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Kovtun A.

INVESTIGATION OF THE ALGORITHM FOR CONSTRUCTING SMOOTH SPATIAL CURVES WITH THE ABILITY TO SPECIFY THE CURVATURE AND TORSION AT THE NODAL POINTS

Розроблено спосіб побудови сплайна сьомого ступеня з наперед заданими значеннями кривизни і скруту (використовувався сегмент з двох точок і двох перших, других і третіх похідних на кінцях сегмента). Застосовано новий спосіб контролю форми обводу, що був отриманий шляхом завдання значень кривизни і скруту (як функцій від першої, другої і третьої похідної).

Ключові слова: *сегмент, заданий двома точками і двома першими, другими і третіми похідними, гладкість відповідного ступеня.*

1. Introduction

Such variants of analytical representation of curved lines (contours) are known and have application:

a) on the basis of the Ferguson function (1);

b) on the basis of the Bezier function (2), (3);

c) on the basis of rational functions (4), (5).

Cubic parametric curves in the Ferguson form are written in the form (Fig. 1):

$$r = r(u) = r(0)\alpha_0(u) + r(1)\alpha_1(u) + r'(0)\beta_0(u) + r'(1)\beta_1(u), \tag{1}$$

where $r(0)$, $r(1)$ – vectors of given two points; $r'(0)$, $r'(1)$ – tangent vectors at given points; u – a parameter ranging from 0 to point 1 varying from 0 to 1; $\alpha_0(u)$, $\alpha_1(u)$, $\beta_0(u)$, $\beta_1(u)$ – functions of the third power of the parameter u:

$$\alpha_0(u) = 1 - 3u^2 + 2u^3,$$
$$\alpha_1(u) = 3u^2 - 2u^3,$$
$$\beta_0(u) = u - 2u^2 + u^3,$$
$$\beta_1(u) = -u^2 + u^3.$$

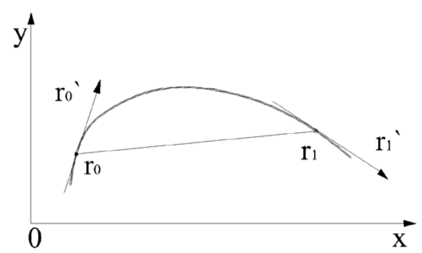

Fig. 1. Cubic parametric curve in the Ferguson form

As can be seen in Fig. 1, the controlling factors are two points and tangent vectors in them. On the basis of a curve in the Fergusson form, vector-parametric cubic splines are constructed.

In the practice of constructing curvilinear contours, it is not always possible to define tangent vectors, and, moreover, to determine the necessary length, which affects the shape of the curve. As a rule, in engineering, the primary data is a point series of points without tangents.

Cubic curves in the Bezier form (Fig. 2) have the form:

$$r = r_0(1-u)^3 + 3r_1u(1-u)^2 + 3r_2u^2(1-u) + r_3u^3, \tag{2}$$

where r_0, r_1, r_2, r_3 – vectors of the points 0, 1, 2, 3; u – a parameter ranging from 1 to 3 varying from 0 to 1.

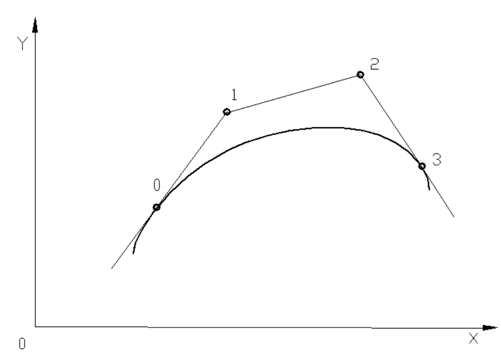

Fig. 2. Vector-parametric curve in the Bezier form

As can be seen in Fig. 2, points 1 and 2 do not lie on the curve, and the vectors 01 and 23 are tangent to the curve at points 0 and 3.

