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AUTOMATING THE CONTROL OF MODERN EQUIPMENT FOR STRAIGHTENING FLAT-ROLLED PRODUCTS

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The company Severstal' completed the successful introduction of new in-line plate-straightening machines (PSMs) on its 2800 and 5000 mills in August 2003 [1, 2, 3]. The main design features of the machines are as follows:

- each machine is equipped with hydraulic hold-down mechanisms (to improve the dynamics and accuracy of the machine adjustments and more reliably maintain a constant gap);
- the machines have mechanisms to individually adjust each work roller with the aid of hydraulic cylinders (this broadens the range of straightening regimes that can be realized by providing a measure of control over the change in the curvature of the plate);
- each work roller is provided with its own adjustable drive (to eliminate rigid kinematic constraints between the spindles);
- the system of rollers of the PSM is enclosed in cassettes (to facilitate repairs and reduce roller replacement costs);
- the PSM has a system that can be used to adjust the machine from a nine-roller straightening scheme to a five-roller scheme in which the distance between the rollers is doubled (this is done to widen the range of plate thicknesses that the machine can accomodate).

Thus, the new straightening machine is a sophisticated multi-function system of mechanisms that includes a wide range of hydraulically and electrically driven components controlled by digital and analog signals. The entire complex of PSM mechanisms can be divided into two functional groups: the main group, which includes the mechanisms that participate directly in the straightening operation (the hold-down mechanisms, the mechanisms that individually adjust the rollers, the mechanisms that adjust the components for different straightening regimes, the mechanism that moves the top roller of the feeder, and the main drive); the auxiliary group (which includes the cassette replacement mechanism, the spindle-locking mechanism, and the equipment that cools the system of rollers). Although the PSM has a large number of mechanisms, the use of modern hydraulic and electric drives has made it possible to almost completely automate the main and auxiliary operations performed on the PSM and the units that operate with it.

Described below are the features and the automatic control systems for the most important mechanisms of the plate-straightening machine. The operating regimes of those mechanisms are also discussed.

The hydraulic hold-down mechanisms (HHMs) of the sheet-straightening machine function in two main regimes: the adjustment regime; the regime in which the specified positions are maintained. There are certain requirements for the control system and certain efficiency criteria for each regime.

In the adjustment regime, the control system for the hydraulic hold-down mechanisms must do the following:

- synchronize the movements of the hydraulic cylinders and keep the angular deeflection within prescribed limits;
- maximize speed in adjusting the machine for a new plate size;
- maintain a high degree of accuracy in positioning the mechanisms;

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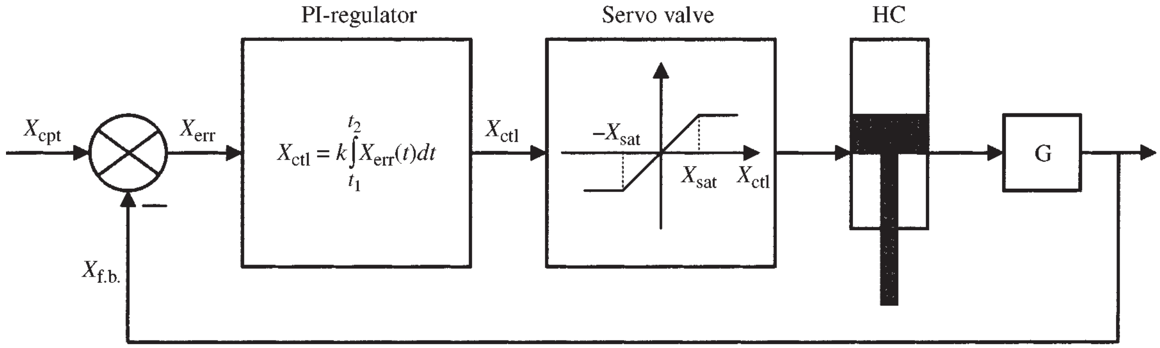

Fig. 1. Block diagram of the control system of the hydraulic cylinder.

The control system has the following requirements when operating in the maintenance regime:

- stabilize the coordinates of the top cassette and the top roller of the feeder with a high degree of accuracy;
- minimize the time needed to return the equipment to the prescribed coordinates when deviations occur (such as due to the force exerted by a plate being straightened).

