The Radiolaria Project

Structural Tessellation of Double Curved Surfaces

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The Radiolaria Project aims to rethink architectural design and manufacturing techniques - it explores the filigree and beautiful skeletons of radiolarians, tiny marine organisms, with their striking hexagonal patterns, and transfers this concept to architectural scale and materializes it in a large scale structure.

Keywords: Panelisation; tessellation; form finding; CNC; mass customization; parametric design; generative design; meshing.

Learning from radiolaria

Radiolaria are tiny unicellular organisms living in the world's oceans. These simple organisms show a huge variety of – in some cases – bizarre shapes. Yet, what they all have in common is a filigree and strikingly beautiful skeleton, predominantly hexagonal.

Ernst Haeckel is much renown as the biologist who first researched the radiolarians in extend, and he brought these studies to a wider public through the publication of his books, above all the famous “Kunstformen der Natur”, which should prove most influential for scientist, artist, designers and architects and ever since.

The radiolarian skeletons that Haeckel portrayed show such a resemblance to architectural lightweight structures, that it is obvious to study their relevance for architecture. Frei Ottos reknown “Institut für Leichtbau” in Stuttgart dedicated three books to these fascinating phenomenon (IL 28 Diatoms, IL 33 Radiolaria, IL Diatoms II).

The new designs that contemporary 3d modelling software lay at our hands, demand for innovative structural solutions. The radiolaria project aims to study the abiotic principles behind the self-generation of the radiolarian skeletons and transfer these to non-standard architectural designs, preserving both their structural stability and their amazing beautiful aesthetics. The project focuses also on the consistent application of parametric generative design and its realisation through mass customized CNC fabrication.

Ernst Haeckel, Calocyclas, Table 31 Kunstformen der Natur(Leipzig 1904)
**Starting the project**

To gain a deeper insight on the subject, the project was initiated with a theoretical research phase over all aspects that would be touched in the process: a) Radiolaria: Shapes and surface effects. b) Diatoms: Surface Nets and Irregularities c) Architectural reference: space frames buildings d) Space frame detailing: node systems.

The research made clear that there has not been a comparable major non-standard structure erected before. The study of existing node elements also suggested that an innovative approach would be necessary for our purposes.

**Analogue tessellation exercise**

To illustrate the complexity of the rather abstract panelisation problem we introduce a hands-on analogue technique for the hexagonal tessellation of any kind of surfaces.

Since even a trivial soccer ball can only be panelized with a certain combination of hexagons and pentagons this is also true for more complex shapes, like that of the radiolarians, where we can observe 5 and 7 sided polygons among the hexagons. Also all polygons can vary slightly in size and shape, while an overall homogenous appearance is maintained. Therefore we have to know that the radiolaria skeletons are the result of a solidification process: Free floating spherical drops of organic liquid arrange in the densest possible setup – the hexagonal packing. In a morphological sequence this arrangement stabilises and finally solidifies through the deposition of silicate material along the the contact edges (Helmcke, 1984). The underlying geometric principle, the closest packing of spheres is a very wide spread phenomenon in organic and abiotic nature (Thompson, 1942). Our technique will utilize it for the subdivision of a complex non standard surface design.

Students design a surface in Maya or Rhino, the results are then materialized using a 3-axis CNC milling machine.

For the packing of the surface we use circular “panels” made from foam rubber with three different sizes. The medium size is used primarily, large and small discs are only to be inserted where the medium size does not fit any more.

The shapes are covered as tight as possible with the circular panels, however on a curved domain there will inevitably come a moment where the standard medium sized panel will not fit in anymore, and a larger or smaller panel is required.

We will also be able to observe that in most of these cases also the number of adjacent panels changes, namely 5 for the smaller and 7 for the larger elements. These imperfections in the packing are already known from the research part and we can even categorize them accordingly (Helmcke, 1984). However it is important to understand, that these so called “net defects” are not errors in a negative sense, they should be rather seen as tools to control and steer the panelisation process of the surface.

To achieve a complete tessellation, the methods and results may differ a lot. We encourage all students to set up rules and explore their own technique and document the steps consistently.

From the circle packing we can easily deduct a hexagonal tessellation by connecting the small wedge spaced gaps between three adjacent disks with connective lines (Grünbaum, Shephard, 1986).
The lines will form the edges of a network of always 3-valent vertices. Each disk will be enclosed by a pentagon, hexagon or heptagon, depending on the number of neighbours. If we also connect the centre points of touching disks, we obtain a second triangular tessellation with 5, 6 and 7 valent vertices.

We call the disc panel pattern a Delaunay-triangulation, the hexagonal network we know as the Voronoi or Dirichlet Tessellation (Okabe, 2000). They are dual, i.e. they can both be transformed into the other (Grünbaum, Shephard, 1986). This relation can be used as the mathematical basis to explain the geometric laws behind the amazing skeletal structures of the Radiolarians and diatoms.

