ARCHITECTURE OF BUILDINGS AND STRUCTURES. CREATIVE CONCEPTIONS OF ARCHITECTURAL ACTIVITY

UDC 72.01

S. A. Stessel'

IMPLEMENTATION OF COMPUTER MODELING METHODS IN THE DESIGN OF NONLINEAR ARCHITECTURE OBJECTS

Scientific Research and Construction Institute for Civil Construction LTD «LENNIIPROYEKT»
Russia, Saint-Petersburg, tel.: +7-921-55-77-947, e-mail: siarheistsesel@gmail.com
Leading Architect M-3

Statement of the problem. A systematization of modern computer-based methods of envelope surface geometrical modeling (system of bearing structures and enclosure which form exterior face surfaces) which are used in nonlinear architecture is necessary. Consideration of problems of geometrical surfaces which can be used as a base of spatial structures and coverings.

Results. A comprehensive analysis of possible variants of complex form computer modeling in nonlinear architecture has been developed. The methods have been described which allow a designer to create on the basis of specified geometrical model parameters. The work also features a study of their physical characteristics by means of numerical procedure and visual effects generation of complex computation. Possible ways of effective implementation of computer modeling capabilities have been outlined. The method can be used to tackle a wide range of design projects.

Conclusion. The main types of envelope forming in architecture of buildings and structures have been determined, the method of optimization of complex forms surface modeling process in architectural design has been proposed.

Keywords: nonlinear architecture, geometric modeling, methods of surface modeling.

Introduction

Architects these days are making use of new software model of designing shape as there are more and more powerful technologies offering countless opportunities. Obviously in modern architecture complex shapes are becoming more aesthetically appealing with calculation software dealing with them increasingly easier.

According to Professor of the History of Architecture and Technology at the *GSD* Antoine Picon, computing technology should now be viewed as a cultural phenomenon that has fundamentally changed a modern lifestyle around the world. It is now not about whether it is good or bad to use computing technology in engineering practices but about which way architecture will take influenced by it [1].

It is becoming increasingly important to design spatial computer models to detect and understand shape generated by abstract ideas in painting, biology and mathematics or non-linear sciences. Modern architectural objects are so important that they could not be designed employing traditional methods. A lot of research has to be done prior to designing them, mathematical algorithms and logical conditions meeting specific requirements have to be created. There are still constructional, aesthetical, functional aspects to this. However, a shape does not just have to be designed but also modelled and strategically described.

It is first of all in human's mind where modelling takes place, a general conception is used for mental images and then they take shape using a computer model. It should be noted that an advantage of a computing approach is that the technology of modelling itself is capable of transforming the original image.

There are a lot of factors influencing search of an optimal solution of the shape of a envelope. It is mostly based on functional and technological as well as compositional and planning tasks at hand. Aesthetics is of importance as well, which involves searching for an expression, perfect general proportions, rhythmic divisions (glazing and cladding "grid") of the envelope surface. A good choice of the envelope shape assists the solution of construction tasks. It was a Spanish engineer A.Torroja argued that the best structure is the one that is reliable due to its shape but not the strength of its material [2].

Computer modelling and graphics are underpinned by two fundamental subjects, i.e. analytical geometry and optics brought together by the art of programming [3]. The tools are software complexes *CAD, CAM, CAE,* etc. A common element of all of these systems is a mathematical model of the geometry of an object being designed. A theoretical foundation of geometric modelling is differential and analytical geometry, variational calculation, topology and areas of computational mathematics [4]. A shape in computational mathematics is designed based on geometric parameters of structures and envelopes specified according to surfaces. A theoretical researcher of architecture J. Kipnis wrote: "No cultural practice owes so much to a technological apparatus of another practice as architecture does to geometry" [5].

1. Classification of surfaces. In order to get a full insight into a variety and properties of surfaces that can be designed by means of geometric modelling, their classification has to be studied.

