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RESEARCH ARTICLE

Framework for automatic generation of facades on free-form surfaces

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Abstract
New design tools have created a growing interest for presenting complex geometries and patterns. The need to form curved geometries of facades, without incurring high construction costs and time increases, presents one of the most complex design challenges for any project. In this paper, we present and demonstrate a new computational framework for the creation of patterns on top of facades, via cladding of panels and honeycomb structures. The tool describes a given region on a base model; dealing particularly with location, size and orientation of general geometric features on the surface of such model. The user inputs curves that manifest the desired user's intention for the panels and a set of seed features that correspond to the initial boundary conditions of a Riemannian metric tensor field. The system interpolates the tensors defined by input features and input curves by solving a Laplace-Beltrami partial differential equation over the entire domain. We show a fast clustering and search operations for correct panel utilization based on size quantization as design variable and implemented via Voronoi segmentation. We present honeycomb structures that can be retrieved from the fundamental mesh producing another option for facade creation and ideation. The system connects to a geometric modeling kernel of a commercial CAD package; the system places features on top of the base model facade using boolean operations from the core geometric engine via its programming interface calls. With this computational tool, thousands of clad panels can be visualized and developed within minutes.

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1. Introduction

The facade of a building is often the most important aspect from a design standpoint. It is the first impression for any observer and can set the tone for the rest of the building. Also, from the engineering perspective of a building, a facade is of great importance due to its impact on potential energy reduction and efficiency. Iconic buildings often use geometric envelopes (e.g. exterior) to differentiate themselves from surrounding structures. The cladding of free-form surfaces is one of the tools used during construction and fabrication of building envelopes. Cladding applies one material over another to control the infiltration of weather. It also can be used for aesthetic purposes. These various applications have put facade design at the crossroads of both technology and art (Boswell, 2013).

The high end of the market for new constructions is responsible for the majority of free-form architecture (see Figure 1). The goal of the utilization of free-form surfaces is to achieve aesthetically pleasing nature-like designs. For centuries, architects have been exploring ways of constructing such surfaces. That is the case of The Selfridges building in Birmingham, England, (see Figure 2). The varying curvature and non-developable shape of the building precluded efficient modularization of structural components or formwork, which prompted the designing team to look at more homogeneous and unconventional methods of facade construction (Ed Clark, 2005). The complexity of these structures becomes greater due to nonstandard size of the components required for each project. Complex forms can be generated in CAD software packages, analyzed for performances, directly sent to automated machinery for fabrication, and constructed using the three-dimensional layout on the site. Despite the fact that the design and CAD technology have allowed for such freedom to control the architectural form, there is still a debate on what can practically be constructed (Huzefa, 2013).

Patterning design on curved surfaces for physical models is prevalent as a core component. From aesthetic to utilitarian, this patterning is traditionally created by hand using a computer-aided design system or sometimes is automated with the use of tailored scripts for each distinct 3D model.

In recent years, advancement of various design tools such as CAD systems and 3D printing also influenced architects' ability to explore forms and stimulate their imagination. This freedom of design is not without limitations and potential dangers. Projects can go over budget and even become unrealizable if architects do not model details during the construction design phase. They also need to ensure fabrication feasibility and cost-estimate guarantees. When correctly applied, the ability to model details that are ready for manufacturing becomes a significant advantage because it eliminates task redundancy. This trend in construction projects has narrowed the boundaries between architectural design and fabrication.

When considering the aspects of aesthetics and construction processes, we see the necessity to explore advanced approaches for the development of patterned surfaces for architecture. This should be done before a project is built, thus reducing errors, delays, and cost overruns.

In the rest of the chapter, we introduce a general framework for isotropic or anisotropic elements on arbitrary free-form surfaces that change in size and orientation depending on the user's intent. The research presented here is situated at the meeting point of discrete differential geometry, architectural geometry, mesh generation, and mechanical design.

1.1. Problem statement

Reducing surfaces into discrete parts and individual panels is a major challenge for the construction of free-form structures (Huzefa, 2013). The replacement of cost-driving components by reasonable alternatives is called value engineering and the optimization of panels or tiles is called rationalization. Three-dimensional surfaces are directly linked to the size, orientation, and placement of these patterned features. Changing any of these parameters affects the aesthetics of the surface and its final cost. In practice, creating elaborate facades that use non-standard features are both time and cost prohibitive because of complex assemblies, uniqueness and fabrication effects. The problem centers on how to effectively apply a limited number of part sizes in a given space.

Also it is a tedious job for designers produce repetitive components (tiles or panels) through a trial and error methodology when producing free-form surfaces used as roofs or facades. They spend hours programming and developing algorithms, rather than producing iterations of their designs.

We believe that excessive time allocated for ideation and development depends on five core limitations that make patterning ineffective when using current CAD systems. First, these patterns of panels do not always follow a given boundary, which is cutting the pattern or showing less of it. Second, the patterns are not applied directly to curved surfaces if this is the case the designer has to use a manual approach for creating patterns on a given model. Third, generation of general patterns with embedded different size and orientation is not practical on a model by conventional means. Fourth, generalized patterns that develop on the surface from a given example feature are not available as a standard tool for CAD systems. And fifth, a way of selecting the right panels from a set of standard dimensions is not a trivial task in a surface with thousands of panels.

1.2 Related work

Problems in geometry can be solved using tools and techniques borrowed from linear algebra, integral calculus, differential calculus and multilinear algebra. Discrete differential geometry connects classical mathematical structures embedded on smooth curves and surfaces, to polygons, meshes and simplicial complexes. In turn, the study of discrete differential geometry drives efficient algorithms to solve problems in computer graphics (Witkin and Kass, 1991; Turk, 1991, 2001; Heeger and James, 1995; Wei and Levoy, 2000; Praun et al., 2000; Efros and William,