Variation from Repetition

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Abstract. Making double curvature surfaces in architectural design is nontrivial and presents many challenges. Design and fabrication of these complex shapes requires systematic approaches. Most current design and fabrication processes distribute adaptable patterns over modulated variable surfaces. But to produce variation with this method means many machining hours and a budget that a conventional architectural project cannot afford. An alternative method to achieve such complex shapes would be to overlap identical elements on a grid. This paper presents an approach to fabricate such complex surfaces from the repetition of a series of identical elements.

Keywords: Double curvature; adaptability; automation; digital fabrication.

Introduction

Recently we have seen increasing interests in using double curvature shapes in architectural design (Burke 2007, Hensel 2006, Oosterhuis 2006, Kolarevic 2003). This is mainly encouraged and facilitated by the power of the 3D modeling software, which offers more accurate control of complex geometry models and also new methods to generate them (Leach 2005, Knecht 2003, Wendland 2000, Kolarevic 2005). Such exploration in part has been motivated by architects’ desires to include more expressiveness in the final building shapes. The study of how to build those complex shapes has become an interesting research agenda.

Massive experimental explorations are required to produce double curvature surfaces. To define the emergent taxonomy of principles and strategies on how to control such surface variations is a great challenge. Variation from pattern propagation, deployment of different kinds of automated construction process, and robotics components are some of the methods used by architects and engineers to achieve complex surface in architectural design.

Variation from pattern propagation is based on the repetition of a pattern while adapting such pattern to local geometry. The pattern is usually applied in structural objects for continuous variation of skins to cover those structures. In automated construction process, there are examples of robotic weaving machines designed to weave structures and produce large-scale 3D concrete printing and digital fabrication. Another strategy to achieve complex geometry is to use robotic components that allow shape shifting and maintain adaptability. However, all of these methods require a production process beyond the means of a conventional architectural project’s budget.
An alternative to this challenge is to focus the efforts on digital aided production in molds or prototypes of complex elements and then reproduce those elements using conventional technologies. The challenge then is how to produce variation from a series of identical elements. This paper offers an approach to address this challenge by exploring strategies of combination, non-periodic repetition, overlapping and material properties such as torsion and bending.

**Variation from Propagation**

Several software applications provide functionalities to achieve double curvature surface in geometric modeling. They allow users to propagate a pattern along a curve, or a plane in the three-dimensional space. ParaCloud, Digital Project, Generative Components are some of them. Using this kind of applications to produce variation is complex but feasible. Computer numerical control (CNC) equipments such as milling machines or routers, can produce a cube, a cylinder or a Nurbs surface, etc., by processing the coordinates in the 3D files that describe a path to cut, to sand, or to perforate. The file is essentially a collection of points in the three-dimensional space. But to produce variation in this way means a lot of hours of machining. Furthermore, each unique part requires a separate file to describe the machining path, thus increasing cost and time. From the fabrication point of view it means that every part is an original piece.

**Robotic weaving**

Peter Testa Architects (Chang, 2005, Rohrbacher 2005) have been collaborating with the carbon fiber industry in the design of a weaving carbon fiber tower prototype. Their motivation is to offer a solution to the crowded urban contexts with a higher high-rise building. The challenge is to go higher with a lighter material. This is a challenge because the majority of the material in large structures is to support itself. Their proposal is to have robotic spiders weave carbon fiber to produce the main structure, while recording local variation of the structure according to local requirements. Although this is a hypothetical project, it is highly plausible that such technique can achieve consistency in shape fabrication, while more material can be added where it is needed. The desired result of this weaving process is a heterogeneous structure inflecting on its shape changes of pattern provoked by internal as well as external inputs, any part in the entire structure is specific and also different than the others.

**Large scale printings**

Developed at the University of Southern California by Dr. Behrokh Khoshnevis, Contour Crafting Technology (CCT 2008) is a large-scale concrete printing system conceived for manufacturing parts as well as constructing the whole building. This technology prints layer by layer, using the previous layer as a support for the next one. It can print a relative wide range of shapes in a short time. Conduits and other installations like plumbing and air-conditioning can be embedded during the printing process. The printing process is similar to a 3D rapid prototyping machines, printing section by section.

**Programmed brick arrays**

The Digital Fabrication Group of the ETH Zurich Department Architecture, directed by Prof. Fabio Gramazio and Prof Mathias Koheler (DFG 2008), is focused on research about new strategies of production and the development of new methods for digital fabrication. They have programmed a 5 axis KUKA
robotic arm for freeform production and robotic assemblage of building components, generating new brick arrays for both structural and ornamental motivations. Arrays with minimal differences of position and rotation between one brick and the next one are virtually impossible to be reproduced by hand. This work opens a new range of possibilities to generate complex shapes based on repetition of identical elements. It also demonstrated what a robot can achieve in terms of precision and elegance.

