MACHINE TOOL CONTROL SYSTEMS AND INTERPOLATIONS OF SPLINE TYPE

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The article focuses on a list of options for using spline interpolations, often referred to as interpolation of higher types. The article pays attention to several representatives of control systems. The issue is also conceived in relation to the preparation of the NC program by CAD/CAM, where the data is prepared for control systems. The available functions of CAD/CAM systems are very diverse. The preparation of the NC program is also related to the issue of postprocessors and therefore they are mentioned in the article as well. Let this article be a basis for those who are interested in the creation of NC programs using non-standard interpolations and serve as an introduction to this issue.

Keywords: *NC program, CAM, interpolation, control system*

1. Introduction

When using a CAD/CAM system for creating NC programs, we must have an adequate postprocessor which ensures the conversion of CL data (cutter location data) to the NC program. CL data is the output from the CAM system. The postprocessor falls within the chain in Fig. 1, which summarizes the process of an automated NC program creation process. Therefore it is necessary to respect initial conditions given by the other blocks in the chain next to the postprocessor. Fig. 1 is an attempt to illustrate the fact that the postprocessor is not necessarily part of the CAM system (although CAM producers strive for it). The postprocessor can be a stand-alone program and due to its main function – automatic NC program generation based on processing of the CL data file – it can be argued that it is in essence a compiler. The CL data file contains all necessary information to create a specific NC program. The CAM system user (the production engineer) sets the tolerances for toolpath generation and these are then reflected in the resulting set of coordinates in the CL data. Besides the coordinate system, tools and coordinates of toolpath points, the CL data file consists of information about tool changes, feed-rate value, spindle speed value and sense of rotation, desired cooling, type of interpolation, etc.

We can import the NC program into the machine tool control system. However, if we consider the use of spline interpolation, we must determine whether the control system used supports spline interpolation. If the control system does support spline interpolations, we have to determine their types and specify their format. This is not so simple. We also need to know whether the CAM system used supports the generation of toolpaths by means of spline interpolations. And again, if so, in what format these interpolations are generated. The postprocessor has to prepare the data adequately for the needs of the control system

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used. The advantage of using spline interpolation is that the control system receives the data prepared for controlling the toolpath as a smooth curve. When using linear interpolation, then at the point where two linear interpolations are connected, the curve shows corners. Fine surface roughness can be achieved when spline interpolation is used as well as low tolerance requirements on toolpaths. Moreover, high demands on accuracy lead to smoother characteristic of feed-rate along the toolpath.

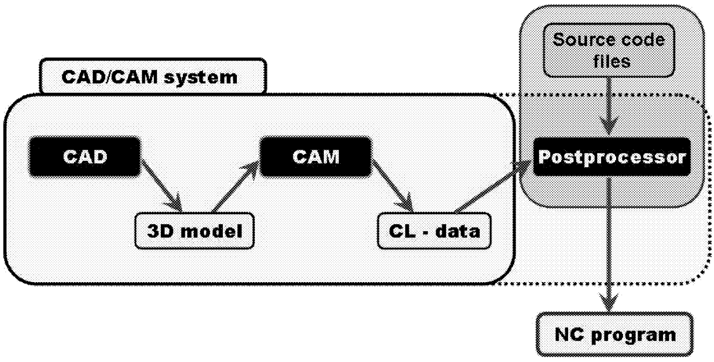

Fig.1: NC program creation process

2. Spline interpolation options of selected control systems

Now let us mention the possibilities of using spline interpolations in selected control systems. It is clear that it is not possible to enumerate all control systems, but Siemens, Heidenhain and Yamazaki Mazak control systems will be mentioned.

Siemens

Sinumerik control systems, which are produced by Siemens are equipped with a wide range of programming options for smooth curves in the NC program. The best equipped type is Sinumerik 840. Three types of interpolation are designed strictly as a spline interpolation. They are A-spline (Akimov spline), B-spline and C-spline (cubic spline) and all information is contained in the literature [6]. A-spline passes through the specified points and rarely causes oscillation of the curve. B-spline does not pass the specified control points of the control polygon (the assignment for the approximation B-spline) and also very rarely leads to oscillating curves. B-spline designation (used by the manufacturer for this interpolation) is misleading because in reality it is a NURBS (Non-Uniform Rational B-spline) as it is also possible to specify the weight of control points. Because this interpolation is labeled as B-spline in the SINUMERIK control system, I will use the label for this paper as well. Only where appropriate, the designation will be complemented by NURBS abbreviation in parentheses.

The next interpolation is a C-spline, which also passes precisely through the specified points. Because it is designed with the assumption of continuous curvature, it can often lead to oscillating curves. The use of the A-spline interpolation is suitable if the curve contains large pitch changes (e.g. a stepped curve). C-splines can be used as the substitution in cases where the interpolation points lie along an analytically calculated curve (e.g. circle, parabola, and hyperbola). This is presented in the literature [6].

B-spline interpolations are mainly conceived as a general format for spline interpolation programming using CAD/CAM systems. In the CAD/CAM system standard toolpath points are first calculated, as if they were a linear interpolation. Based on these points we calculate the interpolating spline that passes through the points obtained. The curve is transferred to the control system using the parameters for equations of approximation spline. This interpolation is selected primarily to transfer data from CAD/CAM because it does not cause an oscillating curve in large field of applications.

