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Design of a CNC Machine Tool Monitoring System Based on LabVIEW

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ABSTRACT

To address the challenges associated with CNC machine tool condition monitoring and fault diagnosis, this study proposes a new method for the monitoring system of CNC machine tools. The system comprises two distinct components: the upper computer and the lower computer. The upper computer is based on LabVIEW, which is used to develop the interactive interface program. This enables the system to perform a range of functions, including questioning, command issuance, data acceptance, data decoding, data display and data storage. In the lower computer section, three-channel current sensors and three-channel temperature sensors are utilized, with the sensors and the acquisition card integrated to facilitate the acquisition of data and its subsequent upload to the upper computer. The efficacy of the system is validated through field trials, which establish the foundations for the rectification of CNC machine tool malfunctions.

1. Introduction

Computer Numerical Control (CNC) technology plays a pivotal role in the modern manufacturing industry, with its advancement directly influencing the automation and intelligence levels within the sector. The real-time monitoring and intelligent maintenance of CNC machine tools have emerged as key areas of interest within the industry. The conventional approach to monitoring CNC machine tools relies on manual periodic inspection and post-failure maintenance. This method is associated with several limitations, including low monitoring accuracy, prolonged response time, and elevated maintenance costs (Feng, C et al.2024; Sun, W et al. 2020; Zhang, L et al. 2019). The implementation of real-time data acquisition and analysis for machine tool operation can facilitate the timely detection and early warning of potential failures, thereby enhancing the reliability and productivity of the machine tool (Wang, J et al. 2023; Bao, X et al. 2023; Hu, H et al. 2023).

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language developed by National Instruments (NI). Its intuitive programming interface, powerful data processing capabilities, and rich hardware interface support make it an ideal tool for developing complex monitoring systems (Xu, S et al. 2022; Liu, X et al. 2023; Yang, Z et al. 2021).

The monitoring system developed in this paper is capable of acquiring the operating parameters of a CNC machine tool, including current, temperature, and vibration, through the use of sensors and data acquisition devices. The transfer of data to the LabVIEW platform is facilitated through the data interface, allowing for the real-time monitoring of the machine tool's operational status through the utilization of data analysis functions. The operation of the machine tool can be observed intuitively, allowing for rapid reaction to any abnormal situations. The implementation of a LabVIEW-based CNC machine tool monitoring system offers considerable benefits in terms of enhancing the efficiency of machine tool monitoring, reducing maintenance costs, and extending the lifespan of the equipment. Furthermore, the system has the potential to play a pivotal role in a wider range of industrial applications.

2. Data Detection Principle

During the process of machine tool machining, the varying states of the machine tool and the power of the machine tool motor result in corresponding changes in motor current. Consequently, monitoring the current indirectly to assess the machining state of the machine tool is a common method of monitoring (Luo, D. 2022). Figure 1 illustrates the configuration of the machine tool transmission system. The motor is coaxial with the No. 1 axis, the chuck is coaxial with the No. 3 axis, and the middle of the No. 2 axis. The first axis is

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associated with gear number one, the second with gears two and three in a left-to-right sequence, and the third with gear number four.

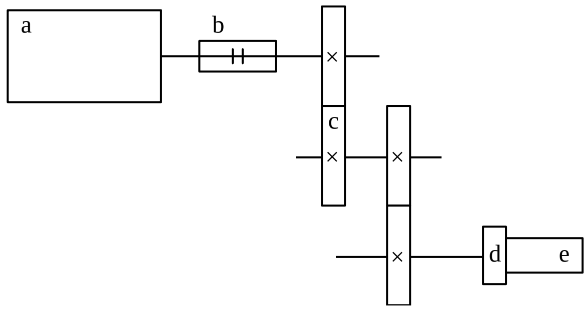


Fig. 1. Drive train. a: motor. b: coupling. c: gear. d: chuck. e: workpiece

Axis 1 is analyzed and axis 1 satisfies equation 1.

$$T_L - T_1 - T_{f1} = J_1\theta_1 + B_1\theta_2 \tag{1}$$

where i_{12} is the ratio of the gears 1 and 2, T_2 is the torque of shaft 2, T_3 is the output torque of gear 3, T_2 is the coulomb friction torque on shaft 2, J_2 is the joint rotational moment of inertia of the shaft 2, and B_2 is the rotational damping coefficient of the shaft 2.

