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Development of Low-cost Wireless Monitoring System and Its Implementation on Computer Numerical Control Machine Tool

Muhamad Aditya Royandi,[1,2] Iman Apriana Effendi,[2]
Asep Indra Komara,[2] and Jui-Pin Hung[1*]

[1]Graduate Institute of Precision Manufacturing, National Chin-Yi University of Technology, Taichung 41170, Taiwan
[2]Department of Manufacturing Design Engineering, Politeknik Manufaktur Bandung, West Java 40135, Indonesia

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We propose a low-cost wireless monitoring system and describe its initial deployment on a computer numerical control (CNC) machine tool as a data acquisition (DAQ) and collection device. It employs a piezoelectric sensor that can detect and analyze signals corresponding to the deflection of the tool holder and reaction force of the cutting process. The sensor readings are acquired wirelessly to prevent interference with the cutting chip. The wireless system was constructed with commonly accessible hardware, such as the Arduino Due and nRF24L01 wireless module. A Windows Forms application can then use a serial communication interface to process and collect data. In addition, the program includes a data storage system, data processing that displays signal properties (maximum and minimum amplitudes, root mean square, and frequency), data visualization that displays data in the time and frequency domains, and an alert function through the mobile application WhatsApp. The low-cost monitoring system, with an estimated hardware cost of approximately USD 225, can achieve a sample rate of approximately 350 samples/s. The feasibility was evaluated by a comparative study. Final validation tests in the machining process demonstrated that the monitoring system exhibited good agreement with an existing DAQ device and sensor, with a maximum root-mean-square error (*RMSE*) of approximately 2.16% of the measured vibration features.

1. Introduction

In the era of Machine Tool 4.0, machine tools are becoming more affordable and offer more functions.(1,2) Other technologies supporting machine tools (bearings, spindles, controls, and drivers) also play roles in their continuous development.(3,4) However, other essential aspects required to develop machine tools in Industrial Revolution 4.0 must be considered, such as the machine's ability to be more intelligent and more automatic and to have a higher level of connectivity. Machine Tool 4.0 is a new generation of intelligent machine tools that are connected, widely accessible, adaptive, and autonomous,(5) which was developed by

*Corresponding author: e-mail: hungjp@ncut.edu.tw
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implementing several technologies such as a cyber-physical system (CPS), IoT, and cloud computing. CPS technology, which is then applied to machine tools to become CPS machine tools (CPMTs), is the primary system in Machine Tool 4.0, which can maximize its function when collaborating with IoT technology and cloud computing.

Furthermore, CPMT technology comprises many subtechnologies from various scientific disciplines. Therefore, its development is gradual and continuous, based on multiple types of research that have been conducted. In addition to the machine tool itself, an essential component is the data acquisition (DAQ) device, which cannot be separated from the monitoring system. It is essential because collaboration with the computer numerical control (CNC) controller can be used to create a cyber twin machine tool. Subsequently, a monitoring system is achieved when the cyber twin machine tool is integrated with a human–machine interface with specific connectivity. In addition, with the requirements of higher product quality, shorter product life cycles, reduced cost, and highly reliable systems, a monitoring system is a promising key technology.(6,7) Hence, considerable research has been conducted to develop monitoring devices with IoT-based systems in machine tools.(7–18)

Kuntoğlu *et al.* reviewed an indirect tool condition monitoring system. They noted that installing multiple sensors during the development of the tool condition monitoring system can make the system prediction more accurate and sensitive.(19) However, investment is required in sensor systems, DAQ equipment, and data processing and recording software. In addition, because of their high cost and limited system openness, industries, particularly small and medium businesses (SMBs), have not generally adopted relevant established systems.(20,21) Thus, some studies have focused on developing low-cost monitoring systems.

Xing *et al.* proposed the machine tool DAQ to decrease human error, cost, and time in data recording. It was developed using a novel monitoring system based on a low-cost device such as Arduino, a low-cost camera, and an open-source computation platform (Node-RED). Remote data processing features also exist on tablets and can be operated with wireless communication.(22) Liu *et al.* used an Arduino device to read data in an MTConnect-based CPMT, which enables diverse types of real-time manufacturing data. Such data can be collected and managed effectively and efficiently.(23) Zhang *et al.* developed a low-cost and flexible multisensor tool condition monitoring system for a four-axis CNC milling machine at a laboratory scale.(20) Tool wear prediction data were obtained by integrating input data such as power, vibration, and cutting force. Although the system was not compared or calibrated with existing commercial cutting-force and vibration systems, it can be used to establish the relationship between the machining parameters and tool life.(20) Ghani *et al.* proposed a low-cost system that can detect and analyze signals related to the deflection of a tool holder from the cutting force.(24) These signals are then used to monitor and predict flank wear in the turning process. The prediction was built with R-squared values of the regression coefficient between 0.938 and 0.991. The graphical user interface (GUI) was developed using MATLAB.(24) García-Ordás *et al.* proposed a tool-wear monitoring system based on computer vision and machine learning.(25) They claimed that it can be developed with a low-cost investment and rapid approach, achieves high accuracy, and does not require a segmentation stage.(25) Christiand *et al.* developed an online image-based tool-wear monitoring system with modular 3D-printed components for micromilling applications.[26] With this, tool detachment is not required, and tool wear monitoring can be safely conducted outside the machining area. It can be built at a low cost of USD 872, including the camera.[26] In addition to the scope of machine-tool monitoring, the concept of a low-cost monitoring system has also been developed in different fields of study, such as environmental engineering,[27–29] civil engineering,[30–32] and smart applications.[33] This proves that a low-cost system is reliable for further applications.