Consequently, here is how to write this interpolation:

BSPLINE SD=... X... Y... Z... F...
X... Y... Z... PL=... PW=...
X... Y... Z... PL=... PW=...

The following abbreviations are used in the notation:

BSPLINE .... introduction to NURBS interpolation in the NC program,
SD .... degree of the curve (the second or third degree is used in practice) and is expressed after the equal sign,
... . a number is replaced by three dots,
X, Y, Z .... coordinates of points of the curve are reported directly by letter,
F .... feed-rate specification option,
PL .... parameter to determine the distance between knot points is given after the equal sign,
PW .... opportunity to indicate the weight of the control point (the higher the weight, the more the curve approaches the point).

The extension for smooth curves in multi-axis machining was also done for this interpolation in the Sinumerik system. This is performed by simultaneously programming one spatial curve for controlling the tool reference point (tool tip) and one more spatial curve for controlling the second point away from the tool reference point distanced by a constant value on the axis of the tool. This is presented in the literature [2] as well. The extended B-spline interpolation for multi-axis operation is performed as follows:

BSPLINE SD=... F...
X... Y... Z... XH=... YH=... ZH=... PL=...
X... Y... Z... XH=... YH=... ZH=... PL=...

This notation is extended by the following designations:

XH, YH, ZH .... coordinates of control points of the second spatial curve, given after the equal sign

In addition to spline interpolations mentioned above the SINUMERIK control system allows the use of polynomial interpolation, which can be also sorted among the interpolations of the spline type as well. To write this interpolation, we need to know the following syntax:

POLY
PO[X]=(x_e, a_2, a_3) PO[Y]=(y_e, b_2, b_3) PO[Z]=(z_e, c_2, c_3) PL=...

The following abbreviations are used in the notation:

POLY .... introduction to polynomial interpolation in the NC program,
PO[X], PO[Y], PO[Z] ..... marking of the polynomial for a given axis,
x_e, y_e, z_e .... end position for relevant axis of machine tool,

a_2, a_3, b_2, b_3, c_2, c_3 .... coefficients of polynomials,
PL .... parameter interval on which the polynomial is defined (if PL is not specified, then the PL = 1).

Coefficients a_1, b_1 and c_1 are not specified because they are automatically computed using these equations:

$$\begin{aligned} a_1 &= (x_\mathrm{e} - a_0 - a_2 \cdot \mathrm{PL}^2 - a_3 \cdot \mathrm{PL}^3)/\mathrm{PL}\ , \\ b_1 &= (y_\mathrm{e} - b_0 - b_2 \cdot \mathrm{PL}^2 - b_3 \cdot \mathrm{PL}^3)/\mathrm{PL}\ , \\ c_1 &= (z_\mathrm{e} - c_0 - c_2 \cdot \mathrm{PL}^2 - c_3 \cdot \mathrm{PL}^3)/\mathrm{PL}\ . \end{aligned} \tag{1}$$

The notation contains the following designations:
a_0, b_0, c_0 .... coordinates of axes positions at the end of preceding block.

Third degree polynomials at most are used but polynomials of the fifth degree can be entered as well. Polynomials will then have four coefficients instead of two coefficients. Furthermore, the polynomial interpolation can be also used for multi-axis machining operations using the second spatial curve. The second spatial curve is then determined by three other polynomials: PO[XH] = (), PO[YH] = () and PO[ZH] = () under a similar principle to enter. It is also possible to enter the fifth degree polynomials.

Heidenhain

The iTNC control systems made by Heidenhain allow the creation of NC programs based on spline interpolations as well. In this control system smooth curves can be programmed using parameters under which the control system calculates the polynomials for machine tool axes. The general formulation of polynomials is given as follows:

$$\begin{aligned} \mathrm{X}_{(t)} &= \mathrm{K3X} \cdot t^3 + \mathrm{K2X} \cdot t^2 + \mathrm{K1X} \cdot t + \mathrm{X}\ , \\ \mathrm{Y}_{(t)} &= \mathrm{K3Y} \cdot t^3 + \mathrm{K2Y} \cdot t^2 + \mathrm{K1Y} \cdot t + \mathrm{Y}\ , \\ \mathrm{Z}_{(t)} &= \mathrm{K3Z} \cdot t^3 + \mathrm{K2Z} \cdot t^2 + \mathrm{K1Z} \cdot t + \mathrm{Z}\ . \end{aligned} \tag{2}$$

The iTNC control systems are ready to program the smooth curves in multi-axis machining as well. For this purpose, the programmed NC program blocks are extended by parameters of polynomials for rotary machine tool axes having a similar notation as the previous polynomials. The following notations are examples of polynomial equations for controlling rotary axes (the axes of rotation chosen here are labeled A and B, but of course other letters may be used, according to machine configuration):

$$\begin{aligned} \mathrm{A}_{(t)} &= \mathrm{K3A} \cdot t^3 + \mathrm{K2A} \cdot t^2 + \mathrm{K1A} \cdot t + \mathrm{A}\ , \\ \mathrm{B}_{(t)} &= \mathrm{K3B} \cdot t^3 + \mathrm{K2B} \cdot t^2 + \mathrm{K1B} \cdot t + \mathrm{B}\ . \end{aligned} \tag{3}$$

The following abbreviations are used in the notation:
$\mathrm{X}_{(t)}$, $\mathrm{Y}_{(t)}$, $\mathrm{Z}_{(t)}$, $\mathrm{A}_{(t)}$, $\mathrm{B}_{(t)}$ ..... third-degree polynomials, for each machine tool axis,
X, Y, Z, A, B .... coordinates of the end point,
K3X, K2X, K1X .... polynomial coefficients for the X axis,
K3Y, K2Y, K1Y .... polynomial coefficients for the Y axis,
K3Z, K2Z, K1Z .... polynomial coefficients for the Z axis,
K3A, K2A, K1A .... polynomial coefficients for the A axis,

K3B, K2B, K1B .... polynomial coefficients for the B axis,
t .... variable running from 1 to 0 and depends on the feed-rate and length of spline interpolation.