There is currently a number of types of classifications of surfaces. In descriptive geometry surfaces are commonly divided into two major types – smooth and folded. In differential geometry depending on the Gaussian curvature there are surfaces with negative curvature (hyperboloids), with zero curvature (cylinders) and with positive curvature (spheres).

Depending on the method of designing a shape, there can be the following groups of surfaces: transfer, rotation, linear, non-linear and combined ones. Groups of linear surfaces can be developable (cone-shaped, torse, cylindrical) and skewed (with two or three guides) and non-linear ones can be quadratic, cyclic, high-order surfaces and transcendental [6]. A detailed classification of surfaces (Fig. 1) set forth by S.N. Krivoshapko and V.N. Ivanov includes 38 types consisting of subtypes (they are not included in the Figure) [7].

1	**Linear**	**14**	**Peterson surface**	**27**	**Special profiles of cylindrical items**
2	**Rotation surfaces**	**15**	**Bessie surface**	**28**	**Bone surface**
3	**Transfer surfaces**	**16**	**Quasiellipsoid surfaces**	**29**	**Edlinger surface**
4	**Cutting surfaces**	**17**	**Cyclical surfaces**	**30**	**Coons surface**
5	**Surfaces of congruent sections**	**18**	**One-sided surfaces**	**31**	**Harmonic surfaces based on lines**
6	**Continuous topographical and topographical surfaces**	**19**	**Minimal surfaces**	**32**	**Joachimsthal surface**
7	**Helicoidal surfaces**	**20**	**Einsteinium minimal surfaces**	**33**	**Saddle surfaces**
8	**Spiral surfaces**	**21**	**Surfaces with a spherical guide**	**34**	**Kinematic general surfaces**
9	**Helical surfaces**	**22**	**Weingarten surfaces**	**35**	**Second-order surface**
10	**Helical-shaped surfaces**	**23**	**Surfaces with a constant Haussian curvature**	**36**	**Algebraic surfaces of higher than the second order**
11	**Blutel surface**	**24**	**Surfaces with a constant average curvature**	**37**	**Quasipolyhedrons**
12	**Veronese surface**	**25**	**Wave-shaped, wavy, corrugated, ribbed surfaces**	**38**	**Equidistances of double systems**
13	**Tsitseika surface**	**26**	**Umbrella-type surfaces**		

Fig. 1. Classification of surfaces set forth by S.N. Krivoshapko and V. N. Ivanov

In terms of construction and technological designing surfaces can also be classified into graphical, spline, piecewise, fractal, pointed carcass and kinematic.

2. Types of surfaces used in software modelling. A variety of shapes developed in geometry by famous engineers and architects can be expanded and supplemented owing to the methods of designing a mathematical models of geometric objects using software modelling and visual programming.

Fig. 2 shows what the classification of surfaces depending on a method of designing in CAD and computer graphics [4].

Depending on a technology of designing a model there are two types of software modelling – surface and solid. In both cases an envelope (or a few) is/are used to describe a surface. The difference is that while in surface modelling objects are first designed and modified and then there is an envelope, in solid modelling there is first an envelope that completely describes a surface and separates an internal volume from the rest of the space.

There are different technologies of software modelling that help to specify an envelope (Table 1). Choice of a particular one depends on certain designing tasks. For example, in order to design a sample model, a sketch of a shape can be made using a digital sculpting software or an equivalent of a bionic surface using a photo of a natural object.

