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ORIGINAL ARTICLE

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The design of a single-chip tool monitoring system for on-line turning operation

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Abstract Tool condition monitoring systems play an important role in a FMS system. By changing the worn tool before or just at the time it fails, the loss caused by defect product can be reduced greatly and thus product quality and reliability is improved. To achieve this, an on-line tool condition monitoring system using a single-chip microcomputer for detecting tool breakage during cutting process is discussed in this paper. Conventionally, PC-based monitoring systems are used in most research works. The major shortcoming of PC-based monitoring systems is the incurred cost. To reduce costs, the tool condition monitoring system was built with an Intel 8051 single-chip microprocessor and the design is described in this paper. The 8051 tool monitoring system uses a strain gauge for measuring cutting force; according to the force feature, the tool monitoring system can easily recognize the breakage of the cutting tool with its tool breakage algorithm. The experimental results show that the low-cost 8051 tool monitoring board can detect tool breakage in three successive products successfully.

Keywords Tool condition monitoring · Tool breakage · Quality and reliability · PC-based monitoring system · Single-chip microprocessor

1 Introduction

Tool condition monitoring has become a popular topic in the development of industrial automation. Many universities and research institutes are devoted to this study. In a competitive industrial society, the key to survival is to be the first group to achieve total automation. Within the current trend to automate manufacturing processes, the development of automatic detection systems of cutting tool breakage and wear has become an important area, and is currently in vogue. Cutting tool breakage is an especially serious and urgent event that demands immediate detection and recovery, without which a huge amount of defective workpieces may flow into the subsequent production process, leading to both poor product quality and increased difficulties in product management.

Cutting tool breakage greatly affects the accuracy of manufacturing surfaces. Moreover, in response to the recent trend toward manufacturing process automation, many researchers have focused their research on the development of methods for on-line monitoring of cutting tool breakage [1, 2, 3, 4]. In the area of on-line measurement, Lan [5] and Emel [6] take advantage of acoustic emission to detect cutting tool breakage; Altintas [7], Lin [8] and Tseng et al. [9] use the signals of cutting force to monitor the cutting tools; Altintas [10] further attempts to predict the magnitude of cutting force by monitoring the electric current of the servo motor, in addition to using the signals of cutting force; whereas Matsushima [11] and Chen [12] use the electric current of the spindle motor to predict the cutting tool breakage.

In the area of signal processing, taking into consideration that time domain signals are difficult to process, the often-used signal processing methods are: (1) FFT [13]: transform time domain signals into their discrete Fourier transforms and then use the discrete Fourier transforms to extract the specific features of the underlying signals. (2) Wavelet transforms [14]: transform the time domain signals into Wavelet coefficients and use these coefficients as the basis for extracting the specific characteristics of the underlying signals. (3) Time Series Analysis [15]: include Auto Regressive (AR), Moving Average (MA) and Auto Regressive Moving Average (ARMA). For example, Wu [16] uses AR and ARMA models to process the cutting and vibration signals; Pandit [17] uses AR and ARMA methods to apply on

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the wear of cutting tools. Dornfeld [18] further explores the wear of turning lathe using AR model and neural network methods. In recent years, fuzzy logic, genetic algorithms, expert systems, fractals, and chaos theory have all been employed as tool monitoring methods [19]. Artificial intelligence is likely to be another future direction in automatic monitoring.

The last step of various monitoring systems is to perform the processed data collected via experimental or on-line measurements. The cost and robustness of various PC-based monitoring methods pose important problems for the implementation of these procedures. To overcome these problems, one can apply mature single-chip technology to finish the tasks and approach the real-time function. This research focuses on the turning lathe on-line cutting tool monitoring single-chip technology as a low-cost, feasible method. In a nutshell, under our approach, the cutting tool breakage recognition rules are stored in an 8051 single-chip. This cutting tool monitoring equipment uses a strain gauge type sensor to detect the cutting force, then the signals are amplified, filtered, converted from analog to digital, and finally uses the 8051 software program to infer the cutting conditions based on changes in the cutting force and send warning signals on a timely basis, so that operators can take immediate action to avoid serious losses from the occurrence of tool breakage.

2 8051 Single-chip tool monitoring system

Based on the machine tool operation methods, the 8051 single-chip tool monitoring system can be designed to execute 3 working models.

Data acquisition system Under this model, the 8051 single-chip tool monitoring system is a 12-bit data acquisition system with a data sampling rate as high as 100 KHz. This system has a pre-amplifier with an input resistance as high as 10^8 Ω and gain set to be 1–200, and a differential amplifier with gain set to be 1–400 to construct a signal amplifying system with a final gain of about 1–80,000; a 45 Hz low-pass filter; a 12-bit high-speed AD converter (AD1674) that has a sampling maintenance function with maximal conversion time = 10 μs; a RS-485 interface consisting of SN75176IC to be put on-line with the main control station. The real-time cutting data of the many tool machines in the shop floor can be transmitted to the PC main control station via the network interface to facilitate the monitoring and the immediate handling of any emergencies.

Stand-alone alarm mode The 8051 system does not have the network function under this model. After the cutting force data for a particular tool has been collected, the 8051 system determines breakage based solely on the tool breakage recognition rules stored in ROM, not on the PC of the main control station. The advantage is that it is a simple system with a simplified circuit. The disadvantage is that this 8051 system does not have sufficient hard drive to store the cutting data. Once the cutting tool is replaced, the cutting data associated with the previous tool is gone.

