

6th CIRP International Conference on High Performance Cutting, HPC2014

Research and development of a cross-platform CNC kernel for multi-axis machine tool

Sergej N. Grigoriev^a, Georgi M. Martinov^{a*}

^aMoscow State Technological University "STANKIN", Vadkovsky per. 3a, Moscow 127055, Russia

* Corresponding author. Tel.: +7-499-972-9440; fax: +7-499-973-3885. E-mail address: martinov@ncsystems.ru

Abstract

The demand for cross-platform solutions for real-time control systems is determined by the necessity to reduce the development cycle time, to provide broad opportunities of configuring the CNC system for multi-axis machine tools and to simplify the implementation of application solutions for shop floor. The paper proposes an approach of building a portable CNC kernel based on platform independent libraries. Open architecture CNC system offers levels of abstraction in the kernel for implementing various HMIs, accepting different part program language versions and using different fieldbuses. An example of adapting cross-platform CNC kernel for multi-channel and multi-axis machine tool is illustrated.

© 2014 Published by Elsevier B.V. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).

Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: Cross platform CNC kernel; Portable real-time software; Multi-protocol control system;

1. Introduction

CNC systems architecture is heavily influenced by various aspects of the computer industry development [1,2]. For developers, this often creates problems of continuity and support of the previous solutions. End users face the problem of network integration and technical support of CNC systems from different manufacturers, as well as problems with the transfer of part programs to other control systems and retraining staff. To solve these problems, the OMAC (Open Modular Architecture Controller) project promotes the idea of unifying CNC systems via the Web through OMAC XML schemes [3]. Such decision was conditioned by the current situation, but did not focus on future development. At the same time, global CNC manufacturers continue to steadily develop, including the direction of simplifying the integration of CNC equipment into a common information environment.

Today it is important to define the concept of system development, so that it has a development perspective for the foreseeable future. Innovative control systems should provide machine builders with the ability to use it not only for traditional treatments, but also for new technologies, such as

additive processing technology, hybrid processing technology (where two or more different energies are simultaneously applied to the same point), technology processing based on new physical principles, technology of machining on machine tools with new (non-traditional) designs. In addition, for the control system to be prospective, it should provide end users with the ability to create and integrate their own «know-how».

2. Definition of the requirements for cross-platform CNC kernel

The decision goes beyond the classical control systems [4]. A modern control system is constructed on the basis of the synthesis of heterogeneous computing components, such as conventional control systems (CNC systems, PLCs and motion controllers), industrial computers and specialized control systems, which are incorporated in the information-computing environment via industrial networks [5,6].

The key requirements are illustrated on Fig. 1.

Platform independence implies the possibility of using the CNC kernel software on different hardware and software platforms. As a result, the CNC system does not depend on the

production of hardware or operating systems being changed or stopped. This requirement allows selecting the system platform (hardware and operating system) in accordance with the necessary computing demand for controlling the particular process equipment.

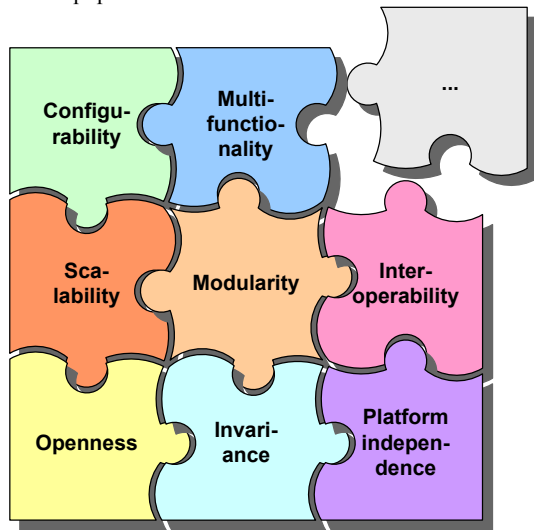


Fig. 1. Key requirements for a control system.

