



A case study: monitoring and inspection based on IoT for milling process

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Received: 24 February 2021 / Accepted: 29 August 2021 / Published online: 10 September 2021
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Abstract

Cyber-Physical Machine Tools (CPMT) is currently recognized as a new generation of machine tools that align with Industry 4.0 needs as a smart, well-connected, advanced accessibility and more adaptive and autonomous solution. It can be achieved through standardized design method and communication protocols. This article presents a case study on monitoring and inspection based on Internet of Things (IoT) for milling process toward CPMT. The proposed solution is capable to work in both G-code and Standard for Product Data Exchange Compliant with Numerical Control (STEP-NC)-based controller. The proposed case study demonstrated the controller's capabilities. An IoT-based monitoring architecture was implemented for milling process monitoring. This approach is suitable for both standard. The interpreted machining information will be utilized to enable the machining parameter update and enable monitoring and machining integration and finally extendable for control activity. The monitoring and inspection approaches can achieve high accuracy of machining process condition detection and enable measurement of machined parts to fulfil CPMT needs and I4.0. The case study validated that the developed monitoring approach performed well and was highly sensitive to any changes during the machining process, specifically on the tool condition. While in the inspection approach, the reliability of the machined model was 99.97%. Based on the results of both the approaches, it is confirmed that both tasks can be designed and support digital factory and other manufacturing process stages in the future such as preventive maintenance, inspecting, sizing, assembling and others.

Keywords Machining · Monitoring · Inspection · Milling · Wireless · IoT · STEP-NC

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1 Introduction

Machine tools play an essential role in responding to the Cyber-Physical Production System requirements to advance the CNC machine tool, making it well-connected, accessible, adaptive and autonomous toward the Cyber-Physical Machine Tool. In CPMT, the information and communication technology such as Cyber-Physical Systems (CPS), Internet of Things (IoT) and cloud technology is adopted and adapted. As a possible solution of CPMT, [1] describes CPMT as the integration of machine tool, machining process, computation and network that permit machining process monitoring and control. In contrast, [2] describes CPMT as integrating machine tool with machining process in cyberspace through computation and networking ability to create CPS. With CPMT, machining performance and efficiency can be significantly improved. Development of CPMT requires integrating machine tool vertically and horizontally [3].

Vertical integration is term as end-to-end digital integration that integrates the entire engineering process, including

design, process planning, manufacturing, assembly, etc. Some previous study that had been implemented for open CNC system and open CNC control respectively are [4–11]. Yusof et al. [11] developed an open CNC systems interpreters which composed stand-alone component features. Through these features, both G-code and STEP-NC data extraction can be configured and this makes the interpreter capable to handle both G-code and STEP-NC program. Furthermore, with this type of features, the interpreted information could be utilized for the next level such as monitoring, inspection, optimization and others [12–14].

Horizontal integration is the integration of machine tools with other manufacturing facilities and resources that include robots, conveyor, measurement devices and others to realize a collaborative production system [2]. The critical requirement of horizontal integration of machine tool with other manufacturing facilities and resources is divided into three: first, acquiring accurate and reliable information; second, data integration and communication capability; third, advanced human-machine interface. All this capability could be determined through a monitoring system based on IoT approach with Service-Oriented Architecture and utilized STEP-NC-interpreted information.

Coordinate measuring machines (CMM) are commonly used as automated inspection machines to measure manufactured products' validity. It is cost-effective to provide precise, more accurate dimensional inspection systems to meet advanced practical product requirements in modern manufacturing. CMM inspection has several benefits over traditional inspection methods, including versatility, performance, high reliability and accuracy and higher level of automation and incorporation capabilities. Also, to use CMMs safely and reliably in a computer-integrated manufacturing operation, they must be used in coordination through CAD software. CMM inspection involves CAD inspection planning; it utilizes offline measuring and simulation, and monitoring and sensing inspection plan execution.