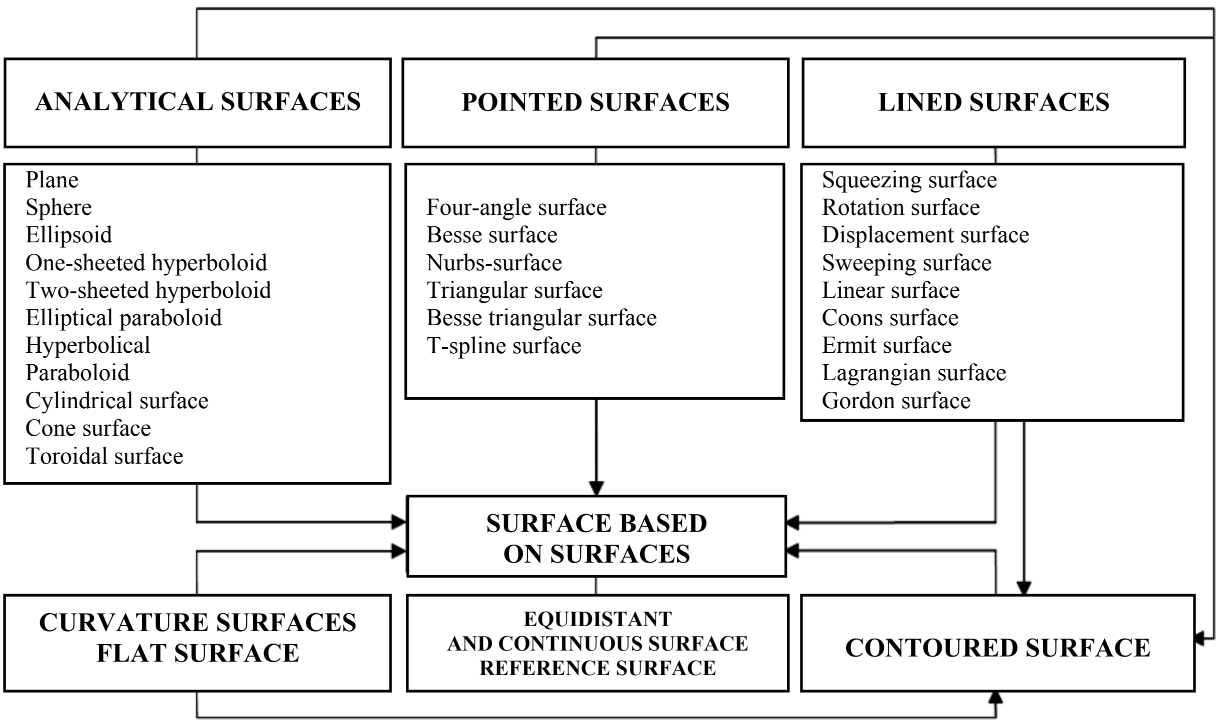


Fig. 2. Classification of surfaces in CAD and computer graphics

In order to design an accurate and detailed project of envelopes *Rhinoceros + + Grasshopper (Robert McNeel & Associates), Revit + Dynamo (Autodesk)* can be employed. By exporting the data into other applications construction calculations can be performed and models for production as well as photo-realistic visualization can be designed.

Generally in designing complex geometric objects obtained as a result of transformations of more simple ones are employed. "Transformation" is what is done with an object or their groups to create a new geometric object. What changes an object without changing its nature is called modification or editing (replacement, rotation, scaling, mirror reflection, change of a shape). Therefore editing of an object is changing its data for a constant structure. Geometric objects are described by scalar values and vectors and editing is changing scalars and vector components.

Table 1

Major technologies of three-dimensional computer modelling

Technology	Description	Software
Polygonal modelling	Cubic modelling. A shape is modelled by manipulating geometric primitives. Modelling in faces along a specified contour	*3ds Max (Autodesk), Blender (Blender Foundation)*
Modelling using curved lines	Surfaces are designed using splines, curved lines *NURBS*, curved lines *Bezier* and other tools by means of lofting, rotation, etc.	*Maya (Autodesk), Rhinoceros (Robert McNeel & Associates)*
Digital scuplting	Methods: displacement, volumetric and dynamic tessellation	*ZBrush (Pixologic), Mudbox (Autodesk)*
Parametric (procedure or algorithmic modelling)	Designing a model based on specifying parameters, shapes are generated using algorithms (using visual programming)	*Generative Components (Bentley Systems), Rhinoceros+Grasshopper (Robert McNeel & Associates)*
Image modelling	A three-dimensional object is designed using two-dimensional imaging. A point is identified considering perspective and optical distortion, the coordinates are determined and based on them a model is designed	*ImageModeler (Autodesk), Photomodeler (Eos Systems Inc)*
3D-scanning	Digital processing of real-life objects using a special equipment (coordinates of a cloud of points are used to design a polygonal or *NURBS*-surface)	*Zscan (Creaform), Cronos*

