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THE CONCEPT OF REPRESENTATION OF GEOMETRIC SOLIDS IN BUILDING INFORMATION MODELING

Evgeniy V. Konopatskiy, Maxim V. Bezsolnov

Nizhny Novgorod State University of Architecture and Civil Engineering, Nizhny Novgorod, RUSSIA

Abstract. The problem of using the boundary model of geometric solids representation in BIM is formulated. A new concept of solid geometric modeling is presented, which allows to define geometric solids as a selected part of space, according to which geometric solids are represented by an organized set of points by analogy with other geometric objects. The mathematical apparatus "Point Calculus" is used for analytical description of geometric solids. Examples of modeling geometric solids in point calculus are given. The advantages of this approach are the possibility of representation of geometric information in BIM in compact vector form and realization of parallel calculations at the level of mathematical apparatus. The prospect of further research is the use of the proposed concept for the representation of various elements of building structures with the subsequent optimization of the representation of geometric objects in the IFC format. This will significantly reduce the volume required for the transfer of geometric information between the systems of information modeling and computer-aided design, increase their performance and radically solve the problem of interoperability of existing BIM software packages.

Keywords: BIM, geometric modeling, solid modeling, parametric modeling, parallel computing, BREP, IFC

КОНЦЕПЦИЯ ПРЕДСТАВЛЕНИЯ ГЕОМЕТРИЧЕСКИХ ТЕЛ В ТИМ

Е.В. Конопацкий, М.В. Безсольнов

Нижегородский государственный архитектурно-строительный университет, Нижний Новгород, РОССИЯ

Аннотация. Сформулирована проблема использования граничной модели представления геометрических тел в ТИМ. Представлена новая концепция твердотельного геометрического моделирования, которая позволяет определять геометрические тела в виде выделенной части пространства, в соответствии с которой геометрические тела по аналогии с другими геометрическими объектами представляются организованным множеством точек. Для аналитического описания геометрических тел используется математический аппарат «Точечное исчисление». Приведены примеры моделирования геометрических тел в точечном исчислении. Преимуществами такого подхода является возможность представления геометрической информации в ТИМ в компактной векторной форме и реализация параллельных вычислений на уровне математического аппарата. Перспективой дальнейших исследований является использование предложенной концепции для представления различных элементов строительных конструкций с последующей оптимизацией представления геометрических объектов в формате IFC. Это позволит в значительной мере сократить объём необходимый для передачи геометрической информации между системами информационного моделирования и автоматизированного проектирования, повысить их быстродействие и радикально решить проблему интероперабельности существующих ТИМ в строительной отрасли.

Ключевые слова: ТИМ, геометрическое моделирование, твердотельное моделирование, параметрическое моделирование, параллельные вычисления, BREP, IFC

INTRODUCTION

Modern society is rapidly entering the information age. One of the areas of active implementation of information systems is the construction industry. Being conservative by nature, the construction industry imposes special requirements to software products for information modeling of buildings and structures. Such models contain a huge number of components, so in the process of working with them there is a need to operate huge amounts of information in real time. This necessity arises not only at the stage of creating a model of the object in the form of a full-fledged digital twin of capital construction objects, but also for its support at all stages of the life cycle. Existing domestic and foreign BIM are well suited for solving engineering problems with a limited number of construction objects and at this stage cannot provide the necessary performance to create a full-fledged digital twin at the level of neighborhood, district, city or region.

Another disadvantage is the lack of a single integrated software for construction and architecture, combining the capabilities of BIM and CAE. This leads to the need to import information models of capital construction objects into calculation complexes and is the source of the next problem associated with insufficient interoperability of domestic and foreign BIM and CAE. In addition, there are certain problems with the continuity of information models for different versions of the same software product, which significantly complicates digital support of construction objects at all stages of the life cycle, which, unlike software product versions, is counted in decades.