Accordingly, in this paper, we provide insight into the feasibility of applying a low-cost system for monitoring systems and sensor DAQ devices on CNC machine tools. This monitoring system can be developed thoroughly, including in the hardware and software domains. The proposed system was built using a combination of commonly available hardware components. The software application was developed using an open-source platform. The configuration can also be modified to fit specific research or project requirements. Consequently, we present the novelty that a monitoring system (including hardware and software) can be developed using a combination of commonly available devices and open-source software. Moreover, it can achieve acceptable performance. This development can also avoid unnecessary/excessive monitoring performance specifications. In addition, in this study, we also reveal that an affordable monitoring system can be adapted to SMBs. Moreover, an existing CNC lathe machine in those enterprises can be further developed to adapt current trend technology upon the installation of this system.

2. System Description

The system was designed to facilitate the implementation of a low-cost DAQ system for a CNC lathe machine. However, its components should be procured reasonably without compromising the performance or requirements. In addition, this monitoring system was built using the concept of wireless data connection. Thus, the acquired data can be sent wirelessly to a PC. Therefore, it can reduce the possibility of the chip's interference with the sensor or its cable installation. Figure 1 shows the overall concept of the monitoring system.

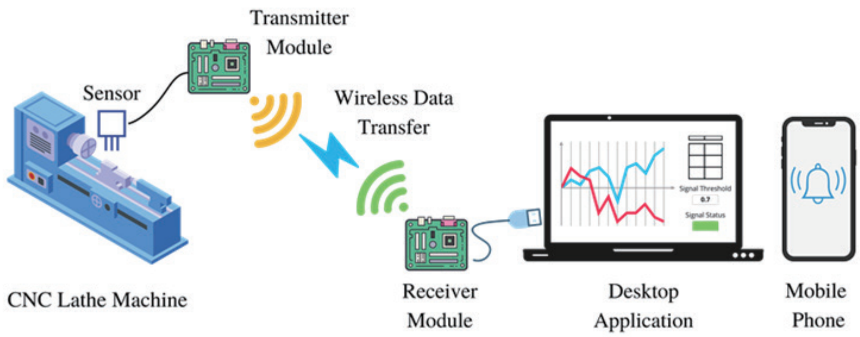


Fig. 1. (Color online) Conceptual design of the system.

2.1 Hardware

This monitoring system consists of a piezoelectric disc sensor, Arduino Due microcontroller, signal conditioning circuit, and nRF24L01 wireless module. A “soft” lead zirconate titanate (PZT) disk with the designation number PIC255 was configured as a sensing unit. The piezoelectric material was a modified lead zirconate–lead titanate disk with a diameter of 10 mm and thickness of 1 mm. This material has a high Curie temperature, high permittivity, high coupling factor, high charge coefficient, poor mechanical quality factor, and low temperature coefficient. These qualities are appropriate for force and acoustic pick-up devices.(34) In addition, the sensor is installed in the tool holder with a clamping mechanism to ensure that clamping is sufficiently strong to hold the sensor and packaging, as shown in Fig. 2.

The Arduino Due microcontroller is a 32-bit ARM-microcontroller-based microcontroller board. It is powered by an SAM3X8E ARM Cortex-M3 processor. It is also equipped with 54 digital input/output pins, 12 pulse width modulation (PWM) outputs, 12 analog inputs, four universal asynchronous receiver-transmitter (UART) hardware serial ports, an 84 MHz clock, a USB on-the-go (OTG) compatible connection, two digital-to-analog converters, two two-wire interfaces (TWIs), a power jack, a serial parallel interface (SPI) header, a joint-test-action-group (JTAG) header, a reset button, and an erase button. The board is ideal for large-scale Arduino projects. This high-performance Arduino Due was installed as the transmitter and receiver modules in this study as its 12-bit analog-to-digital converter (ADC) resolution is superior to that of rival models. Thus, the signal interpretation throughout this monitoring system can be enhanced.

Additionally, the nRF24L01 wireless transceiver module was selected for the monitoring system. The nRF24L01 module is a single-chip 2.4 GHz transceiver designed to facilitate ultralow-power wireless applications. nRF24L01 is designed to operate in the 2.400–2.4835 GHz industrial, scientific, and medical (ISM) frequency band. The maximum programmable air data rate of the module is 2 Mbps. The nRF24L01 module is suitable for ultralow-power system designs owing to its high data rates and two power-saving modes. Therefore, this module is defined as a low-cost wireless module solution.(35)

To interpret the sensor signals, a signal conditioning unit was made as follows.

1. The charge amplifier becomes the primary circuit, since the piezoelectric output signal impedance must be reduced to convert the transducer’s produced charge into a voltage.(36) In

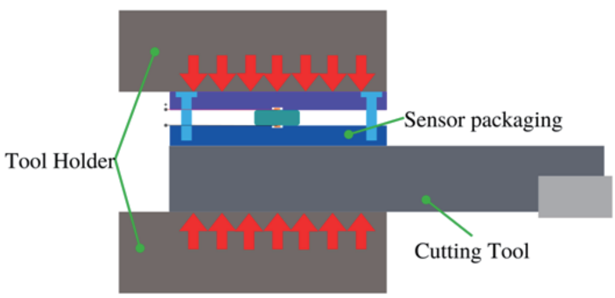


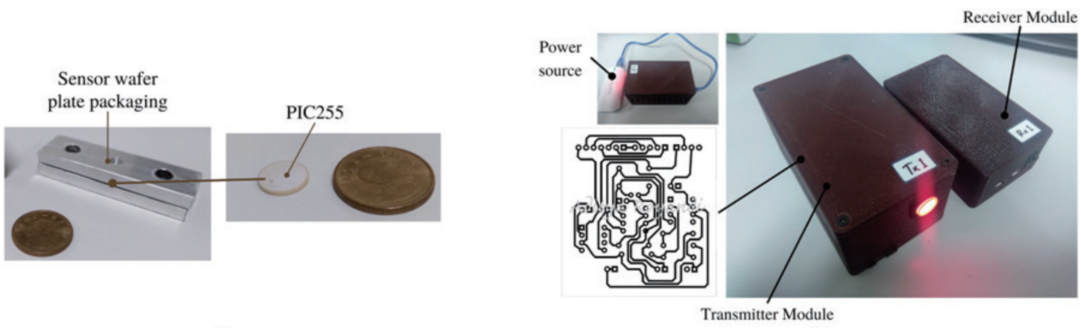
Fig. 2. (Color online) Sensor installation concept.

