

Design and Simulation for Architectural Geometry



Figure 1: Daytime and nighttime scenes of designed roof by using the developed computational tools

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Keywords: Architectural Geometry, Procedural Modeling, Mesh Editing, Computational Design, Computer Graphics.

Abstract

This paper introduces an innovative computational design tool used to edit architectural geometry interactively and demonstrates the process of designing geometry using the developed tool. The background, related work, implementation methods, system framework, and case studies are described. In addition, the designed geometry is evaluated using off-the-shelf structural analysis and construction management tools. An evaluation of the developed computational tool as well as an outline of future work is described at the end.

1. INTRODUCTION

In the last decade, various unique geometries and free-surface shapes have been applied to architectural design by using the technology of parametric modeling (PM). In PM, each design unit is generated from several controllable points using mathematical formulas. Though this approach works well for buildings with regular structure, which can be easily decomposed to each design unit floor by floor or room by room, it is difficult to apply the parameterization to more complicated free-surface structures. In addition, there are some inevitable geometrical problems. One such problem is singular points, in which the number of connected edges is less than or more than six (a regular point). A second problem is on the distortion of unit. It is still a challenge to mesh the entire surface with a regular sized unit. As the result, it leads to the practical problems of structural analysis and construction management. In order to solve these problems, we developed an approach to mesh

the given surface using similarly sized faces and units interactively. It can be made not only step by step but also by editing (type-changing, moving, and canceling) the singular points and changing the mesh-topology even after the entire surface is re-meshed. We believe that this is the

first direct control mechanism for singular points and that this tool can be an important future design tool to create developable architectural geometry for any kind of free surface.



Figure 2: Architectural Geometry designed by famous architects from Wikimedia [Wikipedia 2010]

2. RELATED WORKS

This paper relates to three main domains: digital architectural design, scientific research on architectural geometry, and professional structural analysis tools.

Recently, many unique architectural designs with free surfaces have been developed by using computational tools. Example buildings designed by famous architects such as Zaha Hadid, Herzog & de Meuron, Santiago Calatrava, and Jean Nouvel are seen in the real world as depicted in Figure 2. Several books on digital architecture are used in academic programs in schools of architecture [Terzidis 2006], and it is becoming more popular to learn these processes of design and fabrication among students. In most cases, they use the parametric modeling technology with off-the-shelf commercially available software tools such as Generative Component [Bentley 2010], Rhino 3D and Grasshopper [Grasshopper 2010], and other scripting tools within 3D CG packages.

The scientific research field on computer graphics has also been at the forefront of many research projects with direct application in architectural design, including mesh editing [Hoppe et al. 1993; Surazhsky and Gotsman 2003], vector/tensor field design [Zhang et al. 2006; Zhang et al. 2007; Palacios and Zhang 2007; Fisher et al. 2007], and architectural geometry [Pottmann et al. 2008]. We have also developed some technology to design on a surface, integrating shape grammar and tensor field [Li et al. 2010] and to re-mesh on an architectural geometry surface [Li et al. 2010]. The theoretical background of our tool is briefly explained in the next section.

In a parametric architecture pipeline, after a design is defined the geometry is sent to engineers to complete a structural analysis. In this process, several off-the-shelf analysis tools are used such as Multiframe and Advanced Steel. Multiframe, developed by FormSys (Formation Design Systems Pty Ltd.), is an integrated structural engineering software package to provide linear/non-linear, static/dynamic, and buckling calculations. [FormSys 2010]. Advanced Steel, developed by Graitec Inc., is a plug-in tool for AutoCAD to automatically generate structural CAD drawings [Graitec 2010]. It creates the arrangement drawings, fabrication drawings, list of materials and NC files for steel structure design in architecture

3. METHODOLOGY

The objective of this paper is to introduce the developed computational design tool that re-meshes geometry for architectural design, and to show how the tool is integrated in a practical design workflow.

