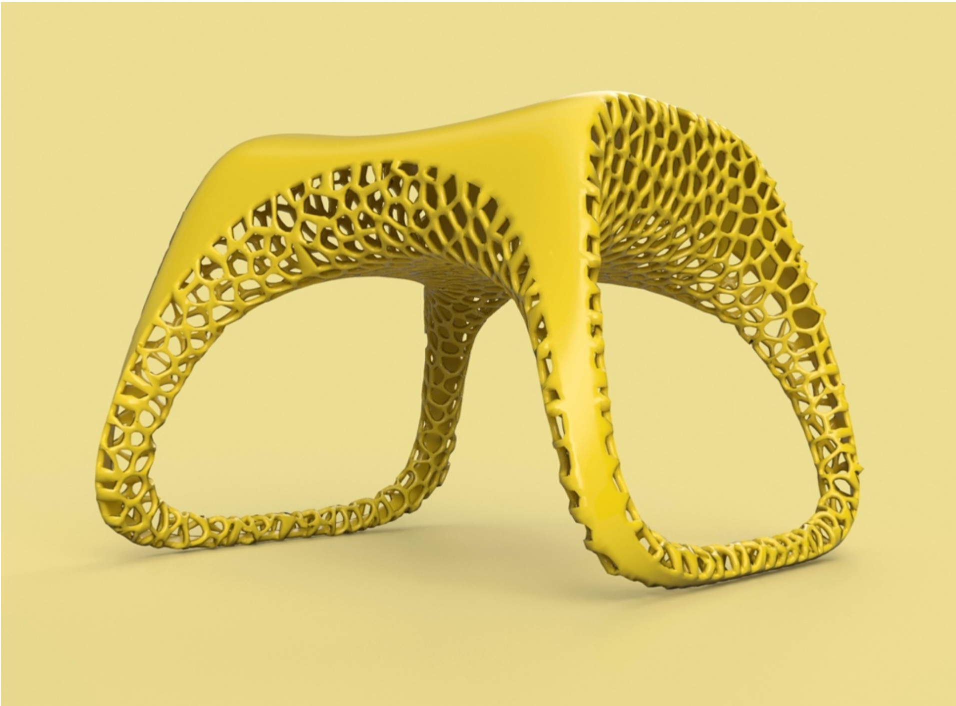

Figure 3. *Stool that combines solid and Voronoi-based sections.*

3.2. Procedural networks

Procedural networks are widely popular in Generative Art. They are based on code segments or algorithms that define physical characteristics of a CAD model [12]. The benefit that they provide is that instead of fully defining forms, textures or animations, which would require massive amounts of data, they define the coding of how these physical attributes will be generated. Procedural networks are very popular in Media and Entertainment for their ability to define the way in which body particles will move in space and be affected by external forces such as gravity, wind or other objects.

The use of procedural networks in industrial design, however, is fairly limited. A reason might be that industrial designers tend to design static bodies that only move when being used by/for the user. In order to explore the benefits of procedural networks in product design, a series of models were developed in MASH, a procedural plugin part of Autodesk Maya. MASH quickly provides exciting and powerful results for complex geometries, ranging from random patterns to more controlled progressions. Patterns created in MASH can be exported in FBX format and imported in most CAD programs. The use of this workflow is innovative by itself as CAD programs like Fusion 360, Solidworks, Inventor, Rhinoceros, etc., which are common for product design applications, do not provide simple ways of creating complex shape patterns such as procedural networks. A limitation of the process to keep in mind is that Maya generates polygon-based geometry. This type of geometry is not parametric and depending on how complex it is, might result in a very dense model to import into CAD programs because of all of its vertices and edges.

Figure 4 shows an application of procedural networks that were developed in MASH and then imported into Fusion 360. A grid of rectangles influenced by a noise signal, which creates a random effect with a strong visual appeal. This effect is applied to a block of translucent material, such as glass or acrylic. When applying light to the translucent material, this creates a very interesting lamp, that takes advantage of how the light refracts at different levels along the edges of the structure.

