Abir Acharjee

Paper: **Optimised Paneling Solution**

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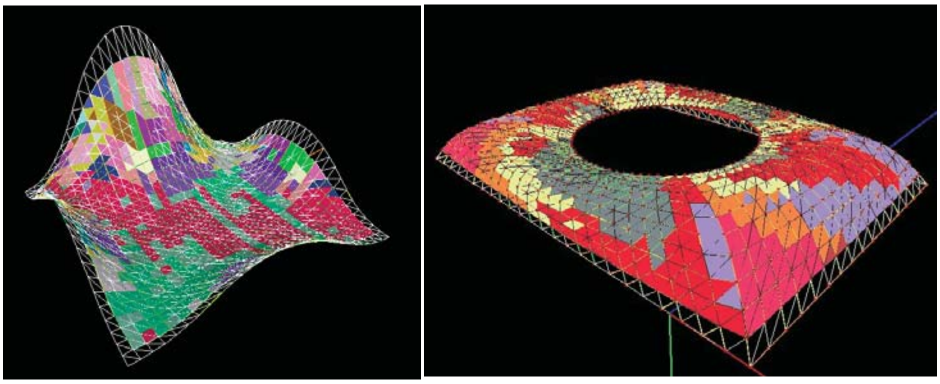
Programmatic freedom and modelling software tools have led to a spectrum of geometrically challenging freeform surfaces. The problem lies on defining these freeform design surfaces in terms of constructible components. Different custom tessellation algorithms have thus been developed in response to this problem. These tessellations produce a large number of different panel sizes and there isn't any standard solution for rationalization of such surfaces. A paneling solution play an important role in this rationalization process.

This paper will try to investigate ways in which a freeform surface can be rationalized to produce an optimised paneling solution. The research develops a generative algorithm combining dynamic relaxation and a particle spring optimization with paneling layout principles. The aim of the thesis is to minimise the number of panel variations that occur in freeform surface. Finally this leads to achieve a trade off between the rationalized geometry and its original counterpart.



Optimised Paneling Solution

Topic: Architecture

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References:

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Keywords:
Rationalization, Paneling, Geometric Optimisation, Freeform surfaces

Optimised Paneling Solution-

Design Rationalization and Optimised Paneling for Architectural Freeform Surfaces

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1. Abstract

Programmatic freedom and modeling software tools have led to a spectrum of geometrically challenging freeform surfaces. The problem lies on defining these freeform design surfaces in terms of constructible components. Different custom tessellation algorithms have thus been developed in response to this problem. These tessellations produce a large number of different panel sizes and there isn't any standard solution for rationalization of such surfaces. A paneling solution plays an important role in this rationalization process.

This paper will try to investigate ways in which a freeform surface can be rationalized to produce an optimised paneling solution. The research develops a generative algorithm combining dynamic relaxation and a particle spring optimization with paneling layout principles.

The aim of the paper is to minimise the number of panel variations that occur in freeform surface. Finally this leads to achieve a trade-off between the rationalized geometry and its original counterpart.

Keywords: Rationalization, Paneling, Geometric Optimization, Freeform surfaces, Particle-Spring System, Dynamic Relaxation

2.0 Introduction

With the emergence of large scale architectural freeform surfaces, the main challenge is to proceed from a geometrically complex design to a feasible and affordable way of production. This leads to the process of "*rationalization"* and achieving a "*paneling solution"*. This process deals with the approximation of a design surface by a set of different sizes of panels that can closely approximate the design surface and can be fabricated at reasonable cost meeting the architect's perception. The main challenge in paneling these freeform surfaces lies in the complex interplay of various objectives related to geometric, aesthetics, structural and fabrication constraints that need to be considered simultaneously [1].

A smooth and continuous flow of the panel edge lines add to the rhythm, aesthetics and continuity of the structure. Quad meshes have lower node complexity. The triangular panels produce better surface approximation and continuity. Curved panels produce superior inter-panel continuity but the cost of these mould fabrication often dominate the panel cost. Planar panels are easiest to produce and cost effective. The cost of construction not only depends on the number of panels and the complexity of the paneling layout but also on the frequency of reuse of different sizes of panel, referred to as "panel types". The aim of this research is to investigate the issue of build-ability of a freeform surface to achieve a cost effective paneling solution which has minimum number of panel types that closely approximates the design surface. The research question is, therefore, what is the degree to which the reduction in the number of panel types affects the cost against the degree to which it deviates from the original surface?

3.0 Background

Dynamic relaxation and particle spring system are used in many cases for form finding. Dynamic relaxation is a numerical method which is often used in structural form-finding to find minimum surface for fabric structures of cable-nets. The aim is to find a geometry where all forces are in equilibrium. One of the early examples of the use of Dynamic relaxation in architectural design was the Great Court roof of the British Museum [2]. Particle system has received a lot of attention from the early pioneers of digital architecture and is used as a tool for form-finding using digital simulation of various architectural designs. Particle spring systems is used in the development of a three dimensional design and analysis tool which allow the user to find structural forms in real time [3]. A particle-spring approach to geometric constraints solving was presented by Thierry [4].

Parametric design approach has been taken since early twenty-first century for advanced surface rationalization. Using planar quad panels for covering general freeform surfaces with new ways of supporting beam layout was proposed for the computation of multi-layer structures [5]. This was extended to the covering of freeform surfaces by single-curved panels arranged along surface strips [6]. The concept of symmetrization was proposed to enhance object symmetry by controlled deformation of underlying meshing structure [7,8]. The idea of optimizing for repeated elements by altering the vertex positions of a given mesh is explored in the context of quad meshes [9]. A mathematical approach using discreet equivalence classes has been used for triangulated surface such that each polygon falls into a set of discrete equivalence classes [10]. This assumes a fixed topology and uses the k-means clustering of triangles. A related problem of panel mould reuse using different classes of panel geometries was proposed by using a novel 6-dimensional metric space to allow fast computation of approximate inter-panel distances [1]. This does not try to use small number of congruent shapes but address a related problem of what type of surfaces to use for minimizing construction costs.

4.0 Research Method

4.1 Overview of the algorithm

The methodology outlined in this section consists of six steps that need to be addressed in the generation of optimised paneling solution for a freeform design surface. The first phase of the algorithm defines the design surface by a mathematical construct and deals with tessellations which subdivides the surface into a series of triangles that forms the basic mesh. In the second step dynamic relaxation is used to get a better distribution of nodes on the surface [11]. The third step utilises a particle spring system. The particles are released from the surface to get the specified panel edge lengths for the respective edges falling under specified ranges. In the fourth step, panels are casted and laid down on this released surface to achieve a *“Panel Binning Solution”*. In the fifth step panels in each of the panel type are studied in details and *“Mother panel”* for all panel types are declared. In the sixth step, the panels in a panel type are replaced by the mother panel of that panel type.

