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# An approach to building specialized CNC systems for non-traditional processes

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**Abstract**

New technologies, such as: additive, hybrid technologies based on new physical principles, machining of new (non-traditional) structures, etc., envisage new requirements for control systems. The tasks of controlling non-traditional processes go beyond the capability of classical open CNC systems which does not allow them to be used to solve the new range of tasks. An underlying computing platform enabling building on its base specialized CNC systems for non-traditional processes has been created. A limited and at the same time extensible set of software and hardware components that implement the new processing technologies has been defined, and a solution matrix for the subsequent synthesis of specialized CNC systems has been built. The procedure of the synthesis of specialized CNC systems is illustrated by an example of a five-axis water jet cutting machine and a machine for selective laser sintering.


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Keywords: Specialized CNC system; Selective laser sintering; Five-axis water jet cutting; Software and hardware components;

## 1. Introduction

The field of application of new technologies has been rapidly developing lately, including: additive manufacturing technology; hybrid processing technology associated with simultaneous exposure of the material to two or more dissimilar energy factors; processing technologies based on new physical principles, processing on innovative machines, etc. [1].

However, there is still no effective overall approach to building control systems to support these technologies. However, the technologies concerned are used in key industries, and form the foundation for rapid creation of new types of industrial equipment.

The openness of the classical numerical control systems on the market is limited [2,3], although they provide the ability to integrate custom algorithms in real-time subsystem. There is no way to change the principle of controlling devices. Developers of new equipment and machine tool builders are forced to use the CNC systems that implement the control of used devices. For example, the manufacturers of welding equipment based on laser or electronic beam gun are forced to use two different CNC systems in their technological equipment, unless there is a control system that can control both the laser and electronic beam gun.

The authors propose an approach to building specialized equipment control systems based on an underlying computing platform. A method of decomposition and synthesis of hardware and software components designed for controlling technological equipment is proposed. The control system is composed of a set of modules that implement specific management technology.

## 2. Decomposition of CNC systems and the formation of the matrix solutions

A comprehensive pattern of CNC systems for variable technologic devices does not exist. Manufacturers producing Hi-End NC systems with wide ranges of functions have approached a threshold beyond which efficiency is lost. Such CNC systems use in the best case 40-50% of their potential capacity [4].

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Using the method of decomposing CNC systems allows identifying a set of components necessary for the implementation of specific treatment technologies. A limited but extensible set of components allows building a control system for specific technological control tasks based on a minimum set of modules, without changing the basic structure of the computing platform.

As a part of the decomposition of CNC systems the matrix of solutions is constructed (Fig. 1). CNC control tasks are arranged horizontally [5]. The *geometric control task* performs the process of shaping the workpiece. As a part of the task there is a mathematical calculation of tool paths taking into account machine kinematics, correction of geometry of the tool and tool wear, temperature and volume deformations, dynamic constraints and accuracy requirements. The *logical control task* controls the cycle logic of the machine. The *terminal control task* implements the HMI (Human Machine Interface) that largely determines the attractiveness and competitiveness of the control system on the market. *Technological control task* assists the technological parameters of the process (for example, implements adaptive control of the laser power for laser cutting). The *communication control task* provides a link between the modules of the system and implements the exchange of information in real time via industrial protocols. The *diagnostic control task* is primarily responsible for monitoring and diagnostics functions of geometric and logic control tasks [6].

CNC processing technologies are arranged vertically in the matrix. The given matrix fragment includes:

- continuous and pulsed laser treatment, requiring controlling the laser and the deflection system;
- multi-axis machining with the functions of kinematic transformation, electronic gear box and functions of error compensation;
- hybrid and multi-tasking processing, implementing a combination of several technologies for processing;
- water jet machining with the functions of controlling jet pressure and abrasive powder applying.

Both types of laser treatment have common functionalities (laser control, part programs preparation, the communication functions for laser beam deflection), but each has its own specifics. Continuous laser treatment requires the control of laser power. Pulsed laser treatment requires the synchronization of movement and laser pulses as well as the adaptive control of laser pulse frequency.

Algorithms of kinematic transformation and conversion of speeds of the axes are required for multi-axis machining. That demands advanced diagnostic functions, the compensation and prediction of tool wear [7,8]. Multi-axis machining uses multiprotocol communication interface with servo drives that are controlled via the "master-slave" scheme [9].

Hybrid treatment, as well as multitasking, is related to the control of two or more dissimilar devices that have different control principles. It requires the synchronization of multiple influences on the material and special visualization functions of processing [10]. The function of external interpolator allows the system to transfer the interpolation process to an external device and synchronize with it.

