Autori
1
Sarvpriya Raj Kumar
MSc in Product Design
Sapienza Università di Roma
2
Viktor Malakuczi
Ricercatore
Sapienza Università di Roma

Titolo
Avant-garde CAD: Generative Design

Parole Chiave
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Abstract
With the advent of Additive Manufacturing (AM), it is possible to realise complex shapes and structures which would have been difficult to manufacture by conventional processes, therefore AM offers an unprecedented morphological freedom. It enables a wider diffusion of Generative Design (GD), a design approach empowered by advanced computation, allowing the designer to define initial constraints and objectives, then instruct an algorithm to generate numerous variations and optimize the design until the desired solution is achieved. The idea of generative potential was present already at the birth of Computer Aided Design (CAD) over half a century ago, but emerged mainly in the past decade through widely publicized experimental research projects both in academy and in the private sector.
In the next decade until 2030, GD is expected to spread across various industries due to advantages including optimised weight and mechanical performance, better use of raw materials, but also because it enhances the creative process by helping designers to explore and objectively evaluate many unconventional solutions in a brief timeframe. The paper starts with describing the place of GD in the evolution of CAD, then it outlines current technological directions, including topology optimisation, morphogenesis and biomimicry. Afterwards we examine how the design research community and design professionals use GD to achieve various goals, with a particular attention on transportation design (from motorbikes to spacecraft), as this field received the most GD effort so far. Finally, the article concludes by observing how the designer’s role is shifting towards being a “curator” of input data and output geometry, with the consequence that they will need to adapt their tools and their skills. This means not simply new technical knowledge but also a more flexible approach, where research and critical reflection becomes more and more important and the creative act becomes a collaborative endeavour between designer, data, environment, people and algorithms.

Testo

Introduction

The evolution of the material culture in the 2010-2020 decade was dominated by a proliferation of digital “intelligence”: in content-driven digital devices, integrated in various kinds of physical objects (Internet of Things), in sophisticated product-service systems, as well as in the tools of the design practice – even when designers tackle with purely analogue, conventional product categories. We start with the assumption that the next decade (2020-2030) will develop further all the above mentioned trends, but we focus on an evolution of the form-giving practice through a truly “digital native” attitude, through the advanced CAD tools of GD.

In the design practice, Louis Sullivan’s “form follows function” has been a returning slogan, inviting a “sober” handling of forms – sometimes countered (half-jokingly) by alternative versions such as “form follows fun”, "form follows fiction” (also name of an Alessi product line by Stefano Giovannoni) or simply by the observation that digital technology detaches function from form. On the other hand, the use of advanced computation in the design phase opens new frontiers of functional form-giving: advanced CAD tools enable a “form follows force” approach (Li, 2018) through physically realistic simulations and generative algorithms that “evolve” forms gradually, just like Darwinian natural selection does.

This approach, called Generative Design (GD), often leads to surprising results, extremely complex geometries that would be hard to imagine and even harder to draw (or model) with conventional CAD tools. Therefore, beyond its performance-enhancing potential, the evolutionary process of GD implies also a new aesthetic language, reminiscent of natural forms, but result of a design process that is fundamentally different from the “conventional” biomimicry, where a designer emulates forms of biological entities to achieve desirable functional or aesthetic outcomes. Some examples of biomimicry are the improved aerodynamics of Japanese Bullet Trains inspired by the Kingfisher bird’s beak (evolved to smoothly pierce water) or the Velcro fastener inspired by burdock seeds (evolved to cling on animal hair). By contrast, GD does not necessarily imitate already existing biological forms, but it evolves forms which often become similar to natural forms.