Combined model The 8051 system can determine breakage on its own. When there is a major tool breakage, 8051 can automatically submit the Programmable Logic Control (PLC) command to shut down the machine and avoid the subsequent damages. With the RS-485 network to transmit the data back to main control station, the workers in the main control station can monitor several dozen machines and reduce the need of workers on the shop floor.

3 The analysis of the turning monitor theory

In the cutting process, the cutting force is the resultant force for overcoming the deformation and deformation resistance. This is a complementary force with the same amplitude but with the opposite direction and acting separately on the tool and workpiece. The cutting force F can be separated into 3 forces: the main cutting force, F_v, the thrust force F_p, and the feed force F_f, which are orthogonal to each other.

F_v is in the direction of cutting, the same direction as the cutting speed v_c.

F_p is associated with the chip thickness before the cut.

F_f is in the direction of feedrate, the same direction as the feedrate f.

The cutting force, thrust force and feed force are shown in the following equation together with their resultant force F, and the relationship between variables.

$$F = \sqrt{F_V^2 + F_p^2 + F_f^2}$$

where

$$F_p = F_r \cos \kappa_r \quad F_f = F_r \sin \kappa_r \, . \tag{1}$$

Main cutting force F_v is the largest, F_p and F_v are smaller under most circumstances. Depending on the geometry of the cutting tools, wearing condition and cutting volume, the ratio of F_p and F_f to F_v can vary a great deal [$F_p = (0.15{\sim}0.7)F_v$, $F_f = (0.1{\sim}0.6)F_v$].

3.1 The tool wear mechanisms and patterns

In the cutting process, the material of the cutting tool is gradually worn out, which causes the change of the original tool shape. This phenomenon that the cutting tool slowly loses the ability to cut is called tool wear based on the ISO international standard. The mechanisms of tool wear can be categorized into 8 types: adhesive wear, abrasive wear, diffusion wear, erosive wear, corrosive wear, fracture wear, phase wear and oxidized wear. The patterns of tool wear have 3 types: flank wear, crater wear and nose radius wear. The process of tool wear can be divided into initial wear, normal wear and accelerate wear stages. These known tool wear patterns will be used to make judgments for monitoring cutting tools.

3.2 The monitoring methods of tool condition

There have been many methods developed to monitor tool wear on-line directly or indirectly in the recent 20 years [1]. Methods that directly monitor the tool condition include optical scan, the analysis of the radiation of the chips, the measurement of the electric resistance between the tool and the workpiece, the measurement of the change of workpiece size, the measurement of the distance between the tool and the workpiece, etc. Methods that indirectly monitor the tool condition include the measurement of the cutting temperature, the measurement of the signals of the acoustic emission, the measurement of the consumption power of the axial motors, the measurement of the vibration, and the measurement of the cutting force. It is more practical to use the indirect monitoring methods.

In addition, if several signals from the indirect methods can be combined to determine breakage, the accuracy of the monitoring can be greatly increased. Cutting force is very sensitive to tool wear. When the cutting tool is no longer sharp due to wear, the cutting force increases; whereas when the tool breaks, the cutting force is reduced because the cutting depth suddenly decreases. Thus, it is easier to detect the failing cutting frequency if cutting force is used to monitor the tool wear and breakage. Furthermore, this monitoring method is less susceptible to the interference from the manufacturing system and also gives a higher signal to noise (S/N) ratio. The measured signals will hence be more efficient and reliable. In this study, the cutting force is used to monitor the condition of the cutting tool wear or breakage.

3.3 Tool status recognition rules

In the various types of cutting process, besides the many variables including different cutting conditions, tool shapes, the geometry of the appearance of the workpieces and the conversion of the manufacturing conditions, the monitor recognition rules often fail due to some unpredictable behavior of the tool. Thus, the recognition rules often involve statistics for prediction purposes. The often-used methods in research are fixed limits, stepped limits, floating limits, area technique, cutting pattern recognition of the abnormal cutting, wear estimators and monitoring patterns of neural networks, among which some methods have been successfully applied to individual manufacturing procedures [20]. The applicable areas of the different tool condition recognition rules are summarized as in Table 1 [21].

4 The structure of the on-line tool monitoring system

Factories often give up the use of automated monitoring systems when taking the cost into consideration. Nevertheless, the development of technology has made the automated monitor system more feasible. The key to applying a monitoring system successfully is not the technology itself, but how to reduce the cost by using the fewest sensors and the most general electronic components to provide the functions of the monitoring system. In this research, a low-cost yet powerful single-chip monitoring system is developed, demonstrating that the automated monitor system is feasible in practicality.

4.1 Tool monitoring system design specification

1. Design specification
2. Follow the specification design the circuit hardware
3. Sensor selection
4. Signal processing (including amplifier, filter, A/D converter, noise control)
5. Tool breakage recognition rules
6. Software programming
7. On-line testing

4.2 Experimental equipments and tools

1. HP3245A signal generator
2. SS-5710 analogy oscillator (60 MHz)
3. Fluke 8840A potentiometer with 4 and half digital display
4. HP3562 dynamic signal analyzer
5. TEAC RD-145T signal acquisition
6. HP-7750 Plotter
7. Personal computer (Pentium II)
8. Deemax PICE52 8051 on-line simulator
9. Laboratory designed single-chip monitoring printed circuit board
10. Shop floor turning lathe (T10 line) for testing
11. Power-100 general purpose program writer
12. Deemax general purpose single-chip tester