This kind of curve also does not always satisfy the design requirements in the case when there are no tangents to the curve.

In addition to the cubic curve, the Bernstein-Bezier polynomial curves are also known:

$$r = r(u) = \sum_{i=0}^{n} \frac{n!}{(n-i)!i!} u^i (1-u)^{n-i} r^i. \tag{3}$$

These curves generalize the cubic Bezier curve to higher degrees, but there is also no simple and reliable way to obtain a curve with a predefined curvature and torsion, which complicates the design of the channel surfaces.

In addition, the FFD (Free Form Deformation) method is created based on Bezier curves. This is a method of arbitrary shape deformation, where the controlling factors for the formation of a geometric body are points that do not all lie on the surface of the body.

A generalization of the Bezier curve is a rational curve. Let's give the formulas for the curve of the second and third orders:

$$r=\frac{w_0 r_0(1-u)^2+2w_1 r_1 u(1-u)+w_2 r_2 u^2}{w_0(1-u)^2+2w_1 u(1-u)+w_2 u^2}. \quad (4)$$

$$r=\frac{w_0 r_0(1-u)^3+3w_1 r_1 u(1-u)^2+3w_2 r_2 u^2(1-u)+w_3 r_3 u^3}{w_0(1-u)^3+3w_1 u(1-u)^2+3w_2 u^2(1-u)+w_3 u^3}. \quad (5)$$

In these curves, unlike the Bezier curves, it is possible to control the «weights» w_i, which ensures the shape of the curve. In general, they have the same shape as the Bezier curves, and they are not always convenient for the designer either.

Thus, it can be seen that the next study is relevant in the development of other variants of representing algebraic curves, namely: with the help of given two points with known curvature and torsion. This makes it possible to construct a real object more conveniently. And it is possible to control the curvature, torsion and smoothness. That gives additional advantages in the design of smooth channel surfaces.

2. The object of research and its technological audit

The object of research is a mathematical apparatus for describing smooth spline spatial curves given by two points with curvature and torsion values known in them. One of the most problematic places in this apparatus is the imperfection of algorithms used to construct smooth contours – the tendency of existing splines to oscillate (waveform). The reason for this is the insufficient number of works and studies (especially on splines with a predetermined curvature and torsion curve), which make it possible to improve the situation.

To identify the features of the development of spline functions with the curvature and torsion values given at the reference points, a technological audit is conducted. The purpose of the audit is investigation of the ability of this type of splines to give a shape suitable for the design of overpasses for bulk and liquid objects, exhaust manifolds of internal combustion engines, etc. Essential assistance to the developer can be provided by the ability to specify additional conditions: curvature and torsion curves, to adjust the shape of the spline in accordance with the solved problem. The study has a bias towards the practical application of special spline functions and is more closely related to the demands of CAD users, offering additional capabilities to the designer.

3. The aim and objectives of research

The aim of research is development and improvement of the existing mathematical apparatus, which will allow to more accurately and «adequately» set the task to display objects of the real world. This is especially important for the description of channel surfaces in the design of product pipelines that conduct bulk and liquid masses, exhaust manifolds of internal combustion engines, gas turbine engines, etc. That is, for describing real objects, which are subject to increased requirements for compliance with curvature and torsion.

To achieve this aim it is necessary to accomplish the following tasks:

1. To derive a formula for calculating a vector-parametric segment of the seventh power (with two end points, two first, second and third derivatives in them).
2. For given points, values of smoothness, curvature and torsion in them (all of them are a function of the corresponding or mixed derivative), to obtain a vector-parametric segment with the necessary properties for the developer.

4. Research of existing solutions of the problem

Among the main directions of constructing smooth channel surfaces in the resources of the world periodicals, the following trends, used for the analytic representation of smooth surfaces, are revealed, and also the «classical» literature of analytic geometry is used. Such approaches to the solution of the problem can be singled out [1–6]:

– analytical surfaces;
– Coons surfaces;
– Bezier surfaces;
– spline surfaces;
– Hermite surfaces;
– Gordon surfaces;
– transition surfaces;
– rational surfaces;
– NURBS surfaces.

