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INDUSTRY 4.0 IN AUTOMATION OF 5-AXIS MACHINING ON NUMERICAL CONTROL MACHINES

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Abstract. The paper discusses the implementation of Industry 4.0 concepts in automated 5-axis machining on numerically controlled machines. It is shown that the transition to intelligent manufacturing is based on an end-to-end digital data chain from CAD/CAM and technological preparation to operational production management and quality control. The key components of the solution are considered: collection of production data from equipment and sensors, integration of control systems and dispatching, the use of digital models/twins to optimize cutting data and toolpaths, as well as methods for monitoring and diagnosing deviations in the machining process. Special attention is paid to the requirements for traceability and correctness of data, since it is the quality of information that determines the efficiency of forecasting and the stability of the technological process. Benchmarks for assessing the effectiveness of implementation, including performance and quality indicators, are proposed.

Introduction. Modern mechanical engineering is increasingly focused on automation, digital transformation and increased predictability of production processes. This is particularly relevant in 5-axis CNC machining, where the quality of parts and productivity are largely determined by the correctness of technological planning, the stability of cutting parameters and the ability of the system to detect deviations in the process in a timely manner. at fixed technological modes and periodic control at the end of the operation, does not effectively solve the problems of reducing rejects, reducing downtime and ensuring the stability of processing characteristics.

Industry 4.0 concepts involve the creation of an end-to-end digital chain linking design, technological preparation, production planning, operations and quality control. Within this chain, the data generated at various stages of the product lifecycle becomes a central resource for optimization and management. The transition to intelligent manufacturing relies on the integration of CAD/CAM/CAE loops with equipment control, dispatching and process monitoring systems, as well as the use of predictive and diagnostic methods based on sensor data and machine telemetry.

Objective:to review and justify the application of Industry 4.0 principles in the automation of 5-axis machining on CNC machines, to determine the requirements for data, system integration and control algorithms to improve productivity, quality and stability of the technological process.

Tasks:

1. To analyze the elements of Industry 4.0 architecture applicable to 5-axis machining (sensors and IoT, digital twin, MES/ERP, SCADA, PLC, communication via industrial protocols).
2. Describe the automation model of 5-axis CNC machining: the flow of data from design and manufacturing (CAM/CAE) to planning, execution, and control (closed loop control).
3. Define approaches to monitoring and predicting the state of the machining process (vibration/temperature/spindle load control, deviation detection, tool life prediction).
4. Formulate requirements for data integration and quality (collection, storage, traceability, standardization of parameters, cyber security at the production level) and propose efficiency metrics: OEE, dimensional stability, roughness, cycle time, downtime.

Main part. Integration of industrial automation circuits and higher-level systems is expedient from the point of view of distributing functions among the levels of the control and data stack. In general, the following areas of integration are distinguished:

1. Field Level and Control Layer (SCADA/edge–PLC): signal exchange and telemetry, support for production events and status parameters; The specific protocols are determined by the selected hardware and software platforms. For example: OPC UA/OPC DA, Modbus TCP/RTU, as well as specialized machine tool exchange protocols.
2. Dispatch and business layer (SCADA–MES/ERP): Generate events, provide contextual information about production facilities and operations, and ensure data consistency through integration mechanisms. For example: APIs, queues, transactional scripts, data schema negotiation.
3. Network segmentation layer: isolation of the industrial zone, highlighting the contours of the DMZ and logical separation of the corporate and industrial infrastructure.

From the point of view of engineering architecture, the following aspects are critical: the unification of the data model (common parameter names/tags, agreed units of measurement), system time synchronization (NTP/PTP) to ensure the correct correlation of process parameters with technological events, as well as the implementation of cyber resilience measures.

Functional decomposition within a practical architecture for 5-axis machining is typically implemented as follows:

1. PLC/edge → sensors: generation of high-frequency measurement signals, local processing (filtering, calculation of aggregated features), as well as the implementation of operational alarms and protective scenarios.

2. PLC/edge → SCADA: Time series accumulation, event and trigger generation, trending and status logging for HMI visualization and operational support.
3. SCADA/edge → MES/ERP: linking production data to the execution context (order, operation, part), reporting, quality assurance and traceability.
4. Data → analytical subsystem/digital twin: calculation of predictive estimates of wear, stability of technological modes and forecasting of quality parameters; optimization of trajectories/processing modes within the specified criteria.
5. Feedback → PLC/MES: adjustment of process parameters within the permissible limits of the regulation or switching between processing scenarios upon the occurrence of certain conditions [5, 6, 11, 12, 13, 14, 17, 23, 25].

