ISSN 0005-1179, Automation and Remote Control, 2017, Vol. 78, No. 3, pp. 525–536. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © G.M. Martinov, N.V. Kozak, R.A. Nezhmetdinov, A.S. Grigoriev, A.I. Obukhov, L.I. Martinova, 2013, published in Avtomatizatsiya v Promyshlennosti, 2013, No. 5, pp. 8–14.

AUTOMATION IN INDUSTRY

# Method of Decomposition and Synthesis of the Custom CNC Systems

**G. M. Martinov[a], N. V. Kozak[b], R. A. Nezhmetdinov[c], A. S. Grigoriev[d], A. I. Obukhov[e], and L. I. Martinova[f]**

*MSTU "STANKIN," Moscow, Russia*

*e-mail: [a] martinov@ncsystems.ru, [b] kozak@ncsystems.ru, [c] r.nezhmetdinov@stankin.ru, [d] grigorievanton@mail.ru, [e] obukhov@ncsystems.ru, [f] lili@ncsystems.ru*

Received December 11, 2012

**Abstract**—The paper discusses the development of a generic platform underlying the design of custom CNC systems for hi-tech production complexes, where either conventional CNC systems are inapplicable or control tasks cannot be fully accomplished.

**DOI:** 10.1134/S0005117917030122

## 1. INTRODUCTION

With the advent of in recent years new technologies, such as additive manufacturing techniques of products, hybrid technologies of processing (where two and more different energy at the same time work in the same point) [1], the technologies of processing which are based on the new physical principles, technology of processing on machines of new (nonconventional) designs [2], etc., system approach to creation of control systems wasn't created. And it is about the technologies used in strategic industries and creating bases for technological break in the sphere of creation of new samples of an industrial equipment.

Deliveries to Russia of the CNC systems with functions of 5-axis machining and control systems of technological robots, that is the most difficult and innovative control systems necessary for creation of domestic processing equipment, are limited. At the same time the CNC systems of the Hi-End class which nevertheless are present at the domestic market it is only conditionally possible to consider open. Similar systems are completely open only for the producer. As a rule, the option of transfer of own know-how of foreign CNC producer to domestic-owned firms for integration into a control system is not acceptable. CNC systems of the Hi-End class aren't manufactured in Russia, and the released systems owing to architectural restrictions can't form base for creation of solutions of this class. Therefore the problem of creation of the CNC domestic system for control of high-technology industrial complexes is a task of ensuring technological independence of the country.

## 2. CONTROL PROBLEMS IN CUSTOM CNC SYSTEMS

System approach to construction of the CNC systems software assumes allocation of control problems as autonomous subjects to development [3].

The geometrical task provides mathematical calculation of a trajectory of the cutting tool (an tip edge, a stream, the laser, etc.) taking into account features of kinematics of the machine, corrections, restrictions and requirements of accuracy. The logical task realizes control of cyclic automatic equipment of the machine [4]. The terminal task provides to the operator of the machine all necessary functions of control by means of the user interface. It determines appeal and competitiveness of CNC system in the market. The technological task provides the set TP parameters

that is implemented, for example, through adaptive control, control of laser power on all processed trajectory, etc.

During the researches the list of traditional control problems was expanded: it was filled up by communication and diagnostic tasks. The communication task provides link between modules of system and realizes information data exchange in real time (RT) under industrial protocols [5]. The diagnostic task is responsible for collection and the analysis of data on a condition of the equipment and the carried-out TP [6].

## 3. DECOMPOSITION OF THE CNC SYSTEMS AND FORMATION OF MATRIX OF SOLUTIONS

Within process of decomposition the matrix of solutions is developed which columns represent tasks of control (geometrical, logical, technological, terminal, diagnostic and communication), lines—the used technologies. By means of a matrix a necessary set of hardware-software components for configuration of a control system under specific production structure is determined.

The generalized character of the CNC systems for diverse processing equipment is vast. Global manufacturers try to equip the flagman systems with functionality as much as possible. However there is a threshold behind which efficiency is lost, and such CNC systems are used at best for 40–50 % of the potential opportunities. The created matrix of solutions systematizes a set of modules of the CNC system according to technologies which are realized by a control system.

On the basis of a matrix minimum necessary set of modules for the subsequent synthesis of the specialized CNC system is defined. Thus, when developing new technological complexes the customer only defines a set of technologies of processing which need to be provided. Developers of a specialized control system by means of the matrix of solutions choose the modules realizing required technologies of processing and integrate these modules into the CNC system.

The offered set of technologies in the matrix of solutions (Table 1) can be extended as required.

## 4. REALIZATION OF TECHNOLOGY OF CONTINUOUS LASER PROCESSING

Control of processing of products of continuous laser radiation consists in control of the laser and deflector (the device which is carrying out scanning of the working field with a beam by means of the rejecting mirrors) of the CNC system (Fig. 1).