Need for synchronization. Experience in operating the plate-straightening machine in plate shop No. 3 at Severstal' has shown that the most problematic factor in adjusting the machine is the nonuniformity of the forces applied to the hydraulic cylinders. This nonuniformity is due to the asymmetric distribution of the masses of the moving parts of the PSM (in particular, the effect of the weight of the spindle assembly). Displacement of the "hydraulic zero point" relative to the "electrical zero point" in the servo valves is also a contributing factor.* The latter reason is more significant, the smaller the volume of the hydraulic cylinder. Thus, the HHM of the top roller of the feeder is the most sensitive to drift of the zero point.

There are also other factors that affect the dynamism, simultaneousness, and synchronism of the operation of the hold-down mechanisms:

- differentiation of the frictional forces on parts of the hydraulic cylinders due to different combinations of deviations in the dimensions of the mated parts, despite the narrow tolerances;
- differences in the "springing" characteristics and the indices characterizing the inertia of the hydraulic supply channels (due to differences in the lengths of the pipes leading from the servo valves to the hydraulic cylinders).

Thus, since the PSM is not equipped with devices to mechanically synchronize the operation of the cylinders, the transmission of signals of the same amplitude to the inputs of the servo valves inevitably results in a speed difference that can seriously damage the mechanisms.

To minimize and eliminate the effects of the above-mentioned factors, we developed an algorithm for electrical synchronization of the hold-down mechanisms.

The HHM of the top cassette, composed of four hold-down cylinders and four balancing cylinders, is designed to ensure mobile adjustment of the machine to set the required size of straightening gap (in accordance with the thickness of the plate) and maintain that gap with a specified accuracy in the presence and absence of a load on the housings from the straightening force. The hydraulic system of the hold-down mechanism is designed in such a way that only one chamber of the hydraulic cylinders is used as the working chamber. The second chamber is always connected to the discharge channel. The top cassette is lowered when the balancing forces are overcome by the hold-down cylinders. The cassette is raised only by the action of the balancing cylinders. This arrangement has made it possible to eliminate gaps in the positioning of the equipment.

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* The hydraulic zero point is the position that the slide valve occupies when it covers the delivery and discharge mains. The electrical zero point is the control signal that should move the valve to the hydraulic zero point. These points should ideally coincide, but in actual servo valves with zero overlap there is always a certain amount of displacement that results in leakage of the hydraulic fluid.

The HHM of the top roller of the feeder consists of two hydraulic cylinders. Hydraulic fluid is fed into the plunger chamber when the roller is to be lowered and is fed into the rod chamber when it is to be raised.

Control Principles. Individual circuits have been provided (Fig. 1) to control the hydraulic cylinders of the hold-down mechanisms. The control signal (X_{ctl}) sent to the input of the servo valve is formed by a proportional-integral (PI) controller (to improve the sensitivity of the system, we chose to use valves with "zero" overlap). The signal sent to the input of the controller (the error signal X_{err}) is formed as the difference between the control-point signal for position (X_{cpt}) and the feedback signal ($X_{f.b}$). The latter signal is received from the linear displacement gage (G) of the given hydraulic cylinder.

The gages of the HHM for the top cassette are built into the balancing hydraulic cylinders (HCs). The cylinders are installed in such a way that their movements can be considered to be equal to the displacements of the corresponding cylinder rods, with allowance for certain coefficients. The gages in the HHM for the top roller of the feeder are incorporated directly into the hold-down cylinders.

The integral part of the controller is activated only during the final adjustment stage and during stabilization of the prescribed coordinate. When the displacements exceed a certain threshold value, the functions of the PI controller are taken over by a proportional (P) controller with the transfer function $W(s) = k$. Thus, $X_{ctl}(t) = kX_{err}(t)$.

When there are significant differences between the displacements of the working rollers, the difference (error) between the control point and the feedback signal from the linear displacement gage reaches values great enough so that the output signal which controls the operation of the servo valve reaches the saturation zone. In this case, further regulation of the displacement rate and, thus synchronization of the movements of the cylinders becomes impossible as long as the error exceeds the value at which X_{ctl} is greater than the boundary value for the saturation zone (X_{sat}). The limiting error – the largest error for which X_{ctl} does not reach saturation – is inversely proportional to the gain of the controller k: $X_{err} < X_{sat}/k$.