Many of the above-mentioned problems are related to the limited possibilities of representation of geometric information about the shape and position of objects in three-dimensional space or, in other words, the geometric core of BIM. At the moment there are several types of representation of geometric models, which include point, wireframe, boundary, structural and voxel models. The use of point and wireframe models is fraught with significant drawbacks. For example, the computational burden is high. Since the representation of even one geometric solid in the form of a point cloud can load a rather powerful computer. It is simply impossible to operate a set of them in real time. Therefore, the most widely used in BIM is the boundary model [1], which in foreign literature sources is represented by the abbreviation BREP (Boundary REPresentation) or B-rep [2-4]. If we use the CSG structural model, the result is still the representation of a geometric solid in the form of a closed shell [5-7].

Note that it is geometrically incorrect to call a closed shell a full-fledged solid model. This is just such a common convention, which is nevertheless widely used, including the popular data representation format IFC [8], which since 2019 is included in the National Standard of the Russian Federation [9]. All the more so that in computer-aided engineering (CAE) systems realized on the basis of the finite element method [10-12], it is often the volumetric finite elements that are used.

Ideologically the closest to the description of real geometric solids is the voxel model [13-15]. It provides representation of objects as a three-dimensional array of volumetric (cubic) elements. In essence, the voxel geometric model is a generalization of the pixel (raster) model for three-dimensional space and inherited all the disadvantages of raster models, which include:

– large amounts of information required to present voluminous data;

– significant memory overhead;

– a set of problems related to enlarging or reducing images.

In contrast to all of the above approaches, a fundamentally new concept of geometric solids definition was proposed in [16-18], which is devoid of the described disadvantages and can become an effective basis for the creation of high-performance BIM of the new generation.

1. METHODS

According to [19], a solid in geometric modeling is a connected set of points located on the inner side of one outer shell and several inner shells located inside the outer shell, together with the points of these shells. This definition is too complicated to understand and requires explanation of additional terms. But its meaning boils down to the fact that a solid is represented as a closed shell. In English-language literature there is a different but similar in meaning definition of a solid in the form of a closed shell (B-Rep): "A solid is represented as a collection of connected surface elements, which define the boundary between interior and exterior points.". The same approach is described in other works related to the representation of geometric solids in various information modeling and computer-aided design systems.

In contrast, in [16-18] a fundamentally new concept of defining geometric solids as a three-parameter set of points belonging to three-dimensional space was proposed, based on which the point equations of the set of prismatic, pyramidal, cylindrical, conical, spherical, elliptic and toroidal solids in the point calculus were derived.

What is the new concept based on? The simplest of geometric objects is a point. The point itself does not even have a size. It is a geometric analog of an infinitesimal value. However, using a set of points, it is possible to obtain geometric objects of any degree of complexity. As our organism consists of atoms, so any geometrical object of any space can be described by an organized set of points.

Let's consider examples and for this purpose first answer the question - what is the difference between a circle and a circle? In the first case it is a closed curve, in the second case it is an area inside a closed curve or, in other words, a selected part of the plane inside a circle. Generalizing to three-dimensional space, we get the definitions of sphere and ball. As in the plane case, the difference between these geometric objects is that a sphere is a closed shell, and a sphere is the set of all points of three-dimensional space bounded by a sphere, or, in other words, a selected part of three-dimensional space bounded by a sphere. As can be seen from the above examples, geometric solids and surfaces are completely different geometric objects that cannot be identified. Moreover, in [16-18] it is convincingly shown by examples that a surface is a two-parameter set of points, and a geometric solid in three-dimensional space is a three-parameter set. In both cases we are talking about variables or current parameters.

One of the possible realizations of the new concept is the use of multidimensional interpolation tools [20-22]. However, in the absence of the mathematical apparatus of point calculus, which allows any geometric object to be represented as an organized set of points, these works do not implement full-fledged solid models, but models based on parametric porous objects. Significantly better results are given by the geometric theory of multidimensional interpolation [23], already based on the use of the mathematical apparatus of "Point Calculus", which is ideologically better suited for analytical representation of solid models of geometric solids.

There is an opinion that solid models cannot be described by an equation. If we consider only a set of equations in explicit form, this is indeed true. And this is due to the fact that one of the axes of the coordinate system is used as a function. Accordingly, the number of variables of an explicit equation is always one less than the dimensionality of the space in which the geometric object is defined. At the same time, the point calculus, which uses the apparatus of projection on the axes of the global coordinate system, allows to use all coordinate axes, the system of which defines the space of the required dimension. This makes it possible to obtain equations of geometrical solids by means of simple arithmetic operations on coordinates of points and functions from parameters. It is important that the number of parameters corresponds to the dimensionality of the space.