The geometrical task of the CNC system is responsible for the functionality connected with realization of a forming control. On an input the operating program in the ISO-7bit code arrives, at the output the instruction statement setting a trajectory of movement and focus of a laser beam are formed. *The module of control system of a deflection* interacts with deflectors of direct control or with the deflectors having the independent controller of movement via the abstract interface and sends control instructions.

*The module of processing of the laser signals* within a logical task carries out operations of stop/start of the program for an external signal, exercises control of readiness of the laser and its exit to an operating mode. Communication of the module of signal processing with the laser is, as a rule, carried out on the serial interface.

*The module of control and display of parameters of the laser* (terminal task) realizes the configured modes of control and display of the current parameters of the laser in the form of separate screens. By means of the module of control and display the operator sets parameters of operation of the laser and adjusts communications with the laser.

Control systems of laser processing, as a rule, generate the operating programs for three-dimensional model of a product. *The model of preprocessor of 3D module* (terminal task) cuts

**Table 1.** Matrix of solutions

| Technologies | Tasks of CNC system | | | | | |
|---|---|---|---|---|---|---|
| | Geometric | Logical | Terminal | Communicational | Technological | Diagnostic |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Continuous laser processing | Module of control of deflection system | Module of processing of laser signals | Tuning and display of laser parameters; 3D model preprocessor | Module of communication with deflector | Adaptive control of radiation power | Diagnostics and monitoring of radiation parameters |
| Impulse laser processing | Module of synchronization of the movement with laser impulses | Module of processing of laser signals | Tuning and display of actual laser parameters | Driver of control of discrete laser signals | Adaptive control of radiation frequency | Diagnostics and monitoring of radiation parameters |
| Multiple-axis processing | Module of kinematic transformation; Electronic gear; Compensation of deformation on axes; Synchronization of control paths | Realization of Master Slave control on PLC basis | Interface of multichannel control | Multiprotocol interface of communication of CNC system with drives; Realization of Master Slave control on the basis of drives | Module of adaptive processing; Module of setup of the tool after installation | |
| Measurement of the tool and workpiece | Module of processing of measurements | | Display of the mode of measurements and graphics of measuring cycles | | Diagnosing of the cutting tool and its residual firmness | Measuring cycles of preparation of the tool |
| Hybrid and multipurpose processing | Module of external interpolation | Synchronization at control of processing energy | | | | |

**Table 1.** (Contd.)

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| Waterjet processing | The module of correction of a contour in a stream form | Control of parameters of waterjet processing | Display and tuning of parameters of waterjet processing | Realization of communication with the autonomous station of high pressure | Standard cycles of waterjet processing | Diagnostics and monitoring of the station of high pressure |
| Miltiuser access to CNC system | | | Web-client of control of CNC system; Multiterminal control | Web-server of control of CNC system | | Module of remote diagnostics for parameters of systems |
| Integration with systems of the top level | | OPC-server of data of electroautomatic equipment (PLC) | | OPC-server of data of the CNC system | | |

three-dimensional model on layers, converts sections into trajectories of movement of a beam and adds technological command (control of laser power, etc.).

*The module of communication with the deflector* (a communication task) provides communication with the deflector and is realized in the form of the driver of a control card of the device. Depending on a method of control of the deflector it is implemented or in a terminal part, or in a CNC system kernel therefore the communication module provides access to the deflector on the common interface both from a kernel, and from the terminal.

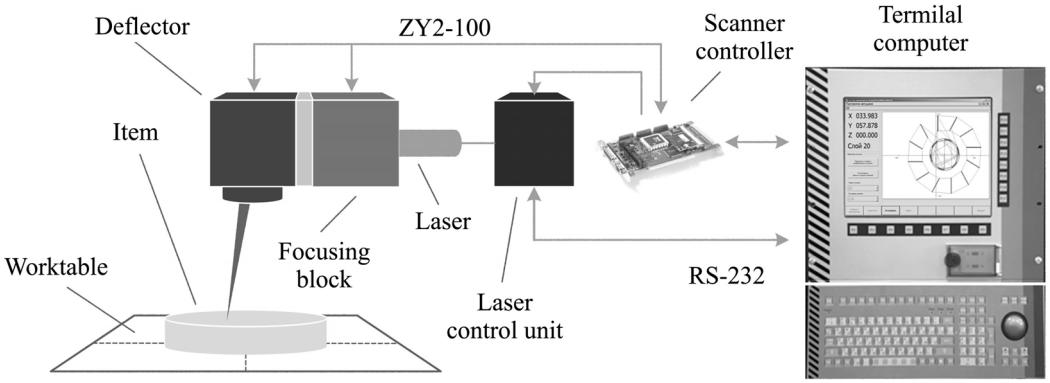


**Fig. 1.** Control system of continuous laser processing device.

Technological process is optimized on time that demands maintenance of the maximum planimetric speed at the accounting of limit accelerations on axes. The module of adaptive control of radiation power (technological task) corrects laser radiation power at change of speed of movement of a beam on sharp turns and curvilinear parts of a trajectory for the purpose of maintenance of constant conditions of impact of radiation on the processed material.