Each of this is not a complete list of these methods has its own disadvantages and advantages, not invented a universal, «magic» method. Usually it is necessary to «pay» for each of the advantages, choosing from the existing algorithms the most suitable tools.

In [7–10], studies are given in which attempts are made to construct vector-parametric segments (and on their basis and portions of surfaces) with «special properties». Successful attempts to obtain a smooth curve with the necessary properties, linking the properties of the segment to the values of curvature and torsion, were not done. With the same success, studies were carried out for pipelines [11]. Attempts were made to control curvature and torsion in the design of NURBS.

The paper proposes a new algorithm for controlling the curvature and torsion of the curve at the development stage. This will enable the designer to more easily and accurately fulfill the technical task.

5. Materials and methods of research

Vector-parametric curves are given in the form $r=r(u)$, which means: for each coordinate there are separate curves, namely:

$$x=x(u),\ y=y(u),\ z=z(u).$$

When specifying a point series, specific values of the parameter u are arbitrarily assigned at each point. The simplest way is to assign values of u that are equal to the ordinal number of the point, that is, $u_i = i$, $i = 0, 1, \ldots, N$. In this case, the spline equations are greatly simplified, since points with respect to the parameter u are located uniformly (this does not mean that they are evenly distributed in space). In addition, the distance between points in the parameter u is equal to one, that is:

$$u_{i+1} - u_i = (i+1) - i = 1.$$

But more appropriate is the assignment of the parameter u, which is equal to the real distance in space, that is:

$$u_{i+1} - u_i = \sqrt{\left(x_{i+1} - x_i\right)^2 + \left(y_{i+1} - y_i\right)^2 + \left(z_{i+1} - z_i\right)^2},$$

where u_i and u_{i+1} – parameters at the point i and $i+1$; x_i, x_{i+1}, y_i, y_{i+1} – the coordinates of the node points.

In this case, it is necessary to solve the system of equations for splines, taking into account the unevenness of the arrangement of points.

6. Research results

It is obvious that a polynomial of the seventh degree is given by eight coefficients, or eight geometric conditions.

Let's propose a variant of describing these conditions, for which it will find a polynomial function of the seventh power in the form:

$$\begin{aligned} y = {} & \alpha_0(u)y_0 + \alpha_1(u)y_1 + h\left[\beta_0(u)y'_0 + \beta_1(u)y'_1\right] + \\ & + h^2\left[\gamma_0(u)y''_0 + \gamma_1(u)y''\right]_1 + h^3\left[\delta_0(u)y'''_0 + \delta_1(u)y'''_1\right], \end{aligned} \quad (6)$$

where y_0, y_1 – given ordinates of the points 0, 1; y'_0, y'_1 – given first derivatives at the points 0, 1; y''_0, y''_1 – given second derivatives at the points 0, 1; y'''_0, y'''_1 – given third derivatives at the points 0, 1; $h = (x_1 - x_0)$ – the difference between the abscissa of the points 0, 1; $u = (x - x_0)/(x_1 - x_0)$ – the parameter, Fig. 1.

$\alpha_0(u)$, $\alpha_1(u)$, $\beta_0(u)$, $\beta_1(u)$, $\gamma_0(u)$, $\gamma_1(u)$, $\delta_0(u)$, $\delta_1(u)$ – functions of the seventh power of the parameter u.