As explained in the introduction, current architectural geometry is created using parametric modeling (PM), in which the designer must parameterize the geometry case by case. In short, it takes much time to design a new geometry because they need to find the proper parameterization for their unique structure. Also, in PM each unit/face may be distorted or ill-structured. In order to avoid these problems, we developed a theoretical framework to re-mesh a surface without parameterization [Li 2010]. However, it is not easy to control the singular points on the surface because the singular points cannot be cancelled by using regular edge operations such as flip and subdivide edges. We developed

4 main operations: 1) type-change, 2) move, 3) remove, and 4) generate singular points.

3.1. Type Change

The most fundamental and common singular points are v5 and v7 in the triangle mesh surface. By using the following 3 operations, any other singular points such as v4 and v8 can be converted to v5 and v7. For example, a v4 vertex can be split into two v5 points connected by two edges. In order to make the editing process more easy, it is better to make all the singular points as v5 and v7.

3.2. Move

Moving a set of singular points involves changing the position of the points while the other remained singular points are not impacted. Analogous to previous work in vector, tensor, or higher order field design, we would like to design an interface that enables the user to select one singular point and move it using drag-and-drop. Unfortunately, this is impossible for points whose valence is not a multiple of 6. This is somewhat surprising and makes singular point control a challenging problem. The most fundamental operations that we provide are singular point pair movement. The three most important movements are as follows: moving a v5-v7 pair, v5-v5 pair, and v7-v7 pair. The v5-v7 can move over the mesh similar to translation or parallel transport [Zhang et al. 2006]. The v5-v5 and v7-v7 pairs move in non-synchronized fashion, so that the user interface allows for selecting the movement of one of the vertices. The pair moves closer/further together, or circles around a fixed point in between them.

3.3. Remove

From Poincare index theory and Conley index theory we know that removing a singular point is not feasible. Canceling two singular points is also not possible. This is another reason why valence control is difficult. While it is possible to cancel for irregular points, they have to be in a specific and uncommon configuration. The two most important removal operations operate on singular point triples. A v5-v7-v7 triple can be removed while generating a new v7. A v5-v5-v7 triple can be removed while generating a new v5. By combining the pair-movement described above, it is possible to cancel the singular points interactively.

3.4. Generate

Generation of a singular point is the inverse operation of removal. We can therefore use the same mechanisms as removal. The only practical difference is that generating a quadruple from a regular point is always possible, while finding a quadruple in the right configuration on the existing mesh is difficult.

Because of the space limitation, we don't explain the details and mathematical proof here. The details are explained in the paper [Li et al. 2010].

The next section illustrates the process to re-mesh on a surface using a sample mesh object, and also explains the framework to integrate the tool in a practical architectural design workflow.

4. WORKFLOW

The following diagram shows our proposed workflow. The first step is to design a free surface in the existing 3D CG modeling packages such as 3DS Max, Maya and Blender. The designed object is exported as an OBJ file, which is then imported into our developed tool. The second step is to re-mesh on the original surface in the developed tool. Several unexpected singular points are generated in the initial re-meshing process, so the user needs to edit the points using the main operations explained in the previous section. Once the editing is completed, the re-meshed data is exported as an OBJ file to a 3D modeling package or structural analysis tool. The material patterns and details are created in the 3D package and geometry data is sent to the structural analysis tools to find the solution as shown in Figure 3.

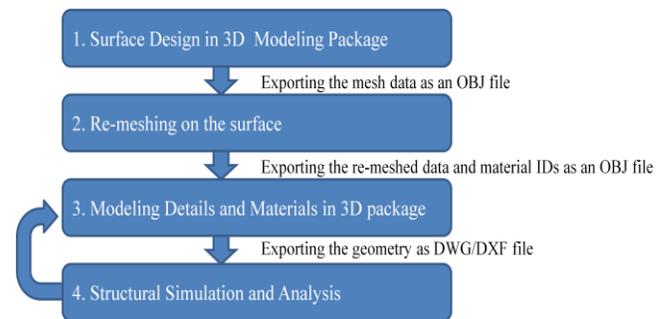


Figure 3: Workflow to Develop Architectural Geometry using our developed tool

4.1. Example Workflow

The following illustrates one example of the workflow described above. As shown in Figure 4, free surface objects designed in 3D packages have several problems. The size of faces is different. The edges are not smoothly lined up. Quad and triangle faces are mixed. Therefore, it is difficult to parameterize the geometry like this. From here, the workflow is explained using the object shown in Figure 4.