The diagnostic task is closely connected with a technological problem in laser systems. The module of diagnostics and monitoring of parameters of radiation forms in the RT mode the decision on correction of value of power of radiation.

## 5. REALIZATION OF TECHNOLOGY OF LOW-FREQUENCY PULSED LASER PROCESSING

The main feature of control of pulse installations consists in need of ensuring strict synchronization between impulses of the laser and movement of workpiece [7]. The moment of achievement of the next point has to coincide with the moment of implementation of an impulse of the laser pumping (Fig. 2). At the same time pulse frequency of pumping shall be withstood with an admissible error, otherwise energy and beam divergence will be insufficient for processing of a point.

*The module of synchronization of movement with laser impulses* (geometrical task) realizes an algorithm of pass of the processed points without reduction of speed that allows to use all benefits of the advancing viewing of a frame and spline interpolation.

In pulse laser systems formulation of logical and terminal tasks is similar to installations of continuous laser processing. Feature of the communication task is existence of the *control driver of the discrete signals* which realizes modulation of radiation in RT directly from the CNC system interpolator.

*The module of diagnostics and monitoring of parameters of radiation* controls mean value of power based on which in RT the decision on best value of radiated frequency is made. The maximum allowable frequency is proportional to the actual average power of radiation.

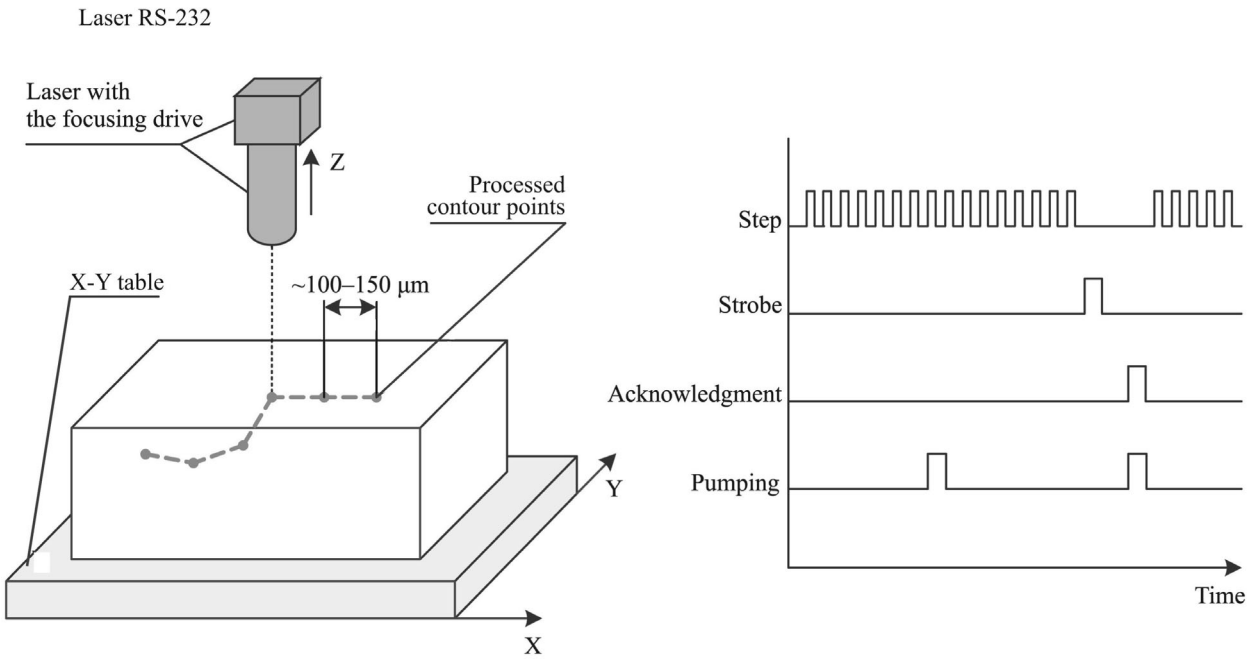


**Fig. 2.** The scheme of interaction of a control system with the pulse laser beam machine.

## 6. REALIZATION OF TECHNOLOGY OF MULTICOORDINATE PROCESSING

The machines realizing multicoordinate processing, as a rule, possess the specific kinematic scheme that requires from a control system of availability of serious resources for calculation of a trajectory of movement of the tool concerning workpiece [8]. The technology of multicoordinate processing is implemented in the matrix of solutions by components of geometrical, logical, terminal, communication and technological tasks.

*The module of kinematic transformation* (geometrical task) makes calculation of increments of positions of the drives necessary for achievement by the tool of the set point that allows to customize the CNC system for machines with original kinematic schemes. The module of kinematic transformation solves the direct problem of kinematics which is coming down to finding of the Cartesian coordinates of the tool proceeding from the set positions of drives, and also solves the return problem—finding of positions of drives on the basis of the set tool coordinates.