Let's find the functions of the seventh power in the form:

$$\alpha_0(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\alpha_1(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\beta_0(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\beta_1(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\gamma_0(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\gamma_1(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\delta_0(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7;$$

$$\delta_1(u) = a + bu + cu^2 + du^3 + eu^4 + fu^5 + ju^6 + ku^7.$$

To find the functions of the seventh power, substituting the values of the polynomials at the nodal points, let's obtain:

$$\begin{array}{llll}
\alpha_0(0)=1 & \alpha_0(1)=0 & \alpha'_0(0)=0 & \alpha'_0(1)=0 \\
\alpha_1(0)=0 & \alpha_1(1)=1 & \alpha'_1(0)=0 & \alpha'_1(1)=0 \\
\beta_0(0)=0 & \beta_0(1)=0 & \beta'_0(0)=1 & \beta'_0(1)=0 \\
\beta_1(0)=0 & \beta_1(1)=0 & \beta'_1(0)=0 & \beta'_1(1)=1 \\
\gamma_0(0)=0 & \gamma_0(1)=0 & \gamma'_0(0)=0 & \gamma'_0(1)=0 \\
\gamma_1(0)=0 & \gamma_1(1)=0 & \gamma'_1(0)=0 & \gamma'_1(1)=0 \\
\delta_0(0)=0 & \delta_0(1)=0 & \delta'_0(0)=0 & \delta'_0(1)=0 \\
\delta_1(0)=0 & \delta_1(1)=0 & \delta'_1(0)=0 & \delta'_1(1)=0
\end{array}$$

$$\begin{array}{llll}
\alpha''_0(0)=0 & \alpha'''_0(0)=0 & \alpha''_0(1)=0 & \alpha'''_0(1)=0 \\
\alpha''_1(0)=0 & \alpha'''_1(0)=0 & \alpha''_1(1)=0 & \alpha'''_1(1)=0 \\
\beta''_0(0)=0 & \beta'''_0(0)=0 & \beta''_0(1)=0 & \beta'''_0(1)=0 \\
\beta''_1(0)=0 & \beta'''_1(0)=0 & \beta''_1(1)=0 & \beta'''_1(1)=0 \\
\gamma''_0(0)=1 & \gamma'''_0(0)=1 & \gamma''_0(1)=0 & \gamma'''_0(1)=1 \\
\gamma_1(0)=0 & \gamma'''_1(0)=0 & \gamma''_1(1)=1 & \gamma'''_1(1)=0 \\
\delta''_0(0)=0 & \delta'''_0(0)=1 & \delta''_0(1)=0 & \delta'''_0(1)=0 \\
\delta''_1(0)=0 & \delta'''_1(0)=0 & \delta''_1(1)=0 & \delta'''_1(1)=1
\end{array}$$

If rearrange all α_0, then get a system for finding it, similarly let's find α_1, β_0, β_1, γ_0, γ_1, δ_0, δ_1. For what let's choose:

$$\begin{array}{llll}
\alpha_0(0)=1 & \alpha_1(0)=0 & \beta_0(0)=0 & \beta_1(0)=0 \\
\alpha_0(1)=0 & \alpha_1(1)=1 & \beta_0(1)=0 & \beta_1(1)=0 \\
\alpha'_0(0)=0 & \alpha'_1(0)=0 & \beta'_0(0)=1 & \beta'_1(0)=0 \\
\alpha'_0(1)=0 & \alpha'_1(1)=0 & \beta'_0(1)=0 & \beta'_1(1)=1 \\
\alpha''_0(0)=0 & \alpha''_1(0)=0 & \beta''_0(0)=0 & \beta''_1(0)=0 \\
\alpha''_0(1)=0 & \alpha''_1(1)=0 & \beta''_0(1)=0 & \beta''_1(1)=0 \\
\alpha'''_0(0)=0 & \alpha'''_1(0)=0 & \beta'''_0(0)=0 & \beta'''_1(0)=0 \\
\alpha'''_0(1)=0 & \alpha'''_1(1)=0 & \beta'''_0(1)=0 & \beta'''_1(1)=0
\end{array}$$