Let's consider an example. One of the most commonly used geometric objects in BIM is a parallelepiped. Parallelepiped is used to model walls, floors, roofs, window and door openings, etc. If you use the BREP boundary geometric model to specify the parallelepiped, then for its parameterization in general case it is necessary to define 6 planes. Each of these planes should be defined with the help of geometrical objects and conditions of their mutual position. In the general case there will be 54 such parameters: 3 points for each of the 6 planes plus 3 coordinates to define each point. Of course, this is not the most optimal parameterization and the parameters can be less, but each of the parameters will have to be replaced by geometric conditions. And the programmatic implementation of each geometric condition is a computational burden on the CPU. When there are few modeled objects on the screen, this load actually remains unnoticeable. But when creating and supporting digital twins of capital construction objects with a large number of elements (for example, with a digital twin of a micro district or a city district) it will be at least uncomfortable to work with such a model. In order to provide more comfortable work, it is necessary to sacrifice the model detailing.

If we implement the proposed concept of solid modeling, in the most general case, only 12 parameters will be sufficient to unambiguously determine the shape and position of a parallelepiped. This was possible because the geometric conditions were described using simple point equations and represented in a compact vector form.

How was this realized in practice? First, a rather primitive geometrical scheme of the solid model of the parallelepiped was developed (Fig. 1).

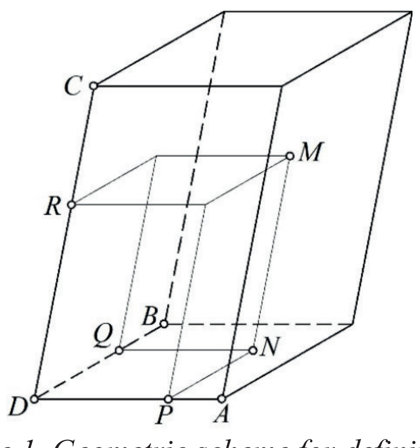

Figure 1. Geometric scheme for defining the solid model of a parallelepiped

To parameterize the solid model of the parallelepiped we will use simple relations of three points of lines DA, DB and DC on its sides (Fig. 1):

$$u = \frac{DP}{DA},\ v = \frac{DQ}{DB},\ w = \frac{DR}{DC}.$$

As a result, we have three point equations of straight lines:

$$P = (A - D)u + D,\ Q = (B - D)v + D,$$
$$R = (C - D)w + D.$$

To determine the current point M of the desired three-parameter set of points, we use the pointwise parallel transfer formula twice:

$$\begin{cases} N = P + Q - D \\ M = R + N - D \end{cases} \Downarrow \quad (1)$$
$$M = (A - D)u + (B - D)v + (C - D)w + D.$$

Equation (1) A, B, C, D – are contains the initial points, which not only form a local simplex of the three-dimensional space to determine the desired set of points, but also uniquely determine the position and dimensions of the parallelepiped in the global coordinate system. The parameters u, v, w in the proposed parameterization (Fig. 1) vary from 0 to 1, ensuring that the interior of the parallelepiped is filled with points.

Using the properties of the point calculus, we can represent equation (1) in another, more compact, form:

$$M = Au + Bv + Cw + D(1 - u - v - w).$$

These two forms of representation of geometric objects in the point calculus are completely identical and can always be derived one from the other. The choice of the form of representation of the point equation depends on the particular problem and is determined solely by the convenience of use.

It should be noted that the points A, B, C, D, M in equation (1) are coordinate vectors. The number of coordinates depends on the dimensionality of space. Transitioning to the coordinate form for three-dimensional space, we obtain the following system of parametric equations:

$$\begin{cases} x_M = x_A u + x_B v + x_C w + x_D \left(1-u-v-w\right) \\ y_M = y_A u + y_B v + y_C w + y_D \left(1-u-v-w\right). \\ z_M = z_A u + z_B v + z_C w + z_D \left(1-u-v-w\right) \end{cases} \quad (2)$$

Thus, for unambiguous determination of all parameters of position and shape of the parallelepiped solid model in the global coordinate system, only 12 parameters were needed without exception.