Synchronization of several axes when processing surfaces of a difficult profile or the organization of the coordinated operations of the executive nodes of the machine is used the *module of an electronic guitar of speeds* (the geometrical task). The module allows the CNC system to exclude the need for a reducer with changeable transfer number (a guitar of speeds) and to considerably increase the accuracy of coordination and positioning of axes. Setup of synchronization of axes is carried out through the coefficients set in the controlling program.

Additional G- and M-command are entered into language of the controlling programs of the CNC "AxiOMA Control" system for the parameter setting and on/off switching of the mode of synchronization. Switching on of the mode of synchronization of axes is carried out by the M902 function, switching off—by the M903 function. Parameters of synchronization are set by the G583 command <driving axis><coefficient of the slave axis>. For example, G583 X0 Y0.5 means that in the synchronization mode as the drive axis the X axis is, and as the slave axis the Y axis is with the coefficient 0.5.

The module of compensation of errors (geometrical task) compensates errors of the feed screw (for linear axes), errors of circular axes, errors of dependent axes (for example, a deflection on portal cross-piece on Z axis depending on Y coordinate) (Fig. 3).

Multichannel control in the CNC systems is applied to reducing a processing time by parallelization of process of cutting on the multi spindle machines, at the same time there is a reduction of the errors connected with workpiece reinstallation. *The module of synchronization of control channels* (the geometrical task) ensures the coordinated work of groups of axes and synchronization of the controlling programs which are executed on different control channels. Axes of the machine are

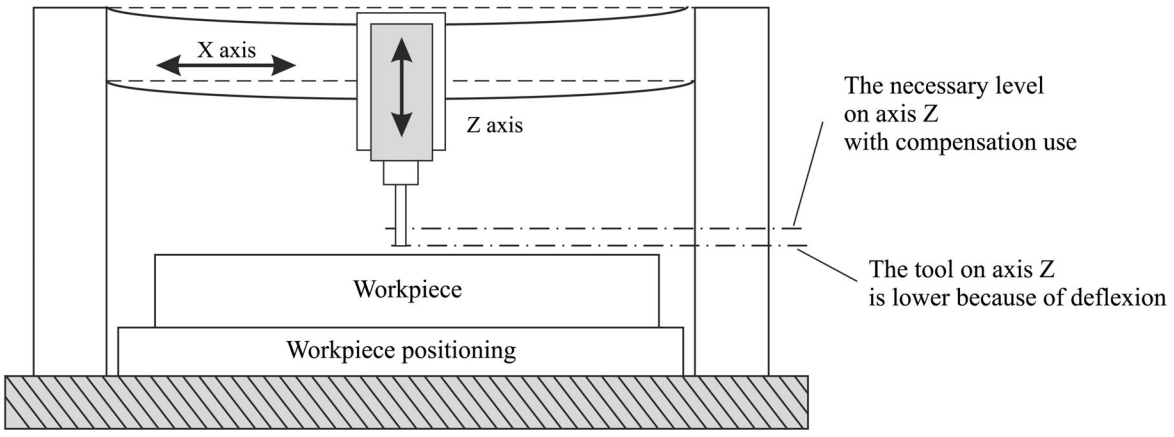


**Fig. 3.** Compensation of an error on axis Z depending on axis Y.

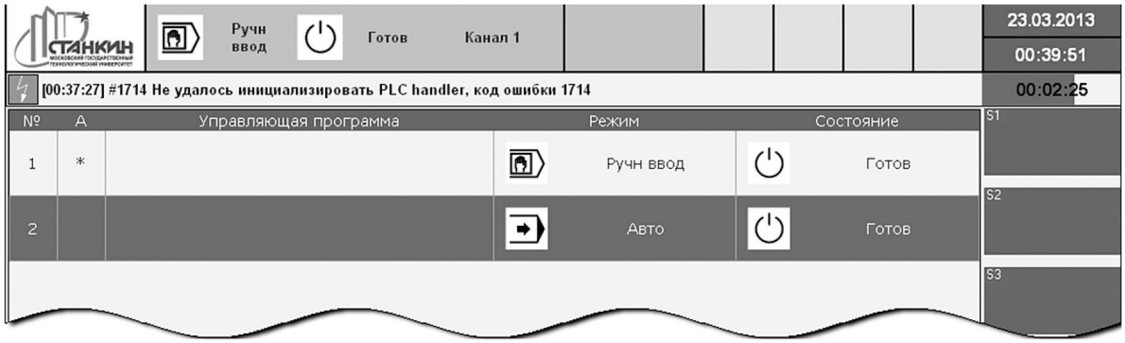


**Fig. 4.** Screen of the choice of the active channel.

logically grouped in channels, the module of synchronization of channels provides in a code of the execute program the mechanism of transmission of an axis from one channel in another. The axis is exclusively taken for the period of its use in a control path and then released.