Invariance means ensuring the consistency of control process in a variety of implementation ways; it may be an in-house solution or one based on OEM equipment.

The *openness* of architecture allows machine builders and end users to integrate their know-how in the area of high-speed cutting technology, including special canned cycles, interpolation algorithms, kinematic transformations, adaptive management and etc. in the CNC system.

The *scalability* of the system allows "cloning" existing functionality several times, and is provided via the multi-channel support of CNC system. The axes are attached to the channel, and each channel can execute its own part program, and as a result, several part programs can be run on CNC system concurrently. Most often, this feature is used for multi-spindle processing or for the joint control of the machine tool and the loader.

Configurability means the ability to configure the CNC system for different technological tasks, and different price categories.

Multifunctionality of the system means the ability to implement different processing technologies and the opportunity to support a wide range of peripheral devices. This requirement is used in multi-tasking machine tools that allow performing for a single setup of the workpiece, for example, turning, milling and grinding operations or mechanical and laser processing, with the hardening of certain surfaces performed after machining. Another area of use is hybrid treatment [7]. For example, laser-assisted machining was developed in an effort to reduce the manufacturing costs and is associated with the machining of ceramic [8]. In laser-assisted machining the laser is used for changing the structure of material in the cutting area [9].

Modularity supposes the rejection of the monolithic construction of the CNC and the transition to a modular composition, where the hardware and software components implement the specified interfaces to enable their integration in the CNC. Changing separate components does not disturb the operability of the control system provided their interfaces are kept.

Interoperability implies smooth flow of information between control systems from different manufacturers. In the modern distributed manufacturing, compatibility is taken primarily as an opportunity to exchange part programs between different CNC systems [10,11,12].

The concept of building a cross-platform CNC kernel and ensuring the requirements will be considered in the example of the model of connecting peripheral devices, the model of the virtual machine and the model of a data processing pipeline.

3. Architectural model of connecting peripheral devices to the CNC kernel

The openness of the control system architecture is concentrated in the levels of abstraction, which ensures the independence of the CNC kernel from the particular implementation of the detachable level and the environment to connect to the kernel (Fig. 2). Components developed by specialists of MSTU "STANKIN" are in the blue area.

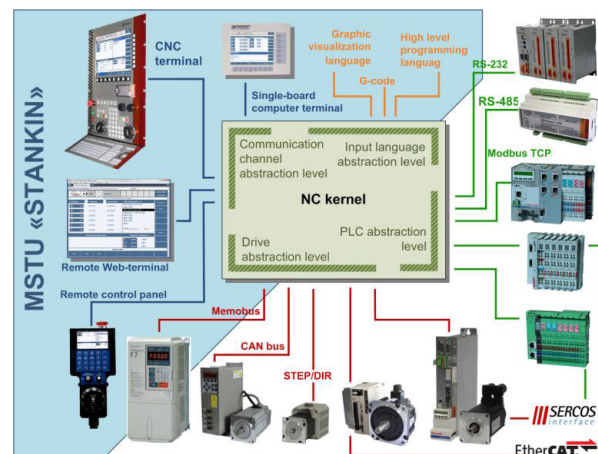


Fig. 2. Variants of arranging the control system.

Abstraction at the level of the input language (Fig. 2) allows defining the part program in different ways, without modifying the CNC kernel. The classic version presumes defining the part program in the G-code. The creation of parametric part programs, routines and canned cycles is done with the help of a high level programming language using variables, loops, conditional and unconditional jumps, math and string functions. The ability to define the geometry of simple parts processing using a graphical *.dxf file is implemented. The abstraction at the level of the input language allows adding new forms of defining the part

program without modifying the CNC kernel, as, for example, in the STEP-NC language [13].

Abstraction at the level of the communication channel (Fig. 2) allows connecting different terminals as clients to the control system without changing the CNC kernel thereof. Standard supply uses the regular terminal for the HMI (Human Machine Interface). The CNC system can be equipped with a simplified terminal based on a single board computer, remote control panel or remote Web-terminal based on a Web browser.