For axis 2 to be analyzed, axis 2 satisfies equation 2.

$$\begin{cases} \dfrac{\theta_1}{\theta_2} = \dfrac{T_1}{T_2} = i_{12} \\ T_2 - T_3 - T_{f2} = J_2\theta_2 + B_2\theta_2 \end{cases} \tag{2}$$

where i_{12} is the ratio of the gears 1 and 2, T_2 is the torque of the shaft 2, T_3 is the output torque of the gear 3, T_2 is the coulomb friction torque on the shaft 2, J_2 is the joint rotational inertia of the shaft 2, and B_2 is the rotational damping coefficient of the shaft 2.

$$\begin{cases} \dfrac{\theta_2}{\theta_3} = \dfrac{T_4}{T_3} = i_{34} \\ T_4 - T_r - T_{f3} = J_3\theta_3 + B_3\theta_3 \end{cases} \tag{3}$$

here i_{34} is the ratio of the 3 and 4 gears, T_4 is the input torque of the gear 3, T_r is the load torque of the shaft 3, T_{f3} is the coulomb friction torque on the shaft 3, J_3 is the joint rotational moment of inertia of the shaft 3, and B_3 is the rotational damping factor of the shaft 3.

From equations (1), (2) and (3), we get

$$\begin{aligned} T_r = {} & i_{14}T_L - \left(i_{14}T_{f1} + i_{34}T_{f2} + T_{f3}\right) \\ & - i_{14}^2\left(J_1\theta_3 + B_1\theta_3\right) - i_{34}^2\left(J_2\theta_3 + B_2\theta_3\right) \\ & - \left(J_3\theta_3 + B_3\theta_3\right) \end{aligned} \tag{4}$$

In normal machining process, under fixed working conditions, the tool, spindle speed, depth of cut and feed rate do not change, so θ_3 is constant at 0. At this time, with external disturbances and other noises ignored, B_1, B_2, B_3, J_1, J_2, J_3, T_{f1}, T_{f2}, T_{f3}, T_L and T_r are constants, so there is a linear correlation.

When the machine tool spindle motor is a three-phase AC asynchronous motor, there are formulas as follows.

$$\begin{cases} T = K_T \Phi I_2 \cos\varphi_2 \\ \Phi = \dfrac{U_1}{4.44 f_1 N_1} \end{cases} \tag{5}$$

where T is the electromagnetic torque, K_T is the motor structure constant, Φ is the flux of the rotating magnetic field, I_2 is the motor current, φ_2 is the rotor lag phase angle, U_1 is the motor voltage, f_1 is the motor electromotive force, N_1 is the number of stator winding turns.

Through equation (4) and (5) can be seen, in the machine tool processing, f_1, N_1, φ_2 constant, when the working conditions change, because the motor voltage is unchanged, the motor current can change, so theoretically can be monitored by the state of the current to determine the state of the machine tool processing. Therefore, the motor current and machine tool state equations can be established in the ideal state.

During machine tool machining, the heat on the motor changes because the current changes and the formula for calculating the heat of the motor is as follows.

$$Q = I_2^2 R t \tag{6}$$

where Q is the motor heat generation, R is the internal resistance of the motor, and t is the time.

The formula (6) demonstrates that a change in current results in a corresponding change in the heat generated by the motor. The temperature of the motor can therefore be used as an indicator of the heat generated by the machine. By measuring the temperature of the motor, it is possible to gain insight into the machine's operational state. When the machine is subjected to a heavy load, the power output increases, leading to an elevated temperature. This suggests that temperature can be employed as a monitoring parameter for the machine's state.

3. Monitoring system design

The LabVIEW-based CNC machine monitoring system employs a dual-computer structure comprising an upper computer and a data acquisition device. Its design allows for the alteration of the requisite operational interface and sensor type to the user's specifications. As illustrated in Figure 2, the system is primarily comprised of devices, including the host computer, data acquisition card, and sensors. The sensor utilizes the principle of mutual inductance to ascertain the operational current of the motor, while the temperature sensor employs a patch configuration to affix to the motor shell. These two sensors then collect the requisite information, transmit the analog signal, and convert it into a digital signal through the ADC integrated within the data acquisition card. The communication between the upper and lower computers is conducted via RS485, which is transmitted through the Modbus protocol. Upon receipt of an information inquiry command from the upper computer, the lower computer reads the real-time information and transmits it to the LabVIEW user interface. The upper computer then analyzes, processes, and stores the received data and information using the information acquisition program.