The syntax of NC program blocks for five-axis machining:

SPL X... Y... Z... A... B...
K3X... K2X... K1X...
K3Y... K2Y... K1Y...
K3Z... K2Z... K1Z...
K3A... K2A... K1A...
K3B... K2B... K1B... F...

The sense of partial abbreviations is obvious from the explanation of abbreviations contained in equations (2) and (3). There is only the introduction to spline interpolation blocks (SPL abbreviation) and the possibility to specify the value of the feed-rate after the letter F. This all can be also seen in the literature [1].

Mazak

In the Mazatrol Matrix control system of Mazak there can be found two options for spline interpolation. The following information can be found in the literature [3] as well. The options are spline interpolation (G06.1) and NURBS interpolation (G06.2). Spline interpolation is for curves that pass through specified points. Then the first spline block of the NC program has the following syntax:

G06.1 X... Y... Z... F...

It is not necessary for the following blocks with other spline interpolation points to begin with the word G06.1. This is necessary only if another type of interpolation is programmed and then the program continues with spline interpolation again. The meaning of the abbreviations is obvious:

G06.1 .... spline interpolation designation,
X, Y, Z .... coordinates of the toolpath point,
F .... feed-rate specification option.

Another option is to use NURBS interpolation, which assumes that the resulting curve does not pass through the specified points, but the specified points are the points of the control polygon. The syntax of the NC program block with NURBS interpolation is as follows:

G06.2 P... K... X... Y... Z... R... F...

Again, blocks with NURBS interpolation that follow do not have to include the designation of interpolation type. Otherwise, the same rule is valid as in the case of spline interpolation. The syntax of this interpolation contains the following abbreviations:

G06.2 .... NURBS interpolation designation,
P .... the number showing the curve order (order = P − 1),
K .... parameter of knot vector,
X, Y, Z .... coordinates of the control polygon point,
R .... weight of the control polygon point,
F .... feed-rate specification option.

3. Postprocessor functions and spline interpolation examples

In this chapter, attention will be paid to examples of spline interpolation notations in the CL data file and the need to translate CL data into the NC program. The list of options will be limited to Siemens NX and CATIA CAM systems.

First, it is necessary to ensure that the postprocessor allows generation of linear interpolation in the NC program. The toolpath in the NC program can be composed of interpolations of different types. In Fig. 2 we can see the difference between CL data and NC programs. The CL data file (in Fig. 2 – left) is observed from the CATIA CAM system. In our case the NC program (see Fig. 2 – right) is generated in a format according to ISO code and specifications of Siemens company for the Sinumerik 840 control system. Fig. 2 also shows the postprocessor functions such as formatting and modalities of application of certain words.

```
$$  End of generation of : Tool Change.17
$$ OPERATION NAME : Profile Contouring.46
$$  Start generation of : Profile Contouring.46
LOADTL/1,1
SPINDL/ 13000.0000,RPM,CLW
RAPID
GOTO  /   17.92919,  142.58062,  142.00000
RAPID
GOTO  /   17.92919,  142.58062,   -8.00000
FEDRAT/  4000.0000,MMPM
GOTO  /   17.92919,  142.58062,  -10.00000
INTOL /    0.00100
OUTTOL/    0.00000
AUTOPS
INDIRV/    0.00473,    0.99999,    0.00000
TLON,GOFWD/       (CIRCLE/     15.92921,    142.59009,    -10.00000,$
       2.00000),ON,(LINE/      15.92921,    142.59009,    -10.00000,$
                               15.93868,    144.59006,    -10.00000)
FEDRAT/  4000.0000,MMPM
INDIRV/   -0.99998,    0.00625,    0.00000
TLON,GOFWD/       (CIRCLE/     15.97927,    151.08505,    -10.00000,$
       6.49512),ON,(LINE/      15.97927,    151.08505,    -10.00000,$
                               15.48769,    144.60857,    -10.00000)
GOTO  /   15.23022,  144.63186,  -10.00000
GOTO  /   14.97350,  144.66199,  -10.00000
GOTO  /   14.74732,  144.69425,  -10.00000
GOTO  /   14.56122,  144.72510,  -10.00000
GOTO  /   14.32710,  144.76968,  -10.00000
GOTO  /   14.14120,  144.80971,  -10.00000
GOTO  /   13.91121,  144.86495,  -10.00000
GOTO  /   13.72901,  144.91326,  -10.00000
```

```
N45 soft
N50 ffwon
N55 R10=6000
N60 R11=4000
N65
N70 ; ========= VYMENA NASTROJE ========
N75 ; NASTROJ: FREZA D7.82 R0.00
N80 ; ==================================
N85 T10 D01
N90 G56
N95 ; ==================================
N100 ; OPERACE: Profile Contouring.46
N105 ; =================================
N110 S13000 M03
N115 G1 X17.929 Y142.581 F=R10
N120 Z142
N125 X17.929 Y142.581
N130 Z-8
N135 M08
N140 Z-10 F=R11
N145 G3 X15.939 Y144.59 I-2 J0.009
N150 G2 X15.488 Y144.609 I0.041 J6.495
N155 G1 X15.23 Y144.632
N160 X14.974 Y144.662
N165 X14.747 Y144.694
N170 X14.561 Y144.725
N175 X14.327 Y144.77
N180 X14.141 Y144.81
N185 X13.911 Y144.865
N190 X13.729 Y144.913
```