Today, the control system supports up to 8 simultaneously connected clients. Large machine tools having a work area of 10 or more meters are equipped with several terminals.

Simplified terminal is usually used when the CNC system is built into an automatic transfer line. In this case, the value of the operational control is reduced because the commands to load the part program and execute it come in the automatic mode from the upper level control system, instead of the machine operator.

The operator uses the remote control panel when it is necessary to monitor and control the process of handling closely to the working area, and using the regular terminal for these ends is inconvenient.

Web-terminals are used to remotely configure the system as a whole, including the setting of servo drives and PLC I/Os. They are also used for remote monitoring of process and machines [14,15].

Abstraction at the level of drives (Fig. 2) allows, without changing the kernel, attaching servo drives controlled through different fieldbuses, including high-speed protocols SERCOSIII and EtherCAT, uniting in a single real-time network servo drive controllers and PLC I/Os.

PLC abstraction level (Fig. 2) allows the CNC kernel to work with stand-alone cycle logic controllers from OEM manufacturers as well as with built-in software-based cycle logic controller (SoftPLC) using passive I/Os.

The proposed concept of building CNC systems with distinguished levels of abstraction suggests the independence of kernel algorithms (interpretation, look-ahead, kinematic transformation, etc.) from the connected peripherals. The kernel operates with virtual components: servo drive, I/Os, control panels and terminals. To add peripheral devices, controlled through new fieldbus, it is necessary to create a wrapper for the fieldbus and to configure the ports of connected devices.

Introducing the levels of abstraction in the CNC kernel allows integrating the equipment from different manufacturers in a single industrial system. The levels of abstraction provide the requirements of openness, multifunctionality, configurability and interoperability of the CNC system.

4. Model of the CNC system according to the type of virtual machine

The control system as a virtual machine has a layered structure with a strict hierarchical arrangement of layers (Fig. 3).

On the lower level, there is the hardware layer. Depending on the way of CNC implementation it could be standard PC

hardware (motherboard, memory, ports, etc.), and specific NC hardware that conforms to fieldbus protocols (SERCOS, EtherCAT, etc.), or single-board computer hardware, for example, ARM architecture. Above there is a layer of real time operating system (RTOS). At present the solutions based on Windows RTX (Real Time eXtension) and RTLinux are implemented, but it is also possible to develop other RTOS solutions, based on Windows CE, VxWorks, etc.

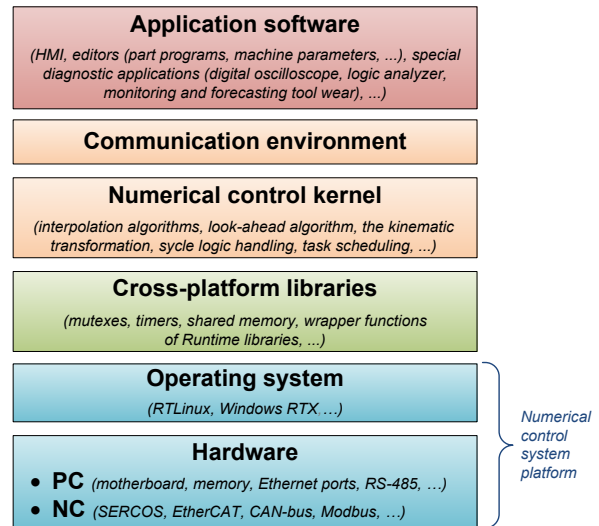


Fig. 3. The cross-platform implementation of control system.

The hardware layer together with the RTOS layer form system platform, which, on the one hand is the basis for the development of CNC systems, and on the other hand, is open to the implementation of new solutions in accordance with advanced trends in the computer industry.