4.2 Description of NURBS Surface

The basic surface geometry is defined by “*NURBS”,* which is industry standard tool for the representation and design of geometry [12]. NURBS stands for Non-Uniform Rational B-Splines. It offers a common mathematical form for both analytical and freeform shapes. The main components of a NURBS surface are the “*control points*”, its associated “*weights*”, “*knots*” and “*degree*”. Various surfaces can be generated by moving their control points and changing the density of tessellation. The control points have an associated polynomial equation named as the *“basis”* function. A rational B-Spline is defined as the ratio of the two basis function in *“u”* and *“v”* which are the two directions of the parametric space of the UV coordinate system [13]. Two polynomial equations i.e. basis-U (Ni,p) and basis-V (Nj,q), where the shapes of the basis functions are determined by the knots vectors xi, and defined by the following formula for the u-direction and alike for the v-direction [11,12].

$$N_{i,1}(u) = 1 \quad \text{if } x_i <= u < x_{i+1} \qquad (1)$$
$$= 0 \quad \text{otherwise}$$

$$N_{i,p}(u) = (u-x_i)\, N_{i,p-1}(u) / x_{i+p-1} - x_I + (x_{i+p} - u)\, N_{i+1,p-1}(u) / x_{i+p} - x_{i+1} \qquad (2)$$

Subsequently the final calculation of the NURBS curve is determined by a parametric equation which calculates the points on the curve for u and v respectively.

$$P(u) = \sum_{i=1}^{m} N_{i,p}(u)\, P_i \quad \text{and} \quad P(v) = \sum_{j=1}^{m} N_{j,p}(v)\, P_j \qquad (3)$$

Given *m* is the number of control points vertically and *n* is the number of control points horizontally. From (1) and (2), $N_{i,p}$ (u) and $N_{i,q}$ (v) are the B-spline basis functions with degree *p* and *q*; P_i and P_j are the array of m x n control points. From (3) the resultant P(u) and P(v) define the points on the surface for a specific u,v location. The code uses a double loop that calculates the NURBS equation for all the control points and returns a 3D vector containing the XYZ position of the points on the surface.

4.3 Description of Dynamic Relaxation

The aim of the relaxation process is to find a geometry where all forces are in equilibrium and to have a better distribution of nodes throughout the surface. The panel edge lengths are used as weights in the NURBS equation and determine the direction that gets the majority in the optimization. The relaxation process only affects the position of the nodes in the parametric space; therefore the nodes are free to move around on the surface through manipulation of their respective "*u*" and "*v*" coordinates.

4.4 Description of the Particle Spring System

The main aim for the inclusion of a particle spring system is to fix the initial panel edge dimensions to a fixed number of lengths before the panels are formed. This reduces the variations in panel edge lengths for the overall topology. Four variation of lengths (6, 8, 10, 12 variations) will be tested. The system consists of a series of particles which act as the nodal points for the original surface and a set of springs which connect the nodes via the specified tessellation pattern. The preliminary positions of the nodes are derived from the mentioned NURBS algorithm. At each iteration, the movement of the nodes are established depending on the ratio of the actual length to ideal spring length [14]. The spring lengths are compared against a series of ideal lengths, which are calculated prior to optimization. Each of the three sides of the panels are analysed individually. The springs are released from the surface one at a time and if their lengths are within a defined range then they are re-sized based on the ideal length of that range (Figure 1).

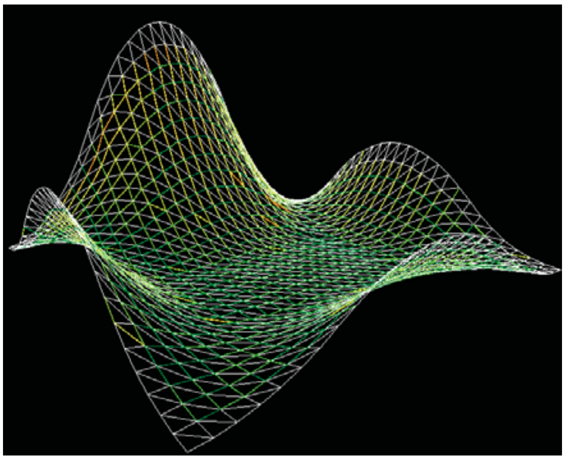


Figure 1. Surface after releasing with set number of lengths

4.5 Description of the Paneling Layout

"Panel types" refer to the different sizes of panels on the surface. Two panels with same panel types must have their respective edge lengths within specified *"tolerances"*. *"Kink Angle"* is the angle between these two panels (Figure 2).

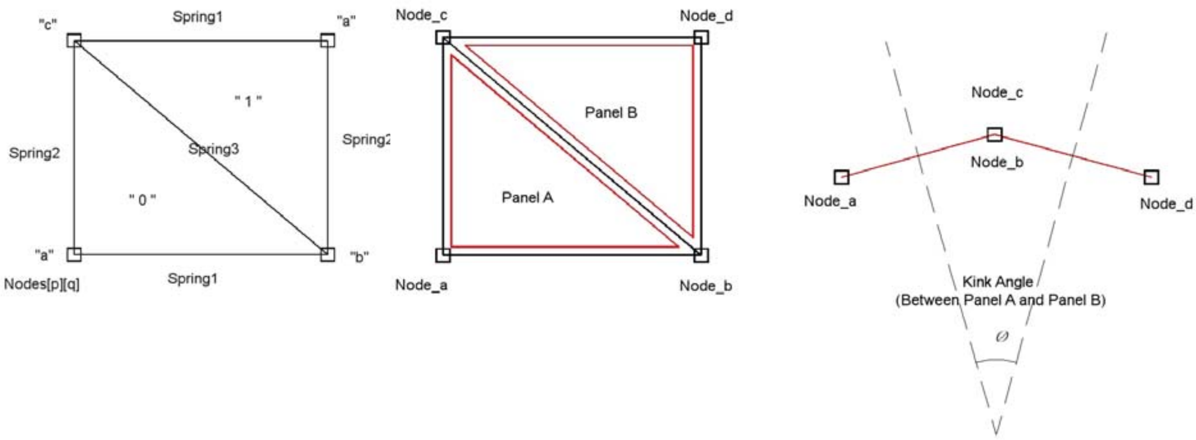


Figure 2. A node with two panels and the kink angle between them

4.6 Description of Panel Binning Solution

The *"Panel Binning solution"* is the process of extraction of the number of panel types. Two panels are selected and each of its edges are analysed. The respective shortest sides, medium sides and longest sides for these two panels are compared. If the differences in lengths are within the specified tolerance they are assigned the same panel type or if they do not match with the existing panel types a new panel type is declared. This is repeated with all the panels (Figure 3).

