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Modular Design of Specialized Numerical Control Systems for Inclined Machining Centers

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Abstract—Modular design of specialized numerical control systems for inclined machining centers is proposed, on the basis of the AksiOMAKontrol computing platform. The specifics of inclined machining centers are discussed; their kinematics is analyzed; and requirements on the control system are systematized. An additional set of machine and measuring cycles, specialized M functions, and operator-interface screens must be introduced. The network architecture of the control system is illustrated for the example of the NAKLON 535 machine.

Keywords: inclined machining center, numerical control system, network architecture, SoftPLC, EtherCAT
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Inclined machining centers for the fastest possible turning and milling of complex parts are currently becoming available [1–3].

The benefit of turning and milling centers in relation to traditional lathes is the presence of a high-speed mill spindle. This permits the machining of very complex parts, with high precision (because the transfer of the part from one machine to another is eliminated). It also reduces the equipment and time required for auxiliary processes such as readjustment of the blank and preparation of the auxiliary equipment and tools; that permits more efficient use of the equipment and frees up production space [4].

The NZ2000 machine (MoriSeiki, Japan) is equipped with two or three revolving heads for the turning and milling of complex parts. One head is attached at the bottom, so that several parts can be machined at once. The configuration of the machine eliminates stays and increases the productivity in turning long parts, thanks to the balanced operation of two cutters in parallel, in different reactions. The characteristics of this machine are given in the table.

Characteristics of machining centers

Parameter	NZ2000 (MoriSeiki)	SuperNTJX (Nakamura-Tome)	TTC Serie (Spinner)	NAKLON 535 (OAO Sasta/Stankin Moscow State Technical University)
Number of revolving heads	2	1	2 (1)	2
Number of spindles	2	2	2	2
Maximum machining diameter, mm	320	245	250	380
Maximum machining length, mm	810	1090	400	1000
Number of tools	16 × 2	24	12 (24)	12 × 2
Power of primary drive, kW	22	15	15	30
Power of counterspindle, kW	22	15	15	30
Speed of primary drive, rpm	0–5000	0–6000	0–5000	0–4000
Mass, kg	8300	14000	4600	10000
Length × width × height, mm	3930 × 2320 × 2740	4718 × 2922 × 2445	2500 × 1900 × 2200	6065 × 2160 × 2320
Numerical control system	MoriSeiki MAPPS IV	Fanuc 31i-A	Siemens/Fanuc	AksiOMA Kontrol
Speed of milling spindle, rpm	6000 (12000)	8000 (12000)	or (6000)	7000

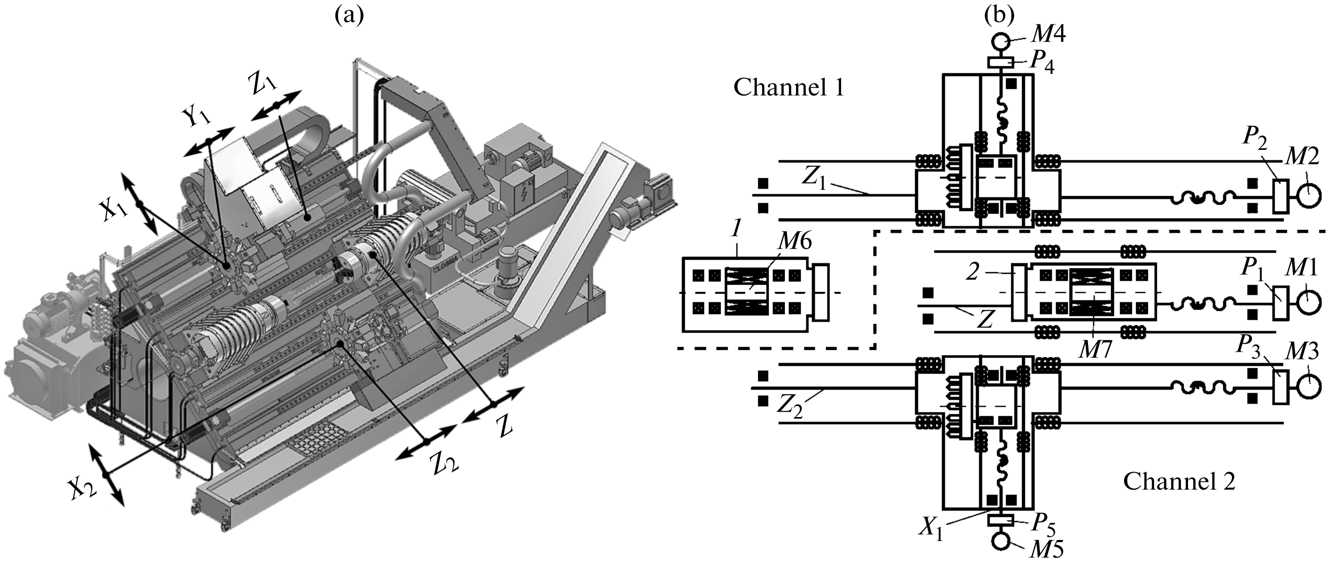

Fig. 1. Inclined NAKLON 535 turning and milling center: (a) general view; (b) kinematic system; (*1*) primary drive; (*2*) counterspindle.