$$\begin{array}{llll}
\gamma_0(0)=0 & \gamma_1(0)=0 & \delta_0(0)=0 & \delta_1(0)=0 \\
\gamma_0(1)=0 & \gamma_1(1)=0 & \delta_0(1)=0 & \delta_1(1)=0 \\
\gamma'_0(0)=0 & \gamma'_1(0)=0 & \delta'_0(0)=0 & \delta'_1(0)=0 \\
\gamma'_0(1)=0 & \gamma'_1(1)=0 & \delta'_0(1)=0 & \delta'_1(1)=0 \\
\gamma''_0(0)=1 & \gamma''_1(0)=0 & \delta''_0(0)=0 & \delta''_1(0)=0 \\
\gamma''_0(1)=0 & \gamma''_1(1)=1 & \delta''_0(1)=0 & \delta''_1(1)=0 \\
\gamma'''_0(0)=0 & \gamma'''_1(0)=0 & \delta'''_0(0)=1 & \delta'''_1(0)=0 \\
\gamma'''_0(1)=0 & \gamma'''_1(1)=0 & \delta'''_0(1)=0 & \delta'''_1(1)=1
\end{array}$$

Having solved the system using the Cramer method, let's define:

$$\alpha_0 = 1.0 - 35u^4 + 84u^5 - 70u^6 + 20u^7;$$

$$\alpha_1 = 35u^4 - 84u^5 + 70u^6 - 20u^7;$$

$$\beta_0 = -20u^4 + 45u^5 - 36u^6 + 10u^7;$$

$$\beta_1 = 35u^4 - 84u^5 + 70u^6 - 20u^7;$$

$$\gamma_0 = -5u^4 + 10u^5 - 7.5u^6 + 2u^7;$$

$$\gamma_1 = 2.5u^4 - 7u^5 + 6.5u^6 - 2u^7;$$

$$\begin{aligned} \varphi_0 = {} & 0.166667u^3 - 0.666667u^4 + u^5 - \\ & - 0.666667u^6 + 0.166667u^7; \end{aligned}$$

$$\varphi_1 = -0.166667u^4 + 0.5u^5 - 0.5u^6 + 0.166667u^7.$$

Thus, a vector-parametric segment is found, determined by 2 points and given the 1-st, 2-nd and 3-rd derivatives in them:

$$r(t)=\alpha_0 r_0+\alpha_1 r_1+\beta_0 r_0'+\beta_1 r_1'+\gamma_0 r_0''+ \\ +\gamma_1 r_1''+f_0 r_0'''+f_1 r_1''', \quad (7)$$

where r_0, r_1 – vectors of points 0, 1; $\alpha_0(u)$, $\alpha_1(u)$, $\beta_0(u)$, $\beta_1(u)$, $\gamma_0(u)$, $\gamma_1(u)$, $\delta_0(u)$, $\delta_1(u)$ – functions of the seventh power of the parameter u.

From differential geometry, for a vector-parametric curve in the form:

$$r=r(t);\ \ [x=x(t); y=y(t); z=z(t)].$$

Curvature is given by the formula:

$$k^2{}_1(t)=\frac{\begin{vmatrix}x'' & y''\\ x' & y'\end{vmatrix}^2+\begin{vmatrix}y'' & z''\\ y' & z'\end{vmatrix}^2+\begin{vmatrix}z'' & x''\\ z' & x'\end{vmatrix}^2}{(x'^2+y'^2+z'^2)}. \quad (8)$$

Torsion is defined by the formula:

$$k_2=\frac{(r'\,r''\,r''')}{(r'\times r'')^2},$$

where $(r'\,r''\,r''')$ – mixed product; $(r'\times r'')$ – vector product.

Obviously, torsion is real only for a three-dimensional curve, which corresponds to our case (the construction of smooth channel vector-parametric surfaces).

Let's apply the algorithm:

1. Let's set the two points r_0 and r_1 and the first derivatives in them r_0' (x_0', y_0', z_0') and r_1' (x_1', y_1', z_1').

2. Next, let's define the curvatures at these points k_0 and k_1. Let's specify the second derivatives x_0'', y_0'', x_1'', y_1''. From the formula (7) let's find z_0'' and z_1''.