Fig.2: The difference between CL data and NC program with linear and circular interpolations (left – CL data, right – NC program)

Linear interpolation is not the only interpolation which can be used in NC programs and therefore the postprocessor must allow adequate translation of circular interpolation and spline interpolation as well. Fig. 2 shows the differences between the CL data containing a combination of linear and circular interpolation (left) and the generated NC program also containing a combination of linear and circular interpolation (right). An example of linear interpolation is marked by dark frames (in Fig. 2) and an example of circular interpolation is marked by light frames (in Fig. 2). Further postprocessor function is evident. The right sense of circular interpolation (G2, G3) must be generated. We can also add that the feed rate in the NC program are generated using the R-parameters.

The postprocessor is then functional for generating linear interpolation, circular interpolation and their combinations. Finally, the postprocessor must be able to process spline interpolation and to generate the correct translation into the NC program. An example of CL data, including spline interpolation is shown in Fig. 3. It is obvious that this is a completely different description of the tool movement compared with linear or circular interpolation. This CL data file is observed from CATIA CAM system as well. After the

```
LOADTL/1,1
SPINDL/ 13000.0000,RPM,CLW
RAPID
GOTO  /   17.92919,   28.58062,  142.00000
RAPID
GOTO  /   17.92919,   28.58062,   -8.00000
FEDRAT/  4000.0000,MMPM
BEGIN NURBS_SIEMENS (D=3,F=4000.000,AXIS=    0.00000,    0.00000,    1.0$
0000)
N0, XT=   17.92919, YT=   28.58062, ZT=   -8.00000,DK=    0.00000,W=   $
 1.00000;
N1, XT=   17.92919, YT=   28.58062, ZT=   -8.66667,DK=    0.00000,W=   $
 1.00000;
N2, XT=   17.92919, YT=   28.58062, ZT=   -9.33333,DK=    2.00000,W=   $
 1.00000;
N3, XT=   17.92919, YT=   28.58062, ZT=  -10.00000,DK=    0.00000,W=   $
 1.00000;
END NURBS
BEGIN NURBS_SIEMENS (D=3,F=4000.000,AXIS=    0.00000,    0.00000,    1.0$
0000)
N0, XT=   17.92919, YT=   28.58062, ZT=  -10.00000,DK=    0.00000,W=   $
 1.00000;
N1, XT=   17.93086, YT=   28.84889, ZT=  -10.00000,DK=    0.00000,W=   $
 1.00000;
N2, XT=   17.85166, YT=   29.24362, ZT=  -10.00000,DK=    0.80445,W=   $
 1.00000;
N3, XT=   17.60723, YT=   29.69917, ZT=  -10.00000,DK=    0.37943,W=   $
 1.00000;
N4, XT=   17.37818, YT=   29.98402, ZT=  -10.00000,DK=    0.35983,W=   $
 1.00000;
N5, XT=   17.11219, YT=   30.21514, ZT=  -10.00000,DK=    0.35277,W=   $
 1.00000;
```

```
N45 soft
N50 ffwon
N55 R10=6000
N60 R11=4000
N65
N70 ; ========= UYMENA NASTROJE ========
N75 ; NASTROJ: FREZA D7.82 R0.00
N80 ; =================================
N85 T10 D01
N90 G56
N95 ; =================================
N100 ; OPERACE: Multi-Axis Curve Machining.16
N105 ; =================================
N110 S13000 M03
N115 G1 X17.929 Y28.581 F=R10
N120 Z142
N125 X17.929 Y28.581 M8
N130 Z-8
N135 G1 X17.92919 Y28.58062 Z-8.00000 F4000.0
N140 BSPLINE SD=3 F4000.0
N145 X17.92919 Y28.58062 Z-8.66667 PL=0.00000
N150 X17.92919 Y28.58062 Z-9.33333 PL=2.00000
N155 X17.92919 Y28.58062 Z-10.00000 PL=0.0
N160 BSPLINE SD=3 F4000.0
N165 X17.92919 Y28.58062 Z-10.00000 PL=0.00000
N170 X17.93086 Y28.84889 Z-10.00000 PL=0.00000
N175 X17.85166 Y29.24362 Z-10.00000 PL=0.80445
N180 X17.60723 Y29.69917 Z-10.00000 PL=0.37943
N185 X17.37818 Y29.98402 Z-10.00000 PL=0.35983
N190 X17.11219 Y30.21514 Z-10.00000 PL=0.35277
```