Solving the given problem by decreasing k leads to a loss of speed in the adjustment of the PSM and a decrease in control accuracy during the straightening operation. Thus, to keep the control signal from reaching the saturation zone when there are substantial displacements, the system was designed so that the input of the controller is fed not the actual required value (X_{rq}) but an increment (ΔX) of a magnitude such that the condition $k\Delta X < X_{sat}$ is satisfied. The control point is increased by the amount ΔX after the position of the cylinder has been changed by the amount corresponding to the increment having the largest lag relative to the cylinder's direction of motion. The adjustment of the control point is continued until the difference between the required value and the actual position of the mechanism becomes less than the increment: $X_{rq} - X_{f.b} < \Delta X$.

Then the input of the controller is fed the value X_{cpt}, which is equal to the required adjustment: $X_{cpt} = X_{rq}$. The adjustment is thus completed.

Use of the principle of a stepped increase in the control point makes it possible synchronize the movements of the cylinders and set the control point with a high degree of accuracy for almost any ideal repetition factor.

Mechanisms for Individual Adjustment of the Working Rollers. The plate-straightening machine is designed so that each working roller can be moved vertically, which is done by means of a hydraulic cylinder acting in concert with a V-belt drive. The cylinders are supplied with power from servo valves operated with proportional control. A linear displacement gage is built into each cylinder to obtain a feedback signal on the position of the roller. Since these gages are actually transmiting information on the position of the cylinder rods rather than the working rollers themselves, the following conversion is performed to obtain the rollers' coordinates:

$$X_{rol} = k_{red}X_{f.b},$$

where k_{red} is the gear ratio of the drive; $X_{f.b}$ is the position of the cylinder rod measured by the linear displacement transducers.

Thus, a position feedback circuit is provided to control the position of each working roller. Figure 1 presents a diagram of one of the circuits.

The control signals are generated by means of the PI controllere, which has made it possible to achieve a high degree of accuracy in adjusting the system without sacrificing speed.

The individual drive of the rollers. The above-described design is based on the use of individual ac drives with motors of different powers fed from frequency converters. Each individual drive offers the following advantages over a group drive:

- greater reliability thanks to the absence of additional loads on the components of the mechanisms due to differences between the linear velocities of the working rollers and the speed of the plate;
- the possibility that the machine could continue to operate if one or even several drives malfunction; in this case, the corresponding rollers would be removed from the straightening zone;
- the possibility that the linear velocities of the rollers could be individually corrected in accordance with the actual speed of the plate; such a correction could be made either as a preliminary measure (on the basis of measured and calculated values) or during the straightening operation (on the basis of the data obtained from the frequency converters, which employ artificial intelligence).

The main drive of the straightening machine rotates nine straightening rollers and two housing rollers. This drive must be highly reliable in operation, since the fact that the PSM is installed in the mill line means that sizable production losses can be incurred if the drive fails to work properly even for a short period of time.

The requirements that must be satisfied by the drive are determined by the operational and design features of the machine as a whole:

- the plate being straightened must create a rigid kinematic coupling between the straightening rollers, the rollers of the housing, and the adjacent sections of the roller conveyors;
- the plate should undergo elongation during the straightening operation as a result of plastic deformation, with the increments in length being different on each working roller due to the differentiation of the bending radii; this situation leads to a nonuniform increase in the speed of the plate as it moves toward the end of the PSM;
- it must be possible to use working rollers of different diameters (this being done, for example, due to nonuniform wear or regrinding);
- the loads on the rollers should be differentiated in accordance with the chosen straightening regime;
- reverse straightening should be possible.

In light of the above factors and the actual operating regimes of the plate-straightening machine being discussed here, the following requirements can be established for the electric drive:

- regulation of speed within broad limits, including startup of the motors under load;
- operation in the reverse regime;
- a rigid characteristic $\omega = f(M)$;
- high degree of accuracy in maintaining the prescribed speed;
- fully synchronous operation.

The element base. The drive of the rollers was built with the use of asynchronous three-phase motors having a short-circuit rotor. The motors were designed by the German company VEM. They can continue to function under severe overloads and are reliable in operation.