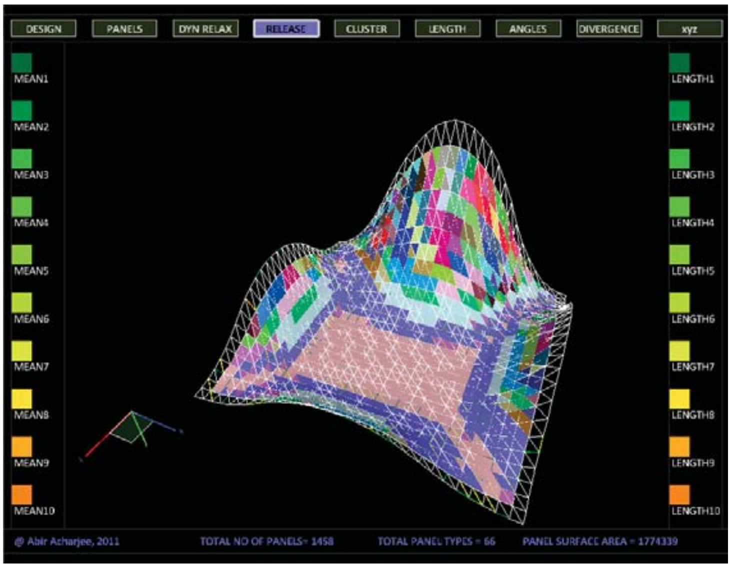


Figure 3. Panel type's extraction

4.7 Formation of Mother Panel and Description of Panel Mapping

Panel edge lengths and areas of each panel in a panel type are analysed and they are sorted with respect to their areas in that group. The minimum panel for each group is declared as a *"Mother Panel"* of that group (Figure 4). The panels in a particular group are replaced by the mother panel of that group. The mother panel dimensions can be used for fabrication purposes. A variable offset for every panel is calculated based on the panel's area, its panel type and the mother panel for this panel type. The tolerance used in the panel edge lengths contribute towards the divergences.

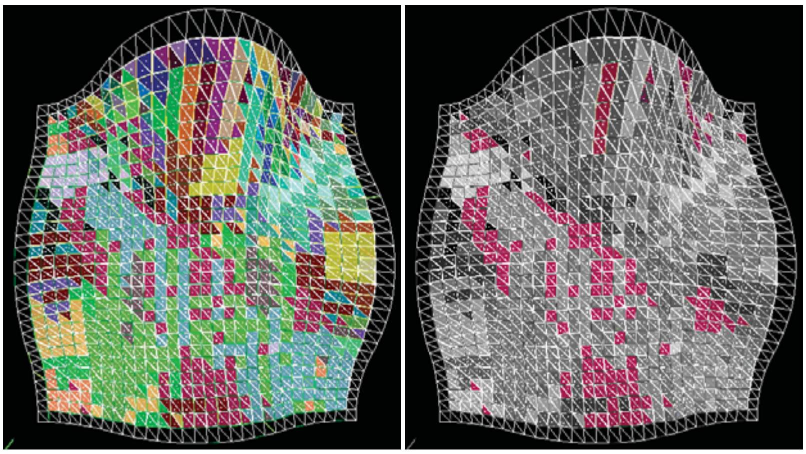


Figure 4. Showing all panel types (left), showing one panel type in red (right)

5.0 Experiments

5.1 Parameters for the Experiments

The experiments aim to pick up from the constructional phase of a design project and assume a defined topology which needs to be resolved for fabrications. Thus a single surface is defined as opposed to testing multiple surfaces. The system unit is defined as *"mm"* (millimetre) with a maximum tolerance of 0.1 mm. Seven categories of node samples, which are controlled by the density of triangular grid, are taken in total and the standard deviation of the panel dimensions for each node category help to determine the cost-effective density of the tessellation for initial experimentation.

The first set of experiments deal with dynamic relaxation to analyse the extent of its ability to reduce the variations in the panel edge lengths. After releasing the nodes using particle spring optimization the reduction in the number of panel types is analysed. The deviation of each node from the original surface is tested for understanding the overall deviation. The difference in the kink angle between two consecutive panels of the original surface and that of the optimised surface estimates the angular deviation. The change in structural efficiency is analysed by the change in structural stress. All these factors are tested for all the four different length variations and add up collectively to the success of the algorithm.

5.2 Analysis of Dynamic Relaxation

Dynamic relaxation settles down to a stable state after 300 iterations. Initial analysis of the spring lengths shows that out of total 2352 panel edge lengths there are 2071 different panel edge lengths. The performance of the algorithm is tested and it shows reduction in the range of panel edge length by about 27% and reduction in their standard deviation by about 12%. The maximum and minimum values are brought down by approximately 28% and 23% respectively (Figure 5).

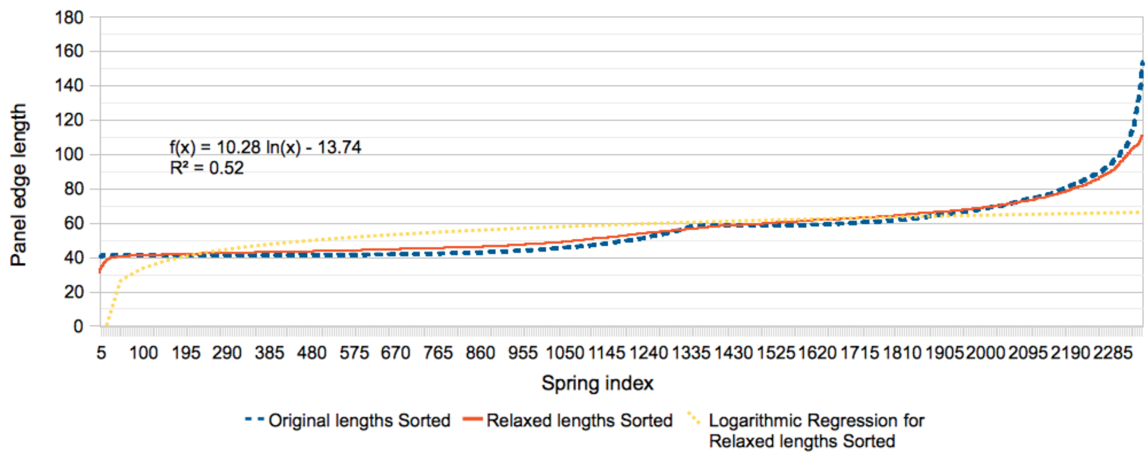


Figure 5. Reduction in panel edge length variation

Analysis of the node movements after relaxation shows that the nodes move differently to attain the equilibrium lengths (Figure 6). Analysing the difference in the kink angle between the original surface and the dynamically relaxed surface, helped to understand the effect of relaxation on the surface smoothness. A small change in the kink angle is observed (Figure 7).