**Parametric node design**

The closest equivalent engineered structure to the filigree skeletons of the radiolarians would be a single layer space frame. Whereas the tiny skeletons are grown monolithic entities we have to break down the system into two distinct components: Nodes and struts. The struts or beams can be cut from pre-fabricated standard tubes. The nodes must provide a precise, rigid and bending resistant connection of the struts. They are geometrically defined by the angles between the 3 adjacent struts so each node is a unique element. There are basically two solutions to this problem:

A) A flexible standard prefab node that can be manually adapted to its position in the network.

B) A parameter controlled mass customized node system that is digitally adapted to its position beforehand and then produced.

We used RhinoScript to parametrically define nodes that can be automatically adapted to their specific position in the network. All intelligence and adjustments are already in the node design itself - before they are installed, yet even before they are manufactured. The machine can manufacture these elements at high speed and precision, regardless of the objects being all identical or different.

Each student was assigned to design his own parametric node. All results were judged according to rigidity, aesthetics and feasibility for mass production and assembly.

The winner node that outperformed all others due to its simple and yet sophisticated setup while even maintaining aesthetic references to the radiolarian skeletons. The node is composed of two parts only, a bottom and top half that can be wedged together by a screw through a central hole.

The mounts for the struts are milled into the node top and bottom halves with a ball-point tool that has just the same diameter as the struts to ensure a stable and accurate mounting, using just a single milling operation.

**Installation design**

This space frame system would be suited to work as a structure for a light weight roof, façade or pavilion. The site where we intended to test it in a large scale installation is a corridor of the Digital Design Techniques Department of the local Architecture Faculty, equipped with extra features like stairs, glasswalls and platforms. The installation should be understood as built mission statement to identify with the main objectives and resources of the department: Analogue and digital form finding techniques, parametric design and non-standard manufacturing techniques. It should also look at the way users perceive the new space of the corridor and react to it.
For the design of the master surface we provided a special design tool and technique. This special Maya script integrates dynamic spring simulations and virtual force fields to combine two classical analogue form finding techniques: soap films and hanging models.

The user defines a rough topological model of the installation, the support points in the 3D site model, and the strength and behavior of the dynamic springs and forces. These deform the initial shape during the simulation as under the effect of an inverted gravity force and surface tension, until it reaches a state of equilibrium.

The results of a little design competition were reviewed and three winners were chosen to be combined into the final design that was again exposed to the dynamic simulation to negotiate them into a new shape optimized.

The final design incorporates a diversity of elements, all fused into one unit. The surface arises from the floor in a gently curved megacolumn to develop into a wide funnelled canopy. It bends around the office glass wall that offers no area of support and so tapers and finally rolls up to form a horizontal tube that connects to the big southern canopy. Another diagonal funnel shaped column connects to the opposite wall.

To get full control about the process, and aiming to transfer the methodology of our manual panelisation technique to the digital world, we implemented our own tessellation tool in RhinoScript.

The specific method that closest identifies with our approved hands-on panelisation technique is the advancing front technique (AFT). An AFT generates an unstructured triangular grid, i.e. the valence (the number or surrounding triangles) of the mesh nodes can vary. Since the algorithm is based on the creation of equilateral triangles of a preset edge length on the surface an even spacing between the points is maintained.

The advancing front algorithm is started by dividing the border of the surface domain into line segments of equal length – the initial front. From each of these edges then the front marches forward by placing a point in the domain such that it forms an equilateral triangle with the end points of the generating front edge. The new edges of the triangle then all together form the new front, and from their edges new edges and triangles are created by placing new points or snapping to existing points on the front. This marching process continues till the entire surface is covered with triangles and the front eliminates itself (Farrashkalvat, Miles, 2001). During this process our application also constantly computes the dual Voronoi cells based on the newly created triangles. For points along the border we project extra vertices on the border, resulting into a row of pentagons enclosing the entire network. This effect can also be observed on radiolarian skeletons (Helmcke 1990).

**Grid generation**

The digital equivalent to our analogue surface subdivision technique lies in the meshing or grid generation software, used to tessellate surfaces for display and rendering purposes or for finite element computation of engineering software.
Optimization
The outcome of the tessellation is optimized using a relaxation algorithm after Lloyd. For each polygon in the voronoi diagram we compute the centroid, then we move the generating point of the polygon to this point and recompute the cell. This algorithm globally smooths out local irregularities caused by strongly deformed polygons. The process can be iteratively repeated and is visible both on the level of the Voronoi cells and the edge flow of triangles (Du, Gunzburger, 1999).

Structural analysis
Structural calculations of the structure were done in RSTAB, a 3D Finite Element Software. Since the master surface is generated as a form-find upside down structure, it is pre-optimized and compression forces predominant. However, the load bearing behaviour changes because of the struts dead load, the flexural strength of the struts and the variable bending stiffness of the knots. For an example, the deformation and the flexural forces of a complete wooden structure are higher compared to a structure with aluminium struts and wooden knots. In both cases, the profiles had been optimized on compressive and flexural stress and along with this the total weight of the aluminium structure was less.