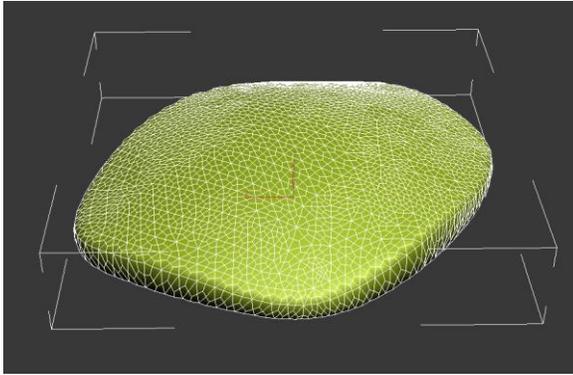


Figure 4: Input Mesh Object.

The left image of Figure 5 is the initial output of re-meshing for the input mesh object. Based on the topological invariant known as Euler characteristics, it is mathematically impossible to avoid generating the singular points, which are connected to 5 or 7 edges instead of 6. The blue point shows the singular vertex with 5 edges, and the orange one with 7 edges. The middle and right images in Figure 5 show the changes of mesh topology before (left) and after (right) a move operation of v5-v7 path. The path is shown in green. We assume that the singular points are expected to cancel as many as while possible keeping the geometry.

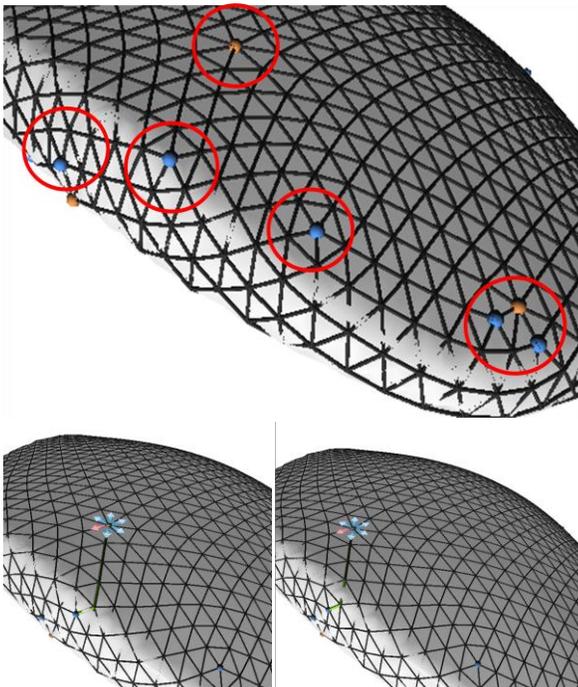


Figure 5: Singular Points (Top) and v5-v7 Pair-Move Operation (left and right)

First, the user picks up a pair of v5 and v7 points. The system has a function to find the shortest path between the points which is visualized with thicker green frames. Once the shortest path is defined, the system shows the six directions to move (5 are shown in blue and one selected direction in pink). The user can select one of the directions by using up and down keys, and move the v5-v7 pair and path by typing the “G” key. For each step, the mesh topology is updated/changed. If the changed triangle faces become distorted, the smoothing function (by typing the “O” key) makes the faces more regular.

As explained in section3, a v5-v7 pair can be canceled when it hits another v5 or v7 point. Therefore, the main task is to find the v5 and v7 pair and the destination of the pair. Sometimes the topology changes in unexpected ways, so the user needs to pay attention to the topology, too. It is a little difficult to predict how the topology will be changed by editing at the beginning, but it can be done intuitively with very little practice.