Modelling an object can include designing one of some bodies (selection) sometimes using different operations – Boolean, rounding, joining, flatting. Different modificators (bending, rotation, etc.) can be applied. It should be noted that crossing curved lines and surfaces are fundamental as there are involved in most operations on geometric objects in parametric modelling.

3. Free surfaces. Computer technologies allowing one to design complex shapes were borrowed from auto- and aviadesign. In designing *Guggenheim* Museum in Bilbao the software *CATIA* was used which is common in ship and machine building, spacecraft and military industries. Using *CATIA, Gehry Technologies* (co-finder and head F.Gehry) designed *BIM*-software package *Digital Project* for modelling so-called free surfaces. *Digital Project* is widely used in designing non-linear objects. In particular, it was employed in designing the Beijing National Stadium ("Bird's Nest"), Soumaya Museum in Mexico City, National Museum of Qatar.

Free surfaces are those different from canonic ones (a cube, plane) that can be obtained by dragging a profile along a three-dimensional curved line, designing a spline surface using control points, smooth joining of two pieces, etc. Hence technologies for designing free surfaces originally used for mechanical engineering (designing complex technical objects, e.g., blades of a turbine, an aircraft fuselage are currently employed in architectural designing while modelling envelope surfaces.

Depending on certain characteristics there are three classes of surfaces — A, B, C [8] (Table 2).

Table 2

Classification of free surfaces

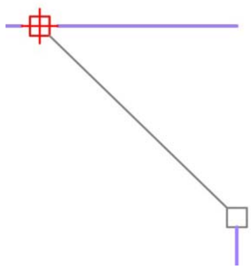
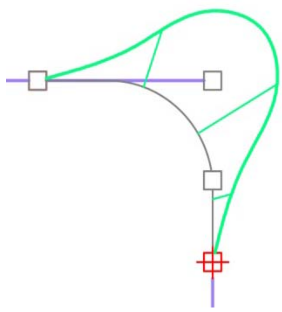
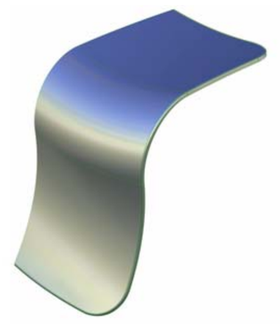
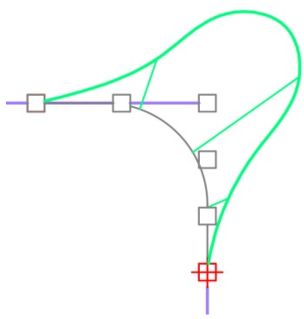
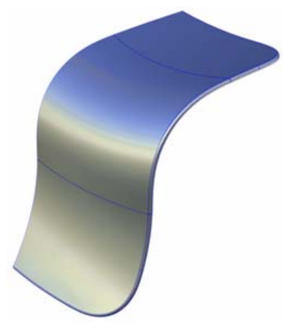
Characteristics	Class A	Class B	Class C
Distance between each point of adjoining pieces (parts of a surface)	≤ 0,01 mm	≤ 0,02 mm	≤ 0,05 mm
Angle between tangents to a surface on faces of two adjoining pieces (parts of a surface)	≤ 6´ (0, 1º)	≤ 12´ (0, 2º)	≤ 30´ (0, 5º)
Continuity (coherence) of curvature. A control parameter is curvature of a piece of a surface along its own contour	Coincidence of curvature no more than each 100 mm of the contour of adjoining pieces	No such requirement	
Final parts of a surface (invisible from the front surface)	Thoroughly developed	Rounded contours are on a surface	No such requirement
Acceptable deviation of a surface. Measured by comparison of a piece of a surface with a similar piece of an aesthetic surface	≤ ± 0,5 mm for large surfaces, ≤ ± 0,2 mm for small surfaces	≤ ± 1,0 mm for large surfaces, ≤ ± 0,5 mm for small surfaces	No such requirement