The multifunctional SuperNTJX turning and milling center (Nakamura-Tome, Japan) includes two spindles, a revolving head, and a milling head with automatic tool replacement. Simultaneous machining of parts by means of the spindle and counterspindle of the revolving head and also the milling spindle reduces the machining time. The characteristics of this machine are given in the table.

The TTC machine (Spinner, Germany) is equipped with rigid slipping guides to suppress vibration, which permits excellent cutting parameters. The system includes 12-position high-speed revolving servo heads, built-in motorized spindles, and a driven tool for all 12 positions. The table compares the characteristics of Russian and imported machining centers.

The specialized numerical control system for the NAKLON 535 machine is based on the AksiOMAKontrol computing platform developed at Stankin Moscow State Technical University [5, 6]. This platform has open modular architecture (OMA) and a cross-platform core [8, 9].

The NAKLON 535 multifunctional machining center matches the characteristics of its foreign counterparts. However, its design includes innovations that may be converted to competitive advantages if the user adopts the correct approach [11, 12].

Kinematic analysis of the NAKLON 535 machine permits determination of the number of control channels and the number of axes that may be simultaneously active; linkage of the axes to the control channels; and optimization of the machining conditions [7, 9].

The NAKLON 535 inclined machining center (Fig. 1a) is equipped with longitudinal (X_1, X_2) and transverse (Z_1, Z_2) axes of the upper and lower supports; and a basic spindle and counterspindle (with the possibility of longitudinal displacement along the Z axis) to ensure parallel machining. Two parts, attached respectively to the spindle and counterspindle, are simultaneously machined by tools mounted in the lower support and the milling spindle.

Interpolation is possible for both spindles in the turning and milling system. That permits the insertion of not only milling tools but turning tools. Simultaneous machining of solids of revolution by two tools (on one or two sides) increases the productivity and also the tool life thanks to compensation of the radial cutting forces.

The kinematic system of the inclined machining center requires two-channel control (Fig. 1b). Channel 1 controls the upper support (axes $X1$ and $Y1$), the longitudinal axis $Z1$, and the spindle W. Channel 2 controls the lower support (axes $X2$ and $Z2$), the longitudinal axis Z, and the counterspindle $W1$.

The operation with several channels in the AksiOMAKontrol numerical control system is adjusted in terms of the machine parameters; the number of accessible control channels is determined, and the axes are linked to a specific channel.

By systematizing the requirements on the numerical control system in complex technological systems, we may isolate a group of general requirements for any machine tool: openness; modularity; trajectory correction; remote control; and so on. We may also identify a family of particular requirements for specific equipment, with specific operational characteristics [5, 6].

The particular requirements on inclined machining centers are as follows.

(1) Multichannel structure, permitting parallel fulfillment of several control programs within a single numerical control system. In the AksiOMAKontrol system, a screen permits operation with two control channels; it displays information regarding the current coordinates of the axes, the spindle speeds, the G and M vectors, and the selected program in each channel. The active channel has a machine-tool panel and functional and machine keys for starting, stopping, and editing the control programs.

Specialized functions of the higher-level language are provided for operation in multichannel mode through the primary control program: channel_load, which loads the control program in the channel; channel_run, which loads and runs the control program in the channel; channel_start, which starts (or restarts) the control program in the channel; channel_stop, which stops the control program in the channel; channel_reset, which resets the channel; and channel_wait, which waits for the end of the control program in other channels.

(2) Multispindle machining. By means of the primary drive, counterspindle, and milling spindle, the blank may be machined simultaneously by several tools. In multispindle machining with a numerical control system, a specialized mechanism is required for the detection of collisions in the control program when machining with two spindles. In addition, a specialized M function is required for transfer of the part between the spindle and counterspindle.

(3) A set of specialized turning, milling, boring, and measuring cycles. The machine cycles are implemented as parametrized G functions (G281–289 for turning; G81–89 for boring; G181–189 for milling; and G581–585 for measuring); expansion of this set by the user is possible. The use of cycles simplifies the formulation of the control programs, by the adoption of existing technologies for recessing, successive hole machining, thread cutting, and measurement of the parameters of the tool or blank [10].

