ISSN 1068-798X, Russian Engineering Research, 2019, Vol. 39, No. 12, pp. 1080–1083. © Allerton Press, Inc., 2019.
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Prospects for CNC Machine Tools

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Received March 10, 2019; revised March 12, 2019; accepted March 15, 2019

Abstract—The main global trends in the production of high-technology CNC systems are identified. Topics analyzed include system architecture; the use of high-speed industrial networks based on fieldbus technologies; the potential of multiple-channel and multiple-axis machining; spline interpolation in the machining of complex contours and free surfaces; and five-coordinate machining with 3D correction of the tool radius and length. In the light of global trends, decisions are made regarding the development of the AksiOMA Kontrol CNC system.

Keywords: CNC systems, ProfiNet, SERCOS, EtherCat, control channels, spline interpolation, five-coordinate machining

DOI: 10.3103/S1068798X19120153

Today, although more manufacturers are entering the field, there are still only a few suppliers of high-end CNC systems [1]. The major producers of high-technology control systems are Fanuc, Siemens, and Heidenhain. Bosch Rexroth is now also a leader in the control of highly complex machine-tool systems, with its MTXadvanced CNC system, which outperforms other products in key respects [2].

To assess whether Russian companies that are relatively lacking in experience may be globally competitive with existing manufacturers of CNC systems, which invest thousands of person-hours in their development each year, we will analyze the AksiOMA Kontrol CNC system developed at Stankin Moscow State Technical University in the light of global trends [3].

GLOBAL TRENDS IN HIGH-END CNC SYSTEMS

We may track global trends by studying CNC systems that are representative of those currently on the market and embody state-of-the-art technology. We will study the distinctive characteristics of high-end CNC systems.

Multiple-Channel and Multiple-Axis Machining

All high-end CNC systems are capable of multiple-channel and multiple-axis machining.

In multichannel machining, a separate control program covers each control channel. The simplest example, with two-channel machining, is a lathe with a spindle and a counterspindle and with two turret heads. In one channel (the spindle and the first turret head), the workpiece is machined on one side (the first setup); in the second channel (the counterspindle and the second turret head), the workpiece is then machined on the other side. The workpiece is shifted to the second setup by its transfer to the rotating counterspindle, without stopping. The number of control channels may be increased to control an automatic loading unit, for example.

In multiple-axis machining, the key characteristic is the total possible number of simultaneously interpolated axes in all the control channels. Spindles switched in rotary-axis mode are taken into account here.

In the FANUC 30i/31i/32i-MODELB CNC systems, 15 channels, 96 axes (coordinates), and 24 spindles are controlled simultaneously. The Siemens (Germany) Sinumerik 840D/Disl (SolutionLine) system controls 93 axes (including spindles) in 30 channels. The Heidenhain iTNC-530 CNC system is able to control 18 axes and two spindles within a single channel.

The leader is the Bosch Rexroth MTXAdvanced CNC system, which is able to control 250 electrical and hydraulic axes and 60 spindles with a 0.25-ms cycle in 60 channels. The system has elegant architecture and uses VxWorks as the real-time operating system. The Fagor (Spain) CNC 8070 system controls 28 axes and four spindles in four control channels. The Mitsubishi (Japan) M800W system controls 32 axes and four spindles in four control channels.

The AksiOMA Kontrol CNC system offers eight control channels, each of which can simultaneously accommodate 32 axes and four spindles. Note that these constraints are imposed by the program. The capacity could be increased if the computational capabilities of the platform were increased.

Architecture of CNC Systems

High-end CNC systems are assigned to the PCNC class (personal computer numerical control). According to Moore's law, this ensures doubling of the processor speed every 1.5–2 years. Most such systems are based on PCNC-2 architecture [4]. In that case, two computers are used: one provides the real-time core, while the other has an operator terminal.

Some manufacturers employ CISC processors of x86 type, while others prefer RISC processors of Power PC type. This choice is not of fundamental importance and is largely determined by cost considerations. However, there are exceptions. For example, the SINUMERIK 840Di system is based on PCNC-3 architecture, in which the basic computer provides the real-time core, while the terminal is a single-circuit computer integrated into the primary computer in the form of expansion circuits. The Fagor CNC 8070 system employs PCNC-4 architecture. In that case, the same computer serves as the real-time core and provides the operator terminal.