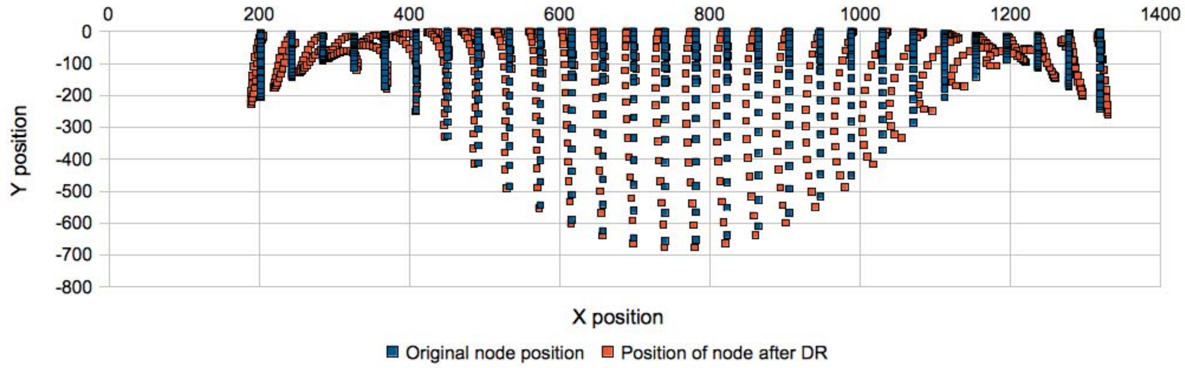


Figure 6. Movement of the nodes after dynamic relaxation

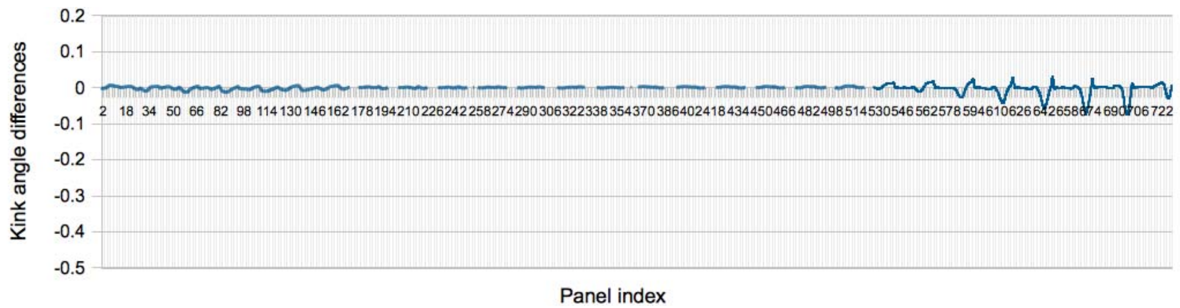


Figure 7. Difference in kink angle between the original Surface and the dynamically relaxed surface

Seven ranges of average kink angles are mapped to panel colours of the surface. The change in kink angle is mostly seen in the area near one of the saddle point (Figure 8).

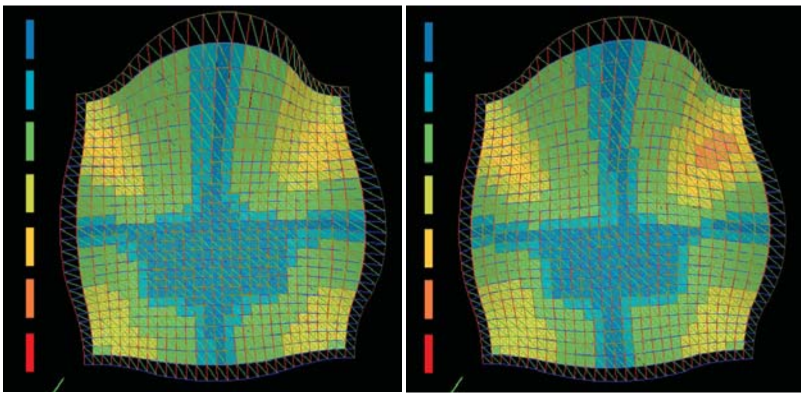


Figure 8. Mapped kink angle colours for original (left) and relaxed surface (right)

5.3 Optimization of Panel Edge Lengths and Release function

Having reduced the level of variations and total length range through dynamic relaxation, the following investigations are initialised from the relaxed position of the nodes, with all the four variations. The ideal rest-lengths are achieved through an analysis of all the panel edge lengths and dividing the actual range of spring lengths by the number of variations required. For each average value two ranges are assigned which serves as a guide for the springs (Figure 9).

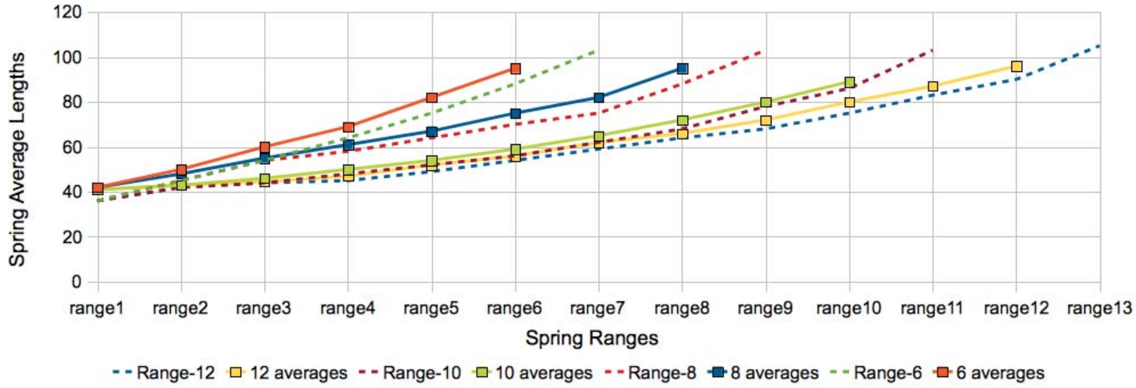


Figure 9. Average lengths for different variations in spring lengths

Spring 1 and Spring 2, which make the main quadrilateral of two panels, are released. They were constrained to various numbers of average lengths. For testing the accuracy of the optimization technique, the final rest lengths of the springs are analysed. Most of the springs are successful in achieving the averages (Figure 10,11)