the proposed system, a charge amplifier was implemented using an AD-8541 operational amplifier. It is a single, dual, and quad rail-to-rail input and output amplifier, with a 2.7–5.5 V single-supply operation and 45 µA amplifier of supply current.

2. Because AD-8541 requires a (−) voltage supply, an extra circuit consisting of a voltage converter was added. The ICL 7660 used in this design offers a positive-to-negative voltage conversion feature for an input range of +1.5 to +10 V.
3. A voltage divider circuit determines the voltage signal range that the microcontroller may receive. This circuit modifies the value of the signal passing through it on the basis of the ratio of the inserted resistors. This resistor comparison value is multiplied within the program to restore the voltage to its actual value. This circuit was developed because of the limited voltage signal range that the microcontroller unit can read, which is 5 V.
4. The voltage amplifier amplifies the converted charge to the suitable voltage level.
5. The specifications of the piezoelectric disc transducer indicate that its bandwidth can be up to 20 kHz. However, since the sensor will be implemented in the machine tool for different functions (one of them is vibration signal acquisition), a low-pass filter is needed to remove the unwanted signal during the acquisition process. In addition, vibration signals greater than 5 kHz are designated as noise in the cutting process.[37,38]
6. A power bank provides electricity to this system. It connects to the Arduino via a USB connector, which is typically used for programming. The DC voltage pin of the Arduino can then be used to fulfill the circuit's remaining voltage requirements.

Figure 3(a) shows the wafer-shaped sensor packaging design. This package also includes a tape conductor line connecting the piezoelectric sensor to the connector pin and an isolator tape to prevent circuit shorts. This connector pin serves as the link between the sensor and transmitter system. Figure 3(b) shows the design outcomes in the electronic domain. The result was an electronic circuit constructed on a printed circuit board (PCB). In addition, both transmitter and receiver modules include enclosures to shield the circuit from external interference. In addition, as the transmitter module and sensor require a cable to connect them, a simple cable reel was also manufactured to facilitate installation.

Table 1 shows the approximate expenses of each component at the time this report was written. The cost of constructing one monitoring system (excluding the 3D printing enclosure)



(a) (b)

Fig. 3. (Color online) (a) Sensor wafer plate packaging and (b) packaging of electronic circuit and microcontroller.

Table 1
Estimation cost of components.

Components	Qty	Cost
Arduino Due	2	99
nRF24L01 wireless module	2	8
Piezoelectric disk PIC 255	1	21
Power bank 5200 mAh	1	10
AD8541 Amplifier	2	16
ICL7660 Inverter	1	3
Passive electronic components	10	1
Magnet	5	5
Supporting components	1 set	62
Total = USD 225		

was estimated. The supporting components include a jumper cable, PCB board, male in-circuit serial programming (ICSP) headers, female headers, cable heat insulation, small outline integrated circuit to dual in-line package (SOIC-to-DIP) adapter, buttons, and screws. These components supported some needs in building the monitoring system, especially the transmitter module. Table 1 shows the cost of the proposed system to be USD 225. Therefore, this is an inexpensive monitoring system. This monitoring system costs approximately one-tenth of the cost of the existing sensor and DAQ system (excluding the license of the desktop application for gathering the data). In addition, the monitoring system underwent multiple stages of development. Previously, this monitoring system could only gather samples every 0.014 s or 70 S/s. The sample rate remained relatively low. For instance, changes in the microcontroller and wireless module can enhance the sampling rate of the current system. Currently, this monitoring system offers two channels for sensor placement. Moreover, each channel can perform wireless data capture at approximately 350 S/s.

2.2 Software

In this section, we describe information pertinent to the human–machine interface design of the monitoring system. Thus, the design process was subdivided into microcontroller and communication module development, desktop application design, and mobile phone notification application programming interface (API) configuration.

In information technology, the first step is to define the microcontroller's program. This software includes a microcontroller and nRF24L01 transceiver module activation function. In addition, each program is based on the function of each module, namely, the signal transmitter and receiver modules. When all the modules are properly connected, the first microcontroller transfers data using the while loop and `radio.write` commands. In addition, this module communicates data wirelessly with the other nRF24L01 modules. Subsequently, on the second Arduino, the while loop containing the `radio.read` function will become true, and the serial monitor receives the data through the `Serial.print()` function. The data received on this serial monitor can then be examined via a serial port on a desktop GUI application.

The user interface (UI) of the system was developed using Windows Forms, which is a GUI class library bundled in the .NET Framework. Its major objective is to make the development of desktop, tablet, and PC apps more accessible.(39) The capabilities of this desktop application include data visualization, processing, management, gathering, and sharing. In addition, a mathematical model can be incorporated into the application, enabling data processing to offer a GUI with parameter prediction capabilities during the machining process. Finally, an alert feature is introduced to this desktop application to strengthen its ability to send notifications during unfavorable conditions of the machine.