**Robotic Components**

Hyperbody is a research group at Delft University of Technology directed by Prof. Kas Oosterhuis (Hyperbody, 2008). Their research focuses on programmable buildings including from animation and real-time behaviors. They define architecture as moving structures. They consider the structure as well the skins of buildings to all become programmable. With programming, the structure can transform itself through a series of states and changes of configurations. Architecture then becomes responsive and is adaptable to changing circumstances.

This group has been exploring changing pneumatic structures, sensor and muscles embedded in architectural structures, and how to program all these devices to create controlled behaviors and shape shifting. The implemented muscle technology is contractible reinforced rubber cylinder controlled by pressurized air. An important factor of these muscles is that their pneumatic mechanisms can control their force to apply gradually in any movement. Fast spasms to delicate and soft movements, are driven by controlling the incoming and outgoing of air. Festo muscles are controlled by a simulation software called SIM which is a simple interface of symbols and color representing forces, valves, muscles as well other components. SIM allows discrete manipulation of every element in a pneumatic system.

**Variation from Repetition**

Here we present our prototype system based on variation from repetition of identical elements with a deployable and adaptable grid of panels. Figure 1 shows our prototype system with overlapping panels. The system is composed by three components: panels, grid, and controllers of the grid obturation. The grid can change its configuration globally as well as locally and triggers different panel arrays. The variation of the system depends on the rotational capacity of the grid. The prototype was tested in virtual as well in real space through a series of animation and physical models to explore the interdependence relationships between panels and deployment.

**Panels**

Panels have grid points in two opposite wide angle corners of the panel (or short diagonal). As shown in Figure 2 below, four panels placed in four different planes produce a set, which is the basic unit to contain the grid. Set variation generates gaps or overlapping between panels depending on the set obturation degree. This simple operation can be executed at the global or the local level.

The shape of the panels creates interesting effect for the appearance of the whole. In this particular prototype the overlapping panels look like the wooden tile roofs. Rhomboidal panel has been selected because they offer better overlapping coverage between panels, but other shapes could work on the grid as well. Although the panels of the set look like mirror images of each other, they are of exactly the same shape and size. The apparent mirror
images are actually a rotation; in consequence the panels would be produced by a standard process of fabrication based on repetition. Flat panels can also be bended or twisted to produce simple or double curvature surface and offer additional adaptability.

**Grid**
The simple mechanism behind the systems is a hidden grid. Figure 3 shows how the panel locations are related to the grid. This grid is actually a virtual grid embedded in the short diagonal of the panels. Distance between points on the panel is constant, and the distance between points located on opposite panels is the only variant. The change of the distance of such opposite points of the grid allows panels angle of rotation to change. This effect varies the grid obturation allowing deployment and adaptability of boundaries. Global changes are provoked by simultaneous and synchronized grid movement. Local adaption is achieved through isolated and discrete grid rotation. The grid size in this case is not considered, but it should be in relationship with characteristic of a specific application.

**Controllers**
During the deployment process the challenge is to design or program some kind of choreography of points. The controller's task is to control such point movements. The controller has an abstract role in the mechanism and it is not designed as yet, but it could be from a fixed size element to a robotic muscle like the one discussed earlier. The controllers must be located between opposite grid points. As shown in Figure 4, by increasing or reducing the distance between these points will open or close the panel system.
Animation
Animation software was used to visualize the range of movements of the grid and also to understand the chain of interdependencies of the different elements and the deployment process. Figure 5 shows the different shapes of the deployment of the chain of panels. The animation was designed using a top down organization. In each chain every panel rotation is related to the previous one. It is the same regarding the displacement of every horizontal chain which is related to the previous one. There are levels of reference points in both panels and chains, levels of reference points rotating around or displacing from reference points.

Model
Using the geometry provided by the animation, several panels were fabricated using a simple laser cutter device and they were connected with pins. Elastic bands on the panel back emulate the tension generated by the controllers. Different animation variations were achieved locally. Figure 6 shows variations of different states during the deployment process. Every panel has a degree of rotational independency and also every single panel rotation influences its perimeter. Thereby not all the controller are needed, because the physical model showed that it is not necessary to fill the entire grid with controllers, because every controller has influence in its surroundings and can indirectly control other panel rotations in its perimeter. A further analysis is needed to define in a more accurate way this particular behavior.

Discussion
Various iterations of both digital and physical constructions were explored to fine tune the design of the panel system. This project aims to achieve variation through repetition. Many people found the deployment process and the physical structure of the prototype system intriguing.

Potential applications go from literally translation of the system to interpretation of the principles behind the system. Some literal applications in the architectural field are related to gradually controlling the self-deployment of a structure or transformable façades to adjust sunlight, ventilation and shadows levels, considering the proposal as a dynamic
structure. Another static application of this technique of controlled overlapping is tiling double curvature surfaces with standardized panels.

Other non-literal fields of application could be in the design of changing animated shapes to optimize in real time their performance under variable conditions, instead of design an ‘average’ shape, like hulls, sails and even clothes, using as a reference the dynamic fish scales mechanism.

Acknowledgements

The authors thank Paul Taylor, RIBA architect for his insightful reviews and comments.

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