The motors are controlled by SIMOVERT frequency converters made by the German firm Siemens. Their modular design facilitates maintenance and repair, and the presence of a built-in microprocessor block makes it possible to execute most of the functions involved in controlling the operation of the drive (maintain the prescribed speed with a high degree of stability, recalculate the frequency of rotation in accordance with the actual diameters of the rollers, diagnose the condition of the drive, control the drive's operation, and exchange information on the PROFIBUS network).

Motors of different powers are used in the system because of the differentiated distribution of the moments between the working rollers. Using different motors has made it possible to significantly reduce the cost of the electrical equipment and improve the performance characteristics of the machine as a whole.

The machine has three main operating regimes: the working regime (semi-automatic and automatic), the transport regime, and the cassette replacement regime.

Figure 2 shows a block diagram of the operations connected with realization of the working regime. In the semi-automatic variant of this regime, the operator controls the PSM from a control panel. In this case, the operator can do the following: choose the straightening regime from a database; correct the chosen regime; adjust the regime manually, which

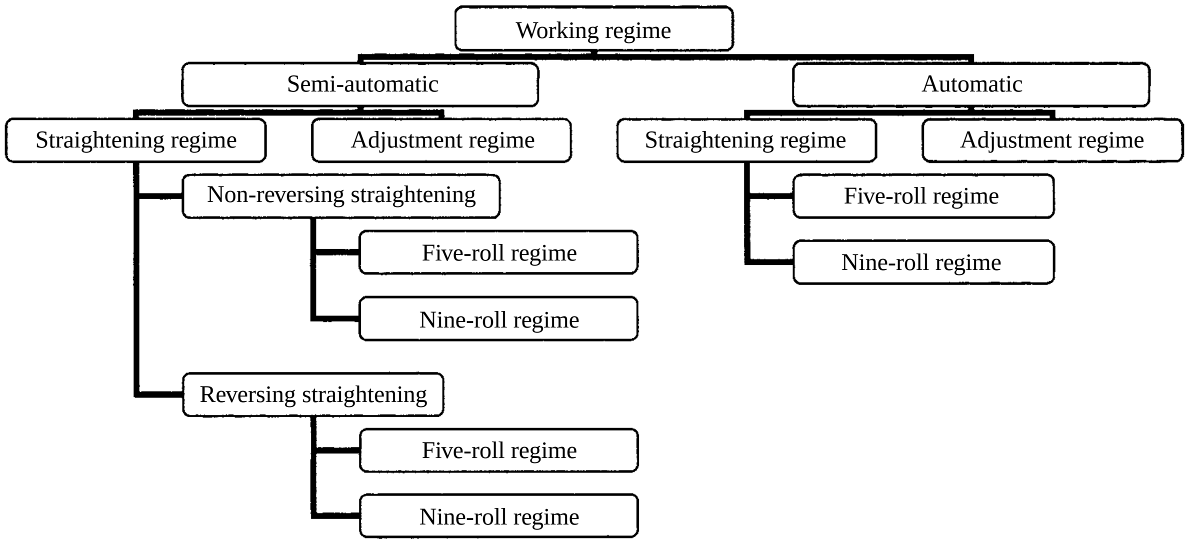

Fig. 2. Block diagram of the working regime of the PSM.

requires that the operator indicate the desired position of the bottom cassette (for five- or nine-roll straightening); adjust the gap between the top and bottom cassettes; set the coordinates for individual adjustment of the working rollers; choose the straightening speed and direction; generate a command to begin adjusting the machine to the specified regime.

The machine is adjusted to the chosen regime automatically. After the adjustment is completed, a signal is sent to the control panel indicating that the coordinates of the mechanisms have been changed and that the rollers have reached their prescribed working speeds.

In the automatic variant of the working regime, the plate-straigthening machine is adjusted on the basis of data sent through a data network from a higher-level system. These data include the following information:

• the thickness of the plate being straightened;
• the group of steels (information on the properties of the material);
• the temperature of the plate at the inlet to the PSM.

The PSM is adjusted in several stages:

• preliminary adjustment based on the plate thickness and steel group, for cold-rolled plates (t = 20°C);
• further adjustment on the basis of data obtained from a pyrometer installed roughly 50 m from the PSM;
• final adjustment on the basis of data obtained from a pyrometer installed at the entrance to the machine.