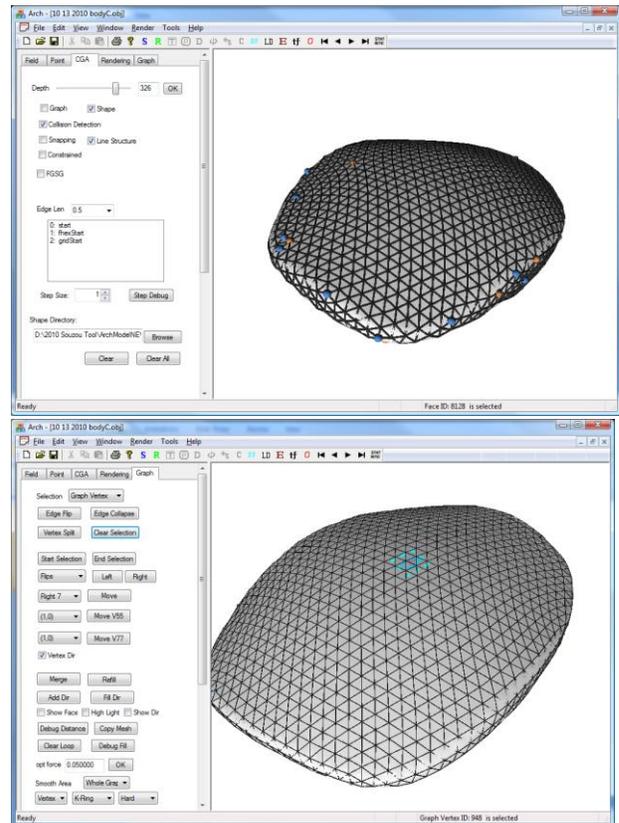


Figure 6: Screen shot images of initial re-meshing (Top) and after editing (Bottom)

Figure 6 shows the screen shot images before (top) and after (bottom) editing singular points. The top image is the result of re-meshing on the original free surface, and several

singular points are generated on the top faces. All singular points are moved to the bottom faces or are canceled by editing the v5-v7 pairs.

The tool is developed in C++ and OpenGL, and is operated in regular Windows PCs

5. CASE STUDY

Here we will discuss a case study to develop a free surface roof structure from re-meshed data using the workflow proposed in the previous section. This workflow is applied in a real building information modeling (BIM) competition called Build Live Tokyo 2010, in which participating teams design a building in 48 hours.

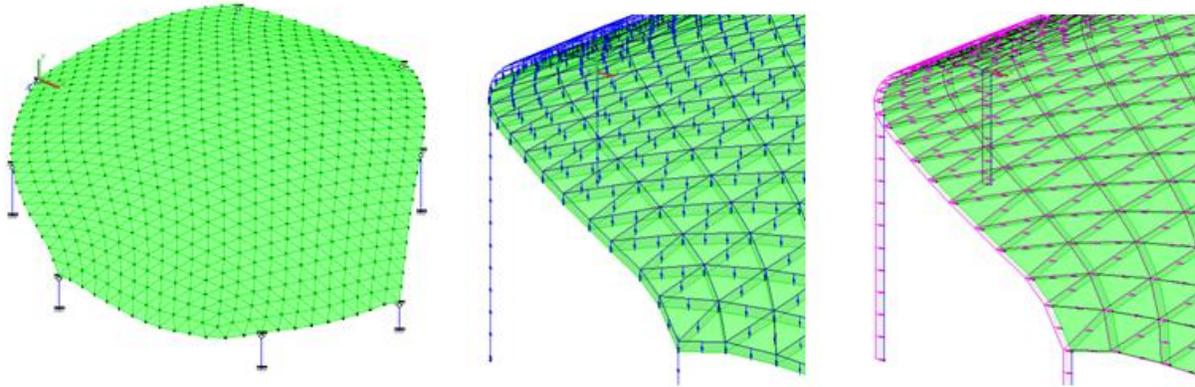


Figure 7: Data Input for Multiframe (left) and the loads for weight (middle) and for earthquake (right)