Class A surfaces (aesthetic surfaces) is a term used in designing and engineering to denote a set of free surfaces with special requirements to accuracy and quality of modelling. Particularly they are made using highly smooth pieces at joining points where not only tangents of surfaces but curvatures need to coincide (*G*2, *G*3 *curvature continuity* where 2 and 3 denote smoothness) (Table 3).

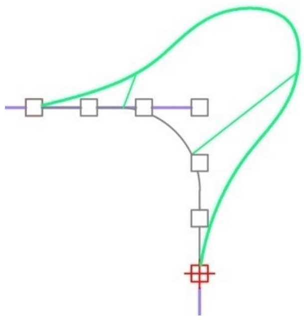
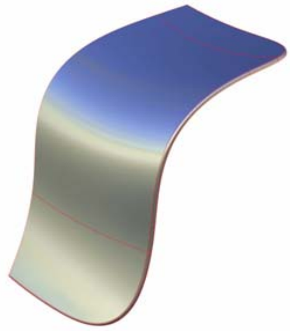
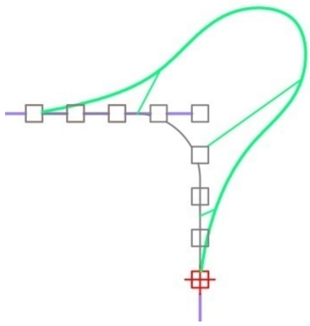
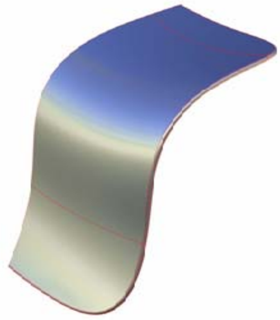
Free surfaces are designed based on modelling using curved lines by means of different operations (lofting, profile squeezing, etc.) or by editing a surface, e.g. using control points.

Table 3

Types of surface continuity

Type of surface continuity	Description	Scheme	Image
G0	Position of a point is determined not only by its position at the joining. Two curved lines come in contact at final points		
G1	Tangent determines the position and direction of a curved line at final points. Two curved lines not only come in contact but they also move in the same direction in relation to a tangent point		
G2	Continuity of curvature between two curved lines determines the position, direction and radius of curvature at final points. Curved lines at the joint do not just move in the same direction but they also have the same radius at final points		

End of Table 3

Type of surface continuity	Description	Scheme	Image
G3	There is the third requirement – planar acceleration. Curved line come in contact, move in the same direction, have the same radius at final points and it has the same smoothness level at specified points		
G4	There is the fourth requirement – smoothness of curvature is to be identical in three dimensions. It is rarely used		

Designing of a complex model in stages is based on a sequence of different manipulations (joining by welding, designing a bridge, displacement).

Systems where surfaces are designed using *NURBS*-surfaces (based on heterogeneous rational B-splines or T-splines) have become most common. In addition, the methods of designing objects using Besse, Coons and Gordon surface are employed. The properties of a free surface are specified by such parameters as control points, a number of pieces, degree (density of control points in an area).