When the "connect" button is pressed, the major operation of the app begins. The data are read and plotted on the various graphs and tables when the button is pressed. In addition, the data collection is processed to display the signal parameter value [root-mean-square (RMS), maximum, or minimum signal] online. The threshold value represents the upper limit of read data. To indicate the condition, the green indicator becomes red when the data value surpasses the threshold value. In addition, if this condition persists for a specified time, the program sends a warning message to a mobile phone via WhatsApp. This functionality was implemented using the Twilio API for WhatsApp.(40) In addition, the data plot components, RMS values, and indicators are organized in the same panel. They are recorded as a bitmap image in local storage and are continuously updated while the application operates. Using the Google Drive application, in addition to being stored in local storage, this bitmap can be automatically stored and updated in cloud storage. This cloud-based bitmap storage function can be used to construct cross-platform data visualization applications.(41) If the export or clear button is hit, the data table is saved to local storage, uploaded to cloud storage using Google Drive, or erased. Finally, a close button is pressed to exit the software. The results of the main UI design for this monitoring system is shown in Fig. 4.

Figure 5 depicts the final output of the WhatsApp notification alert function. This feature is designed to warn the user of undesirable machining process behavior (sensor data value or

Fig. 4. (Color online) User interface of the monitoring system.

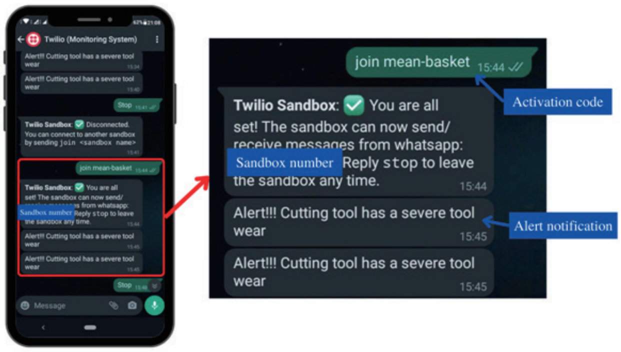


Fig. 5. (Color online) Appearance of WhatsApp alert.

anticipated tool wear value exceeding the threshold). This feature sends notifications to a mobile device through WhatsApp.

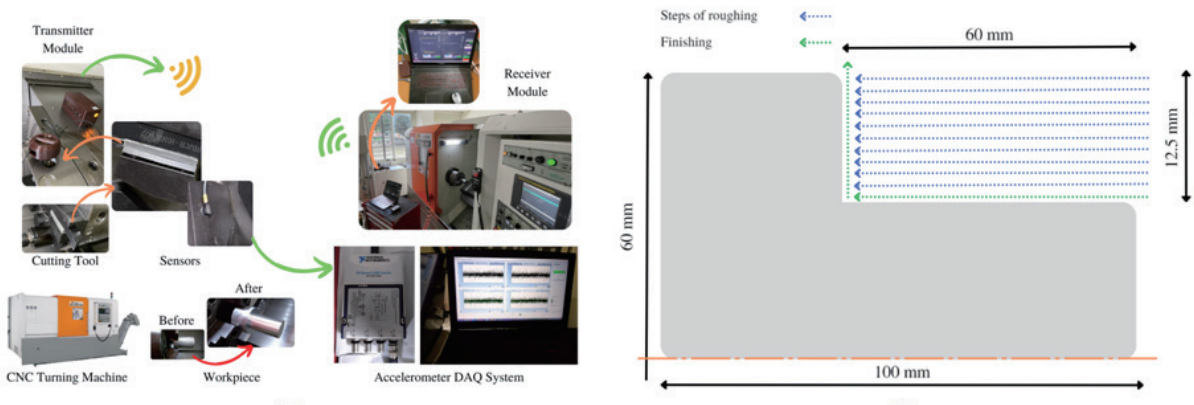
3. Results and Discussion

The evaluation arrangement and results of the proposed system are presented in this section. The evaluation was performed to prove the feasibility and repeatability of data collection during the machining process.

3.1 Evaluation arrangement

The objective of the evaluation phase was to assess the ability of the piezoelectric sensor to capture data. As shown in Fig. 6(a), this evaluation was performed during the machining process. This evaluation included the Vturn-A20 CNC turning machine, cutting tool, workpiece materials, 352C22 accelerometer sensor, and national instruments (NI) DAQ system. Figure 6(b) depicts the geometry of the aluminum bar workpiece being machined with the machining parameters set to a cutting speed of 200 m/min and feed rate of 0.1 mm/rev. The data to be read by the system were determined by the displacement of the sensor. This displacement was caused by the compression generated by the clamped cutting tool (related to the deflection of the tool holder from the cutting force).

The performance evaluation of the system is also required. Some of the above-listed evaluations may be associated with feasibility evaluation, in which it is determined whether this system is feasible for further evaluation and deployment. Therefore, additional evaluations must be conducted. Although other types of performance evaluations are available, the evaluation in this study was limited to a repeatability analysis. Repeatability is the degree of concordance between independent test results obtained at brief intervals by the same operator using the same method on identical test objects in the same laboratory with the same equipment.[42] This measurement activity is based on international organization for standardization (ISO) 5725:1994, which contains six sections that explain the general principles and definitions, the basic method for the determination of repeatability and reproducibility of a standard measurement method,



(a) (b)

Fig. 6. (Color online) Evaluation materials. (a) Machining arrangement. (b) Workpiece geometry.

intermediate measures of the precision of a standard measurement method, and basic methods for determining trueness.