Table 1 The applicable tool status recognition rules

Software techniques	Overload	Breakage	Wear	Gap eliminate	Missing tool
Fixed limits	Best	Good	No	Best	Best
Stepped limits	Good	Good	Good	No	No
Dynamic limits	Best	Good	No	No	Good
Area technique	No	No	Best	No	Good
Pattern recognition	No	Best	No	No	No
Wear estimator	No	No	Best	No	No

4.3 Designs and calculation of tool monitoring system

1. Sensor type: strain gauge with input: 0–400 Kg and output voltage: 0–20 mV.
2. Pro-amplifier: AD624 instrument amplifier with magnify rate: 1–1000.
3. Low pass filter (LPF): 2nd order active filter with cut frequency: 45 Hz and 12 dB/oct.
4. Analog to digital converter (ADC): step comparison type AD1674 chip with sampling rate: 100 kHz (max.) and A/D resolution (12 bits): 2.44 mV.
5. RAM: 62256, 32 kbyte SRAM capability (this enables the cutting tool to record 10,000 data packets with max. 20 kbyte).
6. ROM: 27512, 64 kbyte EPROM for system expansion.
7. PLC terminal:

In: with Counter Reset, Cycle Start and Trigger Signal: PLC 24 V and PLC GND.
Out: Stop signal and Material feed signal.

8. Light display: Cutting force magnitude display, PLC-Cyc display, PLC Reset display, PLC-Trigger display, Sensor OK display, and yellow and red warning display.

4.4 The structure of the single-chip tool monitoring system

The single-chip tool monitoring system can be divided into sensor circuit, signal amplified circuit, filter circuit, A/D circuit, I/O circuit, display signal circuit, communication circuit, CPU circuit, electric current circuit, and software programs. The system structure is shown in Fig. 1. The hardware circuit of the single-chip tool monitor is shown in Fig. 2. The function of each device is described as follows.

4.4.1 The flowchart of the circuit signal

The signal of turning force detected by strain gauge is line-shielded and transmitted to the pre-amplifier (AD624) to amplify the signal 200-fold, then passed to the differential amplifier to remove the offset voltage and amplify 100-fold, and subsequently passed to the 45 Hz LPF to filter the noise signal of high frequencies. At this point, the signal is separated into 2 parts. One is sent to LM3914 for the instant signal display monitor, the other is sent to AD1674 (A/D converter) to convert the analog signal to a 12-bit digital signal. Under normal circumstances, the 8051 cannot process 12-bit data because it is an 8-bit microprocessor. The 12-bit signal needs to be converted into the high 8-bit (D11, D10, D9, D8, D7, D6, D5, D4) and the low 4-bit (D3, D2, D1, D0, X, X, X, X) and separately sent to 2 unidirectional buffers 74244IC. Then, the 8051 will control the bidirectional buffer 74245IC to read in or write out the data.

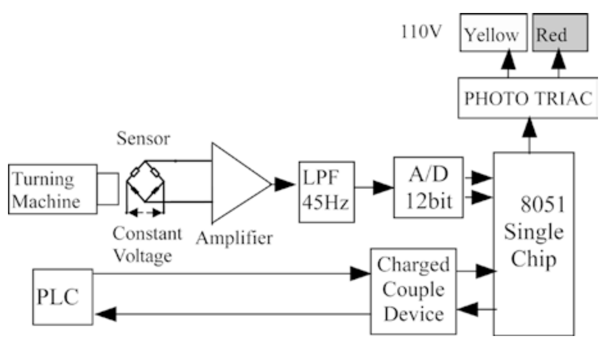


Fig. 1 The diagram of the cutting tool monitoring system structure

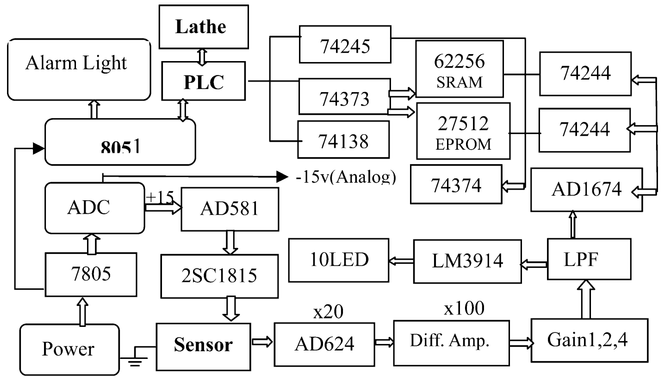


Fig. 2 The hardware circuit of the on-line monitoring single-chip

The function of 74373IC is to handle the address latch. The P0 of 8051 is a data PORT as well as an address PORT (D0, D1, D2, D3, D4, D5, D6, D7) (A0, A1, A2, A3, A4, A5, A6, A7), which needs the address of the latch to separate the address and the data. The 62256 is a 32 Kbyte data memory that stores the cutting tool data, the 27512 is a 64 Kbyte program memory that stores the code of the program, and the 74138 is an address decode IC.