The idea of cross-platform approach involves masking the features of the system platform from the CNC kernel by creating an independent layer of cross-platform libraries. Timers, mutexes, semaphores, shared memory, threads, wrappers of runtime library functions and other specific to the operating system elements are implemented in this layer.

Replacing the execution platform in the CNC system implies replacing the cross-platform libraries, which is a work estimated in several person-months.

The approach is similar to the solution of MS Windows, where porting to another platform is done by replacing HAL (Hardware Abstraction Layer), where computer operating system interacts with hardware devices, without changing the core of operating system.

All software levels located above the platform-independent one are written only using the cross-platform libraries, with no direct call to the RTOS functions.

Above the platform-independent layer there is the CNC kernel level. This level implements part program interpretation algorithms, interpolation algorithms, including spline interpolation (cubic, Akima and NURBS), look-ahead algorithm and kinematic transformation algorithms. SoftPLC

algorithms and scheduling algorithms are also implemented at this level.

At the top is placed the application layer which contains the HMI (Human Machine Interface), different editors, specific diagnostic applications, etc.

The connection between the CNC kernel and the application layer is implemented via the layer of communication environment.

The introduction of cross-platform libraries and multi-level organization of the CNC system software conform to the requirements of platform independence.

5. Variants of cross-platform implementation

Cross-platform approach provides a layout of the CNC system in both single- and two- computer architecture without modifying the source code of the kernel and the terminal.

The NC kernel (Fig. 4) is compiled for:

- platform x86 with the operating system RT Linux, the cycle of the interpolation is in the range of 0.1 - 4 ms;
- platform x86 with the operating system MS Windows and RTX real-time expansion, the cycle of the interpolation is in the range of 0.02 - 4 ms;
- platform x86 with the operating system MS Windows, the cycle of the interpolation is in the range of 2 - 4 ms;
- platform ARM with the Linux operating system, the cycle of the interpolation in the range of 0.1 - 4 ms.

The regular terminal implements the HMI based on PC with MS Windows and .NET software platform. This terminal connecting to the NC kernel based on MS Windows with RTX extension or only MS Windows allows the use of both single- or two- computer architecture of a control system.

The remote terminal is run via a web-browser and is used for remote configuration and diagnostics of control system, as well as for monitoring the production process [16,17].

The simplified terminal is based on .NET Compact

Framework or implemented as a Java client. The control system is equipped with only a simplified Terminal embedded in the automatic line or with terminals with limited functionalities – for large machines [18].

The remote control panel is used when the terminal is located far from the working area or when the working area is too large. The remote operator interface implements limited operator interface, built using Qt on Linux platform with an ARM processor.

The considered solutions illustrate the invariance of the CNC system. The potential of the proposed concept for the implementation of the kernel and terminal of the control system is much broader than the listed options.

6. Practical aspects of the implementation

The increasing demand for big parts is promoting the interest in large machine tools. Aerospace and power generation markets require large structural elements. Large parts that were previously assembled from separate parts are now machined from monolithic blocks, which increases the need for large and precise machine tools. Previously the problem was to find large machine tools for processing products, now the question is the time and the cost of treatment.

A big machine is a relative term, but in general, a “big” machine tool can be defined as a machine center with a work area larger than 1m³ or a lathe that can handle workpieces with the diameter of more than 1m [19]. Although these machine tools execute the same operations as the conventional ones, due to the large size of parts and their massiveness the processing is organized differently. In particular, for the treatment of such details, it is important to reduce the number of part setups, as well as to provide the possibility of measuring directly on the machine and immediate input correction to prevent scrap. In addition, large parts are most often made of new materials, besides monitoring and remote controlling of the process are important. The manipulation of