In addition, this standardization has been utilized in various applications, such as the validation of orthophoto-based impervious surface areas and determination of imperviousness factors,(43) evaluation of the measurement precision of distribution within the lung following intratracheal administration,(44) and ultrasonic testing.(45) Moreover, Suzuki *et al.* proposed an adaptation to the standardization of the statistical design of a measurement precision experiment.(46) D'Aucelli *et al.* developed a MATLAB framework to automate the analysis of the operations of ISO 5725-compliant measuring systems.(47)

Additionally, since our performance analysis approach is more straightforward than reproducibility evaluation under various settings (different laboratories, operators, and equipment),(42) the machining arrangement is also based on Fig. 6 and the description mentioned earlier in this section. Moreover, the final evaluation result is expressed as the standard deviation/root mean squared value of repeatability, and the reliability between the test results must exceed 95%.

3.2 Evaluation results

As indicated previously, the objective of this preliminary review was to determine the viability of sensor readings in this monitoring system. This evaluation was performed by comparing the signal read by the low-cost monitoring system with those read by available measuring instruments. Although the monitoring system has similar properties to a dynamometer, it was not compared with a dynamometer in this comparative study. However, because the monitoring signal displayed by the low-cost system appears to exhibit the same behavior as a vibration signal, an accelerometer was utilized as the instrument for comparison. Figure 7 depicts the outcomes of the comparison of the low-cost monitoring system and the accelerometer. The graph shows that the behaviors of these two signals were in close agreement.

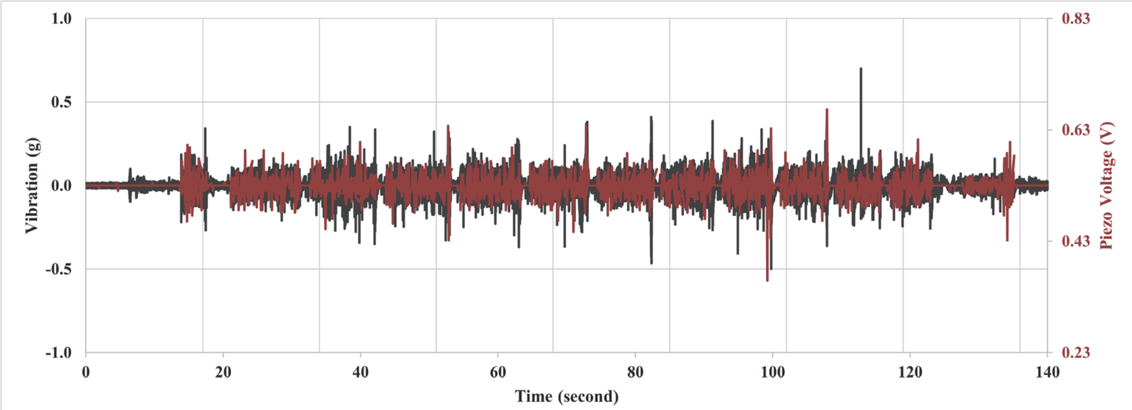


Fig. 7. (Color online) Acquired signals of low-cost and existing systems.

The displayed statistics were in different amplitude units because the sensor values were voltage raw data that had not been transformed into a signal with a different dimension.

Furthermore, a subsequent test was conducted to examine the repeatability of the sensor readings in the monitoring application. This evaluation was conducted in the same laboratory and with the same machine by the same operator using the same cutting parameters. Figure 8 shows the output of the sensor readings from the five distinct machining procedures performed successively on the same day. The graph shows raw data of piezoelectric sensor reading results that have not been calibrated as a vibration signal, which would then be called as dimensionless signal. The graph's vertical axis shows piezoelectric voltage obtained from the piezoelectric displacement related to the deflection of the tool holder owing to the cutting force. At the same time, the horizontal axis corresponds to the time when the data were obtained in seconds. Moreover, the zero output of this sensor should be ratiometric that is relative to the processed signal from the signal conditioning circuit. However, since it was neglected in this study, the idle signal from this sensor has a value of about 0.53 V.

The acquired data were then processed to obtain the RMS value of each signal. For further examination, the entire signal identified each phase of the machining process, and the RMS value was extracted. Thus, the repeatability analysis included both the total RMS and the RMS of each step signal. This can be observed in the bar graph of Fig. 8. A comparison of the experimental results with the highest and lowest RMS values yielded a root-mean-square-error (*RMSE*) value of 2.2%.

According to previously reported results, an inexpensive and open-source platform can generate adequate sensor readings. The outcomes of this study will indicate whether the piezoelectric sensor and this cost-effective monitoring system are feasible, and whether assessment and implementation can be continued in subsequent stages.

Although this monitoring system has undergone feasibility and repeatability analyses, another performance analysis is crucial for obtaining a high degree of reliability, namely, reproducibility,[48] which refers to the performance of the testing device. It consists of a test that can evaluate the consistency of the sensor and replicate measurements under different