5.1. Structural Analysis

The re-meshed data is sent to Multiframe, which is an off-the-shelf 3D frame structural analysis tool. By assigning the loads, supports, and cross section dimensions, the structure is analyzed as an elastic beam element model. The structure has 2030 beams and 713 joints. The stiffness is ignored. The weight of frames, columns, roof panels are set as the dead loads, and the earthquake loads are set as the live loads. The wind loads or snow loads are ignored. The deformations, internal forces, and stresses are computed. Figure 7 shows the screen shot images of Multiframe and the loads settings. Figure 8 shows the result of displacement and the optimal location of support columns.

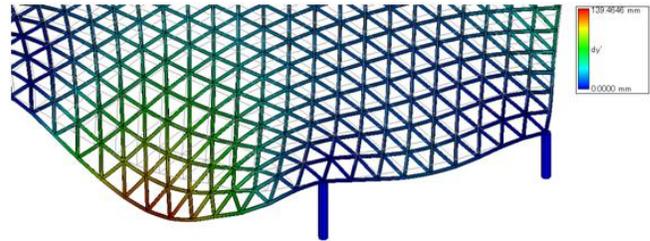


Figure 8: Results in Multiframe.

5.2. Joint Design

The next step is to determine the joint design. We tested several different joints using Advanced Steel, which is a plug-in tool for AutoCAD, to generate structural CAD drawings automatically. Figure 9 shows images of joint designs tested in this project.