4.4.2 The input PLC signals

Counter Reset	PLC-Reset, 24 V Signal
Cycle Start	PLC-Cyc, 24 V Signal
Trigger	PLC-Trigger, 24 V Signal

4.4.3 The output PLC signals

Stop operation	PLC-Stop, 24 V Signal
PLC raw material feed	24 V Signal

4.4.4 Warning display

Yellow light flashed	cutting tool wearing, warning only without stopping (AC 110 V)

Red light flashed	cutting tool breakage, sent emergency stop command simultaneously (AC 110 V)

4.5 The recognition rules of tool breakage

This research uses the Moving Average (MA) method to analyze the cutting signals. Under normal cutting conditions, the maximal cutting force increases slightly with the number of the cut workpieces. When tool breakage happens, the maximal cutting force will suddenly drop by 5% or even more. Thus, one can use 22 First In First Out (FIFO) values to reach the breakage recognition. In the breakage recognition, the maximal cutting force of the most recently cut workpiece is stored in BUF[0], skipping the next 5 maximal forces of 5 workpieces, then the data is compared with the average value of 16 values of BUF[6] to BUF[21]. If the ratio is within $1 \pm 5\%$, the BUF[0] of the workpiece is considered normal. If the ratio of BUF[0] to {BUF[6] + ... + BUF[21]} is bigger than $1 \pm 5\%$, it is then considered a tool breakage.

The FIFO of the maximal cutting force has a total of 22 values, which represent the maximal cutting forces of the 22 consecutive workpieces. The values of the FIFO change continuously. For example, after the 421st workpiece is cut, BUF[0] represents the cutting force of workpiece 421, BUF[1] represents the cutting force of workpiece 420,..., BUF[21] represents the cutting force of workpiece 400. Correspondingly, after the 422nd workpiece is cut, BUF[0] represents the cutting force of workpiece 422, BUF[1] represents the cutting force of workpiece 421,..., BUF[21] represents the cutting force of workpiece 401.

4.6 The program flowchart of the tool breakage recognition rules

As shown in Fig. 3, the tool monitor program flowchart, once the system is turned on, it will immediately execute the watchdog program that continuously clears the timer. If the system functions normally, the timer will not overflow, otherwise, if the system is shut down by any unknown reason, the system will not clear the timer and lead to overflow. Upon restart, the watch dog program will re-execute itself automatically.

The detailed flowchart of the tool monitor program is shown in Fig. 4. When the signal of PLC_Trigger is sent to the 8051, it will execute the service program of Outer_Iinterrupt_1, which handles the sampling job of A/D conversion. Meanwhile, this service program will also activate the Timing_Interrupt_2 service program, which terminates every 1 ms, i.e., the Timing_Interrupt_2 service program is executed every 1 ms to do the A/D conversion. The Timing_Interrupt_2 service program will do 8 instances of A/D conversion. With the 2 top and 2 bottom outliers removed, the mean is calculated from the middle 4 values. This value is one of the 1024 data points of the A/D conversion. Once the Outer_ Interrupt _1 service program completes the 1024 points of the A/D conversion, which is exactly one cutting force distribution point of a workpiece and takes around 1 s, the maximal value of the 1024 points can be calculated. This 12-bit $F_{\max}$ value is then ready to be sent to the FIFO of BUF[22]. Based on the values of FIFO, one can determine whether there is tool breakage.

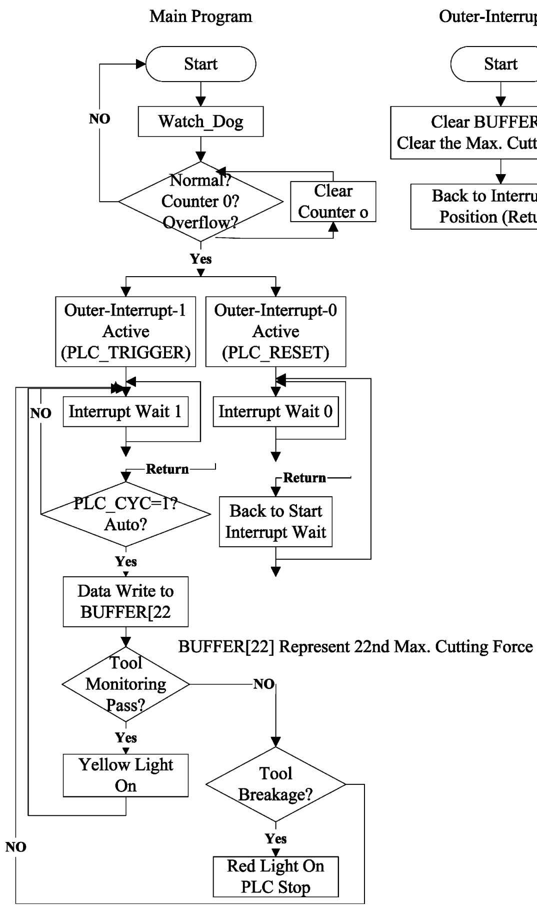


Fig. 3 Tool monitoring program flowchart

If the cutting force signal is recognized as a micro-breakage, the 8051 will send out a signal to flash the yellow light as a warning. If the cutting force signal is recognized as a major breakage, the 8051 will flash the red light as a warning and send out a command to the charge coupled device (CCD) to be converted to a 24 V PLC_Stop that shuts down the machine.

When the program returns to Outer_Interrupt_0, if PLC_Cyc = 1, which means the machine is in automatic mode, the maximal cutting force can be saved in FIFO (BUF[22]); if PLC_Cyc = 0, it means the machine is in manual mode and the maximal cutting force data will be discarded. Furthermore, when the Reset signal of PLC enters the 8051, the Outer_Interrupt_0 service program will be executed, which clears the FIFO and removes all signal data of maximal cutting forces.