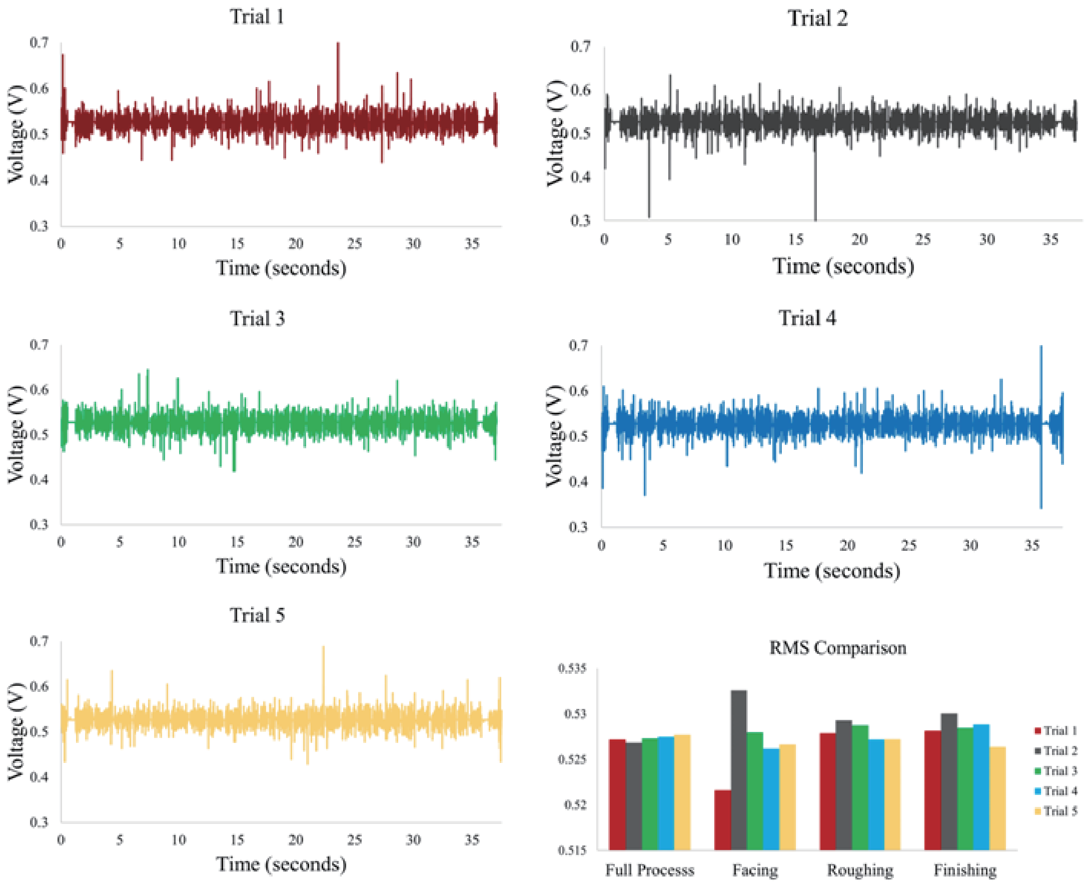


Fig. 8. (Color online) Sensor readings for repeatability analysis.

conditions.(49) In contrast to the repeatability performance analysis, this analysis should be carried out in different environments and with different operators, not only under different parameters. Thus, a more reliable system can be obtained in the future.

4. Comparative Analysis

A comparative analysis was performed to determine the advantages and disadvantages of the proposed system. Such an analysis can evaluate a system's potential for development and use. An existing device with the same principal function as the proposed system was used for the comparison. In this analysis, the hardware and software of the monitoring system were compared with those of the existing system. The object of comparison for the hardware system is the DAQ device, which can measure signals from integrated electronic piezoelectric (IEPE) and non-IEPE sensors,(50–52) as well as the DAQ software from the same manufacturer. The results of this comparison are presented in Table 2.

The data in Table 2 indicate that the existing system is superior to the developed monitoring system. The existing monitoring system can read samples more than one hundred times, according to its specifications. However, when the data gathering feature of the designed

Table 2
Low-cost system comparative analysis.

Compared aspects	Proposed system	Existing device
Number of channels	Two	Four
Maximum sample rate	350 S/s/channel	51.2 kS/s/channel
ADC resolutions	12 bits	24 bits
Input range	±5 V	±5 V
Device cost	Low cost	Very expensive
Functionality	Currently, it can measure the dynamic signal from piezoelectric and MEMS accelerometers	Can monitor signals from IEPE and non-IEPE sensors such as accelerometers, tachometers, and proximity probes
Signal conditioning	Integrated and can be further developed depending on the sensor used	Integrated inside module
Programming approach	Windows Forms application programming	Graphical programming approach
Monitoring application	Customized, depending on its function	Uses available library
Time required for development	Requires development effort for graphical and programming code	Relatively easy because of its graphical approach
Development flexibility	Function development is flexible (depending on needs) since the robustness of the toolbox also relies on its programming code	Relies on the availability of the library and features inside the toolbox
Open-source library	It can be found in the community	Might have to pay for a library
Software cost	Free	An annual subscription is required

monitoring system was implemented, the 350 samples/second sampling rate was in good agreement with that of the existing system. This scenario also played a role in the ADC resolution. Therefore, although the specifications are inferior to those of the current model, the monitoring system developed is more affordable. Additionally, it is practical for use and can be adapted to research or project needs (not excessive).

5. Conclusions

A low-cost system to construct a monitoring system, decrease development costs, and acquire a feasible evaluation result, which can also be further developed for implementation, is described. Typically, expensive sensors, data-gathering equipment, and monitoring applications are required for monitoring systems. This is a crucial problem because all machining monitoring operations require not only a powerful system but also a system suited to the objectives of the research or project. The proposed system also enables SMBs to advance their technology to the point of intelligent manufacturing. In addition, researchers should expand the scope of their research to enhance their research capacity. This DAQ system comprises an Arduino Due, wireless module, and signal conditioning circuit. Additionally, the sensors are piezoelectric. Through the design and development process, the specifications of the monitoring system, namely, the number of channels, maximum sample rate, ADC resolution, and input range, were determined to be two channels, 350 samples/s/channel, 12 bits, and 5 V, respectively. Moreover, this hardware system architecture enables the monitoring system to acquire sensor data wirelessly. Therefore, cable installation, which can interfere with the lathe machining process, is not required. Furthermore, the monitoring application consists of a sensor data collection system that can collect and store data in local and cloud drives as comma-separated values (CSV) files. Moreover, a notification-alert feature exists in this system. Thus, when the signal crosses the threshold, the notification system is engaged and a WhatsApp alert is delivered to a mobile device.

From the results of some evaluation processes and comparative study, we can conclude that a monitoring system can be developed at an affordable cost and with easily accessible components. This system also has an acceptable cost performance for application. Therefore, this monitoring system can be implemented in a different application for further evaluation.