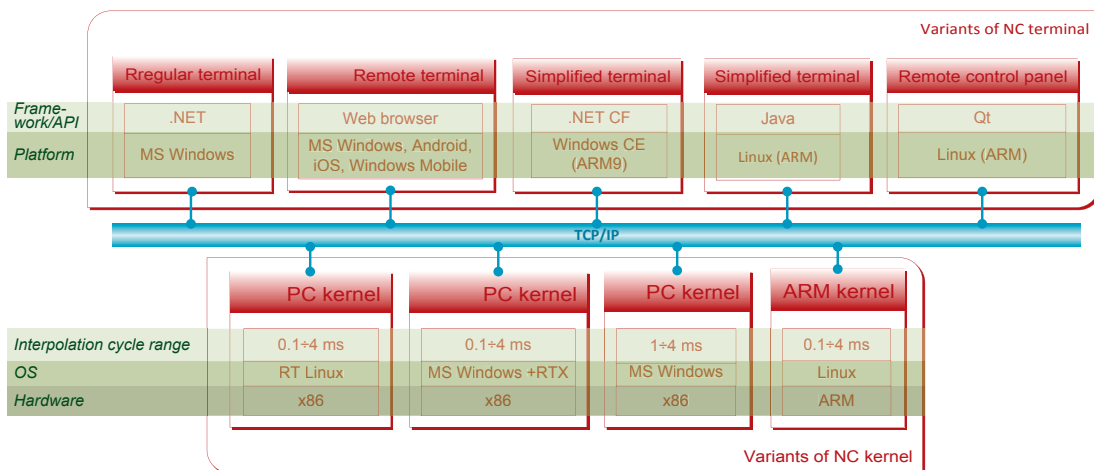


Fig. 4. Already implemented cross-platform variants of CNC system.

large workpieces is more difficult, it takes longer to setup them [20].

Integrated in the concept of building a CNC system, the principles of openness, modularity and scalability allowed implementing a distributed control system for lathe and milling machining center VMG 50/90. Five-axis machining center VMG 50/90 is designed for machining large workpieces weighing up to 125 tons with an accuracy of $\pm 4 \mu\text{m}$. For estimating the dimensions of the working area the sketch of the machine tool and operator are shown in the scale model (Fig. 6). The diameter of the workpiece on the turning table is up to 5 meters, the length of the working area is 14 meters. For controlling the machine tool, the CNC system implements working with two regular CNC terminals and a remote control panel for manual handling in the work area.

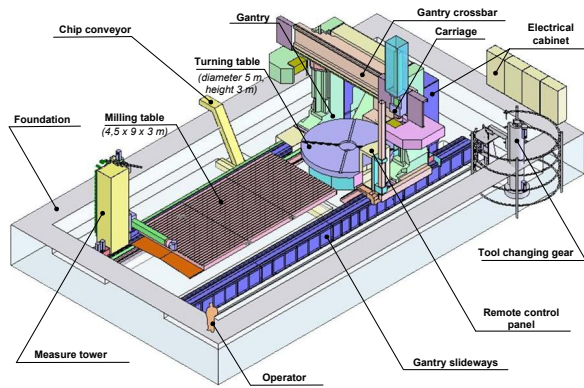


Fig. 6. Sketch of the machine tool.

The CNC system has a two-computer architecture. The CNC kernel runs in the operating system Linux RT with the control board SERCANS, which is the master for the main SERCOS network. The system implements 5-axis machining, uses two control channels and manages the 14 servo drives. Servo drives and I/O PLC modules are combined into a 3-level SERCOS III network according to the master-slave scheme.

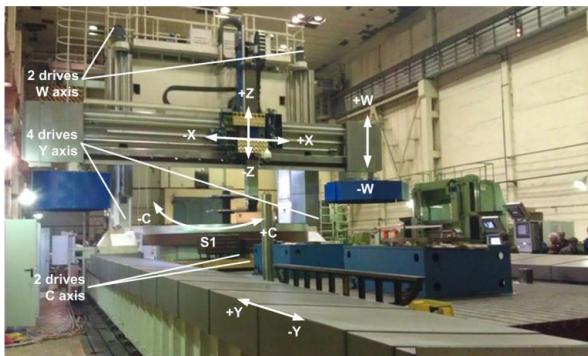


Fig. 7. Physical-axis of machine tool.