Note that all equations of the system (2) are completely identical except for the coordinates of the points. If each of the equations of the system (2) is assigned a separate thread for computation, we will get the result 3 times faster. With this approach, the computational threads are completely balanced. They start and end at the same time, performing the same number of computational operations. This minimizes the downtime of a multi-core processor and optimizes its computational load.

Of course, this is not the only possible parameterization of the solid parallelepiped model. Besides, it should be noted that in equations (1) and (2) the parameters u, v, w change linearly. But the same parameters can also change nonlinearly. Then, by controlling the functions of the parameters, it is possible to construct a non-uniform distribution of points inside a geometric solid and thus model anisotropic geometric solids. Using this approach, it is possible to determine physical properties by means of geometrical solids with non-uniform distribution of points inside the geometrical solid.

The described solid parallelepiped model is a general case of representation of geometrical solids as a selected part of three-dimensional space. In other words, it is a generalization of the BREP boundary model, which can be obtained by fixing the boundary values of the parameters u, v, w:

$$\begin{aligned} u=0 &\Rightarrow BCD. & u=1 &\Rightarrow \alpha \square BCD. \\ v=0 &\Rightarrow ACD. & v=1 &\Rightarrow \beta \square ACD. \\ w=0 &\Rightarrow ABD. & w=1 &\Rightarrow \gamma \square ABD. \end{aligned}$$

Similarly, we can obtain the frame geometric model by simultaneous fixation of two parameters, thus determining all 12 edges of the parallelepiped (Fig. 1). At simultaneous fixation of three parameters, we obtain all 8 nodal points of the parallelepiped, including initial points A, B, C, D. By changing the parameter values from 0 to 1, we can obtain a point geometric model in the form of a cloud of discrete points.

Note that the proposed concept is not limited to geometric solids of simple shape. The same concept can be used to model more complex geometric solids. For example, Figure 2 shows a visualization of a solid model of a channel surface, whose axis is a transcendental curve and whose constituent is a closed curve of the "sinusoid" type, whose axis is a circle.

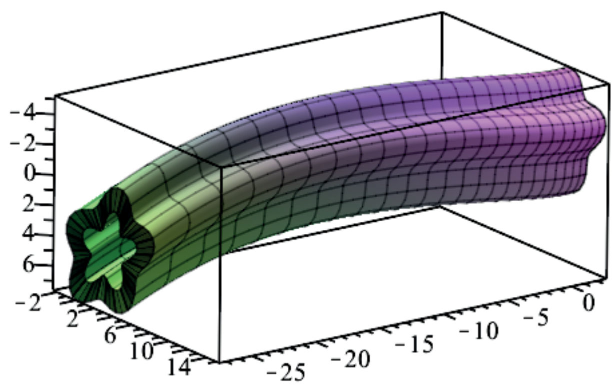

Figure 2. Visualization of the solid model of the channel surface

2. RESULTS AND DISCUSSION

Comparing the proposed solid modeling concept with existing approaches and methods, we highlight several aspects.