*The module of the interface of multichannel control* (the terminal task) realizes components of the user interface for a choice of the active channel, fixing of axes to control channel, displays of current data of channels (a status, an operation mode, etc.) (Fig. 4).

*The module of the multiprotocol interface of communication* (the communication task) uses the objects which aren't depending on the interface of the industrial bus, abstracting algorithms of interpolation and control of electroautomatic equipment from specifics of actuation mechanisms. The type of the interface of specific executive device is set and set up in machine parameters. The coordinated functioning of executive devices in the RT mode is ensured by the put mechanism of a cyclic data interchange using or cyclic inquiry ("pooling"), or interrupt handling.

## 7. REALIZATION OF TECHNOLOGY OF MEASUREMENT OF THE TOOL AND WORKPIECE

Technologies of measurement in the CNC system are applied to tuning control for technological operation and executing of active control in processing.

*The module of processing of measurements* (geometrical task) realizes function of the admission (G75)—the special mode of interpolation to a touchdown. Function is used in measuring cycles in case of measurement of workpiece or the tool. As a result of measurement the CNC system brings correction on installation of a detail and the tool. The module of processing of measurements when receiving a signal of a contact of the sensor from the fast input fixes the current coordinates of axes

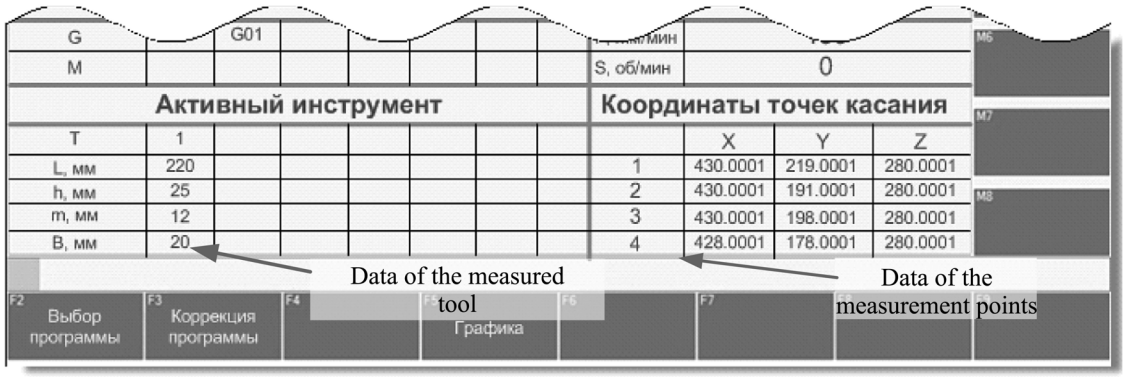


**Fig. 5.** The user interface of the operator in the mode of measurements.

and initiates the subsequent procedure of the emergency stop. Coordinates of a point of a contact are remembered in internal variables of control channel for the subsequent use in a code of the controlling program or a measuring cycle. For example, in a cycle of safe positioning (G101) the current situation is used for calculation of a condition when the probe has reached the set position with the set accuracy.

*The module of display of the mode of measurements* (terminal task) realizes components of display of coordinates of points of measurements, parameters of the measured tool, graphical representation of a trajectory of the measuring probe and the received points of a contact (Fig. 5).

*The module of diagnosing of the cutting tool* (a technological task) carries out diagnosing of the cutting tool and the forecast of his residual hardness in processing. Diagnosing is carried out on the basis of information from the sensors installed in a cutting zone, or information of change of power of drives. On the basis of the built-in model of process of cutting and the obtained data residual hardness of the cutting tool is predicted, and the result is compared with information on the executed technological transition. If necessary the module generates the operating signals on decrease in carrying-in and turns of a spindle for the guaranteed completion of technological transition or the emergency change of the tool in order to avoid breakage.

*The module of standard cycles of calibration and measurements* (diagnostic task) realizes a range of measuring cycles (calibration of the probe, measurement of tools of cutters, mills, drills, measurement of standard geometrical elements of a detail) which can be added with own measuring cycles of the machine tool builder and end user.

## 8. REALIZATION OF TECHNOLOGY OF WATERJECT PROCESSING

Waterject processing as the cutting tool uses a stream of water or mix of water and abrasive material under high pressure. Specifics of the CNC system are connected with control of a stream, control of parameters of supply of abrasive sand and pressure, and also with realization auxiliary M-commands of control of electroautomatic equipment.

The technology of waterject processing in the matrix of solutions is implemented by components of geometrical, logical, terminal and communication tasks.