4. Computing designing. There are a lot of fields emerging as part of non-linear architecture: parametrism, organitech, "digital barocco", landform style, etc. Different principles of designing a shape commonly rely on certain theoretical foundations: chaos, wrinkles, fractals, complexity. Shapes are designed based on different methods of conceptual computer modelling – parametric, tessellation, *L-system*, cellular rifle, swarm intelligence, chimera systems, genetic algorithms.

There can generally be two major approaches in computing designing:

– parametric / generative. Methods: algorithmic, genetic, physical simulation based on a system of agents;

– kinematic/robotics. Methods: adaptive / interactive, artificial intelligence.

The method of parametric modelling has become common in non-linear architecture. It involves use of visual programming, which is a special medium for developing algorithms with intuitively clear interface. Parametrization in software modelling allows one to design and compare a great variety of possible shapes of objects and connections between its components using changes in the parameters or geometric relations in no time. Visual programming made it possible to specify and edit the parameters of models by using similarities of diagrams and graphs of functional block schemes that determine connections between different parameters of a shape being designed.

Unlike classics and modernism where rigid geometric structures are employed and simpke geometric shapes (cube, cylinder, pyramid) are part of a composition, parametric style employs other, totally new geometric objects, e.g. spline and *NURBS*-surfaces. Construction blocks are now new systems such as metaballs, hair, bubbles that are designed and modified by means of visual programming [9]. This way a new architectural aesthetics is evolving originating from geometry, design and modern digital technologies.

Conclusions. Therefore designing a shape in non-linear architecture comes down to searching for an analytical solution of a structural shape which would be the most consistent with functional, constructional and aesthetical requirements. Modern designers normally deal with a variety of tasks. Therefore they are to make use of a variety of shape-designing and compositional methods to enhance aesthetic appeal of construction solutions. It is not surprising that a new architectural language of non-linear architecture blossomed as new digital modelling tools emerged that made a huge difference to variation of shapes. It should be noted that any (even if the most complex) shape emerges based on its geometric specification by using equations to transform into a material structure obeying the laws of physics throught its lifespan. The following was shown in the study:

1. Different types of classifications of surfaces used in software modelling have been presented that can be employed in designing non-linear objects;
2. “Free surface” and “class A surface” were defined. Types of continuity have been described;
3. A classification of the computing designing methods have been demonstrated.

References

1. Picon A. Digital Culture in Architecture: An Introduction for the Design Profession. Boston, Birkhaeuser Publ., 2010. 223 pp.
2. Fernandes J. R., Venturini W. S. Stiffened Plate Bending Analysis by the Boundary Element Method. *Computational Mechanics*, 2002, no. 28. pp. 275—281.

3. Nikulin E. A. *Komp'yuternaya geometriya i algoritmy mashinnoy grafiki* [Computer geometry and algorithms for computer graphics]. St. Petersburg, BKhV-Peterburg Publ., 2003. 560 p.
4. Golovanov N. N. *Geometricheskoe modelirovanie* [Geometric modeling]. Moscow, Izd-vo Fiz.-mat. lit., 2002. 472 p.
5. Kipnis J. Architecture after Geometry — an Anthology of Mysteries: Case Notes to the Mystery of the School of Fish. *Architectural Design*, 1997, no. 5/6, pp. 42—47.
6. Krivoshapko S. N., Mamieva I. A. *Analiticheskie poverkhnosti v arkhitekture zdaniy, konst-ruktsiy i izdeliy* [Analytical surfaces in architecture of buildings, structures and products]. Moscow, Librokom Publ., 2012. pp. 7—22.
7. Krivoshapko S. N., Ivanov V. N. *Entsiklopediya analiticheskikh poverkhnostey* [Encyclopedia of analytical surfaces]. Moscow, Librokom Publ., 2010. 560 p.
8. What is Definition of Class A Surfaces? GrabCAD. Available at: https://grabcad.com/questions/what-is-definition-of-class-a-surface
9. Shumacher P. The Autopoiesis of Architecture. Vol. 1. West Sussex, John Wiley & Sons, 2011. 461 pp.