In the automatic variant, control over the roller conveyors adjacent to the machine is switched over to the control system of the PSM as the next plate approaches the machine. In this case, the plate cannot enter the working zone of the machine until the adjustment is completed.

If it is necessary to pass a plate through the machine without straightening it, the machine is changed over to the transport regime. In this case, the top crossarm and the cassette are elevated a prescribed amount and the speed of the rollers is changed so that it is equal to the speed of the adjacent roller conveyors.

The cassette replacement regime is used in the event of breakage of a roller or when it is necessary to regrind the working and backup rollers. In this case, the operator can control the operation of the auxiliary mechanisms: the spindle-locking mechanism, the roll-out cart, the mechanism that locks the bottom cassette and the cart in position, and the hydraulic cylinder that moves the cart.

The mechanisms are fixed in position by means of noncontact transducers.

PSM Control System. Control of the plate-straightening machine required the development of a powerful, high-capacity system that could provide the desired control accuracy in combination with rapid operation.

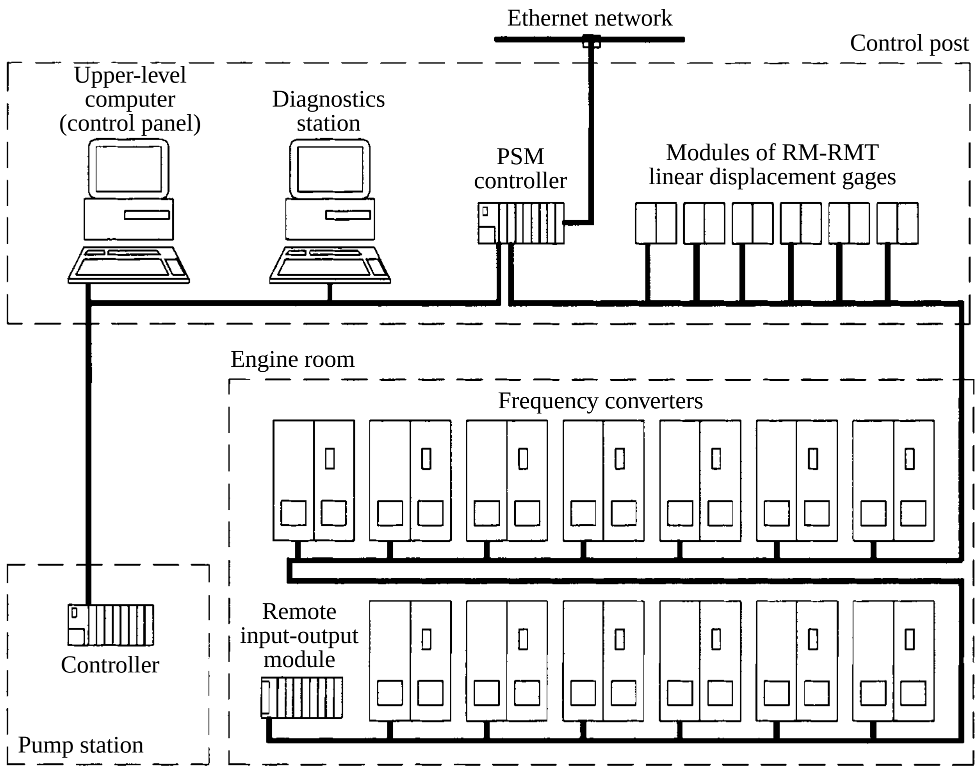

Fig. 3. Network structure of the PSM control system.

The control system that was created is divided into two levels: the base level, and an upper level. The diagnostic system was created as a separate system. A second controller was also provided, to control the pump station of the PSM.

The base level of the control system employs a SIMATIC S7 industrial programmable controller, while the upper level and the diagnostic system were built on the basis of standard computers. The computer used for the upper-level system also serves as the control panel for the PSM.

The different elements of the control system are linked by two loops of a PROFIBUS network (Fig. 3). The first loop functions as the communications link between the controller, the upper-level computer, the diagnostics station, and the pump-station controller. The second loop links the PSM controller with the functional elements of the system (the frequency converters, linear displacement gages, and remote input/output module).

The functions of the control system were divided between the base level and the upper level on the basis of the following principle: the base level was assigned all of the operations that involve receiving data from the sensors installed on the mechanisms, obtaining information from the automated process control system on the plate being straightened, and generating and transmitting control signals for the executive mechanisms (actuators); the upper level was assigned the functions of archiving the control points and monitoring the operation of the control panel.