The Y axis of the main gantry is implemented with 4 servo drives; the axis W - cross of the gantry – and the axis of Cs1

turning tables are implemented with 2 servo drives each (Fig. 7). The configuration of the SERCOS subnets is implemented with the help of CNC machine parameters. The configuration information is transmitted to the master servo drives during initialization via SERCOS parameters.

Bus couplers with a corresponding set of I/Os are built into each electrical cabinet and connected to the main SERCOS III network. The allocation of servo drive controllers and bus couplers in electrical cabinets is shown by the dotted line at Fig. 8.

Two regular CNC terminals and the remote control panel are connected through an industrial hub to the CNC kernel via Ethernet. The user interface screens are synchronized automatically. The CNC kernel accepts control commands only with the active control panel, which provides a special mechanism for the transfer of control between the regular CNC terminals and the remote control panel.

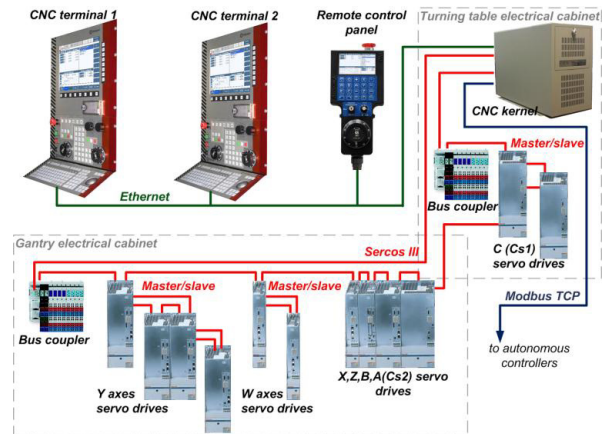


Fig. 8. Decentralized CNC system for VMG 50/90 machine tool.

CNC system implements functions of gantry axes control, volume correction, synchronizing concurrent operator access and interacting with the controller of autonomous equipment.

The test results are summarized in Table 1.

Table 1. Test results of CNC system for VMG 50/90 machine tool.

Parameter	Value
Positioning accuracy	$< 3 \mu\text{m}$ at length of 250 mm
Angular positioning accuracy	$< 0.014^\circ$
Repeatability	$< 2 \mu\text{m}$
Machining accuracy	$< 5 \mu\text{m}$ on diameter 4 m
Accuracy of handling movement of 10 μm along the axis X	$< 0.5 \mu\text{m}$

7. Conclusion

Using a cross-platform kernel allows the control system software to be independent from the specifics of the system platform and provides broad opportunities for configuring the CNC system for multi-axis machine tools.

The proposed solution is based on a multi-protocol control system and allows combining hardware and software

components from different manufacturers. Using a cross-platform kernel ensures the independence of the control system software from the specifics of the platform.

The application of abstraction levels in the architecture of the CNC system allows implementing multiple protocols for controlling servo drives and PLCs and expanding the list of supported OEM equipment, which is important for large machines.

Regardless of the kind of software and hardware COST (Commercially available Off-The-Shelf) or in-house developments, there is a problem of their integration into the control system, and the determining factors are: the openness of architecture of control system, the technologies used and the availability of standardized interfaces for embedded devices.

Acknowledgements

This research was supported in part by Russian Federal target program "National Technological Base" and Russian Federal Program on Support of Leading Scientific Schools grant NSh-3890.2014.9.