The AksiOMA Kontrol CNC system has a cross-platform design [5]. It may be operated both with PCNC-2 architecture (the usual setup: a two-computer system where the core operates under OCRT Linux control, while the terminal operates under OC Windows control, with a .Net platform) and with PCNC-4 architecture (a single-computer system with OC Windows control, a .Net platform, and an RTX real-time expansion).

Fieldbus or Direct PWM Control

In the Fanuc CNC system, the drives are controlled directly, with pulse-width modulation (PWM). In the Siemens and Bosch Rexroth systems, the drives are controlled by PROFINET and SERCOS fieldbuses, respectively. Note that control by fieldbus is ultimately a form of PWM control. The selection of one or the other depends on the chosen automation system [6]. Fieldbuses ensure compatibility of the control-system components and permit the use of drives from different manufacturers.

The AksiOMA Kontrol CNC system employs high-speed Sercos and EtherCat fieldbuses with open protocols [7].

Spline Interpolation in Machining Free Surfaces

In machining press molds, turbine blades, and other complex surfaces, the programming of complex contours and free surfaces proves useful. They are simulated by splines with a continuous second derivative and machined by means of spline interpolation incorporated in the CNC system. In comparison with piecewise linear approximation of the contour, spline interpolation avoids dynamic impacts, decreases the size of the control program by a factor of 4–5, and increases the contour supply on account of the contour smoothness, without loss of precision.

Siemens provides a complete set of spline-interpolation algorithms, including polynomial analysis and frame compression. By analogy with the Siemens system, the AksiOMA Kontrol CNC system employs the Akima spline (ASPLINE), cubic spline (CSPLINE), and NURBS (BSPLINE).

Multiple-Terminal Control

Large machine tools with a working space that extends over several meters employ several terminals to control the machining process [8, 9]. The default option in the AksiOMA Kontrol CNC system is to connect up to eight terminals as clients to a single core [10, 11]. This number may be increased if the computing power of the platform is enlarged.

Programming of Tool Orientation

By programming of the tool orientation in generalized coordinates, regardless of the set of axes and the system's kinematics, the control program may be transferred without change from one machine to another, no matter what kinematic configuration is employed (a spherical table, a rotary head, or a hybrid system).

The AksiOMA Kontrol CNC system employs programming of the tool orientation in generalized coordinates, on the basis of Euler angles or the components of the tool's orientation vector [12].

Five-Coordinate Machining

In five-coordinate machining, up to five coordinates may be employed simultaneously, with compensation of the tool's end displacement when its orientation relative to the workpiece is changed (TRAORI function). This approach takes account of parameters such as the kinematically independent tool-orientation vector, 3D correction of the tool length and radius, and the method used for interpolation of the motion when tool orientation is changed (ORIAXES, ORIVECT).

The AksiOMA Kontrol CNC system compensates the tool radius in end milling, by correcting the contour in the plane formed by the vector n normal to surface and the tangential vector p at the current point of the contour (Fig. 1) [12].

The compensation vector v determines the displacement of the center of the cutting edge relative to the contour point. The modulus of the compensation vector depends on the shape of the tool and its orien-

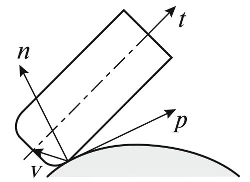

Fig. 1. Compensation of the radius in end milling.

tation relative to the tangent and the normal. In calculating the compensation, we describe the tangent to the contour in the machine tool's coordinate system.

EXPERIMENTS WITH THE AKSIOMA KONTROL CNC SYSTEM

We use an emulator of the CNC system for experiments on the five-coordinate machining algorithms in the AksiOMA Kontrol CNC system. The emulator is a digital twin of the control system.