The following specific functions are performed by the base level of the automation system:

• obtaining the assigned straightening parameters (roller speeds, the coordinates of the top crossarm, and the coordinates of the rollers relative to the crossarm) from the upper-level system;
• processing the parameters and sending corresponding control signals to the actuators;
• obtaining information from the sensors installed on the mechanisms to determine whether or not the PSM is properly set and ready for the straightening operation;
• obtaining information from the feedback transducers installed on the mechanisms to calculate the control actions;
• analyzing the readings of the sensors to determine the accuracy of the data;

TABLE 1. Specifications of the Plate-Straightening Machines

Parameter	Type of machine	
	LPM 2800	LPM 5000
Plate thickness, mm	7–60	10–100
Width, mm	1500–2700	1500–4800
Length, mm	from 5000	from 8000
Maximum yield point of the plate material, MPa	≤850	≤1250
Straightening speed, m/sec	0.3–0.6	0.2–0.6
Straightening force, MN	30.0	50.0
Residual curvature of plate after straightening (throughout the thickness range), mm/m	≤3.0	≤3.0

- exchanging data with the pump-battery station (PBS) of the PSM and transmitting the station's operating parameters to the upper-level system for display;
- receiving signals from the upper-level system for manual control of the machine and the PBS;
- obtaining initial data from the upper-level system for automatic correction and transmission of the data in order to make the appropriate adjustments.

The functions of the upper-level automation system are as follows:

- entering data on the straightening regimes for subsequent selection of the regime and recording that information in a database;
- manually choosing the straightening regime from the database for the corresponding plate (this is done by the operator);
- automatically choosing the straightening regime from the database on the basis of information obtained from the upper-level system;
- manually controlling the machine in the straightening and cassette-replacement regimes;
- indicating the positions of the mechanisms based on readings from the sensors and the positions of the limit switches;
- indicating the presence of a plate in the working zone of the PSM;
- indicating the temperature of the plate measured by the pyrometer;
- visually representing the straightening regimes and machine adjustments;
- visually representing the state of the machine's mechanisms and the PBS for diagnostic purposes.

Remote input-output module ET200 is used to supply power to the unregulated drives. The cabinet containing the relays and contacts for these drives is located a considerable distance from the controller. Use of the module has made it possible to significantly shorten the connecting cables.

Diagnostic System. The heavy concentration of electrical and hydraulic equipment included as part of the PSM – equipment which is located an appreciable distance from the machine itself and is often in hard-to-reach places – makes it more difficult to service the machine and locate the source of problems. To facilitate maintenance of the PSM and shorten repair time, it was necessary to build an advanced diagnostic system.

The system is based on an industrial computer installed at the control post. It diagnoses the state of various mechanisms of the PSM, as well as its hydraulic and electrical equipment. The system can be used to evaluate the condition of the automatic switches, the temperature sensors of the motors, the linear displacement gages, terminals of the local PROFIBUS network, the currents, speeds, and direction of rotation of the motors, and other equipment and parameters.

The diagnostic system can also be used to establish the operating protocol of the PSM. Its archives contains data on the time and types of errors and equipment failures that occur, the coordinates of the mechanisms, motor currents and speeds, and other information.

To make the control system more reliable, the software and hardware of the diagnostics station are identical to the corresponding components of the control system's upper level. When problems occur with the operation of the control computer, the PSM control functions can be transferred to the computer of the diagnostic system.

Conclusions. The NKMZ has worked with its original partners in the Commonwealth of Independent States (CIS) to successfully introduce plate-straightening machines equipped with a modern automated control system. Use of the machines makes it possible to minimize and almost completely eliminate the dependence of the quality of the finished plates on the skill of the machine operator.

The control system, together with its convenient user interface, allows even personnel with no special training to quickly master the operation of the machine.

The production of high-quality products is assured as a result of the exact movements of the machine's mechanisms and the accuracy with which their positions are maintained, which owes to the use of precision equipment with proportional control and special control algorithms.

In addition, the machine is equipped with a sophisticated diagnostic system which also records its key operating parameters. The availability of the system facilitates maintenance and repair of the machine's many complex components.

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