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Development of an Intelligent Milling Tool System

Chih-Cheng Lo,[1] Kuo-Ming Sun,[1] Hung-Ying Chen,[1] Chia-Liang Tseng,[1]
Liang-Yu Lu,[2] Lian-Wang Lee,[2] Wei-Zhen Su,[1] Te-Jen Su,[3] and Chien-Yu Lu[1]*

[1]Department of Industrial Education and Technology, National Changhua University of Education,
Changhua City, Taiwan 500, ROC
[2]Department of Mechanical Engineering, National Chung Hsing University,
No. 145, Xingda Road, South District, Taichung City 40227, Taiwan
[3]Department of Electronic Engineering, National Kaohsiung University of Science and Technology,
Kaohsiung City, Taiwan 807618, ROC

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In this paper, we focus on the temperature sensing and data collection of milling tools during the machining process. The collected data is visualized in real-time dynamic charts using the ThingSpeak platform. In case of temperature abnormalities, users are notified via LINE for inspection or tool replacement. The control system is implemented using a flexible printed circuit board embedded within the concentric cylinder of the milling cutter's handle. The Arduino programming language is used for programming, and temperature measurement is achieved through a K-type thermocouple module combined with an ESP32 microcontroller, utilizing Wi-Fi to transmit data to the ThingSpeak platform for real-time monitoring on computer screens. The system's advantage lies in enabling users to monitor the temperature of milling tools, preventing tool dullness or damage, and improving machining accuracy by reducing the frequency of tool replacement. This system is particularly suitable for milling machines that use cutting fluid. Temperature abnormalities indicate a decrease in cutting capability owing to tool dullness, resulting in increased heat generation during cutting or the insufficient cooling capacity of the cutting fluid with respect to the heat generated during cutting. Such alerts allow timely inspection or tool replacement. However, most modern milling machines come equipped with their own monitoring systems for tool wear and temperature. Hence, in this paper, we primarily focus on monitoring milling tool temperature. The upper-temperature limit for alerting is set at 290 °C on the basis of the expected hardness of tungsten carbide, which is suitable for machining up to this temperature. Currently, a warning temperature of 200 °C is used. This enables users to determine the condition of the tool during operation, ensuring safer use and facilitating better quality control and industrial safety for manufacturers.

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*Corresponding author: e-mail: lcy@cc.ncue.edu.tw

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1. Introduction

Milling machines are high-precision, high-efficiency automated machining equipment. During the cutting process, tool temperature increases with wear, leading to a decrease in tool strength. Cutting generates heat energy, with most of the energy being converted into heat. This results in elevated temperatures of both the workpiece and the cutting tool. Historically, cutting temperature has been calculated on the basis of the average temperature in the cutting zone. Although this provides a qualitative measure of cutting temperature, further research into the distribution of cutting temperature within the machine is needed. One of the most common monitoring methods for CNC machine tools is the installation of overheating protection on the electric motor. However, motors are often located far from the milling cutter, and a significant amount of heat may be generated owing to tool wear before the motor temperature rises noticeably. This makes it challenging to accurately detect tool wear during milling operations. Typically, notifications of tool dullness are only received after issues have arisen, which can lead to wasted time in the machining process. Early warning capabilities could significantly reduce downtime and inconvenience.

In typical tool machining, two primary wear patterns emerge: flank wear and crater wear. Flank wear occurs on the underside of the tool edge, and when it reaches a specified size, it indicates the end of the tool's useful life. The extent of flank wear is measured as the distance between the top of the cutting edge and the bottom of the worn area on the tool's flank. When the width of the worn area on the flank reaches a predetermined limit, the tool is replaced. Crater wear results from a chemical reaction between the workpiece material and the cutting tool and is not considered in this context. Of these two wear patterns, flank wear is the dominant form of tool wear in metal processing. It has been demonstrated that flank wear adversely affects surface integrity, residual stress, and microstructural changes, such as surface hardening. Therefore, flank wear is commonly used as an indicator to assess tool wear. It can be inferred that when flank wear reaches a specified size, the tool has certainly reached the end of its useful life.(1) Thermal phenomena represent a critical concern in metal processing, especially in the end milling of challenging materials. Elevated tool temperatures resulting from thermal effects significantly impact tool wear, tool lifespan, and tool thermal deformation.(2) Furthermore, as milling is an intermittent cutting process, the tool experiences cycles of heating and cooling, which exposes end milling tools to more severe thermal stresses and dynamic heat flux than turning tools. All these thermal effects inevitably exacerbate tool wear, shorten tool lifespan, weaken tool strength, and affect machining precision. It is essential to consider the impact of milling tool temperature on tool strength to optimize machining outcomes.(3) The choice of temperature as the measured parameter stems from the operating conditions of milling tools. Milling tools typically operate at speeds ranging from 360 to 25000 rpm. At such high speeds, any machine or tool holder inaccuracies can lead to vibrations before actual cutting commences, whereas temperature starts to rise only when cutting begins. Therefore, temperature was selected as the parameter to measure. During metal cutting and forming processes, most of the energy consumed in plastic deformation and friction is converted into heat. Dewes *et al.*(4) indicated that tools with wear exhibit increased temperatures. For worn tools, increased surface contact and heightened sliding friction contribute to higher temperatures. Gharibi(5) proposed a correlation between temperature and hardness during machining, facilitating the establishment of temperature threshold warnings based on this comparison.