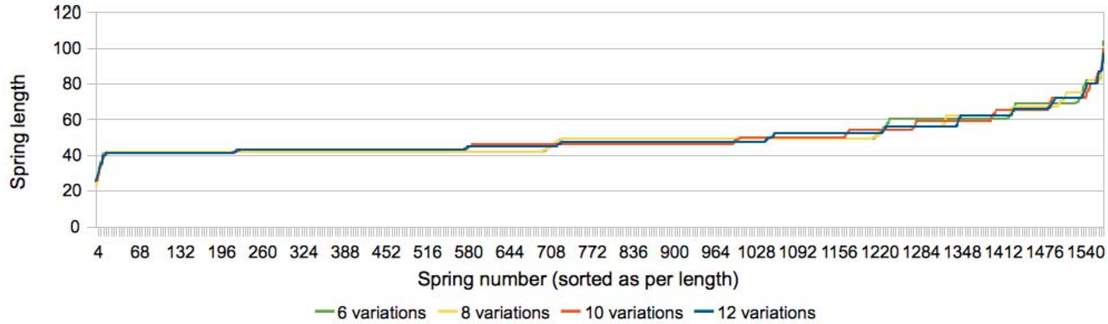


Figure 10. Final rest lengths for all the four variations

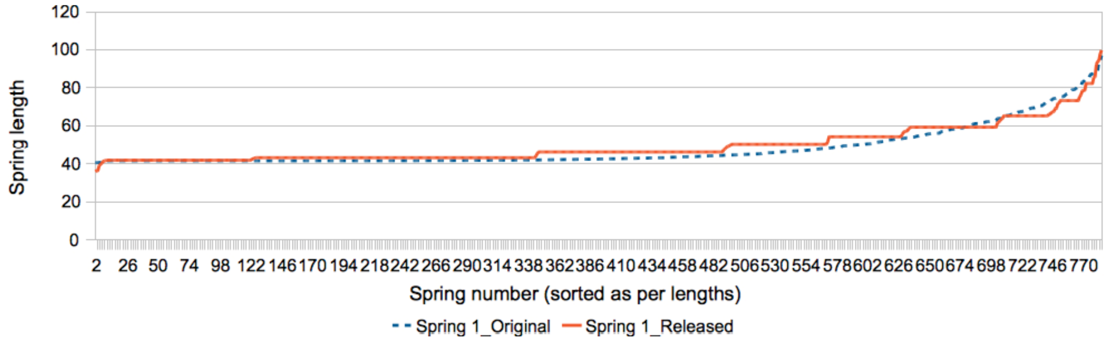
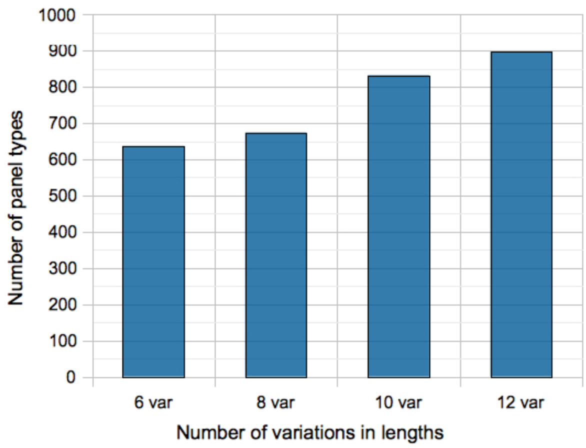


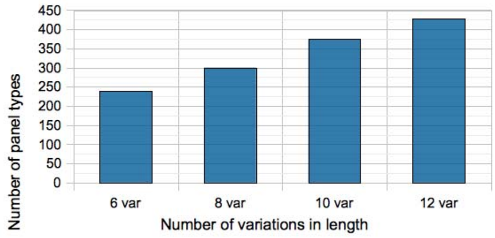
Figure 11. Final rest lengths of spring 1 for 10 variations

5.4 Analysis of Panel Types

The purpose of the Panel Binning solution phase is to group similar panels with certain tolerances. The springs are released with 6, 8, 10 and 12 variations in lengths. Then the panels are casted and the panel binning solution is applied (Figure 12-14).



(tolerance 0.1)



(tolerance 1.0)

Figure 12. (left and right) Reduction in the number of panel types with different variations in lengths

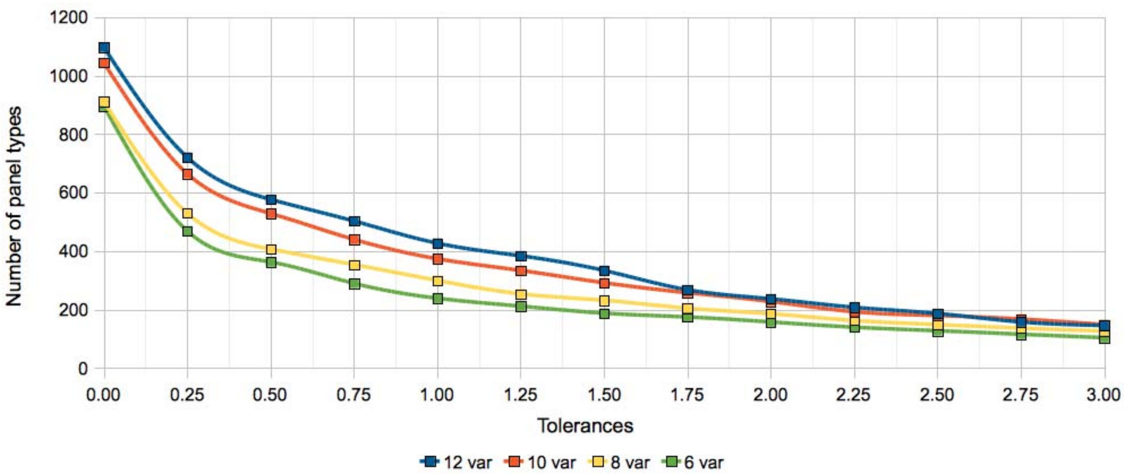
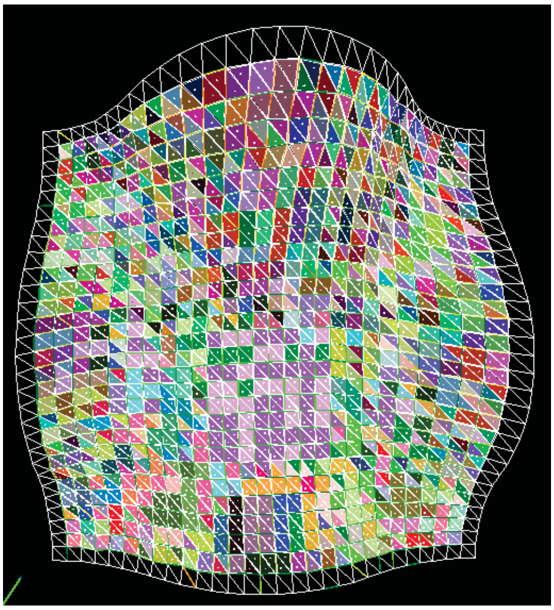
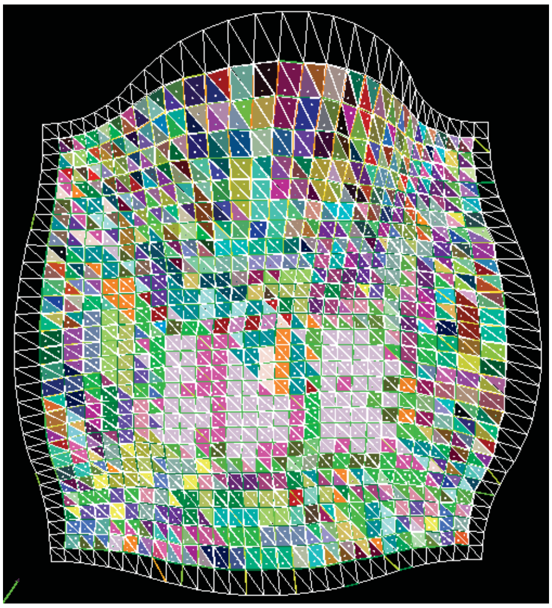


Figure 13. Reduction in the number of panel types with panel tolerances

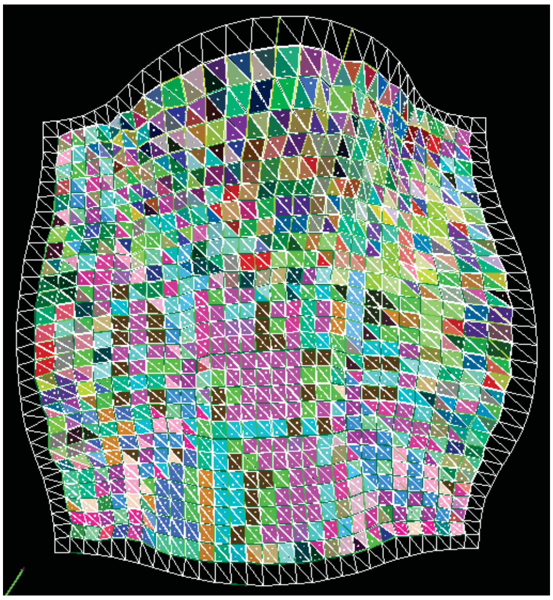
When dealing with tolerance less than 0.1 the 6 and 8 variations produce similar number of panel types. Also there is not much significant difference in reduction in number of panel types between 12 and 10 variations. For tolerance less than 0.25 there is a steady drop in the number of panel types for all the variations. With the increase in tolerance, the rate of decrease in panel types is reduced (Figure 14).