(4) Specialized auxiliary M functions for machining centers with a large number of components: revolving heads of the upper and lower supports; chucks; cooling systems for the tool and machine tool; cooling and hydraulic stations; a chip-transport system; safety shields; an air-supply system; a tool store; a system for automatic tool replacement; and so on.

Control of those components demands a set of auxiliary M functions for functions such as switching on and off the chip-transport system (M50, M51); closing and opening the chuck (M21, M22); opening and closing the safety shields (M54 and M55); and regulating the capture of the part by the counterspindle (M75).

On the basis of those requirements, we have developed network architecture for a numerical control system (Fig. 2). Components include a real-time machine (functioning in the Linux operating system), with the core of the control system and an integrated programmed controller of SoftPLC type; an operator terminal (consisting of an operator panel in the NET platform and a standard machine panel, with optional connection of a governor and a specialized machine panel), connected to the core by a TCP/IP protocol; an input (output) expansion modules for the connection of automatic electric modules and linear measuring devices; the primary drive and supply drive; and the spindle and counterspindle controllers.

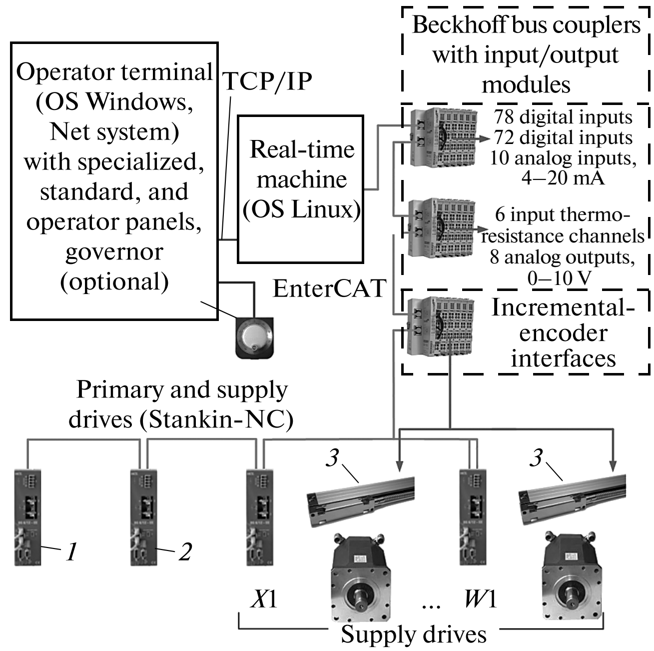

Fig. 2. Network architecture of the numerical control system for the NAKLON 535 turning and milling center: (*1*) spindle controller; (*2*) counterspindle controller; (*3*) measuring scale.

The open high-speed EtherCAT protocol is used for data collection and transfer in the network between the computer modules. The large quantity of electrical equipment connected to the control system calls for the use of three primary input/output modules (bus couplers). That permits distribution of the electrical load among individual devices.

The bus couplers are expanded by passive electronic data input/output modules: 120 digital inputs (15 eight-channel modules); 48 digital outputs (six eight-channel modules); ten analog inputs (two four-channel modules and one two-channel module, 4–20 mA); six input thermoresistance terminals (three two-channel modules); nine analog outputs (two four-channel modules and one single-channel module, 0–10 V); and six incremental-encoder interface modules.

The architecture of the programmable controller for the automatic electric modules includes four components: the programming environment; the SoftPLC

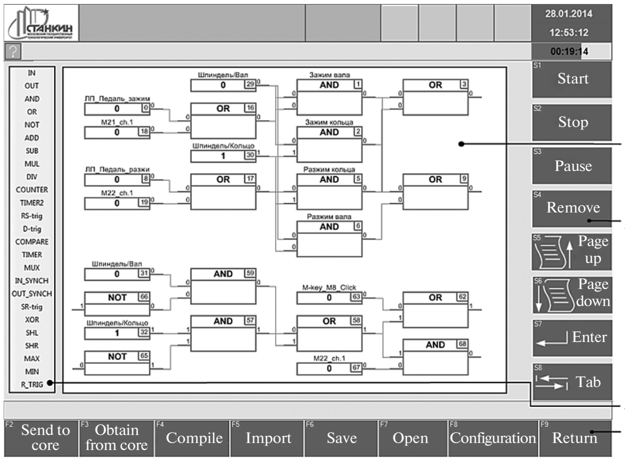

Fig. 3. Development of SoftPLC control programs: (*1*) working region; (*2*) service keys; (*3*) functional blocks; (*4*) keys.