Water jet machining uses adaptive control of jet parameters and correction of jet trajectory according to the form of the jet, which requires the implementation of some specific functions in all control tasks of CNC system.

## 3. Synthesis of specialized CNC systems

With the help of the matrix of solutions the required set of hardware and software components is determined in order to build a specialized control system for specific production equipment.

Firstly, the necessary processing technology and functionalities of the control system are determined. Then, the

| Treatment technologies | CNC control tasks | | | | | |
|---|---|---|---|---|---|---|
| | Geometric | Logical | Terminal | Communication | Technological | Diagnostic |
| Continuous laser treatment | | Processing of laser signals | The preparation of part programs | The communication functions for laser | The adaptive control of laser emission | Diagnostics and monitoring of laser parameters |
| Pulsed laser treatment | Synchronization of movement and laser pulses | | | The communication functions for laser beam deflection | The adaptive control of laser pulse frequency | |
| Multi-axis machining | Kinematic transformation | | Interface of multi-channel control | Multiprotocol communication interface with servo drives | Adaptive compensation | The logic Analyzer |
| | Electronic gear box | | | Control of drives by the scheme "master-slave" | Prediction of tool wear | Digital Oscilloscope |
| Hybrid and multi-tasking processing | The external interpolator | Synchronization of control of different treatment energies | Specialized function of imaging of process of water jet treatment | | Specialized machine tools cycles | |
| Water jet machining | Correction contour according the jet shape | Control system of high pressure station | Displaying and setting of parameter of water jet | Communication with the high pressure station | The adaptive control of parameters | Diagnostics and monitoring of high pressure station |

Fig. 1. The fragment of solution matrix.

required set of components is selected using the matrix of solutions for the implementation of processing technology of the previous step. In the next step, a set of fieldbuses and peripheral devices, which will be connected to the CNC kernel, is determined. After that, the type of control system architecture is determined it will be based on one- or two-computer architecture which depends on the required processing power. In the end, a specialized CNC system for the specific technological equipment is assembled in a modular approach based on the underlying computing platform.

The set of processing technologies of the solutions matrix (Fig. 1) is expanded when necessary.

The solutions matrix systematizes the set of CNC hardware and software components. Determining with the help of the matrix the minimum set of ready-functioning components and composing based on them specialized control systems reduces the time and costs of the development process.

Our experience in the development of specialized control systems for laser engraving machine tool showed that the complete process of development and setup the machine using a universal CNC system takes 14 months. The specificity of the process required a special approach to synchronizing the motion control and pulse laser in spite of the fact that the machine tool had a simple 3-coordinate scheme and minimum PLC peripherals.

The proposed approach with using the solution matrix has been applied in the development of specialized control systems for machines of laser sintering and water jet machining. Compared with the laser engraving machine tool, those machines are considerably more complicated, the CNC system controls more axes and more PLC peripheral devices. The complete cycle of development and setup of specialized control systems for those machines took 8.5 and 10 months, respectively.

## 4. Building a control system for selective laser sintering products from powder materials

Selective laser sintering is carried out by means of drawing on the work plane thin layers of metal or ceramic powder material with the subsequent selective fusion using a scanning laser beam [11].

The control system of the selective laser sintering machine includes an autonomous PLC, a system of laser beam deflection, motion control system (Fig. 2). Work desk and powder supply desk are controlled from the PLC by servo drives in positioning mode. The mechanism of levelling powder is made in the form of the roller, which is moved between the starting and ending positions with the help of a pneumatic cylinder. The control of the laser beam is carried out by the system of laser scanning head, which has a controller with an autonomous interpolator.

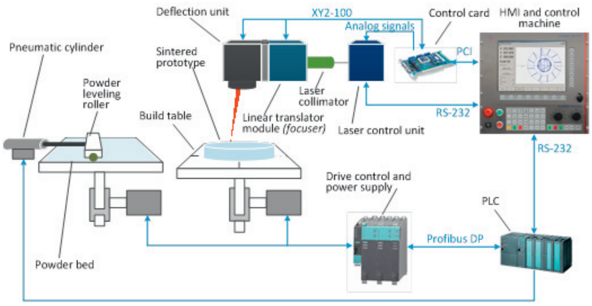


Fig. 2. Hardware-Software complex for selective laser sintering.

The specifics of controlling the selective laser sintering machine require the realization of functions, typical both for continuous laser processing, as well as some elements of the hybrid and multi-task processing (Fig. 3).

Here is the structure of the control system for the selective laser sintering machine, built using the components of matrix solutions (Fig. 4).

The system of the part program preparation, which has the preprocessor of the 3D model, cuts the three-dimensional model into layers, converts the sections into the path of the laser beam, and adds technological commands to control the parameters of laser emission. These actions are implemented in the frame of the terminal control task.