Different measurement methods have been employed by researchers in the field. Toh(6) utilized IR technology to measure the surface temperature of milling cutters. Similarly, Lazoglu and Bugdayci(7) incorporated an IR thermal imager into CNC machine tools for thermal model verification testing. In Ref. 8, an IR thermal imager was used to study the temperatures during the cutting of aluminum alloy, copper, and stainless steel. In contrast, in Refs. 9 and 10, circuits were installed on the tool holder, modifying the tools to accommodate six-pin connectors, and signal cables were routed to the circuit on the tool holder. Currently, temperature detection for milling cutters and workpieces on milling machines is often performed by IR detection, which is a noncontact thermal imaging method that measures the surface temperature of objects on the basis of the thermal energy they emit. It can be used for temperature measurement (IR thermography), using devices including infrared cameras equipped with infrared radiation-sensitive film cameras, as well as for point measurements (IR thermometers). Compared with thermocouple technology, radiation technology offers several advantages. However, factors such as cabin dust, cutting fluids, and debris interference often lead to the use of K-type thermocouple modules when selecting measurement methods.

Wang *et al.*(11) introduced a novel method aimed at providing insights into thermal damage formation and thermal transfer required to understand the mechanics of cutting. They explained how heat transfer and chip formation change gradually with the gradual wear of the tool's flank. In Refs. 12–15, data adjustment systems were integrated with a wireless transmitter and installed on the tool holder. Thermocouples and their connecting wires were positioned near the cutting edge on drill bits or milling cutters, with reception facilitated by an antenna close to the tool holder. UmutKaraguzel(16) proposed the installation of circuits on the tool holder and the placement of thermocouples at the cutting edge; the thermocouple is connected to the circuit on the tool holder via signal cables. Hence, in this study, we utilize flexible PCBs implanted within the concentric cylinder space in the milling cutter's handle. This approach can be applied to most commercially available tool holders without requiring modifications.

On the basis of the information obtained from the literature,(17) it is observed that the temperature during the aluminum cutting processes of the aluminum alloys 7075-T6 and 6061-T6 ranges approximately from 170 to 426 °C. Under identical cutting conditions, the temperatures in the primary and secondary shear zones of the aluminum alloy 7075-T6 are 12% higher than those of aluminum alloy 6061-T6. This is primarily attributed to the higher inherent hardness of the aluminum alloy 7075-T6, resulting in a greater cutting force required for processing. As mentioned in the literature,(17) the milling tool temperature in the primary processing zone of AL6061 reaches a maximum of 176 °C. When simulating the processing temperature using a welding gun rated at 110 V with a power consumption of 40 W for a continuous 10 min, the highest warning temperature for the milling tool is measured to be 219 °C. Consequently, the actual milling tool temperature during the processing of AL6061 can reach the warning level, achieving the goals of improved processing accuracy and intelligent milling tool warning.

The hardware and software used for monitoring CNC milling cutter temperature in this study consist of an ESP32S development board, a MAX6675 K-type thermocouple module, a wireless charging module, and Arduino software programming.(18) The core of this research comprises the ESP32S development board and the Arduino program. The ESP32 is a series of low-cost, low-power microcontrollers with integrated Wi-Fi and dual-mode Bluetooth capabilities. The ESP32 series utilizes the Tensilica Xtensa LX6 microprocessor, including dual-core and single-core variants, and incorporates features such as antenna switches, RF transceivers, power amplifiers, low-noise receive amplifiers, filters, and power management modules. Figure 1 depicts the model used in this study. The ESP32 series control board is programmed using the Arduino programming language.

2. System Architecture

We will introduce both the hardware and software architectures of the system separately. First, we will discuss the hardware architecture of ESP32, which handles data reception and processing. Next, we will introduce the sensor used for temperature detection, followed by an explanation of the program architecture of the monitoring system. The architecture of the milling cutter temperature monitoring system, composed of ESP32, MAX6675 K-type thermocouple module, Wi-Fi module, and the ThingSpeak platform, is depicted in Fig. 2. After writing the Arduino program using the Arduino IDE editor, the compiled program is uploaded to ESP32 for execution. The temperature-sensing end of the MAX6675 K-type thermocouple module continuously sends signals. When the temperature rises to a preset level, the MAX6675 K-type thermocouple module transmits the data signal to ESP32, enabling real-time monitoring. ESP32, through the MAX6675 K-type thermocouple module, receives and analyzes real-time data. Once analyzed, it is transmitted via Wi-Fi and displayed on ThingSpeak, thus achieving the monitoring function.

2.1 ESP32 Microcontroller

The intelligent sensing milling cutter mechanism is illustrated in Fig. 3. Within the yellow box, ESP32 is combined with a MAX6675 K-type thermocouple module and powered by a

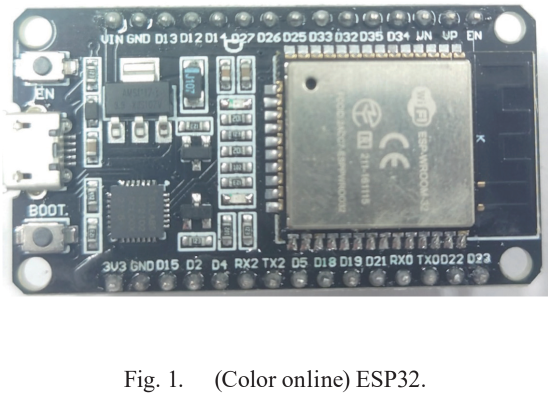


Fig. 1. (Color online) ESP32.