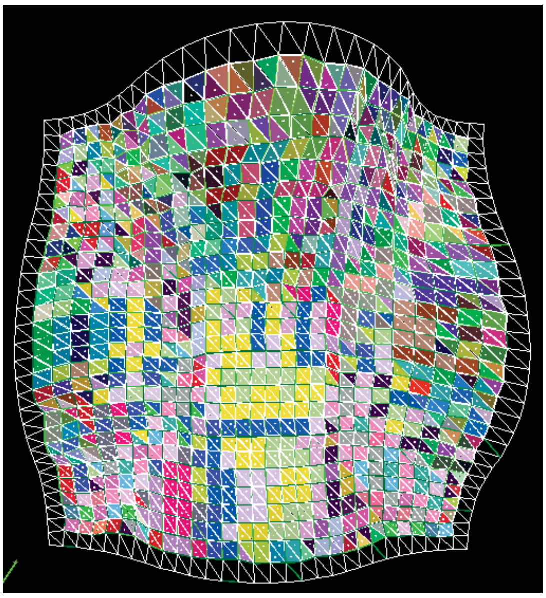
(12 variations – 427 panel types)



(10 variations – 341 panel types)



(8 variations – 330 panel types)



(6 variations – 239 panel types)

Figure 14. Reduction in the number of panel types with different variations in lengths (fixed tolerance 1.0)

Use of dynamic relaxation before the release function slightly increases the kink angle in the area of transition of high to low curvature (Figure 15).

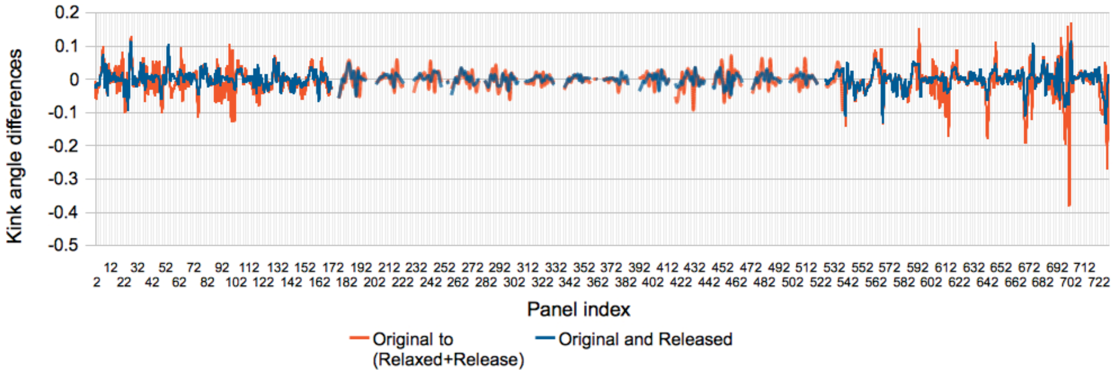


Figure 15. Difference in kink angle after releasing the springs (with and without relaxation in the first stage)

It is interesting to note that, as the number of variations is decreased from 12 to 10 more kink angle variation is seen in the area near the saddle point. With 8 or 6 variations, kink angle gets distributed over the surface. 8 variations give a moderately less kink angle as compared to 6 variations (Figure 16).

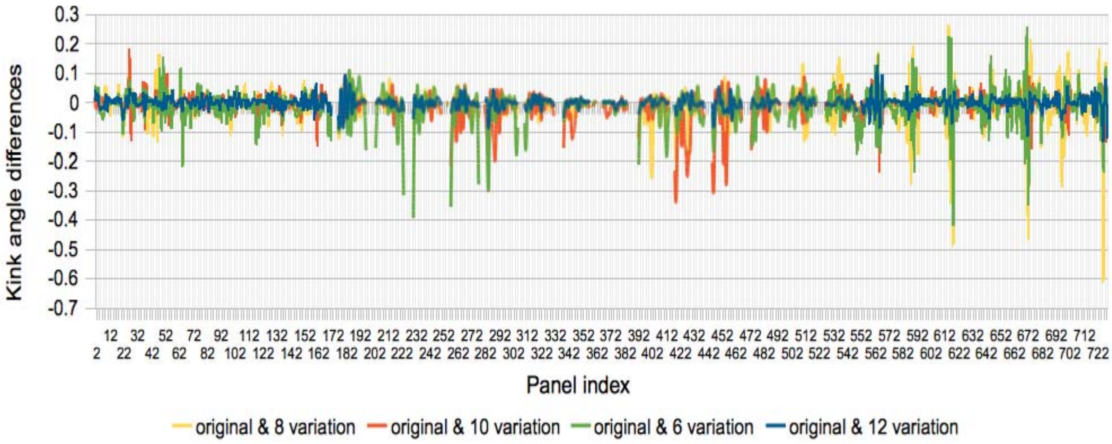


Figure 16. Variations of kink angles with different variations of spring lengths

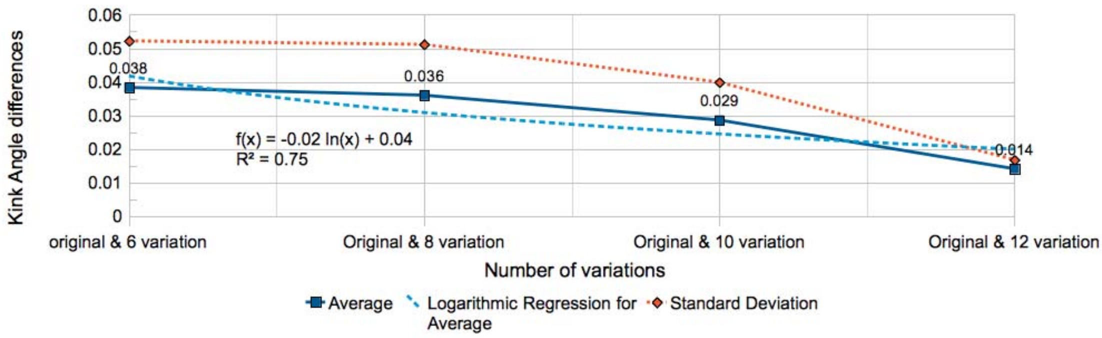


Figure 17. Variations of kink angle differences with variations of spring lengths

Seven ranges of average kink angles ranging from low (blue) to high (red) are mapped on to the panel colour of the surface (Figure 18).

