Title:
Applications of Generative Computer-Aided Design

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Introduction:
The conventional Computer-Aided Design (CAD) has replaced manual drafting on a physical canvas (drawing board) with computer graphics in digital storage. It is largely an extension of human's hand. Recent development in CAD and computer graphics have shown a promising new trend, in which numerical algorithms are constructed as an extension of human's brain. This trend has been given a number of names, such as Generative Design [5,7], Generative CAD [3], and Generative Engineering Design [5,6]. The main idea lies in the word Generative, which captures the nature of these numerical algorithms.

In early explorations of generative methods [5,7], numerical algorithms are used to test a variety of design options based on a set of user-specified system parameters. "Generative" refers to the process of automatically generating different design options. Since 2006, in the computer graphics field, research has been focused on numerical algorithms that can produce fabrication data of parts of a 3D object [2,3]. "Generative" refers to the process of automatic part generation, and assembly instructions.

Generative Engineering Design (GED) usually means application of Generative CAD within industry applications. In a wider context, GED is a part of Knowledge Based Engineering and some workplaces describe it as Generative Modelling using advanced tools of product development [6]. CAD is here considered not only as following tools after physical canvas, but it is becoming more and more adapted to state-of-the-art fields with their specific demands. In [1] authors present the research in product development, which needs to bridge the gap between the unstructured, disruptive ideation process that the designer is comfortable with, and the structured way of storing and indexing knowledge for retrieval through a computer.

Background of Generative CAD:
Even though dozens of years ago, CAD was considered as subsequent tool after a classic physical canvas or a drawing board, there were situations within which designer was limited by modelling possibilities of particular CAD program. However, nowadays programs enable almost any complexity of design, what led to progressive advanced CAD. Generally, there are several fields suitable for application of Generative CAD, e.g. architecture, product styling, civil engineering, product engineering design. In following sections, we describe various applications of Generative CAD, which the authors' workplaces focus on.

Generative Joinery System:
In this section, we describe a generative joinery system that is produced by novel numerical algorithms. The system is able to produce two types of joinery: finger joint [6] and bevel joint. The objective of the system is to process an input triangle mesh model, and generate joints on each planar

face of the model so that the fabricated parts (faces) can be assembled and sustain themselves by friction between the joints.

Given a triangular mesh as input, underline algorithms of the system execute in the following three steps:

1. Planar faces are extracted from the mesh.
2. Connectivity of the planar faces is analyzed.
3. Finger or bevel joints are generated for each mutual edge between two planar faces.

Fabrication of a house model illustrates the generation of a physical model consisting of non-orthogonal planar components. Success is found in the ability to create flat surfaces from the triangle mesh and associated finger joints on mutual edges, including those of high curvature. The original solid mesh model shown in Fig. 1(a) contains a hole on top of the chimney, the door and the windows. Openings in the original mesh are accounted for as edges without finger joints. Here, a watertight solid with holes is possible. This demonstrates the range of possible shapes made of finger joinery.

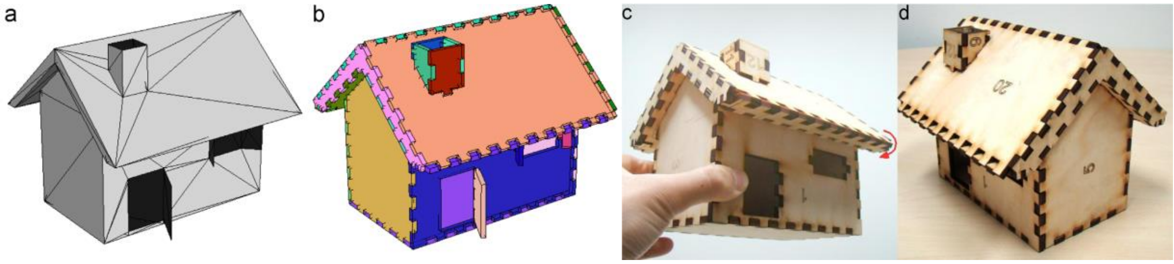

Fig. 1: A house model, 250-230-210mm^3 in size. (a) Input triangle model. (b) Simulated planar structure made of finger joinery. (c) The red arrow in (c) indicates an edge of high curvature. (d) Assembled physical model.

Solid shapes generated with finger joints can also be used as molds for fabrication of shapes and modeled artifacts. A spiral model is introduced as a way to build an interlocking model as one solid from a curved model. Steps were modeled as wedges around a central axis later sculpted into the shape of a spiral staircase. More than one hundred planar parts were laser cut from 5mm plywood sheets and then manually assembled. The plywood staircase model was used to mold a plaster staircase of the same geometry. The plaster staircase was cast of silicon gel as shown in Fig. 2(a). This relatively small model along with low viscosity silicon worked well to fill all voids. Once removed from its mold, the silicon gel provided many levels of model detail in a solid form Fig. 2(c) demonstrating high quality molding. Overall, it took less than one day to complete the entire casting process, which included automatic generation of finger joints based on the mesh model, laser cutting of the planar components, assembly of the plywood model, silicon gel casting, and disassembly of the plywood model.