A step forward in the development of CAD

Following the early development of computer numerical control (CNC) starting from the 1950’s (e.g. the *Pronto* language by Patrick Hanratty in 1957), the idea of Computer Aided Design (CAD) software emerged already in the 1960’s and already then, it was meant as something more profound than a simple drawing tool. As CAD pioneer Sutherland argues, such transformation requires a profound change also in the way designers think: “an ordinary draftsman is unconcerned with the structure of his drawing material. Pen and ink or pencil and paper have no inherent structure”. Instead, according to Sutherland (1975, p. 76), the “computerized version of the design [should be] the master document from which all auxiliary information is derived.” In fact, already his experimental *Sketchpad* software was capable of Parametric Design, whereby modifying one element could trigger a modification of all related elements according to the constraints established by the designer. Such possibility has been a

driver of qualitative development because, as PTC (Pro/Engineer) founder Samuel Geisberg expressed, “The goal is to create a system that would be flexible enough to encourage the engineer to easily consider a variety of designs. And the cost of making design changes ought to be as close to zero as possible.” (Geisberg quoted in Teresko, 1993, p. 28)
After simple freeform CAD and parametric solid CAD, the 2000’s brought to a democratization of “algorithms-aided design”, as Tedeschi, Wirz and Andreani (2014) call it, thanks to new visual programming languages (Generative Components, Grasshopper, Dynamo) integrated in popular CAD packages. While John Maeda already in 2001 urged designers to learn creative programming and “design by numbers”, at least for graphics/art, for the design of physical objects this became feasible only thanks to the user-friendly approach of programming through visually connected nodes. Since that, however, “parametricism “ became a fairly popular (albeit debated) architectural stye (Patrick Schumacher, 2016), characterized by mutually adaptive elements in correlation also with outside influences, leading to differentiated components rather than repetitive modularity. As Carpo (2015) observes, advanced digital fabrication hardware and advanced parametric design software allowed architecture to go beyond the paradigm of constructing from an alphabet of pre-fabricated elements and move towards algorithms controlling dynamically each element of the design.

Generative Design: types and tools
Generative (product) Design today is a further step in the evolution of CAD, enabled by the proliferation of Artificial Intelligence. Advanced implementations rely on Machine Learning and Artificial Neural Networks which allow computers to learn how to perform “creative” tasks without programming explicitly the single tasks: the programmer/designer’s job consists in specifying the requirements and supervising the process. With GD, “the designer formalizes the constraints and objectives required of a satisfactory design in some *expert system*; and defines some *optimization system* to algorithmically satisfy these requirements. GD methods range from fully autonomous implementations that generate absolute solutions, to interactive systems that efficiently generate potential solutions for evaluation by the design team.” (Leary, 2019, p. 203). This generic definition can be branched according to different generative principles that lead to fundamentally different functional advantages and aesthetic values. Custom implementations (e.g. through Grasshopper) may operate on just about any kind of parametric geometry and the generated models can be evaluated according to a multitude of criteria. However, the last few years of development is more characterized by voxel (3D pixel) based approaches; Jackson (2019) distinguishes three types:
a) Topology optimization, where an existing piece of user defined geometry is analysed based on which material is removed from areas that do not carry significant load. It is a subtractive type of GD as it removes (virtual) material repeatedly to achieve the final result.
b) Biomimicry, where the behaviour observed in nature are mimicked. It includes replication of bacterial colony growth, bone structure evolution, as well as growth of roots and branches in trees. It is an additive type of GD as it involves growth of the virtual material.

c) Morphogenesis, where the algorithm maximises the advantage of research based on response of groups of cells to their environment. The growth of actively loaded cells is stronger whereas unloaded cells are discarded.
To practice these three types of GD, there are already various software solutions available:
- Autodesk – Fusion 360 (Implements Morphogenesis in combination with Biomimicry)
- Dassault Systemes – Functional GD (Topological Optimisation in combination with Biomimicry) and XGen (Combination of graphical visual scripting and interactive 3D-modelling
- PTC – Creo GD (Topological Optimisation in combination with Biomimicry)
- Siemens – NX GD (Topological Optimisation in combination with Biomimicry)
- MSC – Apex GD (Topological Optimisation in combination with Biomimicry)

The generative process results in a voxel-based geometry which is then converted into a faceted (mesh) geometry, which is ideal for AM, or it can be optimised for conventional mass manufacturing methods. To sum up, Jackson highlights four key characteristics of GD: it is component focused, goal-driven, constraint bound and executes autonomously.