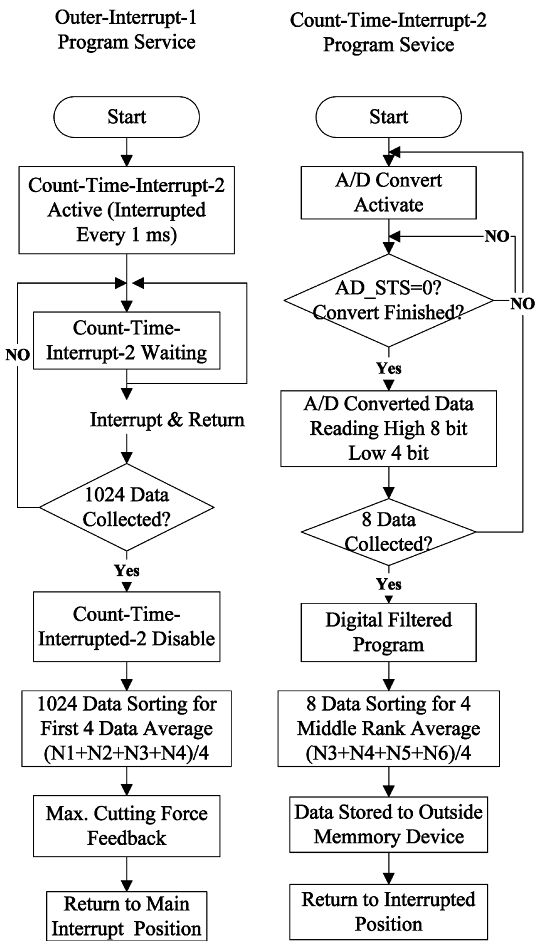


Fig. 4 Detail flowchart of the tool monitoring program

5 The design of the components of the on-line tool monitor system

The structure of the tool monitor system can be divided into (1) sensor circuit, (2) amplifier circuit, (3) filter circuit, (4) A/D circuit, (5) I/O circuit, (6) light signal circuit, (7) communication circuit, (8) CPU circuit, (9) power supply circuit, and (10) reset circuit. The design of the components of the system is briefly described as follows.

5.1 Detection, amplification and filter circuits

The detection circuit of the tool monitor is driven by a constant voltage 10 V or 12 V. Due to the condition that the resultant change of a small cutting force will be even smaller, and the fact that the detector cannot be placed at the cutting position of the tool, the constant voltage power has to be very stable (as much as 12.000 V) to eliminate major measurement errors. Thus, one cannot use the 12 V power directly from the power supply. Even the often-used 7812 constant voltage IC is not suitable because its temperature coefficient is relatively high. The error will not be negligible based on the standards of the detection circuit. A reference voltage IC is the best choice to obtain precision, stability and a constant voltage power nearly free of temperature fluctuation.

Due to the reason that the output signal of the detector obtained from indirect measurement is very weak, an amplifier is needed to appropriately amplify the weak signal. The signal amplifier should have features like low noise signal, zero drift, high precision, wide frequency band, high input resistance, and low output resistance. High-precision sensor circuits, especially like the electric bridge, demand the above qualities. In the process of amplification, filtering, elimination of noise, gain control, resistance adaptation, etc., need to be performed to increase the signal quality. Theoretically, a differential amplifier can eliminate common mode noise and be applied to the amplification of the voltage gain of the electric bridge. However, research shows that when the measurement signal is very small, a differential amplifier consisting of one OP amplifier can easily cause load effect due to low input resistance and signal voltage decline.

$$\left(V_s \frac{R}{R+r}\right) \tag{2}$$

where V_s is signal voltage, R is amplifier input resistance, and r is signal resistance

To reduce the amount of deterioration, R has to be increased, i.e., to increase the input resistance. Thus, the small signal differential amplification circuit (instrumental amplifier) with high input resistance is the best choice.

Although the pro-amplifier (instrumental amplifier) can remove most common mode noise, the residual noise passed through the instrumental amplifier can generate so-called "normal mode noise", which is amplified in each following amplification step. This type of noise is mostly high-frequency signals, which are the major contributor of errors. To increase signal precision and S/N ratio, a low-pass filter can be used to filter the high frequency noise. One needs to be cautious that the filter does not remove the useful high-frequency signals together with the high-frequency noise. The appropriate control is subject to the characteristics of signals. The function of a low-pass filter is basically to allow the passing of electronic signals lower than the cutoff frequency, f_0, and to remove the signals higher than f_0.

The tool monitor systems described in various articles often use several Hz or several tens of Hz as the cutoff frequency. This research uses several groups of different cutoff frequencies of low-pass filters (LPF) for testing to choose the best frequency. The result shows that a LPF around 45 Hz has the best effect on removing high frequency noise. We thus designed a 45 Hz two-step low-pass filter that has a deterioration characteristic of 12 dB/Oct. above the cutoff frequency. One needs to be more careful in selecting the capacitance of a low-pass filter than selecting the resistance. The usual strategy is to select capacitance first and then select the resistance. The current leakage of capacitance may not be too large in order to maintain the stability of capacitance.