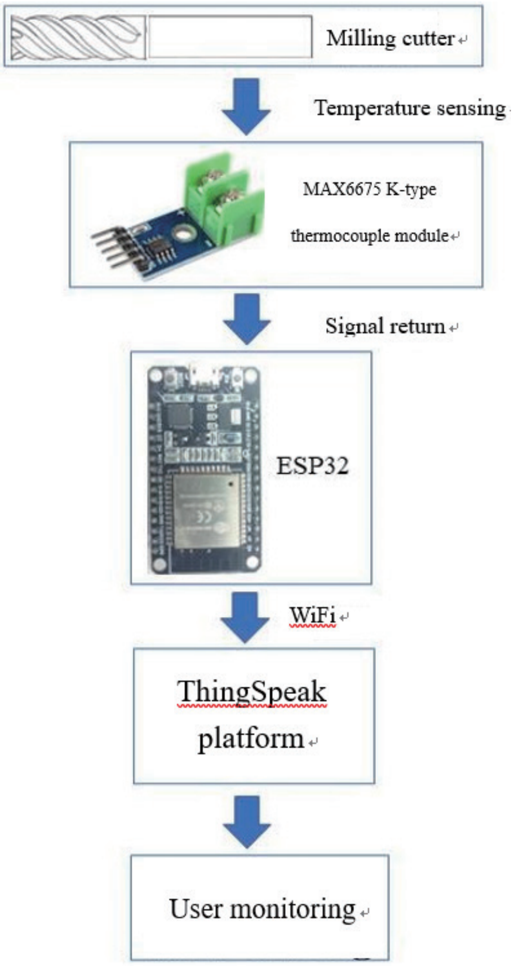


Fig. 2. (Color online) Architecture of intelligent milling tool temperature monitoring system.

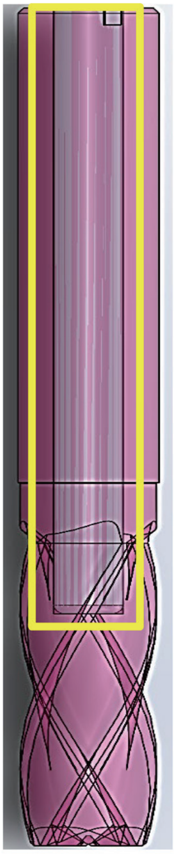


Fig. 3. (Color online) Intelligent sensing milling cutter mechanism.

battery using flexible PCB. This assembly is used to create an intelligent sensing milling cutter, which is a cylindrical rod with a diameter of 6 mm and a length of 72 mm. The MAX6675 K-type thermocouple module is positioned at the contact point with the cutting blade. It continuously measures the real-time temperature of the blade. When the MAX6675 K-type thermocouple module receives temperature signals, it transmits the data back to the ESP32. The data is further transmitted via Wi-Fi to the ThingSpeak platform for dynamic data visualization and monitoring with alerts.

Figure. 4 illustrates a simulation of the intelligent sensing milling cutter mounted on the tool holder. It can be observed that the intelligent sensing milling cutter system is integrated within the milling cutter itself, eliminating the need for mounting the sensing circuitry externally on the tool holder. This internal placement of the sensing system within the milling cutter is optimal because it prevents the possibility of the sensing circuitry being thrown off or misaligned owing to centrifugal forces when the milling cutter operates at varying speeds ranging from 360 to 25000 rpm.

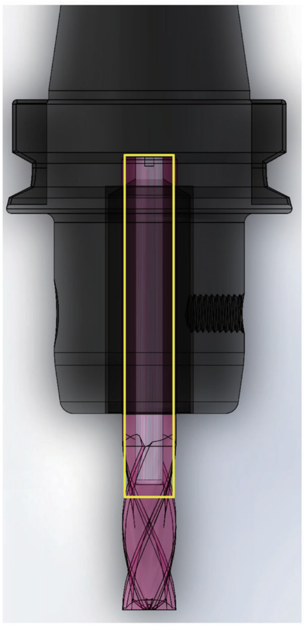


Fig. 4. (Color online) Schematic of intelligent induction milling cutter tool holder clamping.

Table 1 shows a comparison of boards commonly used at present. The selection of the board is based on whether it can fit inside the milling cutter. Therefore, smaller boards are preferred. Although Arduino Micro is smaller than ESP32, it lacks wireless communication capabilities and would require external Bluetooth or Wi-Fi modules. Hence, ESP32 was chosen as the main board for this application. The specifications of ESP32 used in this project are outlined in Table 2, and the pinout diagram is provided in Fig. 5.

In the system architecture, ESP32 plays a crucial role in both data transmission and processing. ESP32 is a microcontroller that is readily available and offers a wide range of operating system choices. Besides the official Espressif Integrated Development Framework (ESP-IDF) extended by the Visual Studio Code, there are other alternatives such as the ESP32 Arduino core for Arduino IDE and MicroPython. ESP32 stands out owing to its built-in Bluetooth and Wi-Fi capabilities, compact size, lightweight, and low power consumption, making it suitable for installation in a confined space within the milling cutter. It boasts excellent expandability, making it the top choice in various aspects. However, for this project, temperature data is in analog form, which ESP32 cannot directly read. Therefore, the MAX6675 K-type thermocouple module is used to convert analog signals into digital ones, enabling ESP32 to read temperature data.

2.2 MAX6675 K-type thermocouple

The sensor employed in this study is the MAX6675 K-type thermocouple module. MAX6675, manufactured by the American company MAXIM, is a K-type thermocouple converter with specifications as outlined in Table 3. It features cold junction compensation, linear correction,

Table 1
Boards commonly used at present.

Name	Size (mm^2)	Bluetooth	Wi-Fi	GPIO	Year of Time
Raspberry Pi 4	85 × 56	Yes	Yes	26-pins	2020
ESP32	55 × 28	Yes	Yes	30-pins	2016
Arduino Uno	53 × 68	No	No	19-pins	2005
Arduino Micro	48 × 18	No	No	20-pins	2019

Table 2
ESP32 specification sheet.