References

1 M. Mori, M. Fujishima, Y. Inamasu, and Y. Oda: CIRP Annu. **60** (2011) 1. https://doi.org/10.1016/j.cirp.2011.03.099
2 T. Moriwaki: CIRP Annu. **57** (2008) 736. https://doi.org/10.1016/j.cirp.2008.09.004
3 E. Abele, Y. Altintas, and C. Brecher: CIRP Annu. **59** (2010) 781. https://doi.org/10.1016/j.cirp.2010.05.002
4 R. Neugebauer, B. Denkena, and K. Wegener: CIRP Annu. **56** (2007) 657. https://doi.org/10.1016/j.cirp.2007.10.007
5 C. Liu and X. Xu: Procedia CIRP **63** (2017) 70. https://doi.org/10.1016/j.procir.2017.03.078
6 L. Janak and Z. Hadas: MM Sci. J. (2015) 794. https://doi.org/10.17973/MMSJ.2015_12_201564
7 P. Kovac, I. Maňková, M. Gostimirović, M. Sekulić, and B. Savkovic: J. Prod. Eng. **14** (2011) 1.
8 S. M. Reddy, A. C. Reddy, and K. S. Reddy: J. Appl. Sci. **12** (2012) 938. https://doi.org/0.3923/jas.2012.938.946
9 K. Mehdi: Proc. 12th Int. Conf. Mechanical and Aerospace Engineering (ICMAE, 2021) 505–510. https://doi.org/10.1109/ICMAE52228.2021.9522429
10 N. Ambhore, D. Kamble, S. Chinchanikar, and V. Wayal: Mater. Today Proc. **2** (2015) 3419. https://doi.org/10.1016/j.matpr.2015.07.317
11 A. Mohamed, M. Hassan, R. M'Saoubi, and H. Attia: Sensors **22** (2022) 1. https://doi.org/10.3390/s22062206
12 B. L. Jian, C. T. Hsieh, and Y. S. Guo: J. Low Freq. Noise Vib. Act. Control **40** (2019) 978. https://doi.org/10.1177/1461348419889502
13 M. N. H. Chikuruwo, L. Maregedze, and T. Garikayi: Proc. Int. Conf. System Reliability and Science (ICSRS, 2016) 60–63. https://doi.org/10.1109/ICSRS.2016.7815838
14 T. F. Abbas, Y. K. Shounia, and R. R. Shwaish: Proc. AIP Conf. (AIP, 2020) 020161. https://doi.org/10.1063/5.0000152
15 F. Ferraz Jr and R. T. Coelho: Int. J. Adv. Manuf. Technol. **26** (2005) 90. https://doi.org/10.1007/s00170-003-1977-3
16 J. Cubas, J. Leoro, D. Reyes, and S.-S. Yeh: Proc. 2016 IEEE Int. Conf. Advanced Intelligent Mechatronics (IEEE, 2016) 184–188. https://doi.org/10.1109/AIM.2016.7576764
17 S. Tangjitsitcharoen and V. Boranintr: Int. J. Comput. Integr. Manuf. **26** (2013) 227. https://doi.org/10.10800951192X.2012.731608
18 T. Moriwaki, S. Tangjitsitcharoen, and T. Shibasaka: Int. J. Comput. Integr. Manuf. **19** (2006) 473. https://doi.org/10.1080/09511920500399177
19 M. Kuntoğlu, A. Aslan, D. Y. Pimenov, Ü. A. Usca, E. Salur, M. K. Gupta, T. Mikolajczyk, K. Giasin, W. Kapłonek, and S. Sharma: Sensors **21** (2020) 108. https://doi.org/10.3390/s21010108
20 X. Y. Zhang, X. Lu, S. Wang, W. Wang, and W. D. Li: Procedia CIRP **72** (2018) 1136. https://doi.org/10.1016/j.procir.2018.03.092
21 H. Kim, W. K. Jung, I. G. Choi, and S. H. Ahn: Sensors **19** (2019) 1. https://doi.org/10.3390/s19204506
22 K. Xing, X. Liu, Z. Liu, J. R. R. Mayer, and S. Achiche: Procedia CIRP **96** (2020) 347. https://doi.org/10.1016/j.procir.2021.01.098
23 C. Liu, X. Xu, Q. Peng, and Z. Zhou: Procedia CIRP **72** (2018) 492. https://doi.org/10.1016/j.procir.2018.03.059
24 J. A. Ghani, M. Rizal, M. Z. Nuawi, M. J. Ghazali, and C. H. C. Haron: Wear **271** (2011) 2619. https://doi.org/10.1016/j.wear.2011.01.038
25 M. T. García-Ordás, E. Alegre-Gutiérrez, R. Alaiz-Rodríguez, and V. González-Castro: Mech. Syst. Signal Process. **112** (2018) 98. https://doi.org/10.1016/j.ymssp.2018.04.035