5.2 The program design of A/D conversion

There are 4 types of common A/D conversion programs: continuous conversion, polling, constant time sampling and interruption. It is usually most convenient to use continuous conversion for A/D control, but the conversion speed of the AD1674 chip is as high as 100 KHz. If continuous conversion is adopted, the data collected in one second can be as much as 200 Kbytes, which is beyond the capacity of the 8051. The polling design is simpler and the program more reliable, except that the efficiency is quite poor with most of the processing time of the single-chip consumed on polling, which is not suitable for our single-chip tool monitor system. The constant time sampling method is usually applied to slow-speed A/D chips. To ensure the conversion is completed precisely, the delay time has to be properly extended, which makes it slower than the polling method; it is likewise not suitable for our single-chip tool monitor system. The monitoring process is in a "waiting" mode in the 3 methods described above, which leads to poor CPU efficiency. The interruption method is usually chosen if efficiency is the design focus. In this method, once the CPU lets CE = 1, $\overline{CS} = 0$, $R/\overline{C} = 0$, A0 = 0 which activates the A/D 12-bit conversion, the CPU can subsequently handle other procedures like executing the main program. Once A/D conversion is completed, the STS port of AD1674 can activate the interrupted port of single-chip 8051 $\overline{INT0}$ or activate $\overline{INT1}$. Following the time that the CPU accepts the interruption, the data can be read in. If we let CE = 1, $\overline{CS} = 0$, $R/\overline{C} = 1$, A0 = 0, the high 8-bit D11D10D9D8D7D6D5D4 is read, whereas if CE = 1, $\overline{CS} = 0$, $R/\overline{C} = 1$, A0 = 1, the low 4-bit D3D2D1D0xxxx can be read in. The 8051 and AD1674 can be processed simultaneously to gain efficiency.

5.3 The program design of sampling

This research combines the continuous conversion, polling, constant time sampling and interruption methods described above. First, the 8051 performs the constant time sampling every 1 ms with the sampling rate = 1 kHz for about 1 s and samples 1024 points for each workpiece. The cutting time of cutting-in and withdrawing of the turning operation only requires approximately 0.5 s, so the design can thus obtain the complete wave figure of the cutting force change. This single-chip activates one interruption every 1 ms and the interruption program continuously converts 8 values in 1 ms. The 8 values are processed by polling for each conversion. Polling is not subject to an efficiency problem here because the conversion speed of the AD1674 is very fast, requiring approximately 10 ms. To convert 10 values takes only 100 ms with 900 ms left for data reading and digital data filtering.

To reduce the effect of interference signals on the sampling values and to increase the reliability of the sampling data, the sampling values need to be processed with a digitized filter. There are many types of filtering methods, such as the limit speed filter and limit amplitude filter used in the program determination method, mean value filter, arithmetic average filter, sliding average filter, etc. This research adopts the combined average filter method that can eliminate the pulse interference. The maximal and minimal values of continuous sampling for N times are discarded and the arithmetic average is calculated from the remaining $N-2$ sampling values. This method can filter the pulse interference as well as the small random interference. The 8 A/D values are sorted to discard the maximal and minimal values and the average value is obtained to avoid the pulse interference. If the sampling rate is = 1 kHz and there are 1024 sampling points, it is like sampling 1 point every 1 ms, the total sampling time being 1024×1 ms = 1.024 s; within each sampling point, 8 points are sampled continuously in 1 ms (requiring 80 μs). The 8 values are sorted to discard the top 2 and bottom 2 values, the average is calculated from the remaining 4 values $N = (N2 + N3 + N4 + N5)/4$. In fact, the total sampling points are 1024×8 points. Since only 1 value is derived for every 8 points, the total sampling points are 1024 (only 1 data instance for every 1 ms).

5.4 Cutting force and sensor circuit

The strain gauge has a limitation of force that it can withstand. For it to be used as the sensor device and to avoid any damage of the sensor structure when too much force is applied during installation, the sensor light has to be incorporated to assist the operator to tighten the sensor to a functional level. Under normal circumstances, when the sensor is installed to the tool holder, it will generate a voltage of 4 mV~8 mV. After this small voltage is passed through the pre-amplifier (IC: AD624) to amplify 200-fold, the voltage becomes 0.8~1.6 V. Based on this feature, a window comparator that is made of a voltage comparator can be designed; when the voltage equals 0.8~1.6 V, the window comparator will output the high voltage of 1. Because the comparator is an open collector circuit, the output current is too small when the voltage is high, thus, a pull high circuit needs to be installed at the output position, which will light the LED of "Sensor OK" to signal the operator to tighten the sensor.

While cutting, the signal changes in the negative direction. When there is no cutting, the signal is 9 V. When cutting starts, the signal increases in the negative direction. The bigger the cutting force, the smaller the signal voltage will be. The usual sensor light circuits will make the light brighter with higher voltage, thus the sensor light circuit needs to be re-designed. We designed a new sensor light circuit described as follows. First, the LM3914IC divides VR_{Lo} (9 Volts) and VR_{Hi} (1 Volt) into 10 portions equally. If the input signal is higher than 9 V, the 10 LED lights are completely extinguished; if the signal is lower than 1 Volt, the 10 LED lights are all on. When the 8th sensor light (the yellow LED light) is on, that indicates the cutting force is slightly high (around 1.35-fold of normal value); when the 10th light (the red LED light) is on, that indicates the cutting force is too high (around 1.75-fold of the normal value), which may be beyond the tool capacity and will lead to breakage and require attention.