CPU	Xtensa® LX6 32-bit
Memory	320 KiB
Wi-Fi	802.11 b/g/n
Bluetooth	v4.2 BR/EDR/BLE
Storage Capacity	4 MBytes
USB Chip	CP2102
USB Connection Interface	Micro-USB
Number of GPIO Pins	30
Rated Power	3.3 V DC

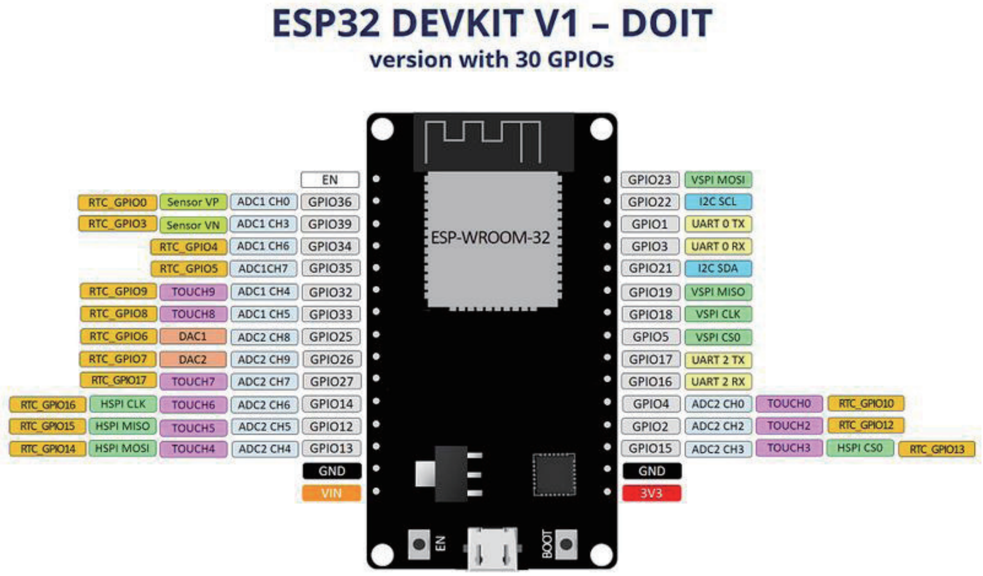


Fig. 5. (Color online) ESP32 pinout diagram.

Table 3
MAX6675 K-type Thermocouple Module Datasheet.

Operating Voltage	DC 3–5 V
Operating Current	50 mA
Temperature Measurement Range	0–1024 ℃
Converter Temperature Resolution	0.25 ℃
Module Dimensions	Approximately 15 × 25 mm^2

and thermocouple break detection, offering a 12-bit resolution. The selection of this module is attributed to the confined space available for sensor placement. This sensor module is compact, lightweight, and can be powered by ESP32.

The program architecture and functionalities of the main program in the intelligent sensing milling tool system are as follows. The system's Arduino program is initially developed using the Arduino IDE editor and then executed by ESP32. An overview of the system's operation can be obtained from the flowchart. The entire system is divided into three main parts, as illustrated in Fig. 6, namely, Sensor Data Acquisition, ESP32 Data Processing, and Wi-Fi Notification. Data processing within the system is handled by ESP32. The required program components are first written and uploaded to ESP32 for execution. Once executed, the sensor collects data, which is then recorded by ESP32. Subsequently, ESP32 transmits this data via Wi-Fi to both ThingSpeak and the user's mobile phone or computer. This enables users to stay informed about the current temperature conditions in real time. The system's architecture diagram aids in defining the design of the intelligent sensing milling tool, whereas the flowchart in Fig. 7 provides insights into the program's operational procedures.

3. Experimental Analysis

This system utilizes a K-type thermocouple temperature sensing module in conjunction with an ESP32 single-chip microcontroller, which is placed in the concentric cylinder inside the milling tool handle to detect temperature. After measuring the temperature using the K-type thermocouple temperature sensing module, ESP32 stores the temperature data and simultaneously transmits it via Wi-Fi to the ThingSpeak platform for data monitoring. This achieves real-time monitoring and alerts while also sending alert notifications through LINE. Since ESP32 cannot directly read analog signals, the MAX6675 K-type thermocouple is used to convert analog signals into digital signals. When using the MAX6675 K-type thermocouple module with the Arduino IDE, the module should be installed first, and then the code can be added to the Arduino IDE for programming. Alternatively, the Arduino IDE library can be downloaded for this purpose. Figure 8 shows the code download for the MAX6675 K-type thermocouple.

The physical setup of this system is depicted in Fig. 9. The MAX6675 K-type thermocouple sensor is powered by ESP32, which is powered by a 5 V rechargeable battery. Real-time data from the ESP32 is displayed on both a computer and a smartphone through the ThingSpeak platform for monitoring the intelligent sensing milling tool temperature rise in real time.

Before writing ESP32 programs using the Arduino IDE, it is necessary to enable the ESP32 functionality within the Arduino IDE to allow for direct writing into the ESP32 MCU. The installation procedure involves configuring the Arduino IDE for ESP32 by selecting the ESP32 board in the Arduino IDE's board manager and installing it. After installation, the Arduino IDE should be restarted, and the program code can then be uploaded to ESP32.