References

- [1] Pritschow G, Altintas Y, Jovane F, Koren Y, Mitsuishi M, Takata S, et al. Open controller architecture - Past, present and future. *CIRP ANNALS-MANUFACTURING TECHNOLOGY* 2001;50(2):463-470.
- [2] Martinov GM, Martinova LI. Trends in the numerical control of machine-tool systems. *Russian Engineering Research* 2010;30(10):1041-1045.
- [3] Xiong-bo M, Zhen-yu H, Yong-zhang W, Hong-ya F. Development of a PC-based Open Architecture Software-CNC System. *Chinese Journal of Aeronautics* 2007;20(3):272-281.
- [4] Minhath, M., and X. W. Xu. Characteristics and Technologies of Advanced CNC Systems. *Encyclopedia of Information Science and Technology*; 2009. p. 519-527.
- [5] Campos G, Hardwick J, Hardwick M. Manufacturing traceability automation using features and nc-functions. *International Journal of Computer Integrated Manufacturing* 2009;22(2):112-128.
- [6] Pengfei L, Tao G, Jianping W, Hongzhao L. Open architecture of CNC system research based on CAD graph-driven technology. *Robotics and Computer-Integrated Manufacturing* 2010;26(6):720-724.
- [7] Martinov GM, Ljubimov AB, Grigoriev AS, Martinova LI. Multifunction Numerical Control Solution for Hybrid Mechanic and Laser Machine Tool. *Procedia CIRP* 2012;1:260-264.
- [8] Chih-Wei C, Chun-Pao K. An investigation of laser-assisted machining of Al2O3 ceramics planing. *International Journal of Machine Tools and Manufacture* 2007;47(3-4):452-461.
- [9] Ding H, Shin YC. Laser-assisted machining of hardened steel parts with surface integrity analysis. *International Journal of Machine Tools and Manufacture* 2010;50(1):106-114.
- [10] Minhath M, Vyatkin V, Xu X, Wong S, Al-Bayaa Z. A novel open CNC architecture based on STEP-NC data model and IEC 61499 function blocks. *Robotics and Computer-Integrated Manufacturing* 2009;25(3):560-569.
- [11] Newman ST, Nassehi A, Xu XW, Rosso RSUJ, Wang L, Yusof Y, et al. Strategic advantages of interoperability for global manufacturing using CNC technology. *Robotics and Computer-Integrated Manufacturing* 2008;24:699-708.
- [12] Mehrdad S, Nassehi A, Newman ST. A novel methodology for cross-technology interoperability in CNC machining. *Robotics and Computer-Integrated Manufacturing* 2013;29(3):79-87.
- [13] Rauch M, Laguionie R, Hascoet JY, Suh SH. An advanced STEP-NC controller for intelligent machining processes. *Robotics and Computer-Integrated Manufacturing* 2012;28(3):375-384.
- [14] Mori M, Fujishima M, Komatsu M, Zhao B, Liu Y. Development of remote monitoring and maintenance system for machine tools. *CIRP Annals - Manufacturing Technology* 2008;57(1):433-436.
- [15] Martinov GM, Ljubimov AB, Martinova LI, Grigoriev AS. Remote Machine Tool Control and Diagnostic Based on Web Technologies. *Proc. of COMA 13, International Conference on Competitive Manufacturing, Stellenbosch (South Africa)*; 2013. p. 351-356.
- [16] Martinov GM, Grigoriev AS. Diagnostics of cutting tools and prediction of their life in numerically controlled systems. *Russian Engineering Research* 2013;33(7):433-437.
- [17] Martinova LI, Grigoryev AS, Sokolov SV. Diagnostics and forecasting of cutting tool wear at CNC machines. *Automation and remote control* 2012; 73(4):742-749.
- [18] Grigoriev SN, Martinov GM. Decentralized CNC Automation System for Large Machine Tools. *Proc. of COMA 13, International Conference on Competitive Manufacturing, Stellenbosch (South Africa)*; 2013. p. 295-300.
- [19] Kennedy B. Big machine tools are just like smaller ones. And they're not. *Cutting tool engineering* 2007;59:8.
- [20] Grigoriev SN, Martinov GM. Scalable Open Cross-Platform Kernel of PCNC System for Multi-Axis Machine Tool. *Procedia CIRP* 2012;1:238-243.