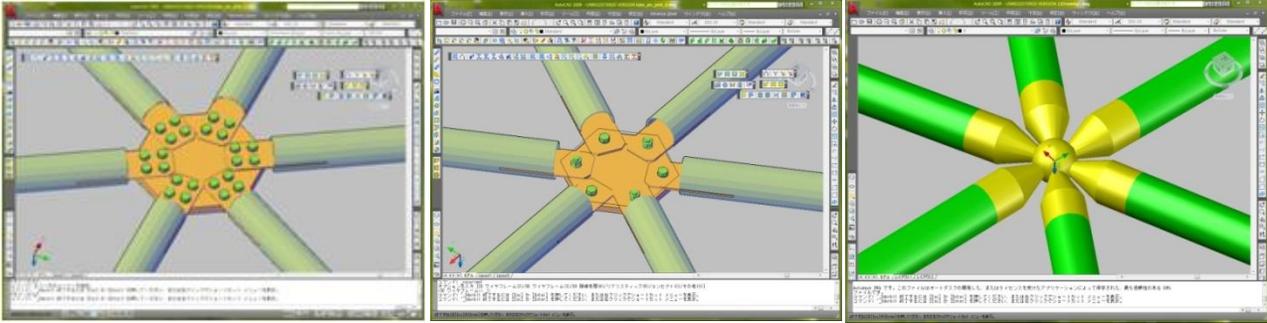


Figure 9: Screen Shot images of Advanced Steel for several joint designs

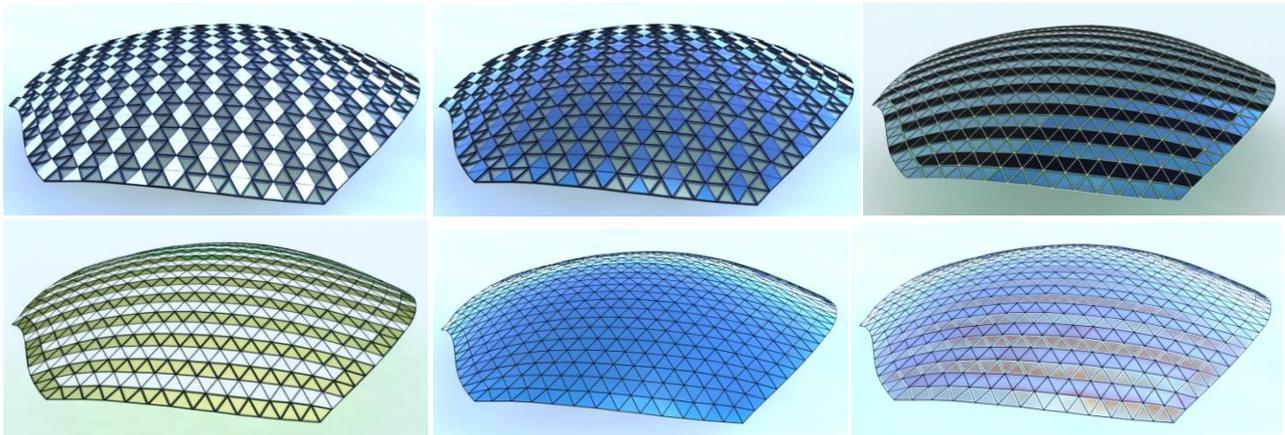


Figure 10: Several Roof Designs

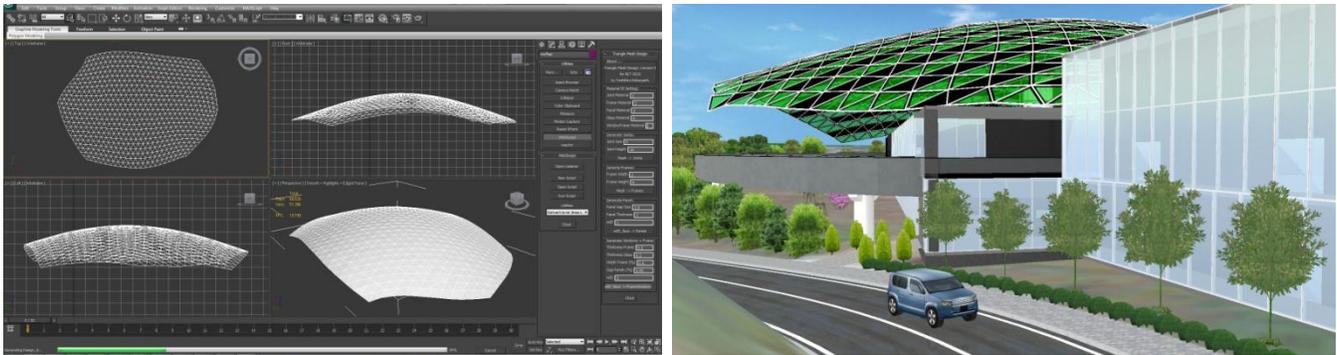


Figure 11: Screen Shot images of customized tool in 3D CG package (left) and VR tool (right)

5.3. Roof Design

Once the structure and the joint design are determined, the last step is to design the pattern and materials for the roof panels (see Figure 10). Several different patterns and materials are generated, visualized, and evaluated visually.

Several alternative designs are generated in 3D CG packages using customized tools in script language, and the designs are then visualized in a virtual reality (VR)

environment [UC-win/Road 2010] shown in Figure 11. The customized tool can generate the geometry for joints, frames, and panels. Each part is parameterized, and the designer can change the size and materials interactively in the common 3D modeling environment

6. CONCLUSION AND FUTURE WORKS

We demonstrated the developed computational design tool to re-mesh a free surface object. An example workflow to design a lattice structure roof using the tool was illustrated. The pipeline to design architectural geometry, re-

mesh the surface, assign the details, and complete a structural analysis was explained. Through the case study, we demonstrated that this tool can be applicable for practical architectural geometry development. In fact, all of the process explained in the workflow was carried out in less than 12 hours during a real BIM competition.

The limitation of the current tool is that it can be used to generate only triangle mesh objects. The future goals are to extend this tool to quad mesh objects and to develop the pipeline to generate any kind of design/geometry on any kind of surface.

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