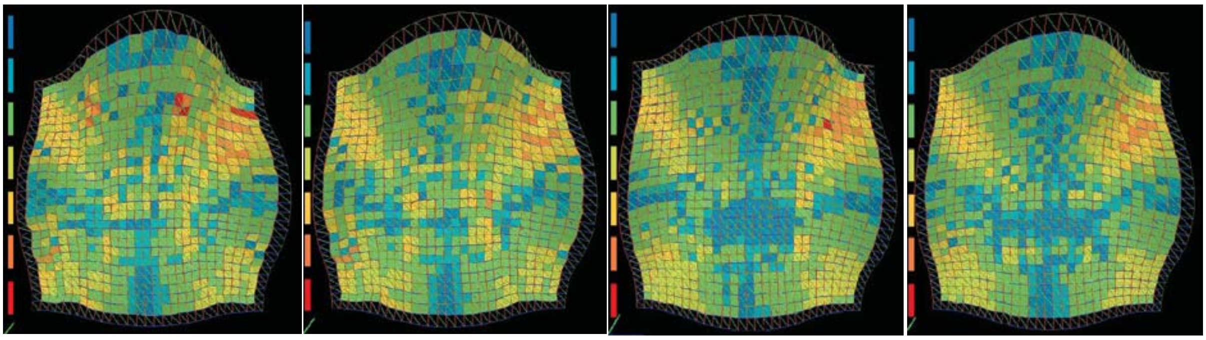


Figure 18. Average kink angle for 6 (left) to 12 (right) variations

In order to understand the deviation from the original surface, the actual XYZ deviations of the node from the original position is studied (Figure 19, 20).

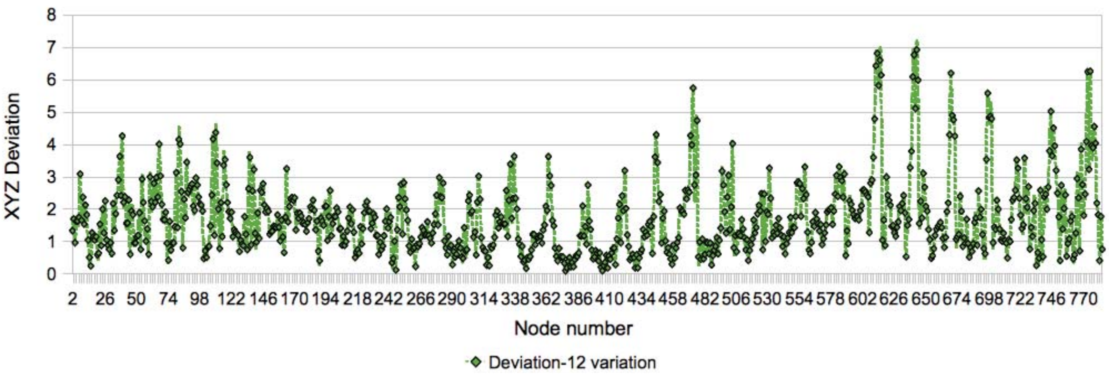


Figure 19. Deviation for 12 variations in spring lengths

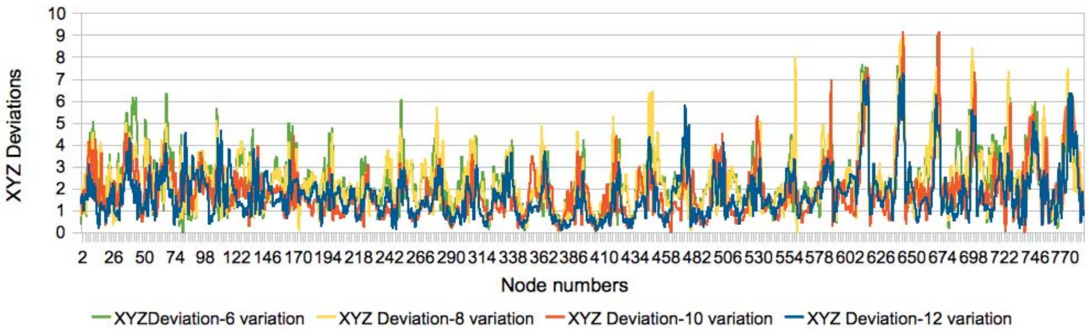


Figure 20. Deviation for all variations in spring lengths

12 variations have a consistent and less deviation throughout the surface. 8 variations have more deviation in the whole spectrum; it is less than 6 variations at the start but is higher in other areas. There is a significant drop in kink angle from 8 to 10 variations (Figure 21).

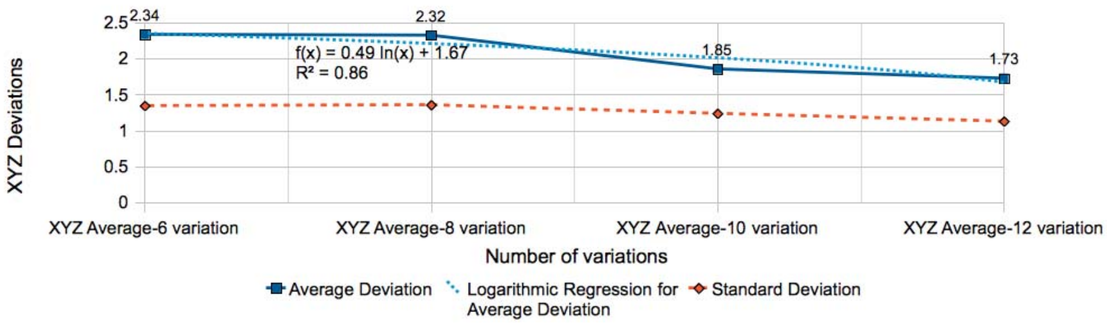


Figure 21. Deviation for all variations in spring lengths

5.5 Structural Analysis

The following experiments aim to find the variation in structural efficiency with the decrease in number of variations in the structure. Structural analysis is performed with pinned edge supports at the edges and fixed connections. Only the self weight of the structure is considered. If the loads and sections are the same, the measure of the structural efficiency of the geometry is done approximately by the stresses. The maximum and minimum stress developed in the members due to axial forces and moment help to get a preliminary understanding of the overall change in the structural forces. It is seen that as the number of length variations decrease in the members there is a tendency of increase in the stress of the members (Figure 22). This is only an indication of how the stresses are developed.

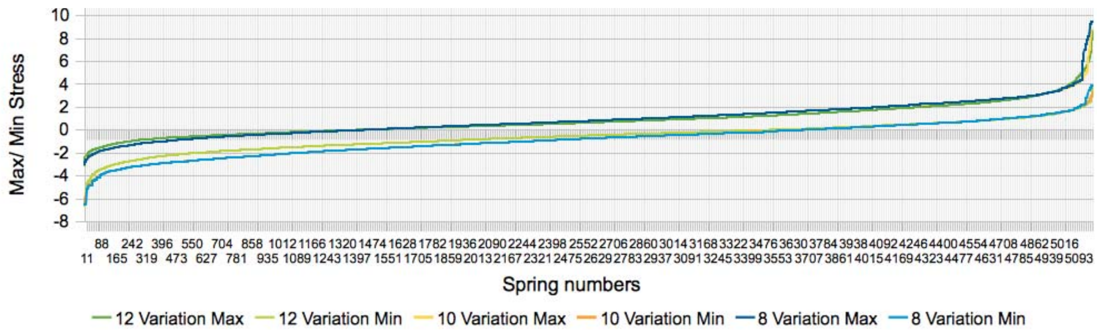


Figure 22. Max and Min stresses for release surface with 12, 10 and 8 variations

5.6 Experiments with *“Example Surface”*

An example surface similar to the Great Court roof of the British Museum is taken to perform a comparative study. With similar setup of experiments like the *“original surface”* all related experiments are performed. These experiments help not only towards the success of the algorithm but also to understand the additional parameters related to the original form of the surface geometry, which affect the paneling solution [15]. The surface is released with the set lengths for the panel edges and panel binning solution is applied (Figure 23-26).