Fig.3: The difference between CL data and NC program with spline interpolations (left – CL data, right – NC program)

```
RAPID
GOTO/176.8811,28.8043,-8.0000
PAINT/COLOR,42
FEDRAT/MMPM,600.0000
GOTO/176.8811,28.8043,-10.0000
GOTO/176.8641,28.9283,-10.0000
GOTO/176.8393,29.0510,-10.0000
GOTO/176.8069,29.1719,-10.0000
GOTO/176.7669,29.2906,-10.0000
GOTO/176.7197,29.4065,-10.0000
GOTO/176.6653,29.5192,-10.0000
GOTO/176.6039,29.6283,-10.0000
GOTO/176.5359,29.7333,-10.0000
GOTO/176.4614,29.8339,-10.0000
GOTO/176.3807,29.9296,-10.0000
GOTO/176.2942,30.0201,-10.0000
GOTO/176.2023,30.1050,-10.0000
GOTO/176.1052,30.1840,-10.0000
GOTO/176.0033,30.2568,-10.0000
GOTO/175.8971,30.3230,-10.0000
GOTO/175.7870,30.3825,-10.0000
GOTO/175.6733,30.4350,-10.0000
GOTO/175.5566,30.4802,-10.0000
GOTO/175.4373,30.5181,-10.0000
GOTO/175.3159,30.5484,-10.0000
GOTO/175.1928,30.5711,-10.0000
GOTO/175.0685,30.5860,-10.0000
GOTO/174.9436,30.5932,-10.0000
PAINT/COLOR,31
GOTO/174.8805,30.5953,-10.0000
GOTO/174.8176,30.5984,-10.0000
GOTO/174.6638,30.6074,-10.0000
GOTO/174.4740,30.6237,-10.0000
GOTO/174.3093,30.6411,-10.0000
GOTO/174.1315,30.6626,-10.0000
GOTO/173.8130,30.7095,-10.0000
GOTO/173.4677,30.7739,-10.0000
GOTO/173.0984,30.8584,-10.0000
GOTO/172.7317,30.9588,-10.0000
GOTO/172.3707,31.0739,-10.0000
GOTO/172.0149,31.2039,-10.0000
GOTO/171.6697,31.3464,-10.0000
GOTO/171.3656,31.4860,-10.0000
GOTO/171.0722,31.6337,-10.0000
GOTO/170.7850,31.7913,-10.0000
GOTO/170.5046,31.9583,-10.0000
GOTO/170.2316,32.1342,-10.0000
GOTO/169.9667,32.3181,-10.0000
GOTO/169.7078,32.5112,-10.0000
GOTO/169.4575,32.7111,-10.0000
...
```

```
RAPID
GOTO/176.8811,28.8043,-8.0000
PAINT/COLOR,42
FEDRAT/MMPM,600.0000
GOTO/176.8811,28.8043,-10.0000
NURBS/
KNOT/0.0434783,0.3478261,0.6521739,0.9565217,1.0000000
CNTRL/176.8767,28.8458,-10.0000
CNTRL/176.8312,29.1774,-10.0000
CNTRL/176.5898,29.7699,-10.0000
CNTRL/175.9293,30.3797,-10.0000
CNTRL/175.3195,30.5731,-10.0000
CNTRL/174.9853,30.5921,-10.0000
CNTRL/174.9436,30.5932,-10.0000
PAINT/COLOR,31
GOTO/174.8805,30.5953,-10.0000
NURBS/
KNOT/0.0122355,0.0230744,0.0438271,0.0577651,0.0885242,0.1122799,
0.1412694,0.1818004,0.1889988,0.2428124,0.2823741,0.2971214
KNOT/0.3061666,0.3168921,0.3283721,0.3977528,0.4192710,0.4320384,
0.4468084,0.5077124,0.5396550,0.6241517,0.7092864,0.7891216
KNOT/0.8524933,0.8682183,0.8818733,0.9167285,0.9267884,0.9680478,
0.9760439,0.9880054,1.0000000
CNTRL/174.6598,30.6048,-10.0000
CNTRL/174.2446,30.6425,-10.0000
CNTRL/173.4620,30.7618,-10.0000
CNTRL/172.6635,30.9638,-10.0000
CNTRL/171.5524,31.3689,-10.0000
CNTRL/170.4533,31.9450,-10.0000
CNTRL/169.2425,32.8492,-10.0000
CNTRL/168.0490,34.0445,-10.0000
CNTRL/167.2509,35.1839,-10.0000
CNTRL/166.3490,36.7807,-10.0000
CNTRL/165.6406,38.4601,-10.0000
CNTRL/165.1245,40.3450,-10.0000
CNTRL/164.8881,41.4643,-10.0000
CNTRL/164.7755,42.0774,-10.0000
CNTRL/164.6826,42.6338,-10.0000
CNTRL/164.4452,44.2708,-10.0000
CNTRL/164.3017,46.1157,-10.0000
CNTRL/164.2574,47.9870,-10.0000
CNTRL/164.2546,48.8728,-10.0000
...
```

Fig.4: Comparison of CL data with linear interpolations and CL data with spline interpolations (left – linear interpolations, right – spline interpolations)

translation of CL data is done by the postprocessor, the corresponding NC program can be seen in Fig. 3 right. Again, this is an equivalent translation of the description contained in the CL data with the fact that it is now adapted to the requirements of the machine and its control system. An example of an initial block of a sequence of spline interpolations is marked by light frames (in Fig. 3) and an example of the spline interpolation is then marked by dark frames (in Fig. 3). It is also clear that in the NC program a combination of linear interpolation and spline interpolation can be included too (see blocks N135 and N140). The postprocessor functions required to generate NC programs with linear interpolation, circular interpolation and spline interpolation for the CATIA system are thus completed.