26 Christiand, G. Kiswanto, A. S. Baskoro, F. Hiltansyah, M. R. Fitriawan, R. G. Putra, S. K. Putri, and T. J. Ko: HardwareX **11** (2022) 1. https://doi.org/10.1016/j.ohx.2022.e00269
27 J. Li and S. Cao: Int. J. Online Biomed. Eng. **11** (2015) 37. https://doi.org/10.3991/ijoe.v11i3.4488
28 A. D. Deshmukh and U. B. Shinde: Proc. 2016 Int. Conf. Inventive Computation Technologies (ICICT, 2016) 1–6. https://doi.org/10.1109/INVENTIVE.2016.7830096
29 C. J. Bastidas Pacheco, J. S. Horsburgh, and R. J. Tracy: Sensors **20** (2020) 3655. https://doi.org/10.3390/s20133655
30 P. Luque, D. A. Mántaras, A. Rodríguez, H. Malón, L. Castejón, J. G. Jalón, and J. L. López, Á. Martín: J. Sens. (2016) 1. https://doi.org/10.1155/2016/1740854
31 V. S. Arumuga Perumal, K. Baskaran, and S. K. Rai: Energy Procedia **143** (2017) 179. https://doi.org/10.1016/j.egypro.2017.12.668
32 S. Komarizadehasl, B. Mobaraki, H. Ma, J.-A. Lozano-Galant, and J. Turmo: Sensors. **21** (2021) 6191. https://doi.org/10.3390/s21186191
33 V. Ahmed and S. A. Ladhake: Proc. 2011 Int. Conf. Computational Intelligence and Communication Networks (IEEE, 2011) 569–573. https://doi.org/10.1109/CICN.2011.122
34 Physik Instrumente: https://www.pi-usa.us/fileadmin/user_upload/pi_us/files/catalogs/PI_Piezoelectric_Solutions_Catalog.pdf (accessed July 2018).
35 Y. Wang, C. Hu, Z. Feng, and Y. Ren: Proc. IEEE Int. Conf. Information and Automation (IEEE, 2014) 902–907.
36 B. Yaghootkar, S. Azimi, B. Bahreyni, and S. Member: IEEE Sens. J. **17** (2017) 4005.
37 C.-Y. Huang and J.-H. Chen: Appl. Sci. **6** (2016) 201. https://doi.org/10.3390/app6070201
38 C.-Y. Huang, R.-M. Lee, and S.-K. Yang: Proc. 2016 Int. Conf. Applied System Innovation (IEEE, Okinawa, 2016) 1–4. https://doi.org/10.1109/ICASI.2016.7539864
39 GeeksforGeeks: https://www.geeksforgeeks.org/introduction-to-c-sharp-windows-forms-applications/ (accessed June 2021).
40 Twilio: https://www.twilio.com/whatsapp (accessed May 2021).
41 M. A. Royandi and J.-P. Hung: Appl. Sci. **12** (2022) 9259. https://doi.org/10.3390/app12189259
42 IS 15393-1 (2003): https://law.resource.org/pub/in/bis/S01/is.15393.1.2003.pdf (accessed July 2022).
43 B. Hejmanowska, W. Drzewiecki, and A. Wróbel: https://www.isprs.org/proceedings/XXXVII/congress/4_pdf/233.pdf (accessed July 2022).
44 J. Takeshita, J. Ono, T. Suzuki, H. Kano, Y. Oshima, Y. Morimoto, H. Takehara, T. Numano, K. Fujita, N. Shinohara, K. Yamamoto, K. Honda, S. Fukushima, M. Gamo: Advanced Mathematical and Computational Tools in Metrology and Testing XI (World Scientific, 2018) 357–364. https://doi.org/10.1142/9789813274303_0036
45 V. Konshina, G. Dymkin, and C. Müller: https://www.ndt.net/article/ecndt2006/doc/P172.pdf (accessed July 2022).
46 T. Suzuki, J. Takeshita, J. Ono, and X. Lu: J. Phys.: Conf. Ser. **1065** (2018) 1. https://doi.org/10.1088/1742-6596/1065/21/212015
47 G. M. D'Aucelli, N. Giaquinto, S. Mannatrizio, and M. Savino: https://www.imeko.org/publications/tc10-2016/IMEKO-TC10-2016-069.pdf (accessed July 2022).
48 G. Zonta, M. Astolfi, D. Casotti, G. Cruciani, B. Fabbri, A. Gaiardo, S. Gherardi, V. Guidi, N. Landini, M. Valt, and C. Malagu: Ceram. Int. **46** (2020) 6847. https://doi.org/10.1016/j.ceramint.2019.11.178
49 Oizom: https://oizom.com/sensor-data-reproducibility-for-enhanced-data-accuracy/ (accessed October 2022).
50 National Instruments: https://www.ni.com/en-id/support/model.ni-9234.html (accessed October 2022).
51 National Instruments: https://www.ni.com/docs/en-US/bundle/ni-9234-specs/page/specs.html (accessed October 2022).
52 S. McFarlane, Advantages and Disadvantages of LabVIEW: https://www.viewpointusa.com/labview/advantages-and-disadvantages-of-labview/ (accessed October 2022).

About the Authors

Muhamad Aditya Royandi received his B.A.Sc. degree from Politeknik Manufaktur Bandung, West Java, Indonesia, in 2016, and his M.Sc. and Ph.D. degrees from National Chin-Yi University of Technology, Taichung, Taiwan, in 2020 and 2023, respectively. His current research involves machine tool design, intelligent machining and manufacturing, and data acquisition system development. (adityaroyandi@gmail.com)

Iman Apriana Effendi currently is a lecturer at the Manufacturing Design Engineering Department of Politeknik Manufaktur Bandung, West Java, Indonesia. His research interests include machine tool design, intelligent machining and manufacturing, and robotics design. (iman@polman-bandung.ac.id)

Asep Indra Komara currently is an associate professor at the Manufacturing Design Engineering Department of Politeknik Manufaktur Bandung, West Java, Indonesia. His research interests include machine tool design, finite element analysis, reverse engineering, and product design and development. (asep.indra@polman-bandung.ac.id)

Jui-Pin Hung received his Ph.D. degree from National Chung Hsing University, Taiwan. Currently, he is a professor at the Graduate Institute of Precision Manufacturing at Chin Yi University of Technology in Taichung City, Taiwan. His research interests are in computer aided engineering, machine tool technology, intelligent monitoring system, and orthopedic biomechanics. (hungjp@ncut.edu.tw)