The interpreter is intended for transforming the commands of the part program into the internal format of control system.

The dispatcher is part of the base computing platform and is responsible for the strategy of interaction between all modules of the system.

The external interpolator sends movement commands to the control system of deflection.

The module communicating with the PLC provides the interaction with the PLC via a predetermined protocol.

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| Continuous laser treatment | | Processing of laser signals | The preparation of part programs | The communication functions for laser<br><br>The communication functions for laser beam deflection | The adaptive control of laser emission | Diagnostics and monitoring of laser parameters |
| Hybrid and multi-tasking processing | The external interpolator | | | | | |

Fig. 3. The set of solutions for the control system of the selective laser sintering.

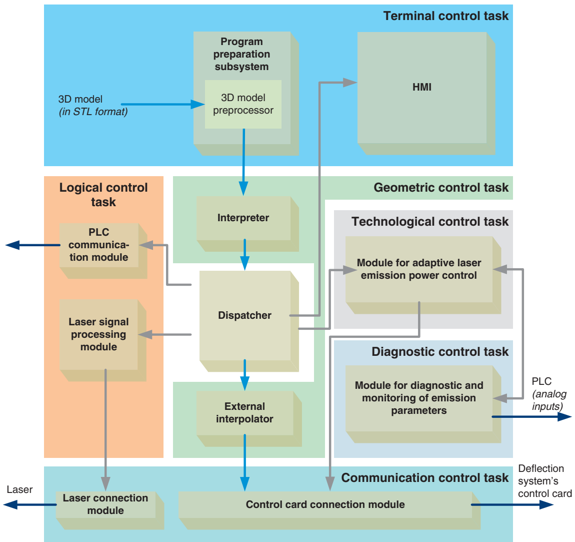


Fig. 4. The module structure of the control system of selective laser sintering.

The module of processing of laser signals in the frame of the logical control task stops and starts the part program according to an external signal, monitors the readiness of the laser and its preparation for operating mode. Communication of the module of processing of signals with the laser is implemented via the serial interface using the laser connection module.

The module of adaptive control of the power of laser (technological control task) adjusts the laser emission during the change of speed of movement of the laser beam on sharp turns, and also during the change of temperature conditions in the area of treatment

The module of diagnostics and monitoring of emission parameters provides information about current conditions process that allows the module of adaptive control to form a real-time solution for the correction values of the laser emission.

Fig. 5. Selective laser sintering machine with control system.

The module of communication with the control card of the deflection system (control task of communication) provides the interaction with the system of deflection, and is implemented as the driver of the control card of the device.

Such a control system (Fig. 5) allows the operator to adjust the necessary technological parameters of processing. User interface permits selecting the modes for technological experiments. Fig. 6 shows the results of the selective laser sintering of products from powder stainless steel as an illustration [12].

On the left side of Fig. 6 there is a photo of experimental samples of 100-micron layers, obtained at different speeds and step of hatching. Rows match the speeds of 80 and 120 mm/sec; columns - step hatching of the 75 and 100 microns. The power of laser emission is 170 W; the diameter of beam is 150 microns. These samples were obtained in argon atmosphere with an impurity of air.

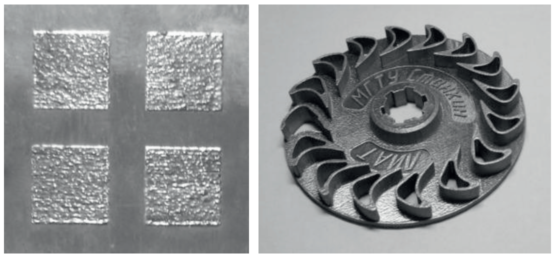

Fig. 6. Experimental sample layers and finished products, obtained by the method of selective laser sintering.

On the right side of the Fig. 6 there is a finished product: the thickness of a layer of 100 micron is obtained at the speed of beam 80 mm/sec and the power of laser emission is 170 W. Creation of products was carried out in an atmosphere of almost pure argon [13].

An analysis of the tests allowed estimating the nature of the influence of process parameters on the quality of products and identifying the area of controlled parameters that provide a solid model of the stainless steel powder at permissible porosity.

The ratio of the two major parameters - the feed rate of the beam and hatching space [14] is shown on Fig. 7. Research was conducted at a power of laser emission 170 W and layer thickness of 80 µm.

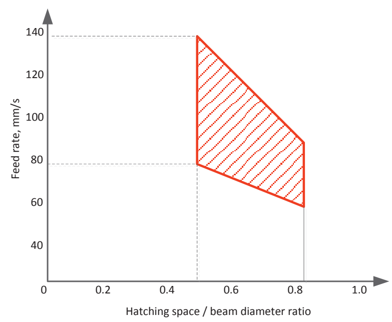


Fig. 7. Area of laser sintering technological parameters.

