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Revolutionary Application and Future Prospect of CNC Technology in Automatic Machinery Manufacturing

Juan Zhang

Lanzhou Vocational Technical College, Lanzhou, Gansu, 730030, China

ABSTRACT
As the manufacturing industry undergoes profound transformation toward intelligent, high-efficiency, and high-precision operations, numerical control (NC) technology has emerged as a pivotal driver in automated mechanical manufacturing, with its strategic value becoming increasingly prominent. This paper systematically examines the integration, key roles, and development trends of NC technology in automated mechanical manufacturing. The study first outlines the fundamental principles and evolutionary history of NC technology, followed by an in-depth analysis of its practical applications and efficiency enhancements in core components such as machining centers, flexible manufacturing systems, and industrial robot integration. Finally, it explores the future trajectory of NC technology within the context of digital and intelligent manufacturing. The research demonstrates that NC technology not only significantly enhances manufacturing precision, efficiency, and flexibility but also serves as an indispensable cornerstone for building future smart factories.

KEYWORDS
Numerical control technology; Automation; Mechanical manufacturing; Machining center; Flexible manufacturing system; Intelligent manufacturing

1 Introduction

In the face of intensifying global competition in manufacturing, traditional mechanical production models have proven inadequate in addressing challenges such as shortened product lifecycles, growing demand for customization, and stringent quality requirements. The integration of information technology with manufacturing processes has propelled the rise of automated and intelligent production systems, which have become essential for industrial upgrading. Numerical Control (NC) technology, through digital programming, enables precise command and control of machine tools and production workflows, perfectly aligning with modern manufacturing's pursuit of "quality, efficiency, and flexibility. " Evolving from basic trajectory control to deep integration with computer networks and artificial intelligence, NC technology has permeated every aspect of automated manufacturing, emerging as a key driver of industrial innovation. Therefore, examining the current applications and future trends of NC technology holds significant theoretical and practical importance for advancing high-quality development in China's manufacturing sector.

2 Numerical Control Technology: Core Analysis and Evolutionary Context

Numerical Control (NC) technology is fundamentally a universal technique that utilizes digital information to achieve automated control of mechanical motion and machining processes. A complete NC system typically consists of a program carrier, NC device, servo drive system, detection and feedback device, and the controlled machine tool itself. The workflow involves: inputting program code—compiled based on part drawings and technical requirements for machining processes, parameters, and displacement data—into the NC device; the NC device decodes, processes, and calculates to output corresponding control command pulses; the servo drive system then converts these electrical pulse signals into precise displacement movements for the machine tool's actuating components, thereby automatically completing the machining task.

The evolution of numerical control (NC) technology mirrors the depth and breadth of information technology integration in manufacturing. Its development can be broadly categorized into three phases: The NC stage, which relied on dedicated control computers with hardware logic circuits, stored programs on punched paper tapes, and featured limited flexibility and single-function capabilities; The Computer Numerical Control (CNC) stage, where the advent of microcomputers enabled software-based numerical control functionality, increased storage capacity, enhanced human-machine interaction, and laid the foundation for modern CNC systems; The Direct Numerical Control (DNC) and Flexible Manufacturing System (FMS) stage, which achieved centralized control and management of multiple CNC devices through a central computer, initially realizing workshop-level automation; The modern integrated, networked, and intelligent stage, where CNC systems evolved into open "smart manufacturing units" with robust communication capabilities (e.g., MTConnect, OPC UA protocols), seamless integration with factory networks (Industrial Internet of Things, IIoT), and synergy with upper-layer MES and ERP systems. This phase also saw the incorporation of AI algorithms to enable adaptive control, predictive maintenance, and other intelligent functions.

3 The Core Application Scenarios of CNC Technology in the Automatic Mechanical Manufacturing

In the system of automatic machinery manufacturing, the NC technology has expanded from the application of single machine to the system integration, and formed a multi-level and all-round application pattern.

3.1 Application in High Speed and High Precision Machining Center

The machining center is the most typical representative of CNC technology at the single machine level, which integrates milling, drilling, boring, tapping and other processes into one. The application of modern CNC system makes its performance be brought to the extreme:

Precision and Stability: By employing high-resolution servo motors, linear grating-scale closed-loop feedback, and thermal error compensation algorithms, the system achieves micron-level positioning accuracy and repeatability, ensuring superior processing quality for critical components such as aerospace engine blades and precision molds.

Efficiency Enhancement: The high-speed spindle (operating at tens of thousands of RPM), rapid feed (with acceleration exceeding 1g), and advanced CNC interpolation algorithms significantly reduce both cutting and non-cutting time. For instance, in automotive engine cylinder production lines, CNC machining centers can complete all machining operations for polyhedrons in a single setup, achieving efficiency several times higher than traditional dedicated machine tools.

Complex surface machining capability: With five-axis CNC technology, the tool can adjust its posture freely in 3D space, enabling precision machining of complex spatial curved surfaces like impellers and propellers – a feat unattainable with traditional methods.

3.2 Central Role in Flexible Manufacturing System (FMS)

FMS is an automated manufacturing system which consists of a unified information control system, a material storage and transportation system and a set of CNC machining equipment. CNC technology plays a dual role of "executive terminal" and "information node".

The foundation of flexible production: The "flexibility" at the core of FMS lies in CNC machines' ability to adapt to different parts through rapid program changes ("soft adjustments"), eliminating the time-consuming and labor-intensive "hard adjustments" required in automated production lines. When production tasks change, the central control system simply issues new machining programs and process parameters to the relevant CNC machines.