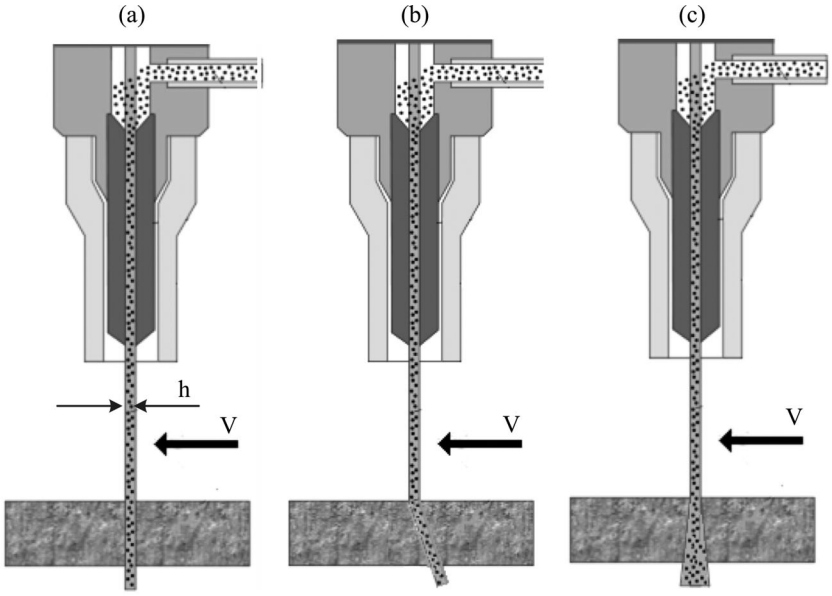


**Fig. 6.** Specifics of waterjet processing.

(a) (b)

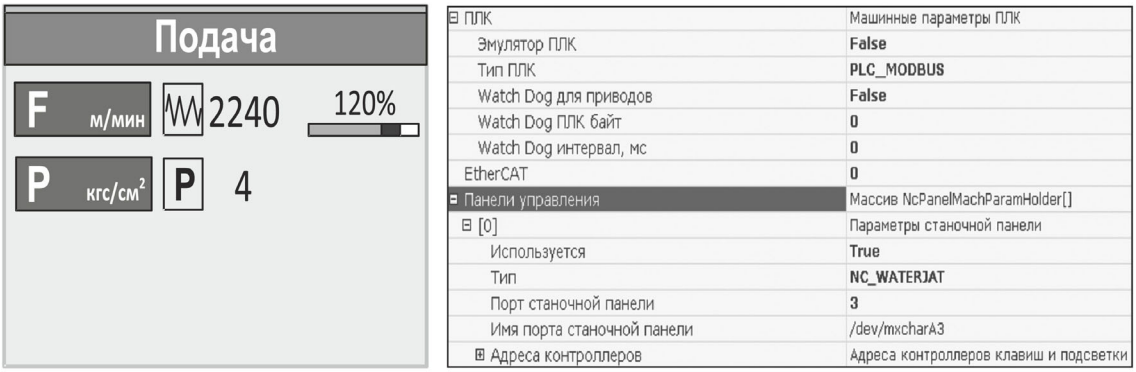


**Fig. 7.** Implementations of the user interface elements of the terminal task in case of waterjet processing.

The module of correction of a contour (geometrical task) is responsible for process of a shaping taking into account physical features of process of cutting of material with a stream:

• cut width error (Fig. 6a). The last is defined by the size of a stream and is set by the operator in system parameters. The algorithm of correction is similar to equidistant correction on the tool size when machining in the plane or correction on tool radius in space;

• deviation from a contour. In the course of cutting of material with the reduction of power of cutting there is a stream deviation in the opposite from the movement direction (Fig. 6b). The algorithm adjusts feed rates and pressure of a stream depending on type of the processed material and thickness of workpiece;

• deviation from a form. According to the energy conservation law, the stream loses energy characteristics at the output from material and aims to describe a cone (Fig. 6c). The algorithm corrects the stream pressure, quantity of the given abrasive when cutting according to thickness and type of the processed material.

Within a logical task [9] by means of auxiliary M-functions is carried out opening (M108) and closing (M109) of the gate of air supply in the cutting head, regulation of giving of an abrasive (M110), inclusion (M111) and shutdown (M112) of high pressure of waterjet processing.

Components of the operator interface (the terminal task) display the current value of pressure of a stream (Fig. 7a) that characterizes process of waterjet cutting, and realize the screen of setup of machine parameters of waterjet processing (Fig. 7b).

The station of high pressure (SHP) which is responsible for water pressure forcing has the independent controller. SHP integrate with the machine electroautomatic equipment controller in a single network (the communication task) with the use of standard industry protocols for a data interchange and control instructions.

Work with high pressure demands control of safety of SHP (a diagnostic task). Distinguish from controlled parameters: pressure in system, temperature in system, impurity of a filtration element of water purification, time of switching of the piston of the animator, water pressure on an entrance in the multiplying gear (has to be $\leq 4$ kgf/cm$^2$). At excess of critical value of any of controlled parameters the control system will stop SHP and will issue the warning to the operator.