After installation, the Arduino IDE should be restarted, and the program code can then be uploaded to ESP32. Before testing, it is essential to create an account and password on the ThingSpeak platform. Login using the ThingSpeak platform account and password on both your

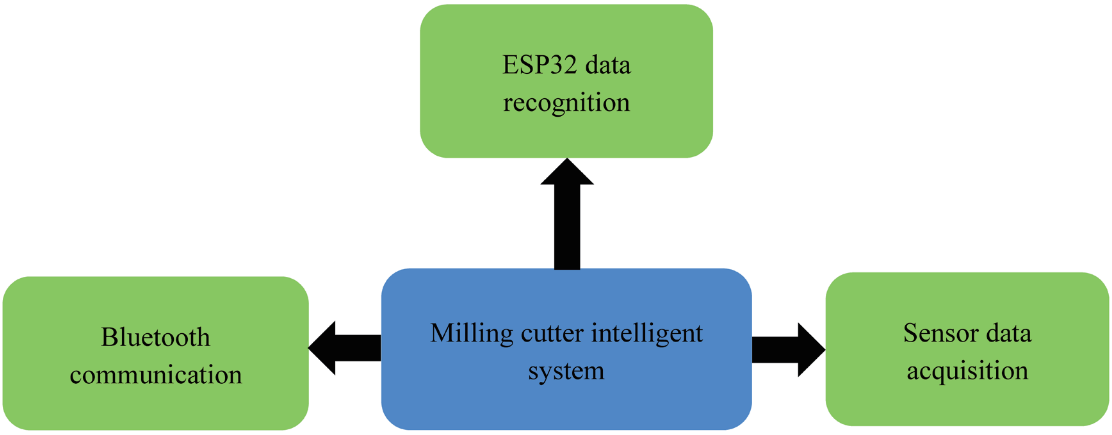


Fig. 6. (Color online) Intelligent sensing milling tool system architecture diagram.

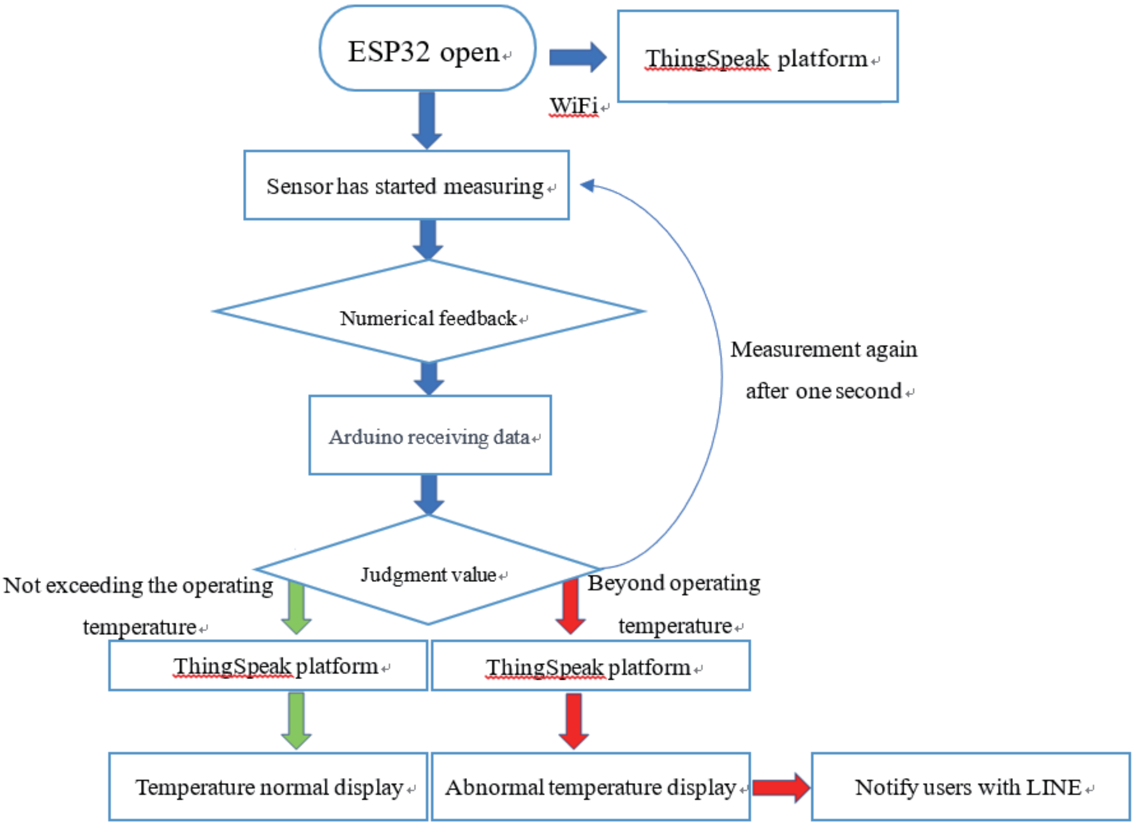
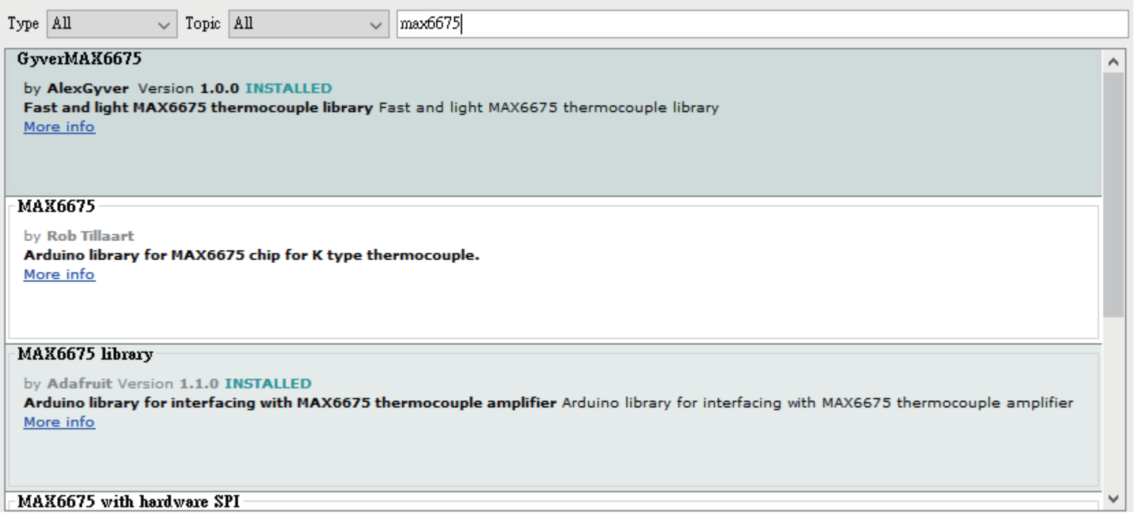


Fig. 7. (Color online) Action flow chart of intelligent sensing milling tool system.