5.5 The design of the communication interface circuit

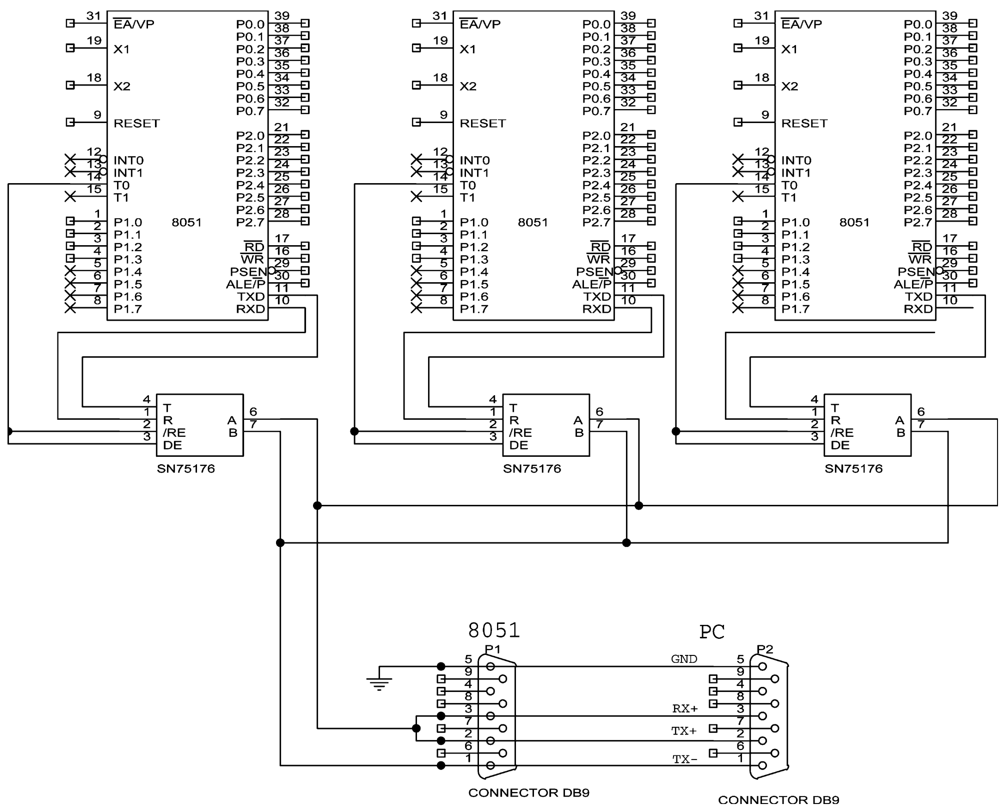
The electric specification standard of RS-232C is limited to transmission rates of 20 Kbps and a transmission distance no larger than 15 m or there will be interference from signal noise. The RS-485 standard has high speed (10 Mbps), long distance (1200 m), and 1-to-many communication standards. Thus, we decided to use RS-485 as the interface to allow several 8051 to be connected to one main control personal computer (PC). If a factory has 32 sets of equipment, this interface can serve the purpose of on-line monitor, i.e., the main control PC can perform on-line real-time monitoring over the running condition of many sets of equipment. Figure 5 shows the on-line monitor circuit of the many sets of 8051 connected to the PC.

Based on the hardware circuit, the DE port and RE port of the 75176 are both connected to the T0 port of the 8051. When $T0 = 0$, there is reception activation; when $T0 = 1$, there is emission activation. The highest baud rate of data transmission is 115,200 baud in a PC. The 8051 serial port can only reach as high as 19,200 baud. One has to be careful in choosing the right baud rate to eliminate the errors of data transmission due to the baud rate being too high.

6 The results and analysis of the experiments

Following the completion of the hardware and software of the tool monitor system, it is taken to the factory to collect the cutting data and the laboratory-made analog circuit tool monitor system (the circuit before entering the A/D chip) is used to collect the cutting signals. The signals are first recorded by a TEAC RD-145T signal acquirer and are analyzed in the laboratory using a PC or an HP-3562 (a motion signal analyzer) to analyze the features of tool breakage. There are many sources of strong noise signals in the factory. It is often impossible to immediately find the best optimization parameters for breakage recognition. The noise interference inside the factory often ruins the results. Thus, the tool monitor is first tested off-line until the accuracy is high enough before it can be used for on-line breakage recognition.

Fig. 5 On-line monitoring circuit of the many sets of 8051 connected to a PC



6.1 The examination method

The functional index of a monitor system includes the precision rate (P) and misjudgment rate (Q). A good monitor system has a precision rate as high as possible and a misjudgment rate as low as possible. The mathematical definition of precision rate and misjudgment rate is formulated as follows:

$$\text{Precision rate } (P)\frac{y-E}{y} \times 100\%$$

where y is the number of actual tool breakage and E is the number of miscount tool breakage by tool breakage monitoring system.

$$\text{Misjudgment rate } (Q)\frac{F-x}{F} \times 100\%.$$

x is the number of actual tool breakage and F is the number of tool breakage judged by the tool breakage monitoring system.

6.2 The experimental methods

Step 1 Tighten the sensor based on the indication of the "Sensor OK" light. When the voltage strength of installing the sensor bolt is in the 5~10 mV output range, the "Sensor OK" light will be on. This light ensures that the installed sensor has a certain stability and will not become unstable from the impact of the cutting force.

Step 2 Adjust the precision adjustable resistance to remove the offset voltage of the sensor and determine the output signal to be approximately 9 V. When adjusting the precision variable resistance to the proper range, the first light of the LM3914 cutting force light display circuit will be on, which means the tool monitor system can start monitoring.

Step 3 When the tool machine is replaced with a new cutting tool, the system is in automatic mode (PLC_CYC = 0). When the PLC_Trigger signal is sent to the 8051, the system starts acquiring the cutting signals of every workpiece. If the reset button of the counter is pushed again, the 8051 will re-record the cutting data of the tool and stop recording when a knife is replaced and the reset button of the counter is pushed.

