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ENVELOPE TESSELATION WITH STOCHASTIC ROTATION OF 4-FOLD PENTTILES

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Abstract. The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope architecture and optimisation between competing environmental performance metrics. Advances in modelling the geometry of building envelopes and control technologies for adaptive buildings now permit the sophisticated evaluation of alternative envelope configurations for a set of performance criteria. This paper reports on a study of the parametric control of a building envelope based on moveable façade components, acting as a shading device to reduce thermal gain within the building. This is investigated using a novel pentagonal tiling strategy considering the component design, tessellation and control methods.

Keywords. Responsive envelopes; moveable façade components; parametric modelling; tiling geometry; stochastic rotation.

1. Introduction

The challenge of developing adaptive, responsive low-energy architecture requires new knowledge about the complex and dynamic interaction between envelope geometry and optimisation of performance metrics. In this paper, we present the results of a building envelope tessellation study based on façade components with rotation. The rotation methods are based on stochastic rotation of panels, primarily responding as a shading device to reduce thermal gain within the building.

This paper reports on the geometry and control aspects of façade subdivision using 4-fold penttiles (also called Cairo pentagonal tiling), a dual semi-regular tiling of the Euclidean plane. The penttile method (Hanafin et al. 2011) is used to define the façade pattern and its subdivision into discrete components.

2. Background

New advances in the geometric representation of envelopes (Pottman et al. 2007), new construction materials (Schittich 2005) and control technologies for adaptive buildings combined with advances in the field of design space exploration (Woodbury et al. 1999, Aish and Woodbury 2005, Datta 2006, Woodbury 2010) now permit the sophisticated evaluation of alternative designs for a set of performance criteria (Radford and Gero 1988).

However, current models lack the ability to handle envelopes of variable geometry (Kolarevic and Malkawi 2006) and do not account for local variations in climate conditions (Guan et al. 2007). These models also do not include multi-skin façades (Saelens et al. 2008). Tools that calculate the performance requirements (solar gain, daylight penetration, heating and cooling loads, ventilation, water use) of a building (Shaviv 1999, Malkawi 2004) require an extensible geometric representation (Malkawi 2006). It is anticipated that rapid, near real-time visual output from such representations would significantly improve the prediction of performance and enable the optimisation of smart, adaptable, net zero energy buildings (Hensen and Augenbroe 2004). To address these limitations in a unified way, this paper reports on developing a responsive envelope based on the tessellation of 4-fold penttiles. Further, it addresses the problem of responsiveness to multiple criteria by applying a stochastic method (Datta et al. 2009) for the rotation of individual panels (Hanafin et al. 2011).

3. Problem statement

To motivate the discussion, of a responsive building envelope, we based our study on the façade design of the “pixel” building in Melbourne. The building was designed with the goal of being a carbon neutral office building and to be used as a prototype for sustainable and environmental buildings. The façade is one of the devices used in the building to reduce its environmental impact.

The façade involves a series of ‘jumbled’ coloured and textured panels that act as an aesthetic to the building façade and as a shading device to reduce thermal gain within the building. Each panel is designed to be positioned and angled in a fixed location based on optimal shading in the Melbourne climate.

Panels will not only reflect or absorb the sun, but also allow views out from the building with perforation and transparency in the materials. In order to further optimise performance, the problem of component motion with respect to changing conditions needs to be addressed. To address this problem, we initially developed the façade subdivision scheme from first principles to investigate its responsiveness to environmental conditions and presented our findings in Hanafin et al. (2011).

Further to this analysis, the stochastic rotation of the south façade of the pixel building was undertaken in order to facilitate understanding the shapes and rules which determine the façade composition. This elevation consisted of jumbled panel façade and precast panels with the cast patterns (Figure 1). The tiling used on the elevations is identified as a Cairo pentagonal tiling, which is a type of polygonal isohedral types of tiling by pentagons (Grünbaum and Shephard 1987).

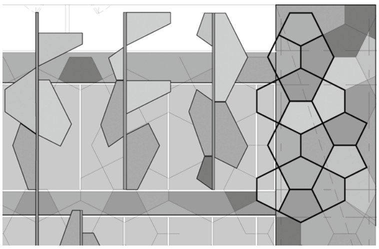

Figure 1. South elevation with Cairo tiling overlaid (source: VDM Consulting).

4. Multiple support method

The Cairo tiling is classified as a regular tiling (each pentagon is identical), However, as the orientation of each pentagon changes, this presents issues with surface-component application in conventional parametric modelling tools. With this in mind, a multiple support method is described that generates an underlying support structure, allowing for the orientation property of four individual pentagons to be applied correctly.

4.1. COMPONENT DESIGN

The geometry of the initial pentagon has a bounding box dimension of 1200 by 900 and a spacing of 1500, which does not replicate into a uniform surface grid (Figure 2). In order to correct this, the overall component needs to be developed to replicate within a uniform surface grid. If the surface grid is developed using the pentagon's width, 1200, the replication becomes more manageable and simply requires control over the positioning of the pentagon within the grid. In order to ensure this correct placement, a spacer is used at the apex of the pentagon which results in the overall bounding box dimensions of the component being 1200 by 1200.