A detailed methodological scheme of system integration of automated machining can be formalized as a set of functional levels connected by a single data model and algorithmic mechanisms for planning, management and adaptation.

In the first step of automating 5-axis CNC machining, telemetry information is collected and synchronized, including: spatio-temporal coordinates of the axes and their actual/command values, spindle state parameters (frequency, modes, setpoints, and actual implementation), actuator electrical quantities and related indicators (e.g., currents and load estimates), feed parameters (command and realized), as well as process sensor signals (vibration, force/moment, temperature and other informative signs). Temporal data binding is a critical condition for correct matching.

Next, a comparison of the prescribed and implemented behavior is performed. For the trajectory, deviations in geometric and temporal characteristics are evaluated, such as: position difference, phase delay relative to trajectory discretization, as well as dynamic mismatch parameters. At the same time, process parameters are compared, including force/moment values and vibration indications, to identify correlations between drive dynamics and changes in cutting conditions.

In addition, a chronology of corrective actions is formed: coordinate displacements, compensation parameters, as well as switching control modes. The next level is to use the accumulated information for training and improving models. Such models include: mode map approximations, tool wear predictors based on multivariate features, as well as planning rules that take into account probabilistic constraints and statistical estimates of process stability. As a result, the system under consideration is formed as an automated model, represented through a set of entities and mappings between them. Key entities include: process object, geometric trajectory, motion plan, executive level, process contours, metrology contours, and alignment logic [8, 10, 16, 18].

At the same time, it is necessary not to forget about the efficiency and reliability of the equipment. The development of effective systems for monitoring and predicting the state of technological processing processes is becoming critically important. The basis for effective monitoring is the collection of extensive data directly from the processing equipment. The key parameters to be monitored are vibrations, temperature and spindle load. Specialized sensors integrated into the structure of the machine continuously record these indicators, transmitting them for further processing. Analysis of the vibration spectrum allows you to identify anomalies associated with tool wear, bearing defects or imbalance of rotating parts. Temperature monitoring in the spindle bearings or cutting area helps prevent overheating and premature wear. Continuous monitoring of the spindle load is an indicator of excessive cutting, incorrect selection of machining modes or the presence of hidden defects in the workpiece.

Deviations from normal operation are identified by comparing current data with reference values or using machine learning algorithms. To predict tool life, models are used that take into account not only the current machining parameters, but also the history of its operation, the material of the workpiece, the type of operation and wear. This makes it possible to predict the residual life of the tool with a high degree of confidence, plan its replacement and avoid unplanned stops and scrap [2, 19, 20, 22, 24].

Data integration and data quality are the cornerstones for the successful implementation of Industry 4.0 principles in machine tool engineering. Data collection must be continuous and reliable. This includes the use of advanced sensors, wireless and wired data transmission technologies, as well as the development of flexible architectures capable of processing large amounts of information in real time. The most important aspect is data traceability, which ensures that each piece of information has a clear origin – which sensor, what equipment, what operation generated it. This is critical for analyzing the causes of failures and optimizing processes.

Standardization of parameters – a single format for describing data, including parameter names, units of measurement and exchange protocols, is necessary to ensure compatibility between different systems and equipment from different manufacturers. This simplifies integration and reduces labor costs for processing and analyzing information. Cybersecurity at the production level is a strict necessity. The machine must be equipped with multi-layered protection systems against unauthorized access, data breaches, and malware, covering both physical networks and the software that controls the machines and production processes [1, 3, 4, 7, 9, 15, 21].

Conclusion. To evaluate the effectiveness of OEE implementation, dimensional stability and roughness, cycle time and downtime. It is advisable to propose a number of key criteria:

1. OEE (Overall Equipment Effectiveness): A comprehensive measure that evaluates equipment availability, productivity, and product quality. The increase in OEE is a direct indication of the improvement of processes through digitalization.
2. Dimensional stability and roughness: These metrics reflect the accuracy of the processing. Improved roughness valuesindicate that it is possible to control and optimize cutting data more accurately.
3. Cycle time: The reduction in the time required to complete a single operation or produce a part is a direct consequence of process optimization and automation.

4. Downtime: Minimizing equipment downtime is one of the clearest indicators of the effectiveness of proactive monitoring and predictive maintenance.

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