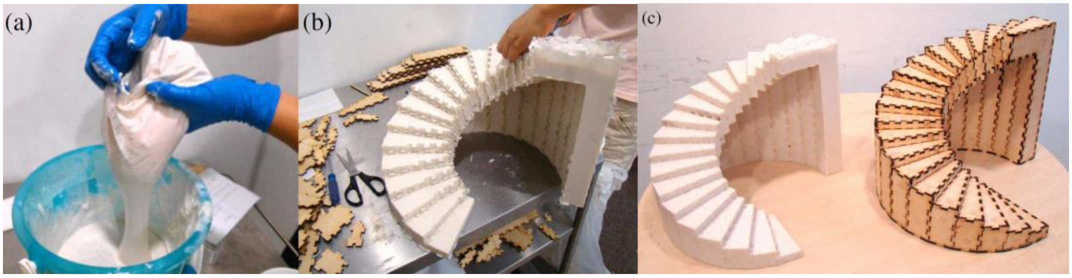

Fig. 2: Casting of a silicon gel model using the finger-joint structure as the mold.

Bevel joinery is an extension of finger joinery. A bevel joint has a slanted joint surface that follows the intersection angle of two adjacent faces. A comparison of finger and bevel joint is shown below.

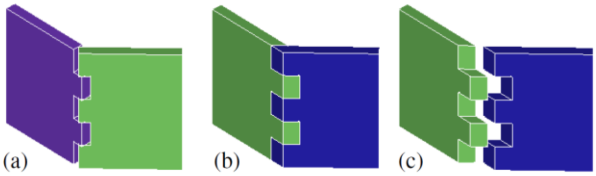

Fig. 3: (a) Finger joints of a watertight structured achieved in [6]. (b) Bevel joints of a seamless structure. (c) An exploded view of the bevel joints in (b).

Fig. 4 shows a bunny model that has concave surface patches. The model is a simplified bunny with 35 planar faces. Our method cannot generate a desktop-sized bunny based on the original bunny model that has smoothly varying surface patches because of a number of limitations. Parts of the simplified model were 3D printed and assembled in 30 minutes. One does not have to follow a specific assembly sequence as each part can be attached to the structure without being blocked by other parts. For example, in Fig. 4(c) a front part on the lower body has not been attached, while its top, left, and right neighbours do not obstruct its assembly path; hence, it can be attached by pressing into the structure. The fully assembled model Fig. 4(d) exhibits small gaps at some joints. These are caused by warping of the parts during 3D printing. When printing a flat plate, the warping artefact is a common problem in most consumer 3D printers. Despite of the issue of fabrication precision, the structure has seamless exterior and interior surfaces.

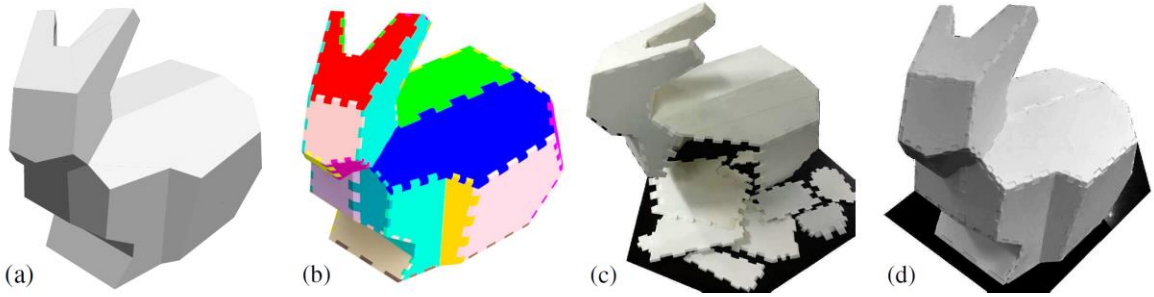

Fig. 4: Bunny produced by 3D printing. (a) Simplified bunny model that has 35 planar faces. (b) Simulated model assembly with bevel joints; each face is indicated by a different color. (c) Partly assembled model. (d) Fully assembled model.

Planar structures made of bevel joinery is stronger and more elegant than those made of finger joinery, while they require a more time-consuming and complicated fabrication process.

Generative Engineering Design:

Generative Engineering Design (GED) is an application of advanced tools of Generative CAD to the product development process fulfilling specific functional requirements (industry applications). Product development workplaces distinguish solid modeling = advanced parametric design, i.e. skeleton engineering design with topological optimization generating functioning assemblies; and surface modeling focused on history tree structured advanced shape design, which enables generating detailed surface-based components of complex shape in case of their Computer Aided Styling (CAS) modification.