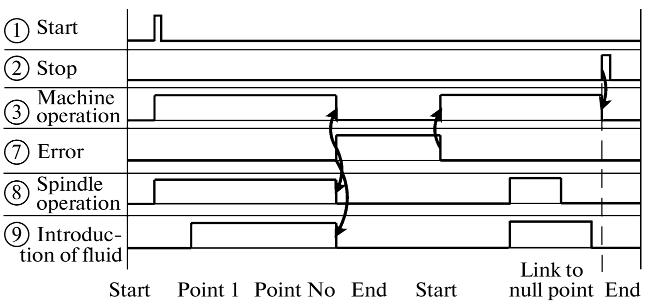

Fig. 4. Fragment of the operational cyclogram for the NAKLON 535 center.

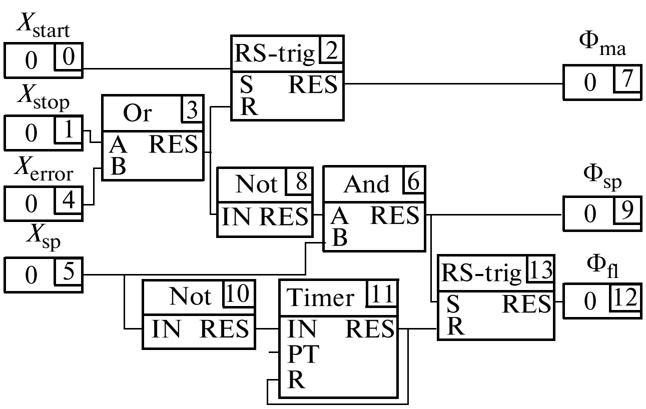

Fig. 5. Program for technological-fluid supply in a SoftPLC environment.

core; drivers for communication with the external devices; and physical input/output modules.

The software is integrated in the numerical control terminal (Fig. 3) and permits programming of the automatic electric systems in functional-block language (IEC 61131). Programming is undertaken in the working region. The functional keys permit compilation of the control programs for the automatic electric modules; transmission of the compiled code from or to the controller core; configuration of the input/output modules; and storage of the program or opening of a previously stored control program. The service keys permit startup, pausing, and stopping of the control program in the controller curve; removal of a functional block to the control program; and navigation in the working region of the control program.

Time diagrams (cyclograms) are used in programming the complex electrical equipment of a machine tool operating with time delay (timers) and counters. As an example, consider the startup of the technological-fluid system for the NAKLON 535 turning and milling center (item 9 in the operational cyclogram in Fig. 4).

We now consider the signals in the cyclogram for introducing the technological fluid. We will determine the dependence of the function Φ_{fl}, corresponding to the start of fluid introduction, on the other functions and signals shown in the cyclogram. The automatic signals for the cyclogram of the technological-fluid system are as follows: X_{start}, corresponding to the beginning of operation; X_{stop}, the signal that ends operation; Φ_{ma}, corresponding to operation of the machine; X_{error}, corresponding to the appearance of an error; and X_{sp}, the signal starting spindle motion.

System operation begins when the Start button on the machine panel is pressed, thereby generating the X_{start} signal. Then, the relay is activated, corresponding to operation of the machine (the function Φ_{ma}). The cutting process requires startup of the machine's spindle (signal X_{sp}). The activation of X_{sp} automatically starts the supply of technological fluid. In the event of error in the operation of the machine, the signal X_{error} stops spindle motion and switches off the supply of technological fluid. After elimination of the error, system operation resumes. For spindle rotation, the signal X_{sp} must be activated. The supply of technological fluid ends 3 s after spindle motion ends. This 3-s delay is required to ensure that the cutting process ends without heating of the tool and the part.

In Fig. 5, we show the program implementing the cyclogram in the FBD language.

Note, in conclusion, that there is market demand for new machining-system designs in which universal numerical control systems are inapplicable because of specific requirements on system operation.

The AksiOMAKontrol computing platform is sufficiently flexible and comprehensive to permit the construction of a specialized control system for new machining centers. The creation of a specialized numerical control system for inclined machining centers entails the addition of a set of machine cycles and M commands and the development of control programs for automatic electric modules and operator-interface screens, in accordance with the specifics of the new systems.

Integration of a programmable controller for automatic electric modules in the numerical control system permits the development and debugging of control programs; tracking of the variables; and in-situ diagnostics of the equipment's inputs and outputs on the basis of specialized functions of the control system's operator terminal.

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