GyverMAX6675

by **AlexGyver** Version **1.0.0** INSTALLED
Fast and light MAX6675 thermocouple library Fast and light MAX6675 thermocouple library
More info

MAX6675

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Arduino library for MAX6675 chip for K type thermocouple.
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MAX6675 library

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MAX6675 with hardware SPI

Fig. 8. (Color online) Max6675 k-type thermocouple module library.

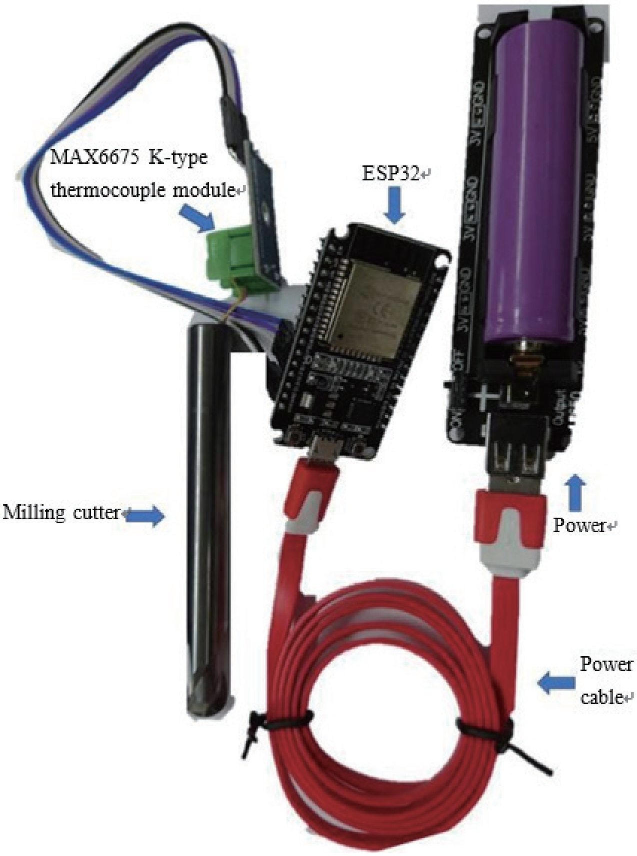


Fig. 9. (Color online) Entity circuit diagram of intelligent sensing milling tool system.

smartphone and computer. Successful pairing between your smartphone, computer, and ThingSpeak is necessary for displaying data. When the ThingSpeak interface on both your smartphone and computer shows the temperature chart, it signifies a successful pairing. Upon successful pairing and account and password login, you can access the ThingSpeak interface as shown in Fig. 10. By clicking on the green label on the smartphone app page, the screen will display the current temperature chart of the intelligent sensing milling tool, as illustrated in Fig. 11. During an alert, a notification is sent via LINE, as shown in Fig. 12. The test alert temperature is set at 200 °C, and owing to data transmission delays, the app displays an alert temperature of 21 4 °C at that moment

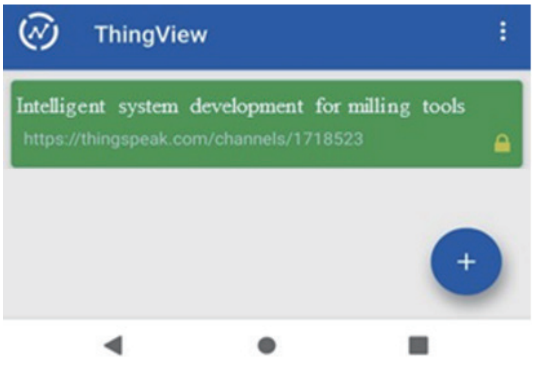


Fig. 10. (Color online) APP to display the successful pairing screen between ThingSpeak and the user's smartphone.