6.3 The results of on-line testing

The production of outer ring bearings during the month of May was used as the monitoring target for the tool monitor experiments. The monitoring was performed in a 2-week period and the experiments for monitoring and data collection were done on 2 days of each week. The total number of turning operations under complete monitoring was 67,039. The system identified 39 cases of yellow light and red light warnings, among which 16 cases were yellow light warnings. The tool was examined after each yellow light warning and no major defect was found, but in subsequent cutting, the size of the workpiece became larger (0.01~0.13 mm). The intervals of the cutting number between warnings of the system were not constant, showing that the conditions of cutting wear and breakage of tools behaved like a random variable. The recognition parameters were then refined in the monitoring process. The preliminary results of the experiments showed that the precision rate of examining the tool breakage was very high, but the amount of workpiece size which was below minimum quality due to tool wear could not be effectively detected. The latter issue awaits improvement in recognition rules for the tool condition or for the application of the sensor to be enhanced. Using this experiment as an example, if the recognition rules are relaxed, the red or yellow light flashes too often and the rate of misjudgment increases; if the recognition rules are made stricter, then it is quite possible that the detection of breakage will be missed. The testing data of the experiment can be referenced in [21].

7 Conclusions

In the real-world factory, there are various types of noise signals, including high-power motors running, heavy machining, the activation of relays, arc-welding machines, the termination of large machines turning on, 220 V alternating current, electro-magnetic radiation, cutting chips, dust, etc., which makes a factory a very tough environment for electronic circuits. This turning lathe single-chip tool monitor system has accumulated many experiences of failures and the experimental circuits have been modified more than a hundred times to adjust to the environment of the factory. The whole process of the experiment can be concluded as follows:

1. The key to a feasible tool monitor system is the sensor, the recognition rules and the setup of the recognition parameters.
2. So far, the sensor is still the bottleneck of the industrial monitor system. Many monitoring systems with reasonable design, high precision and completed set of recognition rules can not reach the expected efficiency because of the limitations from problems of precision, stability, drifting, or noise signals of the sensor device. The development of micro-electronic-mechanical system (MEMS) will facilitate the success of consolidating the application of sensors.
3. The time taken to develop the tool monitor system consisted of: 20% for hardware, 20% for software development and modification, and the remaining 60% was spent on setting up the system recognition parameters, modifying and testing the system function.

4. The results show that the 8051 can successfully detect the breakage within the 3 workpieces from the time the tool breaks. The size of workpieces below minimum quality resulting from the tool wear still cannot be precisely detected; so the tool condition recognition rules still require improvement and addition of other types of sensors to enhance the detection functions of the system.
5. The signals should be sent via differential transmission to eliminate noise interference; although it is simpler for them to be sent via single end transmission, they are more susceptible to noise signal interference.
6. The temperature drift of carbon-covered layer resistance is high (several thousands of ppm/°C), so the sensor circuit should use the precision metal layer resistance with low temperature drift. The usual standard is 25 ppm/°C, 1% or 10 ppm/°C. We judge 1% to be sufficient. The lower the temperature drift should be, the more the resistance usually costs. One should judge carefully to avoid cost increase.
7. In this research, the strain gauge does not have temperature compensation, which causes the detecting signal to drift as the temperature increases. It is necessary to add a temperature compensation circuit to increase precision.
8. The analog current and the digital current should be separated to avoid the noise signals caused by the digital circuit. These noises can reduce the precision of the analog circuit.
9. The analog ground should not be confused with the digital ground. The two grounds can be connected at a single point in the AD chip to communicate with each other. The shorter the ground and the bigger the trunk, the better.
10. Connecting the analog ground and digital ground randomly will lead to the increase of A/D conversion drifting and the increase of noise signals.
11. Based on Olm's Law (current of 0.1 mA passed through 1 Ω, the voltage difference is 1 mV), nonzero ground resistance will lead to error activation of the circuit. To make the circuit more reliable, the ground should be made as large and wide as possible to avoid the difference of electrical activation between grounds.
12. A same-directional amplifier can absorb the ground noise signals and may cause false input signals. An opposite-directional amplifier uses the positive pole (+) input end to connect to the ground directly. This can be seen as having an infinite input end resistance and makes it almost immune to any noise signals of the ground. We recommend the use of the opposite-directional amplifier when signals need to be amplified.
13. A circuit connected to bypassed capacitance can eliminate the noise interference from outside and can also eliminate the noise signals of the IC itself leaking to the outside.
14. The output signal from the sensor is very weak, which makes it easily susceptible to noise interference. The signal should be closely protected via shielding to avoid the noise signals from entering through the transmission line.
15. A metal shell can isolate the noise interference from a machine power supply, while a plastic shell has no such shielding function.
16. Charge-coupled devices can isolate signals and inhibit noise signals. The main advantage of the charge-coupled devices is that they can effectively inhibit pulse noise signals to obtain better signal quality.
17. If possible, one should use a CMOS device for the IC chip. The gate limitation of interference of a CMOS device is much higher than that of a TTL chip, for example, the 74HC series of CMOS ICs is less susceptible to noise interference than the 74LS series of TTL ICs.
18. The current from the power supply contains a lot of high frequency noise signals and ripples. A π-type of filter should be added to reduce the noise signals and ripples.

Due to the competitive advantage of the low cost of a single-chip, there is a huge market for single-chips in the area of industrial control [or operation research?] and monitoring. In the future development of automation, one can expect the application of single-chips to become widespread. In the past, PC-based products dominated the market. However, the light, thin, and small single-chip products will certainly take over due to their increasingly powerful functions and declining prices.

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