In Fig. 4 we can see a comparison between the toolpath described in CL data with linear interpolations (Fig. 4 – left) and the toolpath described in CL data with spline interpolations (Fig. 4 – right). This is specifically the data from the Siemens NX CAM system. Black boxes mark the sections of toolpaths that are in mutual relation in both cases of the description of the toolpath. It is clear that the path described with spline interpolations is shorter than the path described by linear interpolations. The resulting NC program is shorter and the control system does not handle as many blocks of NC program.

```
N105 G55
N110 S5000 M03
N115 G01 X176.881 Y28.804 Z142. F=R0
N120 M08
N125 Z-8. F=R0
N130 Z-10. F=R12
N135 POLY
N140 PO[X]=(176.864,-.0038585,-.0000145) PO[Y]=(28.928,-.0001723,-.0001863) PO[Z]=(-10.,0.0,0.0) F=600.
N145 PO[X]=(176.536,-.1912003,.0099804) PO[Y]=(29.733,-.035829,-.0246697) PO[Z]=(-10.,0.0,0.0)
N150 PO[X]=(175.897,-.161259,.0215404) PO[Y]=(30.323,-.109838,-.0198868) PO[Z]=(-10.,0.0,0.0)
N155 PO[X]=(175.069,-.0966378,.0253866) PO[Y]=(30.586,-.1694984,-.007984) PO[Z]=(-10.,0.0,0.0)
N160 PO[X]=(174.944,-.0004179,.0001847) PO[Y]=(30.593,-.003948,.0000304) PO[Z]=(-10.,0.0,0.0)
N165 G01 X174.881 Y30.595 F=R12
N170 POLY
N175 PO[X]=(174.22,.0019108,.0002294) PO[Y]=(30.652,.0316489,-.0034998) PO[Z]=(-10.,0.0,0.0) F=600.
N180 PO[X]=(173.64,.0020396,.0005113) PO[Y]=(30.741,.016597,.0008452) PO[Z]=(-10.,0.0,0.0)
N185 PO[X]=(172.551,.0130995,.0025963) PO[Y]=(31.016,.0701387,-.0016121) PO[Z]=(-10.,0.0,0.0)
N190 PO[X]=(171.842,.0094222,.000855) PO[Y]=(31.274,.0294563,-.0001426) PO[Z]=(-10.,0.0,0.0)
N195 PO[X]=(170.368,.0583801,.0075639) PO[Y]=(32.046,.141375,-.0052772) PO[Z]=(-10.,0.0,0.0)
N200 PO[X]=(169.337,.0483569,.0021178) PO[Y]=(32.814,.0748829,-.0037013) PO[Z]=(-10.,0.0,0.0)
N205 PO[X]=(168.226,.0814728,.0017639) PO[Y]=(33.921,.0949779,-.0070292) PO[Z]=(-10.,0.0,0.0)
N210 PO[X]=(166.956,.1696039,-.0041712) PO[Y]=(35.709,.1444382,-.0181098) PO[Z]=(-10.,0.0,0.0)
N215 PO[X]=(166.765,.004955,-.0000908) PO[Y]=(36.049,.0028422,-.0001209) PO[Z]=(-10.,0.0,0.0)
N220 PO[X]=(165.611,.261695,-.0168009) PO[Y]=(38.721,.1385813,-.0233835) PO[Z]=(-10.,0.0,0.0)
N225 PO[X]=(165.036,.1141955,-.0080709) PO[Y]=(40.784,.0369843,-.005604) PO[Z]=(-10.,0.0,0.0)
N230 PO[X]=(164.871,.0125035,.0001391) PO[Y]=(41.566,.002803,-.000081) PO[Z]=(-10.,0.0,0.0)
N235 PO[X]=(164.782,.0048608,-.0004392) PO[Y]=(42.048,.0009631,-.0001294) PO[Z]=(-10.,0.0,0.0)
```

Fig.5: Example of NC program with polynomial interpolations for Sinumerik control system

In Fig. 5 we can already see the final NC program after translation of CL data done by the postprocessor. The corresponding postprocessor functions are mentioned e.g. in the literature [4] and [5]. The controller reads thus-prepared data easily and can handle the commands for controlling the tool. This data are fully compatible with the Sinumerik 840 control system. Fig. 5 shows that among certain sections of the toolpath the CAM system cannot create a sequence of polynomial interpolations and therefore the block with linear interpolation has to be inserted (block N165). It is very bad because the smoothness of the curve is not observed, as it is presented in the literature [7].

Fig. 6 captures the part of the NC program with interpolations of spline type for toolpath control using iTNC 530 control system by Heidenhain. The figure also shows the block with linear interpolation (block 31).