3.1 System workflow

Upon activation of the monitoring system, the initialization of the system is the primary objective, which is then followed by the transition to the operational state. Once the data monitoring process has commenced, the lower computer records the data in real-time. However, the data is not uploaded to the upper computer at this stage. Upon issuing an inquiry command, the upper computer transmits this command to the lower computer via the RS485 bus, by the Modbus protocol. If the lower computer fails to receive the inquiry command, the upper computer must transmit it again. Upon receipt of the inquiry command by the lower computer, the data stored within the register is retrieved and subsequently transmitted to the upper computer. Upon receipt of the data code by the upper computer, the data is initially extracted from each sensor. Subsequently, the data is decoded in the IEEE-754 coding format. Once the decoding process is complete, the actual data can undergo three stages of processing. Initially, the data can be displayed in the working interface. Subsequently, the amplitude can be represented through a waveform graph. Finally, the data can be saved in the host computer for subsequent analysis.

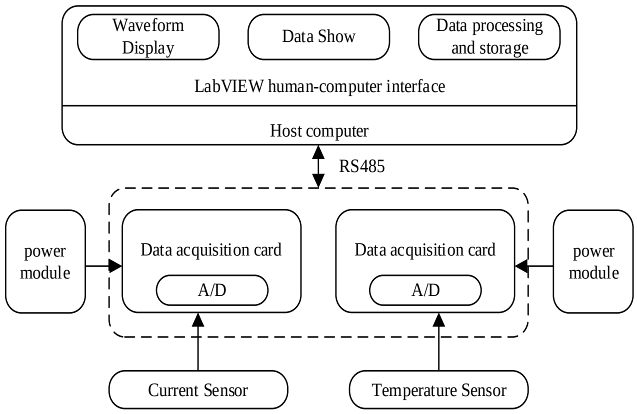


Fig. 2. Overall structural design of the monitoring system

3.2 *System workflow*

3.2.1 *Temperature sensors and acquisition devices*

The temperature sensor employs a patch-type PT100 three-wire platinum resistance temperature detector (RTD), with a temperature measurement range of -50~200℃. This is sufficient to meet the operational temperature requirements of the machine tool motor. The sensor exhibits a measurement accuracy of 0.1 ℃ and is configured in a multi-point distributed mode to prevent the distribution location from influencing the data. Each motor is equipped with three distribution locations, and the temperature of the motor is the average value of the three distribution locations. The PT100-type platinum RTD sensor exhibits acid and alkali resistance, high-temperature resistance, waterproof capabilities, and a robust anti-interference ability, rendering it suitable for utilization in harsh working conditions.

3.2.2 *Current sensors and acquisition devices*

The sensor in question employs an open-ended mutual inductance AC power acquisition module, with a measurement range of 0~60 A. This is sufficient to meet the requisite working current demands of the machine tool, while the sensor's measurement accuracy is 0.0001 A. The sensor is installed in the control cabinet of the numerical control machine tool, where it operates in a stable environment with no mutual interference between channels, thus making it suitable for the simultaneous acquisition of multi-channel current.

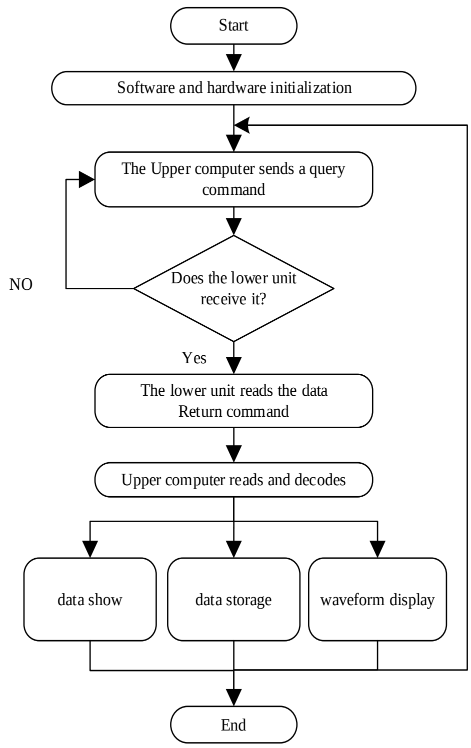


Fig. 3. Workflow diagram

3.3 *System Hardware Design*

It is used that LabVIEW 2018 software be adopted as the programming platform. The loop structure, selection structure, sequence structure, function, and other functions available on the platform should be used to write the block diagram of a data acquisition program for 6-channel data from two kinds of sensors. In addition, the serial communication between the upper and lower computers should be realized by setting up the serial port. The waveform graph control should be employed to set the horizontal coordinate as time and the vertical coordinate as the corresponding measurement value, to display the amplitude of the data in real time. Furthermore, the Signal Processing and Data Acquisition Module can be utilized to set the path for file storage and add Boolean switches to achieve the data storage function. Figure 4 illustrates the interactive interface of LabVIEW.