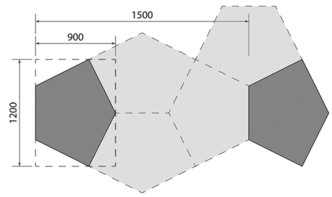

Figure 2. Cairo tiling, Pentagon shape and offset.

4.2. TESSELLATION METHOD

The first step in developing the overall tiling is to establish the surface geometry of a single vertical set of tiles, beginning with the bottom pentagon from the hexagonal collection. A horizontal line was created based on the width of the tile unit. From the start and end points of this line, two vertical lines were created with an initial length of 14.4 m. Between the two vertical lines a base surface could now be generated. The base surface was then subdivided using its U and V parameters. In the case of the U parameter is one as this surface carries a single set of vertical tiles.

With the first supporting surface established, three more are required and can be achieved by offsetting the first. Moving in a clockwise direction the offsetting can be undertaken (Figure 3, Left) by adjusting the start point of the baseline from 0, 0, 0 to: –0.6, 0, 0.6 (left); 0, 0, 0 (top); 0.6, 0, 0.6 (right).

When the component is applied to the supporting surfaces, a pentagon is generated in each of the polygons resulting in multiple pentagons that overlap. Using a data list method, the excess tiles are culled, leaving the desired pattern. The cull function uses a true-false pattern allowing for the desired tiles to be maintained, removing the overlap and producing the Cairo tile (Figure 3, right). With one vertical section complete, offset sections are now required which will allow for a complete façade to be produced. A position count variable is used to achieve this, which influences all four pentagons in a set.

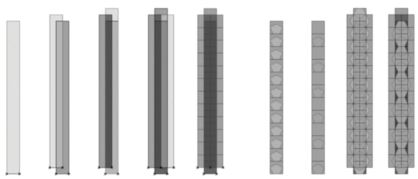

Figure 3. Left Set: Offsetting of the support surfaces and subdivision.
Right Set: Culling of the pentagons to produce the Cairo tiling.

4.3. CONTROL METHOD

With the façade tiling established, the rotation of the individual tiles requires an axis for rotation defined by two attributes, centre point of the base horizontal line and the depth of the component.

The tile data list is used to establish a collection of random values to rotate the tiles producing a “jumbled” pattern. A pseudo random generator was developed that could provide rotation information to all four sets of pentagons within a vertical set with a seed input and range of values. The seed input is influenced by the position count of the tile set, so that each vertical collection will receive a different seed input. The range of values is treated as the minimum and maximum rotational angle in degrees and is adjustable, so that this can be tuned.

The list of values is processed in order to give the rotation information to each set of pentagons individually. This process is repeated producing four lists of rotational inputs that match the size of the original pentagon counts. These lists can then be input to the rotational tool, generating a randomly rotated collection of pentagons (Figure 4).

The multiple support tiling method successfully produces the Cairo tiling but various shortcomings exist. The need to predetermine the overall area of tiling required makes this model very rigid, and requires repetition and manual adjustments to establish the finished tiling. In order to allow for a more flexible and intelligent application of the Cairo tile, a single surface method for envelope tessellation with stochastic rotation is developed.

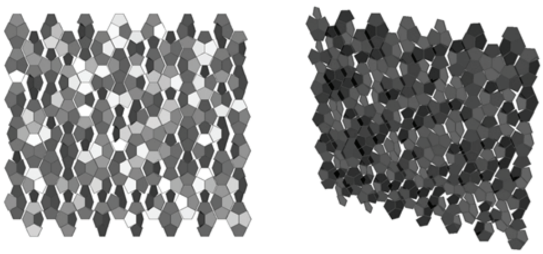

Figure 4. Panel rotation based on stochastic data list.

5. Single surface method

The starting point for the new method is a single surface. This removes the limitations evident in the vertical collections and allowing the overall surface to be changed with the tiling being regenerated automatically. While this approach allows more flexibility, it present more issues in the management and control of both the base surface and component application.

5.1. COMPONENT DESIGN

The pentagonal geometry of the tessellation tiling is extended with two extra inputs, a rotation point for orientation and a tile rotation parameter. Consider the two pentagons, an initial one and its mirrored version as shown in figure 5. When placed within the same surface grid cell it can be seen that there bottom edges are on opposite sides of the cell. The pentagons are grouped into two sets, vertical and horizontal, using the point of rotation as defined in the base component. The point of rotation is placed 2/3 along the tile height to ensure the correct placement of the pentagon within the surface grid. By adding the rotation axis parameter, the each tile is able to rotate from the bottom of the pentagon regardless of its application orientation.

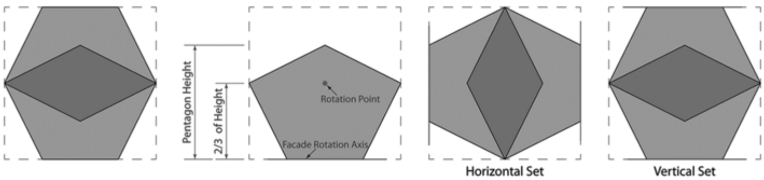

Figure 5. Overlapping mirrored pentagons, Base component with pentagon, rotation point and rotation axis, Horizontal and Vertical sets.