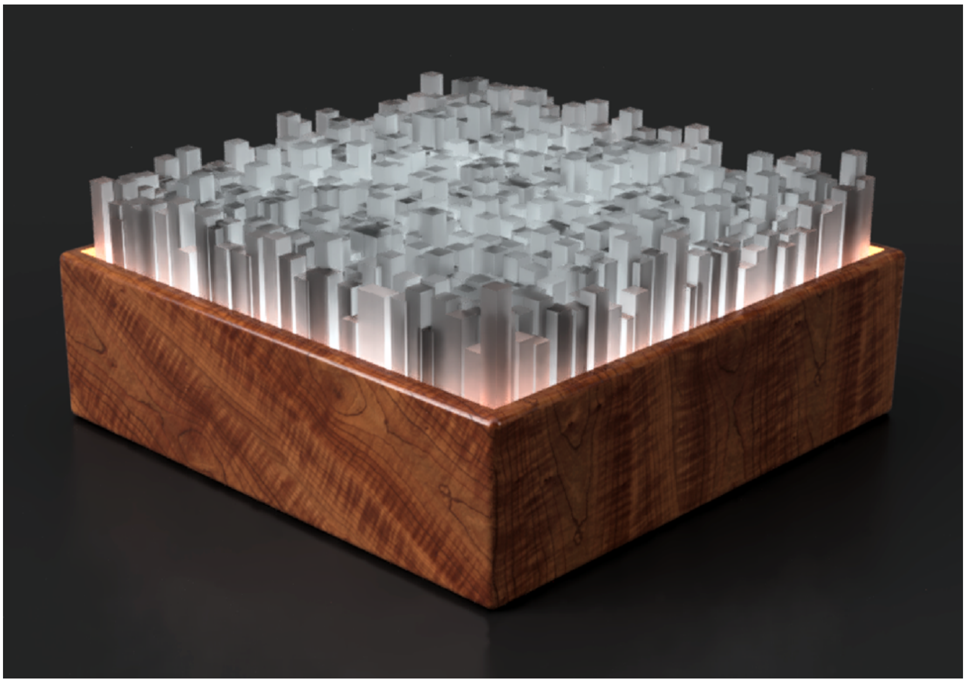

Figure 4. *Table lamp with shade using a grid of boxes with a random pattern.*

The use of procedural networks is applied in a unique way that benefits industrial design. Procedural software such as Maya MASH, was developed for animations. This implies time-based movement that makes the patterns move and transition between positions. For their use in products, designers take a “snapshot” of one of the frames in the sequence and use that to define a static shape for an object. This is one of many applications, of course. There can be very exciting cases in which products have articulated parts and they can take further advantage of the procedural sequences, envisioning a wide range of movement. There are even insightful experimentations on using motion time-based procedural modelling to create complex bodies from their steps as they move through space and time [13].

3.3. Generative structures

Generative Design has captured the imagination of product designers for decades. Up until recently, most designers who integrated nature-based patterns into their workflow did it in a way that was fairly manual. This means that they would generate individual shapes multiply them in patterns with incremental variations of shape, position or scale, in order to achieve an organic transitional flow. Programming software allows for users to develop sets of rules and behaviors that turn into interesting shape grammars. The high knowledge needed for successful programming has limited its adoption across design fields but programs such Grasshopper and Dynamo have found effective ways for making programming more accessible. What makes programs like these better, is that the programming is visual, based on brackets, connectors and widgets, making the generative system easier to understand [14]. Additionally, these programs are easily connected to other CAD applications used for design and manufacturing, making the process of design, simulation and fabrication, a lot more integrated and streamlined.

In 2018, Autodesk released their Generative Design application, which is part of Fusion 360. This tool works radically different to programs like Grasshopper or Dynamo, and it brings the process even closer to what true generative design is. Based on artificial intelligence, this program takes the set rules and goals from the user and creates large amounts of shape grammars from scratch [15]. This process is different from generative patterns such as Voronoi, as it doesn't need a pre-existing shape to base its form, and it's also different from procedural modelling, as it takes data from the user not as directions for creating shapes, but rather as a wish list of goals to be met. With the Generative Design app, the user provides data for areas or shapes that need to be preserved as well as well as obstacles that should be avoided when creating a new form. More importantly, goals are set so that the design is able to support specific loads or physical forces. Once the inputs are complete, the computer takes this information and automatically generates multiple designs, all of which solve the design problems in a unique way. The longer than the program runs, the more iterations that will be produced by the computer. The user then goes and checks on the results, which vary in form, material used, strength, and manufacturing processes, although all of them meet the basic criteria set by the user. Designers are able to pick from these solutions the ones that they feel are better for the application, and they can integrate them into their design, or use them as a base for a new iteration of generative design simulations. This process is novel in product design for several reasons:

- The creation of forms is **automated**, which is one of the key goals of generative design. This process allows for large amount of data to be processed by computers, removing the burden from the user. In many cases, processes like this are limited when run by humans, because of limited time, knowledge, or interest in performing large amounts of calculations, repetitive tasks.

- The amount of solutions that are generated by the software are virtually **unlimited**. This provides a rich foundation to designers to pick the perfect solution, instead of being able to generate only a few iterations, not knowing if they have found the right one.

- The process provides an **increased level of creativity** to the designer. The computer is able to create solutions that many times would had been inconceivable to designers, simply because human brains don't process information the same way that computers do [16]. Additionally, designers can be inspired by the results that they obtain by the software, pushing their creative process to even higher and broader levels.

- With generative design software, the computer is no longer just a passive tool that follows orders of the designer, but it becomes a **dynamic problem solver** that provides unique design solutions. This is perhaps the more substantial contribution of Generative Design to the design field. The computer becomes not only a tool for the designer but an actual collaborator.

Figure 5. *Ceiling lamp combining generative design and procedural networks.*

Figure 5 shows a ceiling lamp created in Fusion 360. What makes this lamp unique is that the actual modelling part of it is minimal, and in fact it didn't have a significant impact in the final shape. Most of the design was created by using generative tools within and outside of Fusion 360. The base of the lamp was created using the generative design tool. In this case, five points were assigned in space: one up high to define where the lamp would be hanged from, and four point that would connect the lamp to the shield. At each of this point, forces were defined in terms of weight load and moving forces to make sure that the structure would be strong enough to hold the weight of the lamp as well as external forces such as someone hitting the lamp accidentally from the side or below. A few areas were also defined as "obstacles" to make sure that the resulting shape remain within a certain envelop and didn't expand too much. The results of the simulation provided several exciting possibilities for the shape of the lamp. One of the solutions stood out because of having a very unique aesthetic that seemed to have a good balance and good potential for looking like a "lamp base". The shade of the lamp was created in Maya MASH. A simple cube was created in the workspace, and a series of procedural nodes were applied to turn the cube into a three-dimensional grid with a progressive deformation. These effects resulted in a progressive pattern that is both geometric and organic, and that creates an interesting contrast with the lamp's base. Once the shade was completed, it was imported into Fusion 360 and combined with the base and lighting fixtures as a traditional CAD assembly.

4. Conclusions

Generative design enables an exciting direction where different workflows and ways of achieving nature-inspired systems can be combined in new and unexpected ways. In the case of the lamp shown in Figure 5, the design combines two ways of creating generative systems. The shade uses procedural networks to create a dynamic pattern with an interesting flow an elegance. This approach shows a process where the designer had a general idea of the effect that the shade would have and used digital tools to achieve this effect with ease. The base of the lamp shows a completely different way of generating shapes, which was based just on goals for supporting weights and forces at specific points. As generative design continues to evolve, it integrates criteria for shape development and optimization with goals for engineering performance [17]. The result are shapes that resemble natural structures as much in the way that they look as they perform in living environments.

Generative design is becoming a key tool for industrial design, providing a wide number of benefits. The most important one is the increased capacity that automation brings to the design process, whether it is as a way of avoiding repetitive tasks that become monotonous and time consuming, or limitations to perform complex calculations. Automation is becoming a key element of industry and designers need to become familiar with it, and to make sure that it’s used in a meaningful way that enhances human productivity, rather than just replacing it. As generative design matures and becomes a common component of design process, it will be easier to find the right balance of aesthetics and performance, so that products out in the market are embraced by consumers while also providing the efficiency that natural systems have.

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