2 Survey of previous monitoring and inspection study

A former researcher has surveyed the recent research that is divided into two parts: machine monitoring and inspection process planning. The discussed details are as follows:

2.1 Machine monitoring

IoT has become the mainstream, and researchers are moving forward to apply wireless sensor network (WSN) to their machine process monitoring. Rizal et al. conducted a series of work in 2014 [15] and 2018 [16] by utilizing a wireless telemetry system and embedded vibration and temperature sensor

for tool condition monitoring. Another research proposed by Zedong and Azman [17] presented a CNC machine monitoring system toward I4.0 implementation. The monitoring system employed a WSN to monitor temperature, vibration, humidity and current performance during the machining process. Similar research conducted by Deng et al. [18] introduced an open CNC architecture to CPS through WSN and low power consumption platforms to enable monitoring and control machining processes. Friedrich Bleicher et al. [19] researched machining process monitoring and control by inventing an embedded WSN and monitoring and control system. Based on the author's knowledge, even though the previous proposed research presented CPS machine tool approaches such as real-time data monitoring and control systems, WSN and others specific motivation, the research was developed fully under G-code environment. Due to G-code obstruction, real-time monitoring and control becomes more complicated for the next level implementation such as data integration and communication, editing on the shop floor, decision-making, control and optimization.

In short, most of the machine process monitoring research presented earlier based on WSN was fully developed under the G-code environment. Instead, little research was carried out under the Standard for Product Model Data Exchange (STEP-NC) environment which includes Hassan and Kadir [20] and Zhong et al. [21]. However, their approaches lack horizontal integration between machine and connectivity with cyberspace. Furthermore, based on the survey [22–24], very little study has focused on the integration of vertical and horizontal integration. IoT approach with SOA allows access to the Internet and enables connectivity between machine and devices, the cloud system and the integration between machine and device which highly support horizontal integration, while interpreted STEP-NC information utilization enables the monitoring and machining integration and control activity support vertical integration to be extendable. In this study, the interpreted STEP-NC information would be directly called to monitoring control interface to enable update on the machining information such as spindle speed as required using Global Function.

2.2 Inspection process planning

The purpose of the Computer-Assisted Inspection Planning (CAIP) framework is to determine the best possible sequences of inspection steps and the comprehensive inspection technique for each feature. Some surveys intend to discuss the planning process inspection [20–23], while some conducted with offline inspection used coordinate measuring machine (CMM) [25–27] and other research discussed online inspection during process [28–31].

Nevertheless, some researchers used closed-loop inspection-based STEP-NC standard [32–37]. Zhao et al. [38]

proposed the implementation of CAPP systems in coordinate measuring machines (CMMs) to improve accuracy in part manufacturing processes.

Based on the previous monitoring and inspection study survey, therefore, to eliminate those issues, this case study launched a new technique by incorporating the monitoring based on IoT with SOA and utilized interpreted STEP-NC information while inspection process planning based on CMM. The monitoring approaches include the integration of Raspberry Pi 3 Model B+, WSN, NodeMCU and CNC milling machine for milling process condition monitoring. NodeMCU is equipped with Wi-Fi module functions as a microcontroller to record all the sensor data and transfer wirelessly to the MQTT server. Raspberry Pi 3 Model B+ is a minicomputer that functions as MQTT server/broker to receive and enable data transfer wirelessly from client to server back to client. The monitoring information will be finally sent back to the CNC machine from the MQTT server. As soon as undesirable condition occurs during machining, STEP-NC interpreted data will be directly called on the monitoring system to enable updating the machining parameter using Global Function. While quality decisions have created the inspection approach due to limitations, these approaches can be made depending on product tolerance requirements. Toward this purpose, the CMM system measures the data; the generated feature details will be compared by the coordinate measuring machine (and the reference data of the model extracted from the CAD system).

The overall structure of this article is organized as follows: an introduction, followed by a survey of previous monitoring and inspection study, case study setup, methods, machining process monitoring result, machining part inspection result and conclusion.

3 Case study setup

To demonstrate the effectiveness and performance of monitoring and inspection approaches, a milling process condition monitoring and inspection of machined part were implemented. The machining monitoring and inspection component specification and setup are presented in Table 1 and Figure 1, respectively.