The last two figures (Fig. 7 and Fig. 8) show the sections of toolpath described with spline interpolation for multi-axis control. Fig. 7 presents the CL data prepared in the CATIA CAM

```
17 Q1 = 600 ; PRACOVNI POSUV
18 Q4 = 600 ; PRIBLIZOVACI POSUV
19 Q8 = 600 ; NAVRATOVY POSUV
20 ; (================================)
21 TOOL CALL 10 Z SQ0
22 L B0.0 C0.0 FMAX
23 L X+176.881 Y+28.804 Z+142. R0 FMAX M3
24 L Z-8. FMAX
25 L Z-10. FQ4 M8
26 SPL X+176.864 Y+28.928 K3X+1.86078E-005 K2X-3.90197E-003 K1X+2.09682E-002 K3Y+1.89123E-004
   K2Y-7.31031E-004 K1Y-1.23615E-001 K3Z+1.78000E-015 K2Z+0.00000E+000 K1Z+0.00000E+000
27 SPL X+176.536 Y+29.733 K3X-9.97782E-003 K2X-1.61263E-001 K1X+4.99237E-001 K3Y+2.46742E-002
   K2Y-1.09843E-001 K1Y-7.19643E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
28 SPL X+175.897 Y+30.323 K3X-2.15417E-002 K2X-9.66380E-002 K1X+7.57138E-001 K3Y+1.98853E-002
   K2Y-1.69499E-001 K1Y-4.40301E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
29 SPL X+175.069 Y+30.586 K3X-2.53894E-002 K2X-2.04697E-002 K1X+8.74246E-001 K3Y+7.97566E-003
   K2Y-1.93426E-001 K1Y-7.73760E-002 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
30 SPL X+174.944 Y+30.593 K3X-1.79250E-004 K2X+1.20000E-004 K1X+1.25190E-001 K3Y-2.70729E-005
   K2Y-3.86625E-003 K1Y-3.24000E-003 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
31 L X+174.881 Y+30.595 FQ4
32 SPL X+174.22 Y+30.652 K3X-2.25900E-004 K2X+2.59464E-003 K1X+6.57789E-001 K3Y+3.50069E-003
   K2Y+2.11512E-002 K1Y-8.11716E-002 K3Z+1.78000E-015 K2Z+0.00000E+000 K1Z+0.00000E+000
33 SPL X+173.64 Y+30.741 K3X-5.13234E-004 K2X+3.57584E-003 K1X+5.77096E-001 K3Y-8.45105E-004
   K2Y+1.91336E-002 K1Y-1.07639E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
34 SPL X+172.551 Y+31.016 K3X-2.59251E-003 K2X+2.08862E-002 K1X+1.07095 K3Y+1.61529E-003
   K2Y+6.52964E-002 K1Y-3.41529E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
35 SPL X+171.842 Y+31.274 K3X-8.55185E-004 K2X+1.19868E-002 K1X+6.97862E-001 K3Y+1.41971E-004
   K2Y+2.90276E-002 K1Y-2.87860E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
36 SPL X+170.368 Y+32.046 K3X-7.56411E-003 K2X+8.10705E-002 K1X+1.40063 K3Y+5.27287E-003
   K2Y+1.25552E-001 K1Y-9.02186E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
37 SPL X+169.337 Y+32.814 K3X-2.11851E-003 K2X+5.47117E-002 K1X+9.78660E-001 K3Y+3.70405E-003
   K2Y+6.37758E-002 K1Y-8.35436E-001 K3Z-0.00000E+000 K2Z+0.00000E+000 K1Z-0.00000E+000
```

Fig.6: Example of the NC program with interpolations of spline type for the control system Heidenhain iTNC 530

```
BEGIN NURBS_SIEMENS (D=3,F=100.000,AXIS=VAR,LENGTH= 55.000)
N0, XT=   67.76826, YT=  -52.67898, ZT=  210.92639, XH=  103.66057, YH=$
  -52.68800, ZH=  252.60063,DK=    0.00000,W=    1.00000;
N1, XT=   67.16855, YT=  -52.70240, ZT=  210.21829, XH=  103.06085, YH=$
  -52.71142, ZH=  251.89253,DK=    0.00000,W=    1.00000;
N2, XT=   66.16709, YT=  -52.34892, ZT=  209.23191, XH=  102.05939, YH=$
  -52.35794, ZH=  250.90615,DK=    2.78157,W=    1.00000;
N3, XT=   64.93429, YT=  -51.23395, ZT=  208.35718, XH=  100.82659, YH=$
  -51.24297, ZH=  250.03142,DK=    1.40420,W=    1.00000;
N4, XT=   63.96272, YT=  -49.91019, ZT=  207.89007, XH=   99.85502, YH=$
  -49.91921, ZH=  249.56431,DK=    1.39289,W=    1.00000;
N5, XT=   63.47366, YT=  -48.75558, ZT=  207.89878, XH=   99.36596, YH=$
  -48.76460, ZH=  249.57302,DK=    2.27356,W=    1.00000;
N6, XT=   63.28510, YT=  -48.03474, ZT=  208.03981, XH=   99.17740, YH=$
  -48.04376, ZH=  249.71405,DK=    0.00000,W=    1.00000;
END NURBS
FEDRAT/  300.0000,MMPM
BEGIN NURBS_SIEMENS (D=3,F=300.000,AXIS=VAR,LENGTH= 55.000)
N0, XT=   63.28510, YT=  -48.03474, ZT=  208.03981, XH=   99.17740, YH=$
  -48.04376, ZH=  249.71405,DK=    0.00000,W=    1.00000;
N1, XT=   63.28586, YT=  -48.03328, ZT=  208.04234, XH=   99.17863, YH=$
  -48.04630, ZH=  249.71299,DK=    0.00000,W=    1.00000;
N2, XT=   63.28662, YT=  -48.03182, ZT=  208.04486, XH=   99.58039, YH=$
  -48.87374, ZH=  249.36446,DK=    0.00904,W=    1.00000;
N3, XT=   63.28738, YT=  -48.03036, ZT=  208.04738, XH=   99.58163, YH=$
  -48.87627, ZH=  249.36339,DK=    0.00000,W=    1.00000;
N4, XT=   63.27808, YT=  -47.99902, ZT=  208.05130, XH=   99.45829, YH=$
  -48.69002, ZH=  249.47051,DK=    0.00000,W=    1.00000;
N5, XT=   63.24892, YT=  -47.89676, ZT=  208.06701, XH=   99.22367, YH=$
  -48.40707, ZH=  249.66830,DK=    0.74392,W=    1.00000;
N6, XT=   63.24150, YT=  -47.87857, ZT=  208.06423, XH=   98.85191, YH=$
  -47.73609, ZH=  249.98253,DK=    0.50081,W=    1.00000;
N7, XT=   63.22772, YT=  -47.83342, ZT=  208.06924, XH=   98.58571, YH=$
  -47.26993, ZH=  250.19557,DK=    1.23610,W=    1.00000;
N8, XT=   63.19145, YT=  -47.73089, ZT=  208.06786, XH=   97.00863, YH=$
  -44.39656, ZH=  251.41981,DK=    0.00000,W=    1.00000;
N9, XT=   63.16837, YT=  -47.65271, ZT=  208.07170, XH=   95.04396, YH=$
  -41.13068, ZH=  252.55720,DK=    9.25877,W=    1.00000;
N10, XT=   63.15478, YT=  -47.56859, ZT=  208.09389, XH=   92.61533, YH$
```