A further step was optimizing the structure to reduce the deformation, the compression and flexural forces. The optimization is an iterative process where master geometry, structural geometry and profiles where changed. During the process, compressive-, tensile- and flexural stresses as well as deformation and total weight are controlled. Minimal changes in the master geometry and thus in the structural geometry combined with an optimization of the profiles respective tubes could lead to a reduction of deformation and total weight.

A deformation of 6 mm was calculated for the final structure of 10x1 mm aluminum tubes at a total weight of 55 kg. The theoretical results and the real deformations and weight were almost identical. This speaks, on the one hand for the precision of the prefabrication and the other hand for the optimization method.

Generative space frame system
The Parametric Node Script analysis the orientation of the adjacent tessellation edges, calculates the corresponding construction plane and accordingly
generates all geometric entities that are needed to produce the node – for every node in the system. The data consist solely of lines and curves that can be quickly processed through 2½ axis-milling operations. The outline of each node is derived from the orientation of the axis in the plane, the 3 node legs that mount the struts are rounded out to look just like the nodes in a radiolarian skeleton. The script simultaneously calculates and draws the strut elements.

**Manufacturing**

The Node elements are manufactured from black MDF panels, 10mm strong. This was the only material that proved to be reasonable cheap enough to fit into the project's budget (1000 €). The necessary thickness of the material is linked with the curvature of the design surface as higher curvature values result in a steeper inclination of the strut angle towards the node plane.

The Nodes are composed of two halves, a bottom and top part. An add-on to the Node Generation Software is used for laying out the geometry relevant for CAM processing in the plane. The node halves are automatically arranged in pairs in a close packing related to the measurements of the stock material. The node components are arranged in a layer system associated with a specific machine operation to guarantee a swift generation of the g-code to feed the router.

The CNC process is structured in several phases, each performed with a special tool. All machine operations are simple contouring cuts and have to be arranged in a logical order to ensure high performance.

The labeling carries the information about the node ID number (+ and – mark top and bottom node components) and an index for the node arm (0 and 1). The third arm is not labelled and can be easily identified as the one without any mark.

The labelling operation was performed by hand, CNC-engraving would have been too time intense.

All struts are cut from 10x1 mm aluminium tubes by hand. Every strut element in the structure is defined by a set of data that contains information about the two adjacent nodes and node legs to be mounted to and the length of the strut. The node generator software outputs these data as a text file. The print outs can be directly used as labels posted on the raw aluminium tube.

**Assembly**

The labeling of both nodes and struts provides all information necessary for the correct assembly since each element refers to the next.
The adjacent struts are inserted into to node mounts and then the node is fixed by tightening a wing nut stuck through the center hole.

Larger segments of the structure are preassembled by successively adding more elements. Since all directions and measures are predefined in the single components, the designated geometry evolves completely by itself. Due to the low friction between MDF and aluminium and the relatively poor strength of the MDF, the final rigidity of the node is only reached by driving extra screws through the node and struts.

The structure was erected in 4 major phases: 1) Megacolumn, 2) Northern canopy, 3) southern canopy, 4) central tube. The positions of all contact node elements were marked on walls and floor. Simple wall-plug hooks are sufficient for the vertical supports. Since the installation is designed as a single structural entity, final stability is only reached when the entire shape is put together.

**Membrane covering**

The radiolaria project gives some possible answers to the construction of non standard architecture, yet it also raises new questions. One is definitely the covering of such a structure. All polygons of the tesselation are non planar and demand a special solution, either with established techniques or innovative solutions.

To give a preview to further development and uses, parts of the structure were covered with a flexible textile membrane. These areas can be lit from behind to illuminate the installation or serve as a screen for beamer projections.

**Technical specifications**

The completed Radiolaria Installation is 14.5 m long, 5.1 m wide and 3.8 m high at an overall weight of
just 55.8 kg. It is assembled from 1040 nodes and 1563 struts, forming 611 polygons, 6240 screws were used.

**Reactions and perception of the project**

The Radiolaria Project was in time completed for the end semester presentation of the architecture department and received overall hugely positive feedback from colleagues and students and generally all passers-by. Most of the participating students had no experience with parametric design, freeform surfaces or CNC fabrication before, and the mass customization of individual nodes for the structure instead of flexible nodes introduced a radical new concept to them. The core feature of the project is indeed the close linking of digital and analogue work: A digital design does not stay in the computer but is immediately realized into a material object, a milled shaped, a prototype node and in the end a large, space containing structure thus making it visible to a much wider public.

**Acknowledgements**

We want to especially thank the Pfeiffer Foundation for sponsoring the project, as well as all participants of the project: Claudia Demeles, Negar Jahadi, Benjamin Koziol, Paul Kwant, Alexander Löhr, Virginia Marini, Tamas Ozvald, Carla Ottaviana, Niklas Rahmlow, Gergana Stavreva, Jan Weissenfeldt.

**References**

Okabe A.: Spatial Tessellations: concepts and applications of Voronoi diagrams (Chichester: Wiley 2000 (2nd Edition)).