1. A distinctive feature of the proposed concept compared to existing methods is the representation of solid models in the form of an organized set of points, where the dimensionality of the space coincides with the number of current parameters.
2. Voxel geometric models are close in their ideology to full-fledged solid modeling. The proposed concept of modeling geometric solids as an organized set of points can be defined as a vector representation of voxel models. After all, if the size of a voxel is set to infinitesimal, it becomes a point, and we ideologically come to the description of geometric objects as an organized set of points, but at the same time we get rid of the above-described disadvantages of the voxel model. Thus, we will get a vector geometric model of solid, which is more preferable in BIM compared to the raster model because it provides a more convenient and compact approach to the use and storage of geometric information.
3. Another ideologically similar approach is the use of finite element methods, finite volumes, boundary elements, etc. In engineering mechanics, it is called analytical solid modeling [24]. It is more related to engineering calculations than to information modeling in construction. If the size of a volumetric element tends to an infinitesimal value (to a point), we will obtain a point solid model, which is close in its meaning to the proposed one, but the computational complexity of the finite element method will tend to infinity and remain unattainable for modern computing systems. At the same time, these same models are described by simple vector equations in point calculus and can be effectively used to calculate the stress-strain state of elements of building structures, buildings and structures. In addition, the proposed concept opens new possibilities for modeling thermal, sound, light, electric, magnetic and other fields.
4. In [25], equations in homogeneous coordinates similar to the system of equations (2) are given. It is noted that they describe the mapping of a linear tetrahedron. As an argument, a verification of the equation using the nodal points of the tetrahedron is given. In Figure 1, these are the points A, B, C, D. Note that if a nodal mesh is created to solve the problem and only the nodes of this mesh will be used in the calculation, then this statement is valid and gives the desired result. But if the parameters are variable, then we will get exactly the solid model of a parallelepiped. It is easy to check this if we substitute the values of the parameters $u=1,\ v=1,\ w=1$ for the system of equations (2). Then the obtained point will be outside the tetrahedron $ABCD$ and will form one of the vertices of the parallelepiped built on its basis.
5. As can be seen from equations (1) and (2) solid models of geometric solids in the point calculus are defined directly in the space in which they are located. This approach allows us to fully realize the new paradigm of three-dimensional design and eliminates the need to use transformation matrices, since all the necessary information about the shape and position of a geometric solid is contained in a rather compact form.

CONCLUSIONS

The proposed approach is very science-intensive and at the moment it has not been fully investigated. Since in fact the mathematical apparatus of vector representation of a new class of geometric objects, previously unexplored, is proposed. But already at this stage it is possible to highlight the advantages of the proposed approach and the prospects for its further use in information modeling of capital construction objects:

1. A new concept of solid modeling directly in three-dimensional space.

2. New methods for storing geometric-graphic information based on the use of compact point equations and computational algorithms based on them.
3. No need to use transformation matrices.
4. Realization of parallel calculations on data at the level of mathematical apparatus "Point Calculus".
5. Realization of parallel computations on tasks due to the use of constructive algorithms of geometric modeling on projective and affine basis.
6. New methods for calculating the stress-strain state of solids based on functionally controlled anisotropy and alternative to the finite element method.
7. Replacing voxel models with vector models.

And this is by no means a complete list of the opportunities that the proposed concept opens up for BIM.

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Evgeniy Viktorovich Konopatskiy – Doctor of Engineering, Docent, Director of the Institute of Information Technology, Head of the Department of Engineering Graphics and Information Modelling, Federal State Budgetary Educational Institution of Higher Education "Nizhny Novgorod State University of Architecture and Civil Engineering" (NNSAGU), 603000, Nizhny Novgorod, Ilyinskaya str., 65, e-mail: e.v.konopatskiy@mail.ru, +7(831)434-02-91.

Евгений Викторович Конопацкий – д-р техн. наук, доцент, директор института информационных технологий, заведующий кафедрой инженерной графики и информационного моделирования, Федеральное государственное бюджетное образовательное учреждение высшего образования «Нижегородский государственный архитектурно-строительный университет» (ННГАСУ), 603000, г. Нижний Новгород, ул. Ильинская, д. 65, e-mail: e.v.konopatskiy@mail.ru, +7(831)434-02-91.

Maxim Vladimirovich Bezsolnov – Postgraduate student of the Department of Engineering Graphics and Information Modeling, Federal State Budgetary Educational Institution of Higher Education "Nizhny Novgorod State University of Architecture and Civil Engineering" (NNSAGU), 603000, Nizhny Novgorod, Ilyinskaya str., 65, e-mail: bezsoff@yandex.ru, +7(831)434-02-91.

Максим Владимирович Безсольнов – аспирант кафедры инженерной графики и информационного моделирования, Федеральное государственное бюджетное образовательное учреждение высшего образования «Нижегородский государственный архитектурно-строительный университет» (ННГАСУ), 603000, г. Нижний Новгород, ул. Ильинская, д. 65, e-mail: e.v.konopatskiy@mail.ru, +7(831)434-02-91.