Fig.7: Example of CL data from CAM CATIA with spline interpolation (NURBS) for multi-axis machining

system. The equivalent section of the NC program of the toolpath marked by a rectangle in Fig. 7 can be seen in Fig. 8. This is a format that uses two spatial NURBS curves prepared for the needs of the Sinumerik 840 control system. Notice that the description has been already mentioned above in the article. What is missing at the beginning of the NC program is

```
N105 BSPLINE SD=3 F=100.0
N110 X67.76826 Y-52.679898 Z210.92639 XH=103.66057 YH=-52.68800 ZH=252.60063 PL=0.0
N115 X67.16855 Y-52.70240 Z210.21829 XH=103.06085 YH=-52.71142 ZH=251.89253 PL=0.0
N120 X66.16709 Y-52.34892 Z209.23191 XH=102.05939 YH=-52.35794 ZH=250.90615 PL=2.78157
N125 X64.93429 Y-51.23395 Z208.35718 XH=100.82659 YH=-51.24297 ZH=250.03142 PL=1.40420
N130 X63.96272 Y-49.91019 Z207.89007 XH=99.85502 YH=-49.91921 ZH=249.56431 PL=1.39289
N135 X63.47366 Y-48.75558 Z207.89878 XH=99.36596 YH=-48.76460 ZH=249.57302 PL=2.27356
N140 X63.28510 Y-48.03474 Z208.03981 XH=99.17740 YH=-48.04376 ZH=249.71405 PL=0.00000
N145 BSPLINE SD=3 F=300.0
N150 X63.28510 Y-48.03474 Z208.03981 XH=99.17740 YH=-48.04376 ZH=249.71405 PL=0.00000
N155 X63.28586 Y-48.03328 Z208.04234 XH=99.17863 YH=-48.04630 ZH=249.71299 PL=0.00000
N160 X63.28662 Y-48.03182 Z208.04486 XH=99.58039 YH=-48.87374 ZH=249.36446 PL=0.00904
```

Fig.8: Part of the NC program after translation done by the postprocessor

only the initial sequence of blocks, where it is appropriate first to use a linear interpolation (with the directional cosines to determine the tool orientation in space instead of angular coordinates for the rotational axes) together with the ORIVECT function and to position the tool in space. After that, via ORICURVE function, we can generate the NC program blocks with multi-axis spline interpolations.

4. Conclusion

The article summarizes the possibilities of using spline interpolations to create the NC program. It is not possible to list all the possible control systems and therefore three representative control systems (SINUMERIK 840, TNC 530 and Mazatrol Matrix) have been selected. The article presents the formats and syntax of NC program blocks for these control systems using spline interpolations. Generally speaking, it is appropriate to use the spline interpolation in order to minimize the number of blocks of NC program. The control system need not process a large number of blocks of NC program as in the case of linear interpolation. In addition, the toolpath is prepared so that the control system can drive the tool by a smooth curve, which has a positive influence on the characteristic of the feed-rate, particularly at high tolerance requirements for the toolpath. When using linear interpolation the NC program contains a large number of blocks which could affect the NC program processing time (depending on the block processing time of the control system). Let this article be a basis for those who want to use spline interpolation to create NC programs. Therefore, basic information about spline interpolations is put forward here, depending on the control systems and the relationship to the CAD/CAM system. Not all control systems have the same spline interpolations and in some control systems they are not included. The same is true even in the case of CAM systems. In some CAM systems spline interpolations are not used and if so, how the data is generated in the CL data it depends on the computational core of the CAM system.

Acknowledgement

A part of the presented results was supported by Ministry of Education and Sport of Czech Republic, grant No. 1M0507 and a part was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS10/262/OHK2/3T/12.

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Received in editor's office: March 28, 2012
Approved for publishing: June 20, 2012