Generative engineering relies partly on generic parametric models. Parametric models are numerically controlled deterministic representations of design solutions which result in a new product with similar geometrical values (quantity indicators such as dimensions, weight etc.), but dissimilar in quality, e.g. aesthetic indicators, subjective user requirements, and needs. It means that generative design in new design and innovation offers more than a geometric model. It offers a whole complex of information about a new product which has not only a deterministic nature, but also a heuristic one [4].

In the following sentences, we describe two approaches using engineering design examples in the automotive industry and mobile working machinery:

1. Skeleton structured design suitable for solid or sheet metal models = based on predefined quantitative parameters as boundary conditions for generated models. They are defined in a form of skeleton, as shown in Fig. 5. Generative design defines phenotype and genotype in various works [1]. In case of presented example phenotype consists of information on sheet metal parameters and genotype is a desired model and code which generates outcome. Model generation process is:

   Input elements definition – generation of simplified representation – profile creation – optimization of model in order to minimize material or fulfil strength limits.

2. Design of surface-based components using shape modeling tools = used within product design within which are not strictly defined quantitative parameters and conditions for generating a set of outcomes. An important feature of surface-based components design is a scheme of separate files explained broadly in [4]. In contrary to skeleton design, here can be input information in a form of free-form surfaces. The goal is to ensure design intent and quality of generated models. Fig. 6 shows adaptation of functional features (clips) of a component in case of boundary conditions change. The depicted two components were generated differently based on technology limitation such as mold opening direction, change of interfacing surfaces and other specifications of joining features.

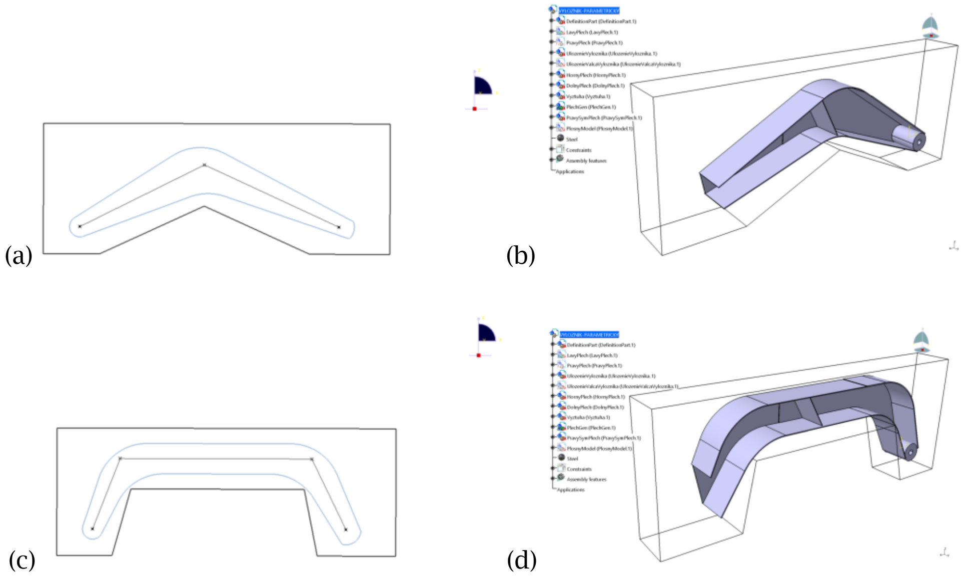

Fig. 5: Generated models of the beam of a mobile working machine. (a) Skeleton and generated planar profile of a V shape beam with definition of input boundary conditions. (b) Generated model of a V shape beam. (c) Skeleton and generated planar profile of a U shape beam with definition of input boundary conditions. (d) Generated model of a U shape beam.

In both approaches, generative model is modifiable in the form of the assembly to have adapted components to each other in case of new output generation. In contrary to surface-based components design, skeleton structured models may be created in various CAD programs. Surface-based components design is conditioned by using higher-level CAD programs. In case of both presented examples of GED, CATIA was used.

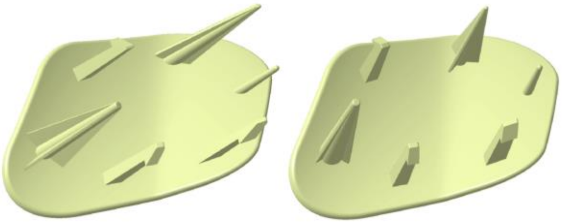

Fig. 6: Two variants of generated models of a surface-based cover.

Conclusion:

Any advanced design efforts are justified in various fields for researchers all around the world. Authors consider Generative CAD to be an essential part of the Fourth Industrial Revolution (also known as Industry 4.0). Even though increasing knowledge of CAD model seems to be ineffective for some insights, researchers try to implement high-level knowledge into real-world applications, which are successful. Generative CAD may significantly help in case of well-defined boundary conditions or requirements, and reduces human intervention; therefore the number of failures decreases. Now, what is the next step? Generative procedure works well only within a specific exploration envelope or a specifically defined task. Future efforts of researchers should therefore focus on exploring results far from the known area to come up with absolutely unique solutions for any design task.

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