The machining was done by utilizing two types of cutting tools: a new cutting tool and a worn cutting tool. Seven channels of signals that are vibration in X, Y and Z direction, thermocouple (contact sensor) and infrared (non-contact sensor) and spindle electric current are utilized to enable machining process condition monitoring. The machining was implemented based on the cutting parameter, as shown in Table 2.

4 Methods

In this article, the implementation method is divided into two methods: monitoring implementation and method of inspection implementation. Both methods are explained as follows:

4.1 Monitoring methodology

The monitoring information is successfully generated through the integration of hardware and software. The monitoring hardware is deployed on a CNC machine, as illustrated in Figure 1. The monitoring hardware includes four types of sensors that are thermocouple, infrared, vibration and electric current sensor to sense the cutting tool's temperature, the vibration of the cutting tool and workpiece interaction and electric current utilized by spindle motor during machining, respectively. NodeMCU as a wireless module enables sensed information to transfer to the cloud through Raspberry Pi model 3 b+ as MQTT broker to MQTT server. The information then subscribed by IoT platform and CNC machine controller enables monitoring information visualization, alarm signal and control activity on the machining parameter as feedback from the alarm signal. Figure 2 illustrated information transfer from the CNC machine back to the CNC machine based on MQTT.

In the MQTT information chain, there are three sections involved which are the following:

- i. Publisher—publisher is from where the information is generated and sent to the MQTT broker. In this study, each sensor information is the information generator, and NodeMCU is a wireless module and publisher to enable information to be sent to an MQTT broker.
- ii. Broker—broker is like a server that collects the information from all publishers, saves the information and distributes the subscribers' information. In this study, the broker is Raspberry Pi, and the subscriber is IoT platform and CNC controller based on STEP-NC.
- iii. Subscriber—subscriber is a section which subscribes sense information coming from the publisher. In this study, the subscriber is an IoT platform and CNC controller based on STEP-NC.

The algorithm design for the complete functionality of the monitoring system is as shown in Figure 3. It starts with ISO14649 code interpretation and confirmation of the interpreted code through 3D simulation and then starts machining. During machining, the monitoring system starts to sense the temperature, vibration and electric current information. The information is transferred to the IoT platform and CNC machine controller in real time.

Figure 4 shows the control action process if any undesirable condition is happening during the machining process. An

Table 1: Monitoring and inspection component specification

| Component | Specification |
|----------------------------------|--|
| Milling machine | Prolight machine centre 3 axis CNC milling machines STEP-NC based controller |
| Cutting tool | High-speed steel |
| Workpiece | Derlin |
| Raspberry Pi | Model B 3+ |
| NodeMCU | ESP8266 |
| Wi-Fi router | Global connection |
| Vibration sensor | ADXL 335 |
| Temperature sensor (contact) | Thermocouple K-type |
| Temperature sensor (non-contact) | MLX 90614 |
| Current sensor | SCT013 |
| CMM | 3D axes, X, Y and Z, which are orthogonal |
| Accuracy | Highly |
| Flexibility | Moderate |
| Best for measuring | Medium parts requiring high accuracy |

alarm is signalled on the monitoring interface, then the control button is clicked, and then the user is prompted by the monitoring control interface. The monitoring control interface is available with the interpreted STEP-NC information, spindle speed updated and information updates shared with the machine motion control interface, which will enable user triggering any changes made on the previous machining parameter.

4.2 Inspection methodology

The processes of measuring machined parts using offline in CMM and measuring the dimensions of the surface feature of the case study is described, as in Figure 5 and Figure 6. Requirements are fulfilled by the attributes of the manufacturing operation and the features are created by machining in the milling process. The machine tool involves techniques, cutting tools and fixtures that established the measurement and

verification requirements that need to be tested offline. The manufacturing characteristics include geometric and dimensional tolerances and specifications for surface properties and provide a basis for calibration and inspection operations. Meanwhile, if the requirements meet the geometric and dimensional tolerances and specifications for surface features, in that case, this will ensure inspection and monitoring those specific performance requirements on each model are satisfied. Therefore, the procedural breakdown eligibility requirements feedback loop on the system will be closed.