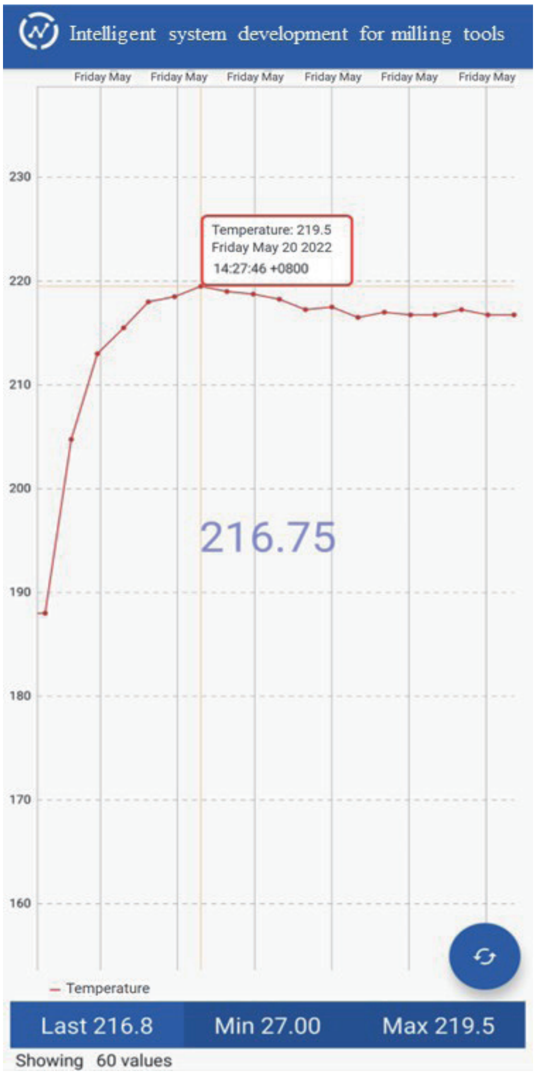
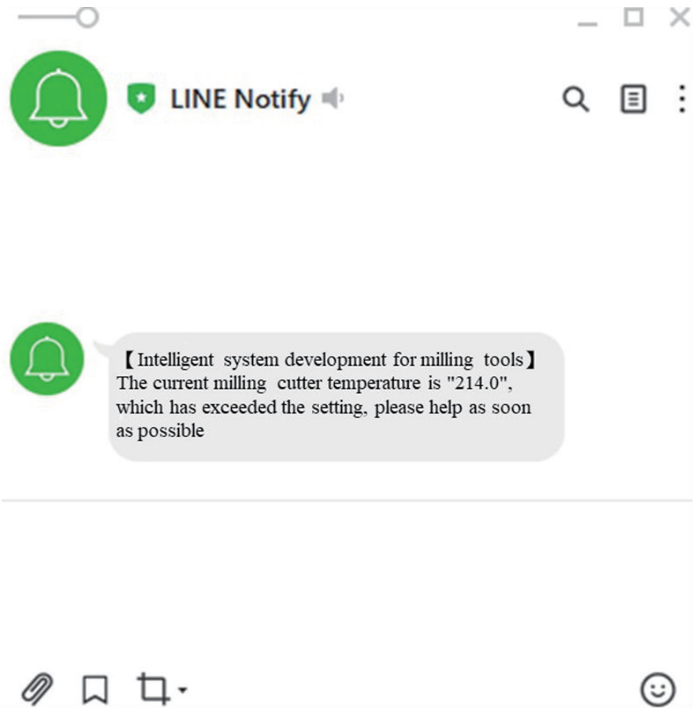


Fig. 11. (Color online) Intelligent sensing milling tool processing temperature smartphone APP screen.



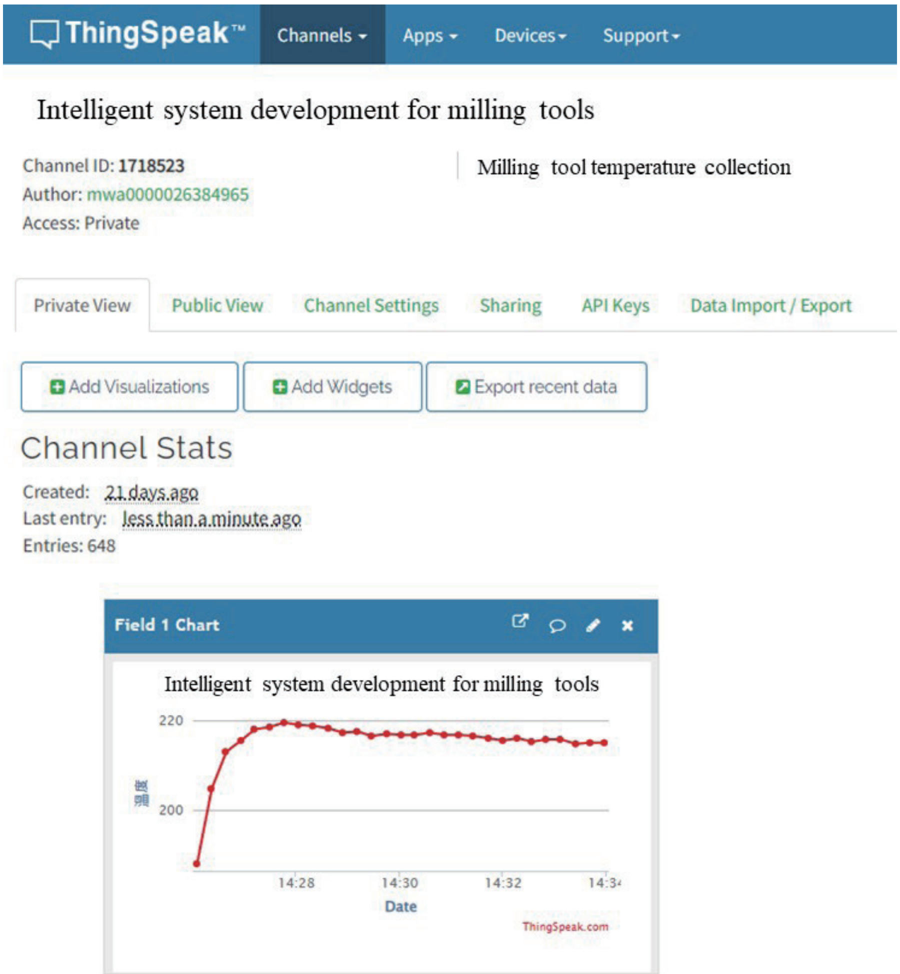
【Intelligent system development for milling tools】
The current milling cutter temperature is "214.0",
which has exceeded the setting, please help as soon
as possible

Fig. 12. (Color online) LINE notification screen for abnormal machining temperature of intelligent sensing milling tool.

Once ESP32 successfully pairs with Wi-Fi, you can access the ThingSpeak interface as shown in Fig. 13. At this point, the current temperature data chart for the intelligent sensing milling tool, as measured by the MAX6675 K-type thermocouple module sensor, will appear on the computer screen.