## 9. PROCEDURE OF SYNTHESIS OF THE CUSTOM CNC SYSTEMS

Synthesis of the custom CNC systems consists in integration of the modules realizing technologies, necessary for the solution of production tasks, into a single control system of a specific technological complex. Integration of modules is carried out with use of the abstraction layers,

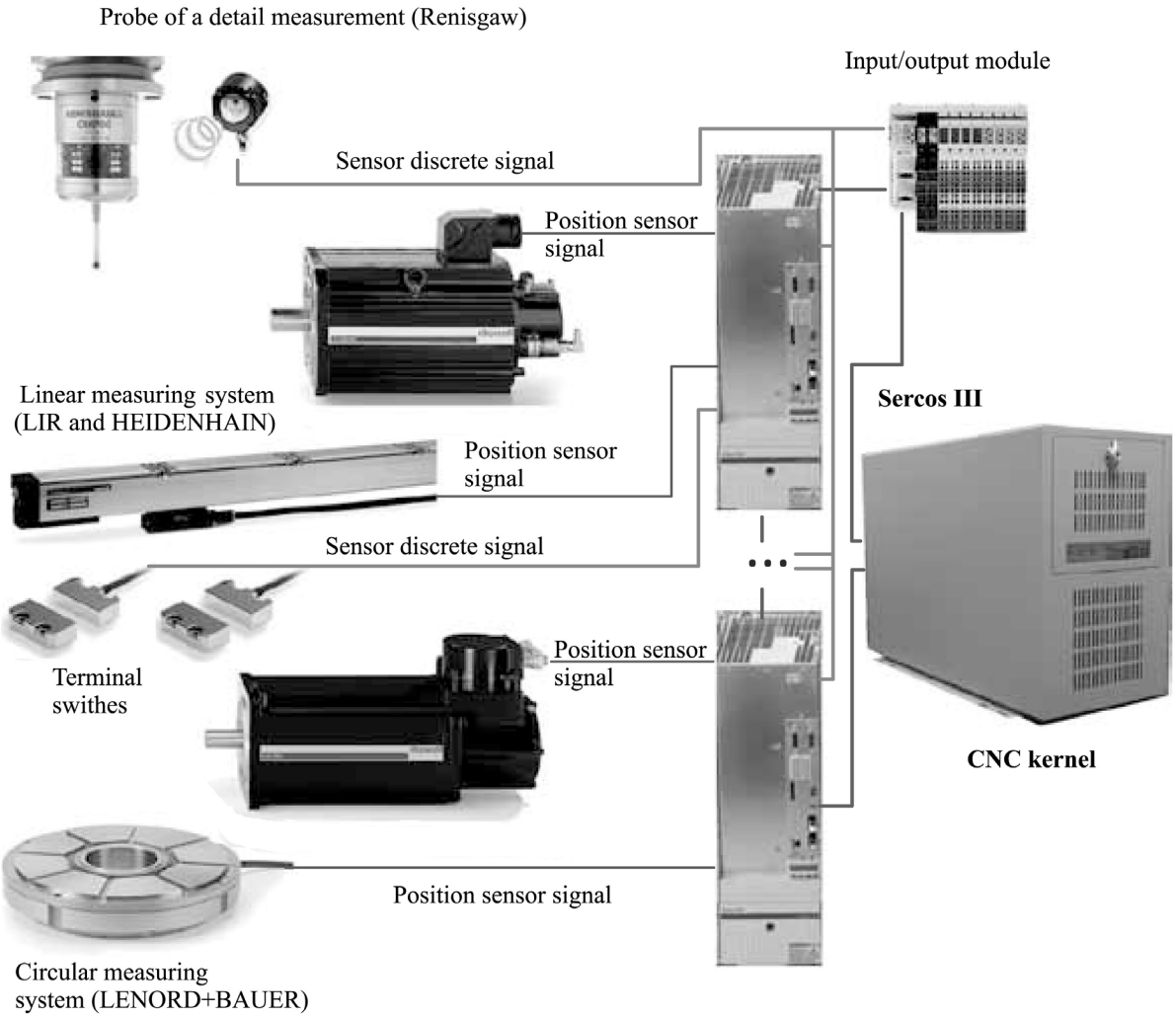


**Fig. 8.** Measuring systems of the processing center VMG 50.

mechanisms of component interaction and interfaces of embedding put in a reference platform of the CNC system.

As an example we will create a resultant matrix of solutions for the multipurpose vertical machining center VMG 50 equipped with the CNC "AxiOMA Control" system. The VMG 50 center is intended for processing of large-size details weighing up to 125 tons with an accuracy of 4 microns. The CNC system of the center realizes multicoordinate processing, carries out measurements with the subsequent corrections and provides the multiuser access. The corresponding set of modules realizing the listed technologies forms a resultant matrix of decisions (Table 2).

Measurements of a detail and the tool in the processing center VMG 50 are implemented with use of opportunities of the servo-drivers capable to quickly handle discrete signals (Fig. 8). The discrete signal about a contact of a probe is transmitted directly to a drive controller input. When receiving this signal each drive remembers the current position (contact coordinate) and stops with the greatest possible acceleration. The CNC system, having obtained information on actuation of the sensor, requests the contact point coordinate from the drives.