5 Machining process monitoring

The Monitoring system based on IoT for interpreted STEP-NC data was developed. In this system, CNC milling

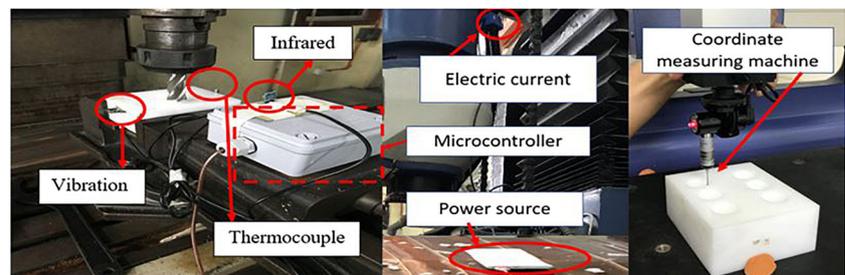
Figure 1: Monitoring and inspection setup

Table 2: Machining cutting parameter

| Cutting parameter | Specification |
|-------------------|---------------------------------|
| Feed rate | 0.1mm |
| Spindle speed | 2500 rpm/261.1m ² /s |
| Depth of cut | 22mm |
| Cutting speed | 250m/s |

machine, every device, IoT platform and monitoring interface are connected through the same IP address, as shown in Figure 7.

The CNC controller’s monitoring interface based on STEP-NC, as in Figure 8, shows the real-time status of temperature for thermocouple and infrared sensor based on the machining process. The real-time information is displayed and continuously updated. Before machining starts, the user needs to select the material of the cutting tool. From the material type, the safe, warning and danger limit are selected. Button safe is coloured with green, warning with yellow and danger with red. An alarm will be signalled whenever an undesirable condition happens. The control action button is selected to enable control of the machining parameter.

There is also an exit and report generation button under the user interface. After the machining process is completed, the interface is closed by selecting the button, and an automatic report will be generated, as shown in Figure 9.

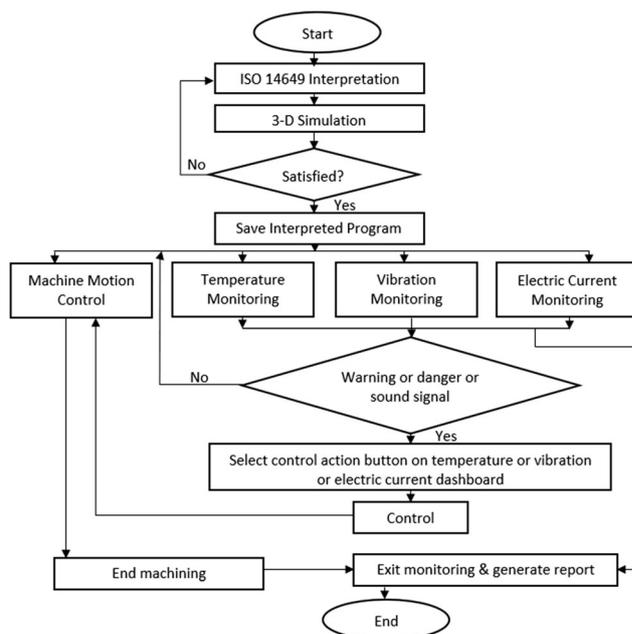


Figure 3: Flow chart of overall algorithm design of the monitoring system

Figure 10 shows another visualization platform for monitoring. This interface could be found directly from the IoT platform. Both interfaces could be accessed online using the same IP address by the machine operator to identify any changes in the machining process in real time for preventive purposes.