The diagram is approximate, because dependencies are nonlinear, but it allows evaluating the basic patterns. Too small and too big concentration of laser emission is unacceptable. Step hatching cannot be less than half the laser beam diameter; otherwise, the temperature gradients and other adverse factors are increased. Setting process parameters beyond designated areas leads to characteristic defects: balling, limited bonding [14], strong oxidation and slag due to over-melting, partial layer melting or layer breakages.

## 5. Building the control system for the 5-axis water jet machine tool

Water jet cutting is the universal technology of high-performance machining of various materials without heating them [15].

The 5-axis water jet machine tool has gantry kinematic (Fig. 8). It has six controlled axes: X and Z are ordinary axes, Y and V are gantry axes, B and C are rotary axes.


Fig. 8. The water jet cutting machine tool.

The CNC system of the water jet machine tool (Fig. 9) includes: the CNC kernel, the HMI, passive I/Os modules, autonomous control system of high pressure station (which provides for operating pressures up to 6000 ATM), security subsystems, controllers of servo drivers (6 axes) and machine control panel.

The set of passive I/Os is controlled by the SoftPLC implemented in the kernel of the CNC system. Servo drive controllers and bus couplers are organized in a single real time network using EtherCAT protocol.

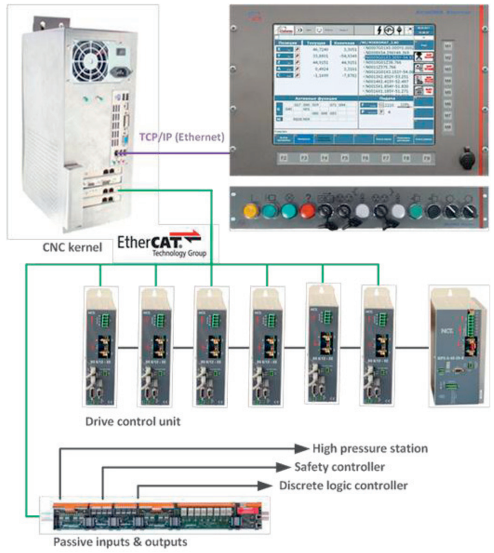


Fig. 9. The structure of control system of water jet cutting.

When selecting components (on the basis of matrix solutions) it is necessary to use a set of functions of two types of technologies: water jet processing and multicoordinate processing for 5-coordinate control tasks (Fig. 10).

In the geometric control task the module of kinematic transformation is implemented to control the biaxial orientation of the jet vector. The module of contour correction is responsible for the process of shaping, taking into account the physical peculiarities of the process of jet cutting material (geometric control task):

- The inaccuracy due to the cutting width. The correction algorithm is similar to the algorithm of equidistant correction of tool radius in space.
- Deviation from straightness: there is a deviation of the jet in the direction opposite to the motion. The algorithm adjusts the speed and pressure of the jet depending on the type of material and the thickness of the workpiece.
- The deviation of the form: on exit from the material, the jet loses energy characteristics and has a conical shape. The algorithm adjusts the pressure of the jet and the quantity of

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Fig. 10. The set of solutions for control systems of water jet cutting.

the abrasive substance in accordance with the thickness and type of the processed material.

The control of the station of high pressure within the logical control task is performed via a special control panel, which is connected to the CNC system. This panel allows controlling the safety barrier, the water jet valve, the power of high-pressure and hydro power stations. M-functions perform the following steps: opening (M108) and closing (M109) the air supply in the cutting head, defining the quantity of abrasive in the jet (M110), switching on (M111), and off (M112) high-pressure water jet processing.

The module of displaying and configuring the parameters of water jet treatment extends the operator's interface in the frame of the terminal control task. The HMI screen displays the actual pressure of the jet, the current consumption of abrasive powders and the action of specific M-commands.

The CNC system implements adaptive control of the feed rate and the quantity of the abrasive substance in the jet, enabling to decrease the impact of waves on the surface quality. As a result, the surface quality improves in comparison with the systems of water jet treatment on the basis of robots-manipulator.

## 6. Conclusion

The decomposition of CNC systems allows forming a matrix of solutions for the control tasks of different processing technologies. The synthesis of specialized CNC systems for concrete technological machines is performed by combining the required hardware and software modules. Using a matrix of solutions significantly reduces the development time and permits the control systems for a wide range of technological equipment enter the market.

The proposed method has been successfully tested in building control systems for selective laser sintering and water jet treatment.

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