Accuracy of movements and measurements is implemented also by the use of the linear and circular measuring systems installed directly on executive elements of the machine. The signal from measuring systems for loop closure of control by position is processed in servo-drivers.

**Table 2.** Resultant matrix of solutions for the multipurpose vertical machining center VMG 50

| Technologies | Tasks of CNC system | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Geometric | | | | Logical | Terminal | Communicational | | Technological | | Diagnostic | |
| Multiple-axis processing | Module of kinematic transformation | Electronic gear | Compensation of deformation on axes | Synchronization of control paths | Realization of Master Slave control on PLC basis | Interface of multichannel control | Multiprotocol interface of communication of CNC system with drives | Realization of Master Slave control on the basis of drives | Module of adaptive processing | Module of setup of the tool after installation | | |
| Measurement of the tool and workpiece | Module of processing of measurements | | | | | Displays of the mode of measurements and graphics of measuring cycles | | | Diagnosing of the cutting tool and its residual firmness | | Measuring cycles of preparation of the tool | |
| Multiuser access to CNC system | | | | | | Multiterminal control | | | | | Module of remote diagnostics of parameters of system | |

## 10. CONCLUSIONS

Application of the decomposition technique in the CNC systems allows to select the restricted and at the same time expanded set of the hardware-software components realizing technologies of processing. Synthesis of the custom CNC systems is executed for a specific technological complex by configuration of hardware-software modules [10] necessary to system. Use of decisions matrix significantly reduces time of development and release for the market of control systems for a wide range of processing equipment.

The offered method is successfully approved during creation of control systems of production units of continuous and pulse laser processing, control systems of multicoordinate processing with technologies of measurement of the tool and workpiece, control systems of waterjet processing [11, 12].

## REFERENCES

1. Martinov, G.M., Ljubimov, A.B., Grigoriev, A.S., and Martinova, L.I., Multifunction Numerical Control Solution for Hybrid Mechanic and Laser Machine Tool, *Procedia CIRP*, 2012, vol. 1, pp. 260–264.

2. Grigoriev, S.N. and Martinov, G.M., Research and Development of a Cross-platform CNC Kernel for Multi-axis Machine Tool, *Procedia CIRP*, 2014, vol. 14, pp. 517–522.

3. Martinov, G.M. and Martinova, L.I., The Analysis of Numerical Control Systems Presented at Metal-processing Technoforum 2009 International Exhibition, Their Novelty and Features, *Avtomatiz. Promyshl.*, 2009, no. 12, pp. 59–65.

4. Martinov, G.M. and Kozak, N.V., Decomposition and Synthesis of the Logic Systems Software Components, *Pribor. Sist. Upravlen., Kontrol', Diagn.*, 2006, no. 12, pp. 4–11.

5. Martinova, L.I. and Martinov, G.M., Organization of Intermodule Interactions in Distributed CNC Systems. Models and Algorithms for Implementation, *Mekhatron., Avtomatiz., Upravl.*, 2010, no. 11. pp. 50–55.

6. Martinov, G.M., Ljubinov, A.B., Martinova, L.I., and Grigoriev, A.S., Remote Machine Tool Control and Diagnostic Based on Web Technologies, in *Proc. of COMA'13, Int. Conf. on Competitive Manufacturing*, Stellenbosch, South Africa, 2013, pp. 351–356.

7. Martinov, G.M., Ljubimov, A.B., and Obukhov, A.I., The Problem of Adaptation of PCNC Systems for Laser Engraving Machines, *Mekhatronika, Avtomatiz., Upravlen.*, 2009, no. 1, pp. 59–62.

8. Grigoriev, S.N. and Martinov, G.M., Scalable Open Crossplatform Kernel of PCNC System for Multi-Axis Machine Tool, *Procedia CIRP*, 2012, vol. 1, pp. 255–260.

9. Martinov, G.M. and Nezhmetdinov, R.A., Cross-Platform Software-Implement Logical Controller for CNC Machine Tools Electroautomatic Control, *Avtomatiz. Sovrem. Tekhn.*, 2013, no. 1, pp. 15–23.

10. Grigor'ev, A.S. and Martinova, L.I., Approach to Building Information Computing Environments of Virtual Manufacturing Corporations, *Mezhotrasl. Inform. Sluzhba*, 2012, no. 4, pp. 31–37.

11. Nezhmetdinov, R.A., Sokolov, S.V., Obukhov, A.I., and Grigor'ev, A.S., Extending the Functional Capabilities of NC Systems for Control over Mechano-Laser Processing, *Autom. Remote Control*, 2014, vol. 75, no. 5, pp. 945–952.

12. Martinova, L.I., Kozak, N.V., Nezhmetdinov, R.A., and Pushkov, R.L., The Russian Multi-Functional CNC System AxiOMA Control: Practical Aspects of Application, *Autom. Remote Control*, 2015, vol. 76, no. 1, pp. 179–186.