Network-based Reconfigurable CNC System Technology with On-machine Monitoring and Intelligent Maintenance

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Keywords: CNC system, Condition monitoring, Quality inspection, Hierarchical bus.

Abstract. A network-based monitorable CNC system was constructed. In order to adapt to the development trend of open CNC system, a four-level open system architecture model is constructed. The model can meet the requirements of functional structure adjustment and subsequent function expansion to realize the function integration of CNC system and the monitoring and processing of machine tool running status. The real-time acquisition of quality and the need for secondary card loading have established a prototype of the CNC system based on the embedded monitoring unit and the on-machine quality detection unit. Based on the analysis of the development status of machine tool monitoring, an embedded monitoring unit based on DSP + ARM architecture is built. This unit can monitor the running status of the machine in real time and connect seamlessly with the CNC system through the field bus. The flexible hardware and software configuration based on the change and demand of monitoring targets utilizes an open architecture and embeds a quality inspection unit to achieve on-machine acquisition of geometric information of the workpiece being machined. The research results provide a feasible solution for the integration of CNC equipment maintenance and system functions.

Introduction

China Manufacturing 2025 Strategic Processing puts higher demands on modern machinery that is complicated, precise, large-scale and automated. Due to the complexity or precision or large-scale features, its single piece cost or processing cost is also quite amazing [1-3]. In order to achieve early prevention of faults and timely elimination, the state monitoring and quality inspection technologies of CNC machine tools have developed rapidly.

The existing monitoring system adopts the plug-in form [4-5] independent of the numerical control system, which cannot achieve seamless integration with the traditional method. At present, some scholars at home and abroad and well-known CNC system manufacturers have carried out remote monitoring research on machine tool performance with numerical control system as the monitoring platform [6], but these monitoring studies can only detect machine specific parameters in non-working state. Evaluation, monitoring and diagnosis of manufacturing systems in a processing environment cannot be achieved.

In addition, the high-performance DSP (digital signal processing) processor greatly enhances the data processing capability of the CNC system. The field serial bus such as SERCO S, PROFIBUS, FSSB, CAN, etc. is used to connect CNC equipment, servo system and spindle drive system of CNC equipment. The operation panel, robot and I/O unit can effectively reduce the complexity of the system connection and further improve the reliability, scalability and maintainability of the system [7-9].

Based on this, this paper develops a hierarchical open-structure CNC system that integrates advanced network and bus technologies and integrates on-machine condition monitoring, quality inspection and intelligent maintenance functions [10].
System Architecture

The system is divided into two layers: the CNC system on-board monitoring unit and the remote fault diagnosis center. The underlying CNC system on-board monitoring unit realizes the normal control of NC machining, and also constitutes the bottom monitoring node with the high-performance MC U architecture controller as the core to complete the acquisition, monitoring and uploading of the on-site signals. The upper-level remote monitoring and diagnosis center combines Internet technology and database technology, adopts the information interaction mode of B/S architecture, and uses the database as the core to store the data uploaded by the underlying CNC system in the database server, thereby realizing system-wide data sharing. Data communication between the upper and lower layers is achieved by a network transmission module installed on the controller. The system structure is shown in Figure 1.

CNC System Design

The establishment of a layered system architecture, based on the essential function of the function-related CNC system is to achieve the trajectory control of the machine tool motor and the reasonable logic control of the switching components. Therefore, the motion control and logic control constitute the basic functions of the CNC system. The system builds a four-level reference model (Figure 2). The four levels are the peripheral interface layer, the system hardware layer, the system software layer, and the application software layer. Based on the application software layer and the peripheral interface layer, the user's special function configuration can be realized, and the operating system layer usually does not have user-level configurability.

Application system non-real-time tasks are processed by the main CPU, real-time fine interpolation and position control P MC real-time logic control, data acquisition, state analysis and optimization, and other continuous tasks with large computational complexity and resource elimination or higher real-time requirements It can be implemented using a separate embedded microprocessor or high speed DSP.

In order to achieve compatibility with traditional device-level analog (4 to 20mA/0 to 5V DC, etc.) and switching signal (24V DC) control modes, the analog control interface is retained in the model and implemented by the axis adapter and I/O. Connection control of power devices. The axis adapter receives the system command pulse or the external pulse generator signal, and is converted into the actual output control voltage by conditioning and amplification; at the same time, the
feedback pulse such as the encoder and the grating ruler can be received, and the position control servo is realized by the axis control module. The I/O adapter mainly performs isolation of the switching signal, power amplifier processing, and reverse and polarity adjustment.

The system software layer consists of three layers. The hardware abstraction and driver layer are located between the operating system kernel and the underlying hardware. It provides device driver functions for upper-layer applications and shields hardware details. It implements device initialization and release, data communication with upper layers, and response services. Requests and exception handling operations. The operating system (OS) mainly provides system service functions such as memory management, file system management, task scheduling, clock management, and resource allocation. The system API layer provides a unified system service and device caller interface for the upper application software. The application software layer consists of different functional modules (FMs), which usually contain one or more functional components (FCs), which are pre-compiled executables. These functional components become the basic unit for "pluggable" user-defined or third-party functional software.

System Design of Embedded Monitoring Unit

The embedded monitoring unit adopts the master-slave architecture of DSP+ARM (advanced RISC machines), which uses DSP to realize the acquisition and preprocessing of the running status signals, and liberates the main processor ARM from the heavy computing tasks, mainly responsible for interface control and Data storage, transmission and other tasks, and the results of the analysis are transmitted to the CNC system via the fieldbus. Moreover, the embedded monitoring unit functions as an independent unit entity to complete the signal processing function, avoiding occupying too many resources of the numerical control system, and simultaneously using the field bus for communication to ensure the real-time interaction of information.