As an illustration, we now present the control program in the part's coordinate system for the milling of a plane when the tool inclination varies from −75 to +75° in each frame (frame N50 includes compensation for the tool radius in end milling):

```
#define STEP 4//plane cutting step, mm
#define DEPTH 4 //cutting depth in mm
#define FEED 600 //cutting feed
#define ANGLE 75 //angle of tool inclination
#define SIZE_X 100
#define SIZE_Y 50
#define SIZE_Z 20
#workpiece(0, 512, 3, SIZE_X, SIZE_Y, SIZE_Z, -SIZE_X*0.5, -SIZE_Y*0.5,0)
N10 M6 T1 D1 // T1 ball milling tool with R=4.5 mm
N20 G90 G190 G45 L17 G40
N30 ORIEULER ORIMKS TRAORI ORIVECT
N40 G01 X0 Y0 Z=SIZE_Z+50 X0 Y0 A2=0 B2=0 F1800
N50 CUT3DF G41 A5=0 B5=0 C5=1 Z=SIZE_Z+40 //enter to contour
N60 G01 X=-SIZE_X*0.5 Y=-SIZE_Y*0.5
N70 G01 Z=SIZE_Z-DEPTH F=FEED B2=-ANGLE
Int y_steps = ceil(SIZE_Y/STEP);
Float y_step = SIZE_Y/y_steps;
Float ycoord=-SIZE_Y*0.5; int sign=1;
for(;y_steps>= 0; y_steps–){
G01 X=SIZE_X*0.5*sign B2=ANGLE*sign
ycoord += y_step; Y=ycoord; sign=-sign; }
N100 G01 G40 Z=SIZE_Z+50 F1800
N120 G01 X0 Y0 A2=0 B2=0
N130 M30
```

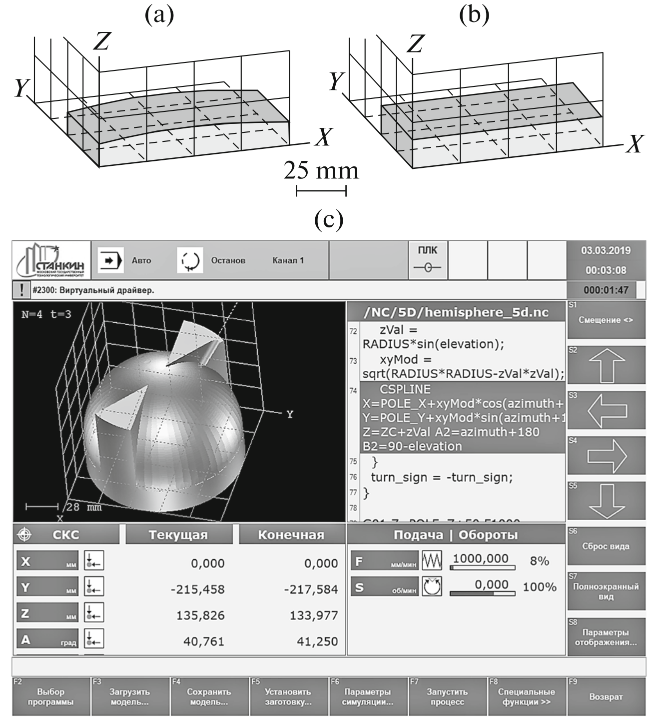

Fig. 2. Results obtained by means of the control program without (a) and with (b) compensation of the tool's end displacement with change in its position; and results obtained in machining a hemisphere (c).

The operation of the contour-compensation algorithm conforms largely to simple geometry. We obtain a plane only with compensation of the displacement of the tool's end, taking account of its orientation (Figs. 2a and 2b).

The operation of this algorithm is also illustrated by the machining of a hemisphere (Fig. 2c). The control program is written in the coordinate system of the workpiece.

CONCLUSIONS

(1) Among the distinguishing features of high-end CNC systems are that they are of PCNC class; and high-speed industrial networks are used for control and interaction with the executive units. In functional terms, they must be capable of multiple-channel and multiple-axis machining and include a set of algorithms for spline interpolation and frame compression. In addition, programmed tool orientation is essential in order to establish optimal cutting conditions. Finally, current control systems must permit multiple-terminal control and must be able to accommodate additional users.

(2) Bosch Rexroth CNC systems may not match the Fanuc, Siemens, and Heidenhain systems in terms of sales volume, but they are superior to those systems in certain key respects.

On the basis of its capabilities, the Russian AksiOMA Kontrol CNC system, although a relatively new development, should be competitive in the global marketplace.

ACKNOWLEDGMENTS

The research was conducted on equipment at the Collective-Use Center, Stankin Moscow State Technical University.

FUNDING

Financial support was provided by the Russian Ministry of Education and Science (project 2.1237.2017/4.6).

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Translated by B. Gilbert