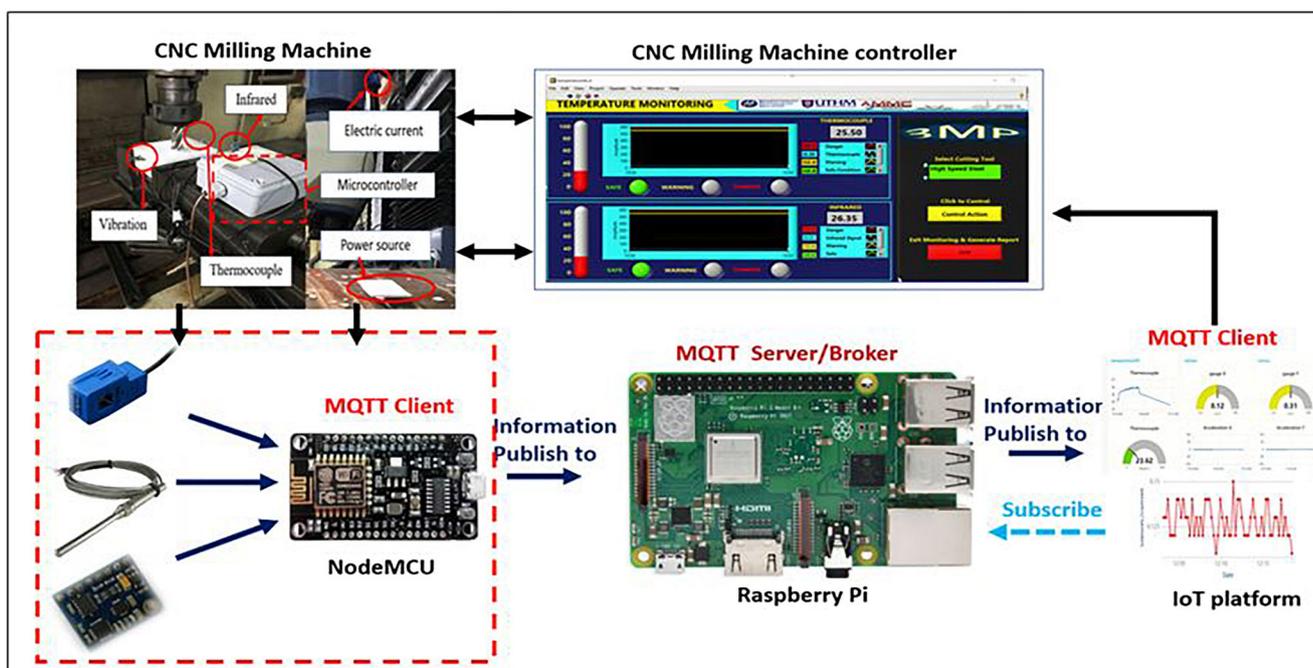


Figure 2: Information transfer over MQTT

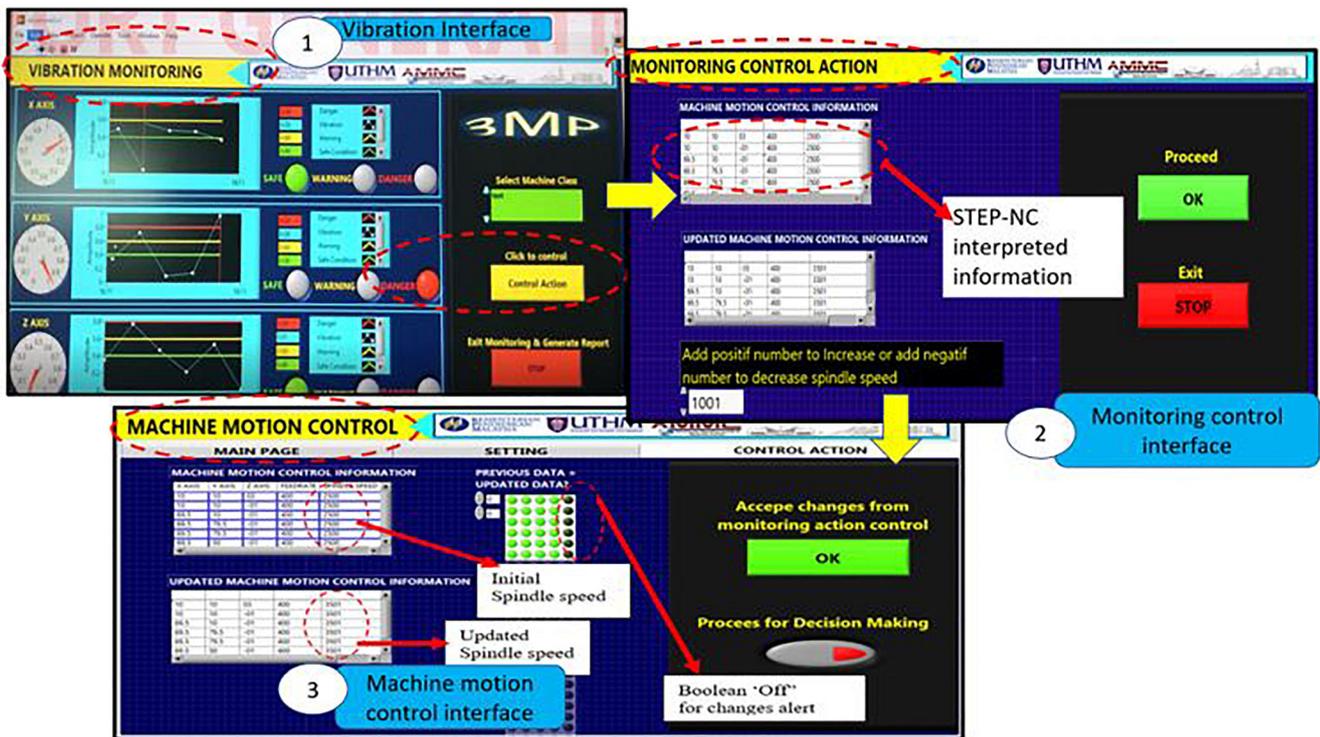


Figure 4: Control action process

Figure 5: Closed loop of the manufacturing process based on CMM techniques

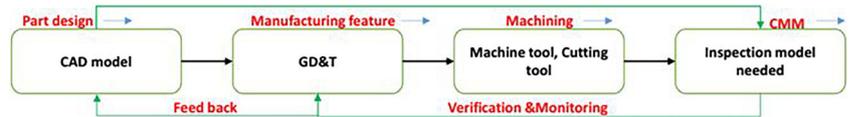


Figure 11 shows the results of temperature, vibration and electric current information during the machining process for new and worn cutting tool.

6 Part for inspection

Description of the part that measured the dimensions of the face planer’s surface, holes and the pockets is shown in Figure 12. However, Table 3 shows the