System Integration and Collaboration: Modern CNC systems are equipped with standard network interfaces that enable real-time reception of job instructions from the FMS master computer and reporting of operational status (e.g., machining progress, tool life, fault alarms). This bidirectional communication capability allows multiple CNC devices to work in concert like a symphony orchestra, with automated guided vehicles (AGVs) or robots sequentially transporting workpieces to achieve mixed-flow production of diverse product types and small-to-medium batches.

3.3 Deep Integration with Industrial Robots

In the automation production line and assembly line, CNC technology and industrial robot technology are moving towards deep integration.

The robot itself as a CNC machine: High-end industrial robots are multi-joint precision CNC machines, with their motion paths fully controlled by CNC programs, ensuring precision and consistency in welding, spraying, handling, and assembly operations.

"CNC Machine Tool + Robot" Work Unit: This is currently the most prevalent integration model. The robot handles workpiece loading/unloading, flipping, and in-machine inspection, while the CNC machine tool specializes in cutting operations. Both systems are interconnected and synchronized through a numerical control (NC) system. For instance, in a smart manufacturing unit, the robot automatically opens the protective door upon receiving the "processing complete" signal from the CNC machine tool, removes the finished product, places a new blank, and initiates a new machining cycle. The entire process is fully automated, enabling 24/7 continuous operation.

3.4 Realize the automation of detection and monitoring

CNC technology extends automation from machining to quality assurance. Digital inspection equipment like Coordinate Measuring Machines (CMM) and laser scanners rely on high-precision CNC motion systems at their core. These systems automatically inspect finished parts according to preset programs, compare them with CAD models, and feed data directly back to the control system. Furthermore, by integrating force sensors, vibration sensors, and acoustic emission sensors into CNC machines, combined with the monitoring software built into the CNC system, real-time online monitoring and adaptive adjustments during the machining process can be achieved. For example, it automatically optimizes feed rates based on cutting force variations or alerts for tool wear, elevating post-facto inspection to in-process control, thereby ensuring the stability and reliability of the manufacturing process.

4 The Transformational Benefits and Challenges of CNC Technology

4.1 Main Benefits

Precision and quality leap: Digital process control eliminates human operational errors, achieving unprecedented consistency in batch production.

Production efficiency doubled: automated operation reduced auxiliary time such as clamping and measurement, high-speed machining shortened cutting time, and equipment utilization rate was significantly improved.

Significantly enhanced production flexibility: The rapid production switching capability enables enterprises to respond agilely to the diversified and personalized market demands.

Process predictability and optimization: CNC simulation software enables verification and optimization of machining programs in virtual environments, reducing trial-cutting losses and lowering production costs.

Improved working conditions and shift in patterns: workers are freed from heavy, repetitive manual labour and hazardous environments, and shifted to more valuable programming, monitoring, maintenance and optimization work.

4.2 Face the Challenge

High initial investment costs: The high-end CNC equipment, its supporting software, and maintenance expenses pose significant barriers for small and medium-sized enterprises.

High requirement for personnel quality: the compound talents who know the mechanical technology and familiar with the NC programming, operation and maintenance are needed, and the shortage of talents is prominent.

Maintenance challenges due to system complexity: When a highly integrated CNC system malfunctions, the diagnosis and repair process becomes highly complex, requiring exceptional technical expertise from the maintenance team.

Data security and interconnection risks: After the networked and open CNC system is connected to the factory network, it faces new security threats such as data leakage and network attacks.

5 Future Development Trends and Prospects

In response to "Industry 4.0" and "China Manufacturing 2025", numerical control technology is evolving in the following directions:

Intelligence and Autonomy: CNC systems will be deeply integrated with AI and ML algorithms. Future "intelligent CNC" systems will autonomously learn and optimize machining parameters, diagnose fault causes, predict tool life, and even generate partial machining strategies based on historical data and real-time sensor information, achieving a leap from "automation" to "autonomy".

Cloud-based and collaborative manufacturing: Leveraging the industrial internet platform, data from CNC equipment (including status, process parameters, and energy consumption) is uploaded to the cloud. Through cloud-based big data analysis and sharing, this enables cross-plant and cross-factory coordination of production resources and continuous evolution of process knowledge bases, establishing a new paradigm of networked collaborative manufacturing.

Integration of additive and subtractive manufacturing: Composite manufacturing centers that combine CNC milling (subtractive) with laser cladding deposition (additive) technologies are gaining traction. CNC systems now seamlessly coordinate these two distinct processes on a single platform, either sequentially or in parallel, paving the way for creating integrated components with complex internal cavity structures or functionally graded materials.

Extreme Pursuit: Nanoscale Processing and Novel Materials Adaptation: To meet the demands of fields like optics and semiconductors, CNC technology is advancing toward nanoscale resolution and positioning accuracy. Meanwhile, for challenging materials such as composites and ceramics, CNC systems need to develop smarter control strategies to adapt to their unique processing characteristics.

6 Conclusion

In conclusion, CNC technology has become an integral part of automated mechanical manufacturing. Its pivotal role ranges from enhancing individual machine performance to empowering entire production systems. More than just a tool for achieving high-precision and high-efficiency manufacturing, it serves as a key enabler for the industry's transition toward flexibility, digitalization, and intelligence. To meet future challenges and seize emerging opportunities, China must continuously advance CNC innovation and applications, strengthen R&D in high-end CNC systems and talent cultivation, and promote deeper integration with emerging information technologies. These efforts are crucial for consolidating the nation's manufacturing foundation and securing new competitive advantages in global manufacturing. The evolution of CNC technology will undoubtedly propel automated mechanical manufacturing into a smarter, more interconnected, and more efficient new era.

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About the Author

Juan Zhang, female, Han nationality, from Lanzhou of Gansu Province, master candidate, associate professor. Research interests: mechanical manufacturing and automation.

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