5.2. TESSELLATION METHOD

This method takes a predefined overall surface and applied two sets, the horizontal pentagons and the vertical pentagons to create the envelope tessellation.

The first step in the horizontal application is to take the dimensions of the surface and divide it by a predetermined tile size, this number is converted to an integer to allow for a clean surface grid to be generated as close to the preferred tile size as possible. With a surface grid established the horizontal component is applied, which at contains two overlapping pentagons and each of their rotation axes. In order to achieve the Cairo tiling, the pentagons need to be culled. The culling process is developed as two vertical sets (columns), as two patterns exist within the overall tiling (Figure 6).

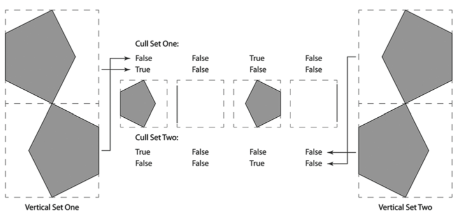

Figure 6. Cull set patterns.

Each vertical cull set is then multiplied by half of a vertical tile count of the surface in order to generate a full list for each vertical set, which is then combined and used as a loop to cull the pentagon set and provide the required pattern (Figure 7, left).

In order to apply the vertical pentagons the surface needs to be redeveloped, as the vertical pentagons grid is offset from the horizontal and in order to contain all the pentagons within the initial surface. The surface is analysed to obtain the actual tile width and height. This allows for two vectors to be established, a positive vector (upwards and to the right) and a negative vector (downwards and to the left). Using the positive vector, a copy of the surface is made and the resulting region intersection calculated. This resulting surface is then copied by the negative vector and the resulting region intersection of these two surfaces is calculated, giving a final surface that has been trimmed by half the actual tile width and height.

As with the horizontal pentagons the surface is then subdivided to allow the vertical component to be applied, follow by a cull process (Figure 7, middle). The cull pattern required for the vertical tiles is based around the first two tiles of the application resulting in the same pattern as cull set one.

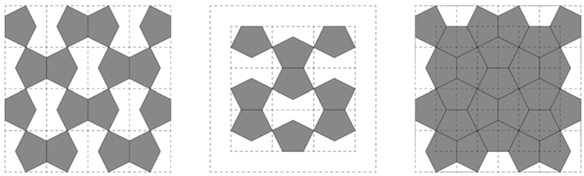

Figure 7. Left: Horizontal tile cull, Middle: Vertical tile cull, Right: Complete tiling.

5.3. CONTROL METHOD

A data set of rotation axes and a data set of tiles allows for the control of the façade to be managed. Rotation information can be developed based on both aesthetical requirements, such as the 'jumbled' pattern, and environmental benefits, such as shading and views.

In order to calculate environmental conditions information is required from both the tile, in the form of a direction vector (tile orientation), and the environment, in the form of an attractor point. A vector is established between each tile and the attractor point allowing for the angle to be calculated between this vector and the tile direction vector. This data set of angles is processed to meet the requirements of either shading or views, and provides the rotation information to each tile. Multiple environmental attractor points can be calculated and optimised based on the desired performance metrics. Both the horizontal and vertical tiles can be developed using the same environmental conditions, or managed as separate sets to meet different requirements.

While this information reacts to environmental conditions, the 'jumbled' pattern is lost due to the uniform nature of using attractor points. In order to achieve a balance between the two requirements a pseudo random generator is used to produce a set of values. These values are then combined with the calculated environmental values in order to provide the final rotational information to the panels.

6. Results

This paper reports on a comparative study of two formal methods for generating responsive envelope tessellation based on the Cairo tiling. The façade schemes investigated alternate component design, tessellation and control methods. The results of these tests are presented here.

The outcomes of the responsive exploration were a flexible façade geometry based on tiling and tessellation, creating order and rhythm within the façade. In order to achieve the desired pattern, the tessellation and control methods become more critical than the tile itself, allowing for the control of the tiles both individually and as a group. This control can be based on stochastic models, allowing for the pattern and rhythm of the tiling to be explored within set parameters and achieve unexpected results. The control can also be very strict and focused, taking advantage of attractor points representing environmental characteristics. The paper presents a new method for supporting tessellation with Cairo tiling. This method addresses the limitations evident in the vertical collections and allowing the overall surface to be changed with the tiling being regenerated automatically. The study is limited in terms of its focus on the geometric control aspects of the representation scheme. Further analysis of the methods incorporating performance metrics derived from local climate variables, material constraints, structural and load considerations, clash detection within the rotational controls and automated control using networked sensors are currently under investigation.

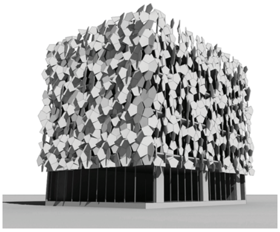

Figure 8. Cairo tile façade visualisation.

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