Generative algorithms in design research

In practice, this means that designers do not define the shape directly anymore, but they collaborate with an algorithm, manage a (non) natural selection process, exert evolutionary pressure, and judge the results. Such judgement can be even shared with the users, as demonstrated with the experimental platform Endlessforms.com, which allows the evolution of 3D geometries through a web interface which takes crowdsourced user input as an evolutionary force to guide the development of abstract virtual forms (Clune and Lipson, 2011).

Research in Design has long used GD tools to achieve extremely complex, biologically inspired shapes through the simulation of biological growth; most notably MIT's Neri Oxman has experimented with the simulation of numerous growth principles (e.g. Bader et al, 2016), sometimes integrating it with real biological growth or inventing completely new ways and materials for digital manufacturing (e.g. Mogas Soldevila, Duro-Royo and Oxman, 2015). Also Italian designers have worked with the expressive potential of bio-inspired generative morphologies, such as Alessandro Zomparelli who uses it for fashion accessories.

By now, even renowned design-oriented companies have embraced GD as a valuable design tool: in 2019, Kartell have launched the A.I. chair, a collaboration between Philippe Starck and Autodesk, which uses GD optimization to achieve a lightweight chair – that is also beautiful and coherent with the personal design language of Starck himself. Weight and performance optimization is, in fact, a major driver in the development of product-focused GD. Such optimization is particularly relevant in the field of transportation: vehicles must be safe but as light as possible in order to minimize fuel consumption; therefore, many researches and industrial actors have invested in advanced experimentation. As usual with technology, high-end applications might soon transfer to various fields of the consumer market, therefore it seems timely to examine some of the most advanced experimentations in the field of transportation design.

Applications of Generative Design in transportation design

NASA | Starting from the most ambitious of our GD examples, NASA's Jet Propulsion Lab (JPL) developed a new lander which will be sent to the moons of Jupiter and Saturn for exploring life or signs of it. As with any space exploration mission, minimizing the overall weight of the spacecraft is a critical aspect, which motivated a GD research effort in collaboration with Autodesk. Optimising the lander frame using Fusion 360 GD software allowed a 35% weight reduction with respect to the original design, while the time required to carry out revisions also reduced from initial two-four months to two-four weeks (Mraz, 2018). In another project named Artemis, NASA collaborated with Jacobs Engineering to develop the next generation space suit – the first major update in the past four decades – for the 2024 moon mission. In the case of the Extravehicular Mobility Unit (xEMU), PTC's Creo GD software allowed some components to become 50% lighter, while the internal lattice structure also enabled constant heat dissipation, thus helping to maintain the temperature inside xEMU (Oberhaus, 2020).

Airbus | In the A320 aircraft a partition is used to separate the airline crew from passengers, as well as to support the structure of the airplane's frame, to which it is attached on 4 locations. GD helped to generate multiple design variants based on the algorithm of slime mold, a single celled organism by utilising Autodesk's Fusion 360 software. Each variant was carefully analysed and finally the optimal design was selected as it weighed 45% less; there was an even more dramatic improvement in terms of raw material usage, reduced by 95% thanks to the AM process used to fabricate the partition (so-called buy-to-fly ratio between material bought and material in flight). The same structural principle could be extended from the partition to the entire airplane frame; according to Airbus (2018), adopting GD in their entire product line could save 465,000 tonnes of CO_2 emissions annually.