Fig. 4. LabVIEW Interactive Interface

As illustrated in Fig. 5, the data acquisition processing program architecture initially intercepts the data from the sensors in order to obtain the data for each sensor. Subsequently, the decoding program is employed to convert the IEEE-754 data format to a floating point type. Subsequently, the decoded data is subjected to two thresholding operations, the objective of which is to exclude erroneous data and to complete the sequence. Following this, the data is aggregated to display the waveforms, utilizing the waveform graph control. Concurrently, the aggregated data is stored.

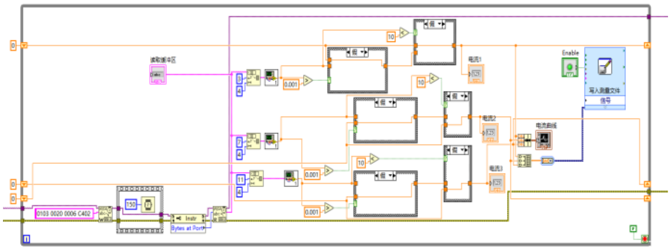


Fig. 5. LabVIEW Program Interface

4. System testing

4.1 Data acquisition

The data acquisition experiments were conducted at the Engineering Training Centre of Qiqihar University, and Figure 6 illustrates the location of the data acquisition site. The CKA6150 CNC machine tool was selected as the apparatus for data acquisition. The machining parameters of the CNC machine can be adjusted to obtain different states of the machine, and in this data acquisition process, four states were selected for analysis, including the normal machining state and the three states of spindle speed abnormality, depth of cut abnormality, and feed abnormality (Wu, Z et al.2024).

Table 1 lists the simulation parameters for the various states. A cylindrical cast iron with a diameter of 60 mm was used as the simulated workpiece for machining purposes. The data for the normal state are set according to the operating experience of the field staff. The spindle speed abnormality comprises two distinct cases, namely an excessively high and an insufficiently low speed. Both of these scenarios have the potential to negatively impact the surface quality and precision of the workpiece. In the event of an increase in the depth of cut, the cutting force experiences a notable surge while the spindle speed and feed remain constant. This results in an increase in the vibration amplitude of the machined workpiece, which has an adverse effect on the quality of the machined surface. Conversely, a decrease in the depth of cut does not typically impact surface quality. In the simulation of an abnormal feed rate, the feed rate is set to twice the normal rate, resulting in a significant increase in the cutting force when cutting the workpiece (X, C et al. 2018).

Tab. 1. Parameters of different simulation states of CNC machine tools.

CNC Machine Status	Spindle Speed (r/min)	Feed Rate (mm/r)	Depth of Cut (mm)
Normal state	500	0.2	1
Abnormal spindle speed	200	0.2	1
	1000	0.2	1
Abnormal depth of cut	500	0.2	2
Abnormal feed	500	0.4	1

4.2 Data analysis

The temperature data presented in Fig.7 illustrate the variations observed across different channels. The four channels, designated as NO, AF, DA, and RA, correspond to the normal state, feed abnormality, depth of cut abnormality, and rotational speed abnormality, respectively. The temperature data exhibits distinctive characteristics associated with different states. As illustrated in the figure, the temperature of a given component may vary across different states. Figure 7(a) illustrates the temperature data of the main motor of the machine tool in a normal state. During this state, the machine tool's power is within the normal range, heat generation is relatively low, and the temperature monitored by the sensor is approximately 25°C. In the abnormal state, the temperature of the motor rises due to an increase in the power of the machine tool and a corresponding change in the measurement of the motor temperature resulting from the use of different cutting parameters in different states. This allows the temperature data to be used to determine the state in question.