After testing with the MAX6675 K-type thermocouple module, the temperature of the electric soldering iron used for heating started to rise to 219 °C. This temperature corresponds to the maximum rated heating temperature for the soldering iron. Subsequently, the temperature remained steady at around 219 °C. During testing, owing to difficulties in the fabrication of the circuit board, it was temporarily not feasible to physically install the system onto the milling machine for actual use. Therefore, we simulated the setup by using an intelligent sensing milling tool holder to hold the cutting tool. The temperature-sensing wire of the MAX6675 K-type thermocouple was inserted deep into the bottom to ensure precise temperature measurements at the contact point at the very bottom, as shown in Fig. 14.

Following that, a simulated processing test was conducted on the intelligent sensing milling tool, as shown in Fig. 15. When the simulated heating temperature reached 214 °C, the combination of the K-type thermocouple temperature sensor module and the ESP32 microcontroller, coupled with Wi-Fi, transmitted the data, which was stored on the ThingSpeak platform. Simultaneously, the information was plotted on the computer screen for real-time dynamic monitoring, as depicted in Fig. 16. Connection for real-time monitoring via ThingSpeak on a smartphone is shown in Fig. 17 As the simulated temperature exceeded the warning value, an alert was triggered, as shown in Fig. 18.



Intelligent system development for milling tools

Channel ID: 1718523
Author: mwa0000026384965
Access: Private

Milling tool temperature collection

Channel Stats

Created: 21 days ago
Last entry: less than a minute ago
Entries: 648

Intelligent system development for milling tools

Fig. 13. (Color online) Computer monitoring intelligent sensing milling tool processing temperature screen.

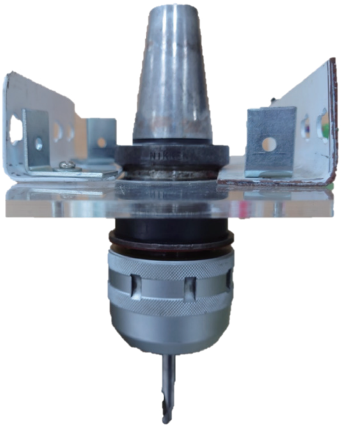


Fig. 14. (Color online) Intelligent sensing milling tool and securely clamped tool.

Fig. 15. (Color online) Interface in heating test of intelligent sensing milling tool.

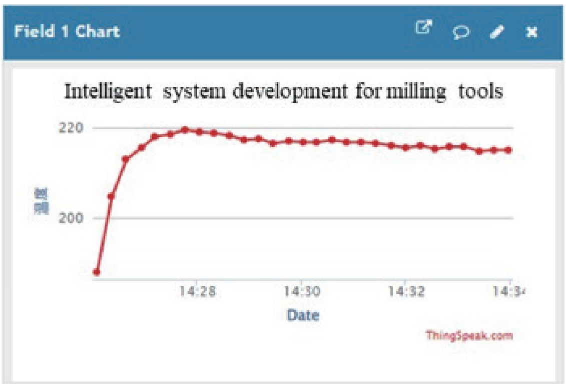
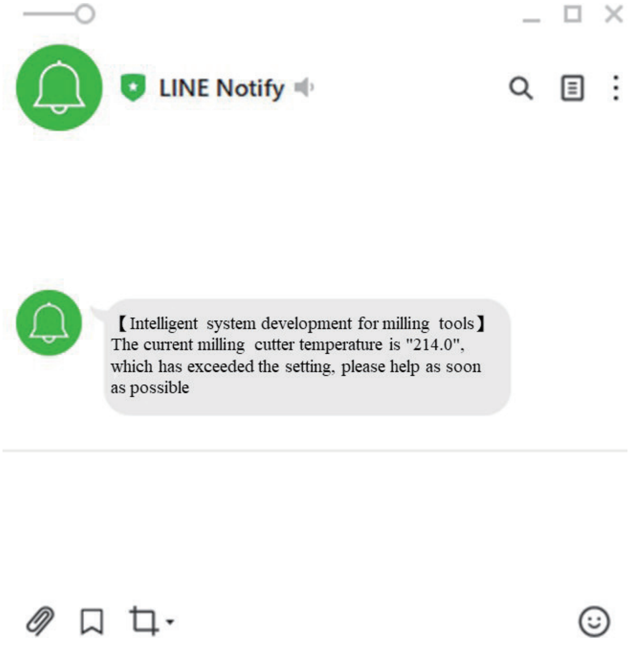


Fig. 16. (Color online) Monitoring of milling cutter processing temperatures on the ThingSpeak platform.

Fig. 17. (Color online) Intelligent sensing milling tool system test screen.



【Intelligent system development for milling tools】
The current milling cutter temperature is "214.0", which has exceeded the setting, please help as soon as possible

Fig. 18. (Color online) LINE notification screen for abnormal machining temperature of intelligent sensing milling tool.

4. Conclusion

In this study, we implanted a flexible PCB into the concentric cylindrical smart sensing tool on the milling cutter handle. The information is simultaneously graphed on the computer screen for real-time dynamic monitoring utilizing the K-type thermocouple temperature sensing module in conjunction with the ESP32 microcontroller chip and using Wi-Fi to transmit messages stored on the ThingSpeak platform. The data on the milling cutter temperature is promptly communicated to users through Wi-Fi transmission. This system can be applied to any milling cutter owing to the small size and lightweight of the ESP32 and MAX6675 K-type thermocouple module used in this study. Because ESP32 is capable of real-time data feedback during program operation, manufacturers can retrieve information from ESP32 through ThingSpeak while users are using milling machines. This enables manufacturers to know the current temperature of the tool in real time and observe the temperature rise of the milling cutter promptly, thereby enabling them to decide whether the tool has become dull and needs replacement. Manufacturers can also obtain real-time data for subsequent development and correction of tool feed rates.

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