BMW | Shifting to examples "on the ground", BMW has developed an alternative experimental frame and swingarm for the S1000RR motorcycle by using Autodesk's Fusion 360 software to render a bionic shape to both structures (Jackson, 2018). While this remains a only concept vehicle so far, it might indicate a shift in motorcycle design, where the frame has been traditionally exposed, visually "advertising" the performance advantages brought by GD. BMW, which has an extensive AM centre, has used GD also in projects aimed at serial production, such as a mounting bracket which is utilised in the retractable roof assembly of the i8 Roadster (Putre, 2018).

Buggati | The automobile company has developed the world's first eight-piston monobloc brake caliper with minimum weight and maximum stiffness in collaboration with Laser Zentrum Nord for its Chiron model. Weight has been reduced by 40% as it has changed from 4.9 Kgs of aluminium to 2.9 Kgs of titanium by AM process (Bravo, 2018). With another project they halved the weight of the world's largest hydraulic rear wing control system using Siemens NX GD software for Chiron PUR SPORT model. The structural components which assist in regulating vehicle aerodynamics are made of SLS sintered titanium, but in this case the optimal structure is achieved through a combination of different materials, as the connecting rods are made of carbon fiber (Sher, 2018).

Volkswagen | For its Type 20 concept, VW redesigned multiple parts of its 1962 classic Transporter microbus, including the steering wheel, the rear-view mirror mounts, the rims (wheels) and the support structure for the rear bench inside the vehicle (Deplazes, 2019). The GD process (powered by Fusion 360) was used across the vehicle for purposes that clearly go beyond performance and might belong to communication design as much as to engineering: in its current state, GD can be used to create a rhetorical visual language in order to convey and reinforce a company's identity as an innovative enterprise.

Il Gladiatore | With the last of the examples, we report on a direct experience with GD. One of the authors, Sarvpriya Raj has developed a chassis for a racing motorcycle for his MSc thesis in Product Design. Here, the initial structure developed was fed into the software along with the parameters like the forces which act on it, the manufacturing process and the material used. Following the principle of topological optimisation, the Functional GD of Dassault Systemes software came up with optimised solutions applying the right amount of material to the areas undergoing deformation and stress, thus reducing the mass by 25%, from 8 to 6 kgs. These structures were refined to generate the final structure to be produced by AM process. The other major advantage was 'part consolidation' i.e. the reduction in the number of parts as a single structure is created instead of multiple parts which join together to form the chassis, thus helping to avoid the problems arising out of limit, fits and tolerance between multiple parts.

Conclusion

The above examples illustrate that GD-driven topology optimization, biomimicry and morphogenesis can help to generate and explore previously inconceivable geometries that not only improve the product's performance (e.g. weight), but also imply a new visual language. To utilise GD's full potential, ideally AM should be used which, although still has limitations in terms of production speed and cost, it also helps to minimize raw material usage as well as harmful manufacturing by-products, therefore GD can be viewed as a design practice to help the transition towards a sustainable material culture. To practice GD, the designer needs to start from a comprehensive set of information regarding which are the areas that are critical for the function and performance; which sections of the part are undergoing high stresses and which areas are free of them; what are the values of loads and forces that act on the part; what is the manufacturing process which will be used to manufacture the product.

As 3D forms are generated automatically and the designer becomes a "curator" of input data and output geometry, design iterations become much faster, thus saving a significant amount of development time. In the future we might expect a further expansion of AI in design, for example in the early conceptual phase: a speculative design video by Foster (2016, for Google X) hypothesises an AI that gathers information about individual behaviour to construct a deep "understanding" about the users in order to help them to achieve their long-term goals of personal growth through generatively designed products. While this might be a longer term vision, already by 2030 we can expect a new niche of Generative Design expert becoming a fairly recognised and widely used professional figure. To do so, however, designers will need to adapt their tools and their skills, not simply with new technical knowledge but also with a more flexible approach, where research and critical reflection becomes more and more important compared to conventional geometry definition, and the creative act becomes a collaborative endeavour between designer, data, environment, people and algorithms.

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