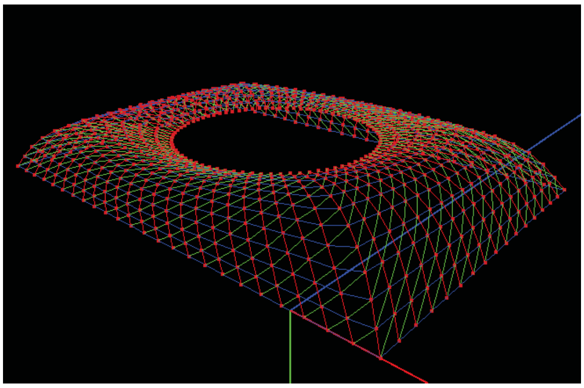


Figure 23-Original surface

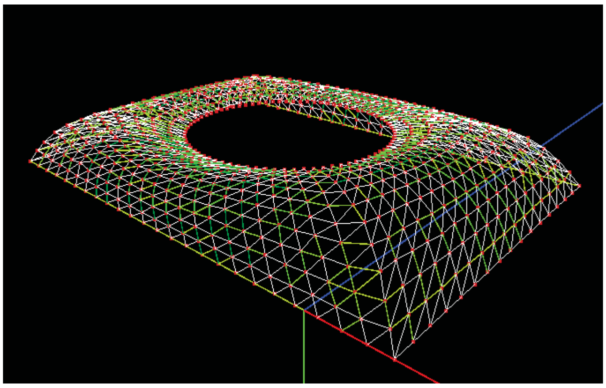


Figure 24- Released with 6 variations

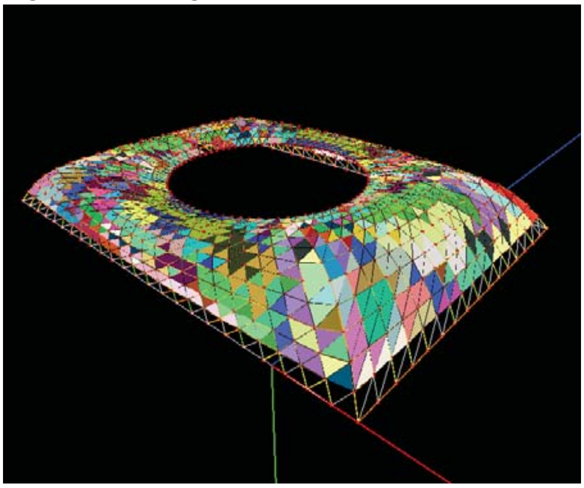


Figure 25 – Original paneling layout

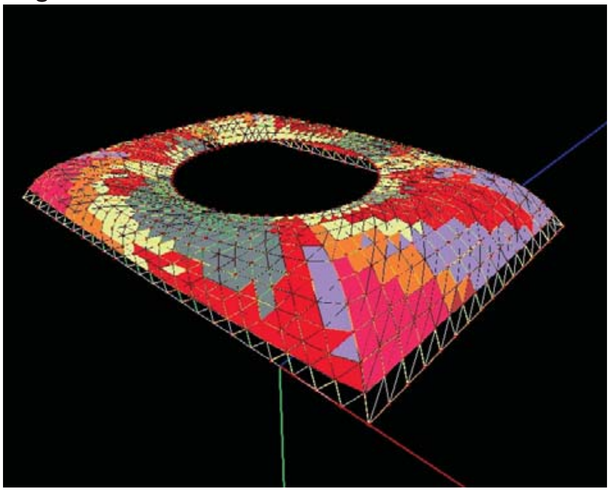


Figure 26 – Optimised paneling solution

6.0 Discussion

With regard to the aim of the paper, the results show that out of the initial 1280 panel types on the original surface the applied algorithm reduces this to 374 panel types, which is a reduction of 70.78% with acceptable average deviation of 1.85 and an average kink angle of 0.029 for a tolerance of 1.0. This can be further reduced with different length variation as per the acceptable deviations, surface kink and tolerances. Analysis of dynamic relaxation results show that the use of relaxation helps to reduce the number of panel types when dealing with less tolerances resulting in a minor increase in kink angle. Dynamic relaxation mostly contributes to the paneling aesthetics by distributing the nodes on the surface and reducing the range and standard deviation of the spring lengths.

Further experiments with the Example Surface reflect that the original surface geometry, its curvature conditions and symmetry influence the optimum panelling solution. The initial curve network and the original organisation of the nodes have a unique influence on the release of the surface. The variations in edge length and the panel geometries influence the effect of the binning solution. Curvature conditions, like the presence of saddle points affects the kink angle change. Interestingly a similar overall rate of decrease in the number of panel types is seen in the example surface as seen with the original surface, with the increase of tolerance.

Feeding in actual design constrains, project specific optimum solution can be achieved. Further details of the panel mapping for the computation of inter-panel distance and the intersection of panel with centreline need to be analysed. The variation of panel types has been reduced but the resultant node and connections between the panel frameworks still remain differentiated and are open for further experimentations. Angle constrains and spring particle geometric solver can also be implemented specially to constrain the kink angles in areas of high visibility. Such a structural design has a lot of complexity and further investigation with loads, predefined member sizes, movable nodes and related structural parameters are required for detail analysis. The study focused on a specific topic of modularity for triangular panels but it can also be extended to different geometric shapes of panels. This can lead to the creation of a tool that could embed the geometric behaviour, manufacturing constraints and paneling logic into a single system.

7.0 Conclusion

This research sets out to analyse some panelization issues concerned with the construction of freeform surface. A method to deal with the number of variations of panel sizes in such surfaces was proposed by using a generative algorithm combining dynamic relaxation and particle spring optimization. The experiments are conducted in three main stages which include the effectiveness of the dynamic relaxation, exploration of panel edge length variations and finally reduction in the number of panel types. The variations in lengths are tested against the node deviations, kink angles, structural efficiency and design tolerances for deriving the optimum panel types for specific projects.

A trade off to reduce the extra panels against the deviation from the design surface can ideally be possible in an actual project scenario. This is a multidimensional issue related to the complex interplay of various objectives related to design, geometric, aesthetics, structural, fabrication and cost constraints that need to be considered in a similar scale with respect to the actual project. The scale on which the two issues of cost and deviation are plotted to find the optimal point of panel complexity would change with specific project and a unique project optimum would be achieved for that project. This tool can be used to trade off the cost of extra panels against the deviation from the design surface. It allows the designer to achieve a paneling solution not only as an intuitive design rationalization tool but also as a method of post rationalization of an optimised geometry for achieving an optimum paneling solution.

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