The hardware platform of the embedded monitoring unit is mainly composed of three parts: signal conditioning module, data acquisition module and data analysis module, as shown in Figure 3.

![Figure 3. Embedded monitoring unit system hardware schematic.](image)

The main function of the signal conditioning module is to filter out power frequency interference, unwanted frequency components other than the cutoff frequency, and automatically adjust the gain.

The data acquisition module mainly performs data signal acquisition, and its CPU adopts the mode of DSP +FPGA (field programmable array). As the main CPU of the acquisition module,
DSP completes the control of the whole module. FPGA is used as the slave CPU of the acquisition module. It is used for the communication of ARM and DSP and the design of the handshake circuit. At the same time, it provides the necessary clock signal and control signal for the acquisition module.

The main function of the data analysis module is to achieve data storage and analysis. The data analysis unit uses ARM as the CPU to complete the reception, storage and signal analysis of the collected data through the dual-port RAM, and interacts with the numerical control system through the fieldbus to achieve a truly seamless connection. The module-based structural design and interaction with the external using the fieldbus ensure flexibility and portability of the unit. Figure 4 shows the program flow chart of the embedded monitoring unit. Figure 5 and Figure 6 show the real-time interface of the monitoring object of the monitoring unit.

**Design of the Machine Quality Detection Unit**

![Figure 5](image5.png)

Figure 5. Real-time display of each motion axis load of the machine tool.

![Figure 6](image6.png)

Figure 6. Real-time display of each physical state of the machine.

The monitoring status information is divided into two categories: the operating state information of the NC machining equipment and the geometric information of the workpiece being machined. The running state information is processed by the above-mentioned embedded detecting unit, and the detection of the geometrical information of the processed workpiece is realized by the on-machine detecting module of the numerical control system.

The on-machine detection module uses the trigger signal of the external three-dimensional probe as the input marker. In the NC machining process, when a certain process is completed, the process of detecting the geometric information of the workpiece is started. The process mainly analyzes the geometric accuracy of the workpiece after the previous process. After the on-machine detection module detects the input quantity of the probe, the actual coordinate of the current measurement point is obtained from the motion control module via the system bus [11].

After all measurement points have been measured, the measurement data will be sent to the error assessment unit. All measurement point measurement data and error assessment unit analysis results are stored in the log detection form in the on-machine detection storage area as a source of information for subsequent process adjustment and fault diagnosis. The machine quality inspection process is shown in Figure 7. Figure 8 is a screenshot of the preliminary analysis of the machining quality by the machine quality inspection module.
Remote Diagnostic Center for System Development

![Diagram of the machine quality inspection process](image1)

Figure 7. Schematic diagram of the machine quality inspection process.

![Screenshot of preliminary analysis results](image2)

Figure 8. Screenshot of preliminary analysis results of machine quality inspection.

The remote diagnostic center is based on the Internet network, which provides detailed functional support for fault diagnosis analysis of CNC machine tools. It stores, analyzes, diagnoses and predicts faults, displays results, prints and transmits the analysis results to the underlying monitoring nodes (CNC) through the network. The CNC system can then use this information to store the information transmitted by the underlying monitoring node (CNC). To carry out related operations to ensure the safe operation of the machine.\textsuperscript{[12-13]} The remote diagnosis centers according to functions are mainly divided into: server database and application analysis system.

**Server Database of the Remote Diagnostic Center**

The underlying monitoring node (CNC) realizes the connection with the remote diagnosis center based on the TCP protocol and the FTP protocol (Fig. 9), and uploads the monitoring data to the central server database, which processes the data, such as storing the contents stored in the database, query, modify, and delete operations. The real-time data mainly includes the current machining parameters and data acquisition parameters of the machine tool, the setting parameters of each channel, the original waveform data of each channel, the spectrum data of each channel, and the process parameters. Historical data is stored using a certain compression strategy. When the machine is running normally, the data storage density and quantity increase. When the machine is abnormal, the density and quantity are reduced. The characteristic data is data indicating the substantial state of the machine tool after the signal analysis processing (time domain analysis, frequency domain analysis, correlation analysis, trend analysis, etc.) of each monitoring signal.

![Remote Diagnostic Center Server Login Parameter Settings Interface](image3)

Figure 9. Remote Diagnostic Center Server Login Parameter Settings Interface.
Machine State Remote Diagnostic Center Application Analysis System

The monitoring and diagnosis center application analysis system mainly performs related processing analysis on the information transmitted to the server database, and can be divided into a module dynamic test and signal analysis system, and a fault diagnosis and prediction system. Figure 10 is a screenshot of the relevant information that the CNC system passes to the center when the machine has an alarm.

Conclusion

Aiming at the monitoring and operation control of CNC machine tools, a solution based on the integrated monitoring of the embedded monitoring unit and the on-machine quality detection unit is proposed. The overall model of the system and the specific structure of the embedded monitoring unit and the on-machine quality detection unit are given. By utilizing the advantages of bus and assembly technology, the flexible configuration of the hardware and software of each functional unit of the system is realized, and the monitoring and detection unit is portable and scalable, which is in line with the development trend of flexible and integrated CNC system. The data acquisition, its preliminary analysis and storage are all completed on the numerical control system, and the numerical control system realizes the corresponding machine running status display and adaptive maintenance strategy based on this data and the interactive information obtained from the remote monitoring center through the network, and will monitor. The detection data is uploaded to the database server to achieve high information sharing and provide rich data resources for remote maintenance mode applications.(Project Reference No.: GJJ180986 Project Title: Theory and Method of Intelligent Manufacturing and High Performance Closed Loop Manufacturing)

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