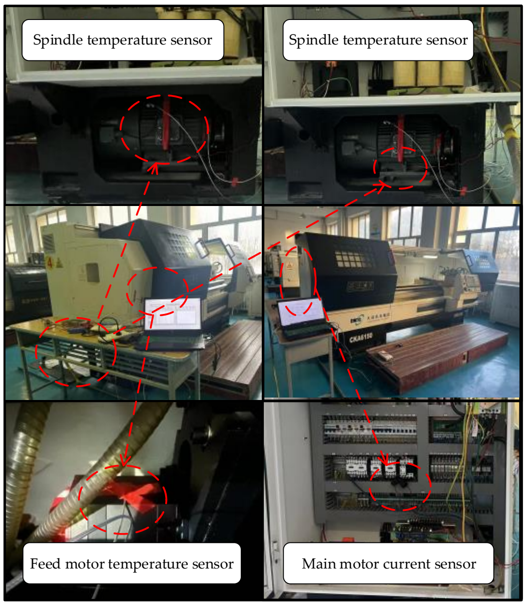
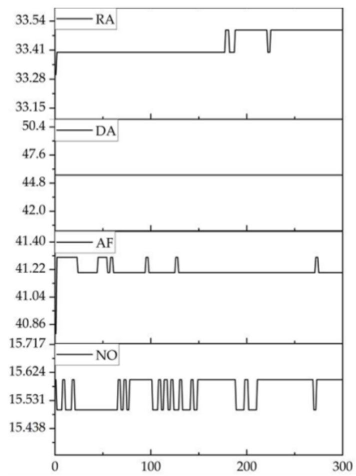
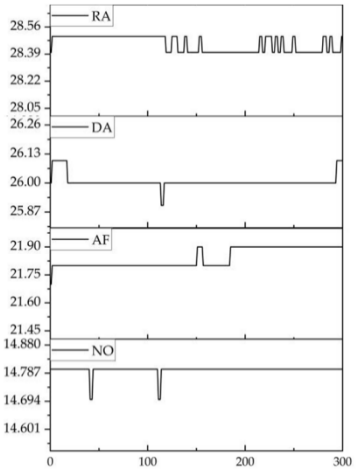


Fig. 6. Field data acquisition

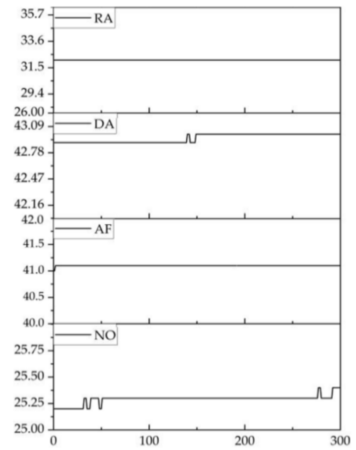
Fig.7 illustrates the six data channels in their normal state. Following data processing, the different channels are aligned with each other. During the machining process, the normal state is divided into three cycles, with each cycle cutting a layer of cast iron. As the machining time increases, the temperature rises slowly. The current data undergoes periodic changes. During machining, when switching the machining process, the current data changes accordingly (Yue, C et al. 2023).



(a)



(b)



(c)

Fig. 7. Temperature data analysis **(**a) Main motor (b) X feed motor (c) Y feed motor

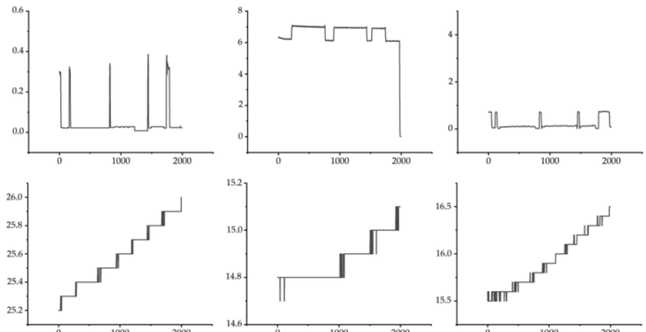


Fig. 8. Capturing data

6. Conclusions

This study proposes a LabVIEW-based monitoring system for CNC machine tools. The upper computer program is designed using LabVIEW and includes functions such as data display and data storage. A multi-channel acquisition card is used to facilitate multi-channel and diverse data collection. Communication between the upper and lower computers is achieved through the serial port. The system was tested on the machine tool, with data collected from six channels. This data is analyzed to identify differences in temperature and current readings across different operational states. The results validated the system's efficacy and practicality, providing data support for subsequent fault diagnosis and offering theoretical insights and technical guidance for the development of similar monitoring equipment.

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