3. Let's set the torsion values at these two points kr_0 and kr_1. Next, let's set the values of the third derivatives with respect to the two coordinates x_0''' and y_0''', x_1''' and y_1'''. Finally, from the formula (8) let's find z_0''' and z_1'''.

4. All the necessary input data are obtained, substitute in the formula (6).

By execution: there is a vector-parametric segment (7), and we can set the first, second and third derivatives (which automatically gives a curve of the third order of smoothness) to the discretion of the developer. In addition, it is possible to control the values of curvature and torsion even at the stage of constructing a spatial curve.

7. SWOT analysis of research results

Strengths. The strengths can be attributed to the obtained results: a vector-parametric segment is found, determined by 2 points and given by the 1-st, 2-nd and 3-rd derivatives in them. An algorithm for the vector-parametric segment has also been developed, with the 1-st, 2-nd and 3-rd derivatives being given at the discretion of the developer (which automatically gives a third-order curve of smoothness). In addition, it is possible to control the values of curvature and torsion even at the stage of constructing a spatial curve.

A new algorithm for describing smooth channel vector-parametric surfaces is investigated, useful properties of which can be used in constructing real-world objects.

Weaknesses. The weaknesses of this research are due to the small number of completed finished models performed using the method, which is explained by its novelty.

Opportunities. To the additional opportunities that ensure the achievement of the aim of the research may be attributed and the likely external factors:

– increasing demand for specialized software;

– development of smooth channel vector-parametric surfaces is an advanced direction of research, industry, especially «science-intensive» requires more and more perfect approaches and algorithms;

– research results can be integrated into CAD packages that are in demand both in Ukraine and abroad.

Threats. The threats in implementing the research results are related to the current political and economic situation, which is caused by a lack of funding, a slow upgrade of the machine and machine park, a weak introduction of heavy CAD, and so on.

Costs for enterprises promise to be small due to non-commercial type of development.

About exact analogs is not known, at least in open sources.

Thus, SWOT analysis of research results allows to identify the main directions for further development of more advanced algorithms and software, their promotion to the newly opened external and internal IT markets.

8. Conclusions

1. A formula is derived for calculating a vector-parametric segment of the seventh power (7) (with two end points, two first, second and third derivatives in them). The formula allows more flexible control over the shape of the desired spline, arbitrarily setting the initial data.

2. A vector-parametric segment (7) with the properties necessary for the developer is obtained at given points 0, 1, the curvature k_1 and torsion k_2 in them. Moreover, the smoothness of the third order is ensured automatically (by virtue of the equality of the derivatives, up to the third, at the ends of the segment). *The curvature values* k_1 and *torsion values* k_2 are a corresponding function or a mixed derivative: r', r'', r'''.

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ИССЛЕДОВАНИЕ АЛГОРИТМА КОНСТРУИРОВАНИЯ ГЛАДКИХ ПРОСТРАНСТВЕННЫХ КРИВЫХ С ВОЗМОЖНОСТЬЮ ЗАДАНИЯ КРИВИЗНЫ И КРУЧЕНИЯ В УЗЛОВЫХ ТОЧКАХ

Разработан способ построения каналовой поверхности на базе сплайна седьмой степени с наперед заданными значением кривизны и кручения (использовался сегмент из двух точек и двух первых, вторых и третьих производных на концах сегмента). Применен новый способ контроля формы получаемого обвода путем задания значений кривизны и кручения (как функций от первой, второй и третьей производной).

Ключевые слова: сегмент, заданный двумя точками и двумя первыми, вторыми и третьими производными, гладкость соответствующей степени.

Kovtun Alexander, *PhD, Associate Professor, Department of General Technical Subjects, Izmail Faculty of Odessa National Maritime Academy, Izmail, Odessa Region, Ukraine, ORCID: https://orcid.org/0000-0002-6531-2561*