dimensions of the model and the normality reading in each section, to gain the inspection point. In addition, the result demonstrated the average error shown in Table 3 is 0.2854 of the case studies based on normality and CMM machine.

7 Discussion

The case study found that the monitoring system based on IoT for interpreted STEP-NC data is validated and performed well. Real-time information was enabled through a different type of

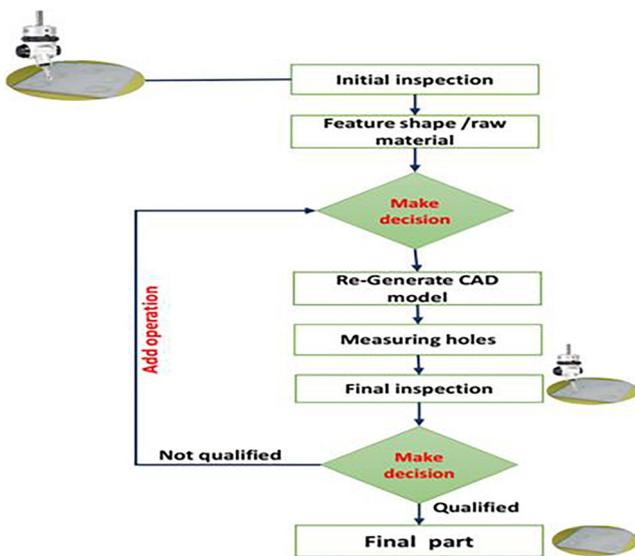


Figure 6: Operational architecture of the inspection model with CMM

Figure 7: Machine and device connection through the same IP

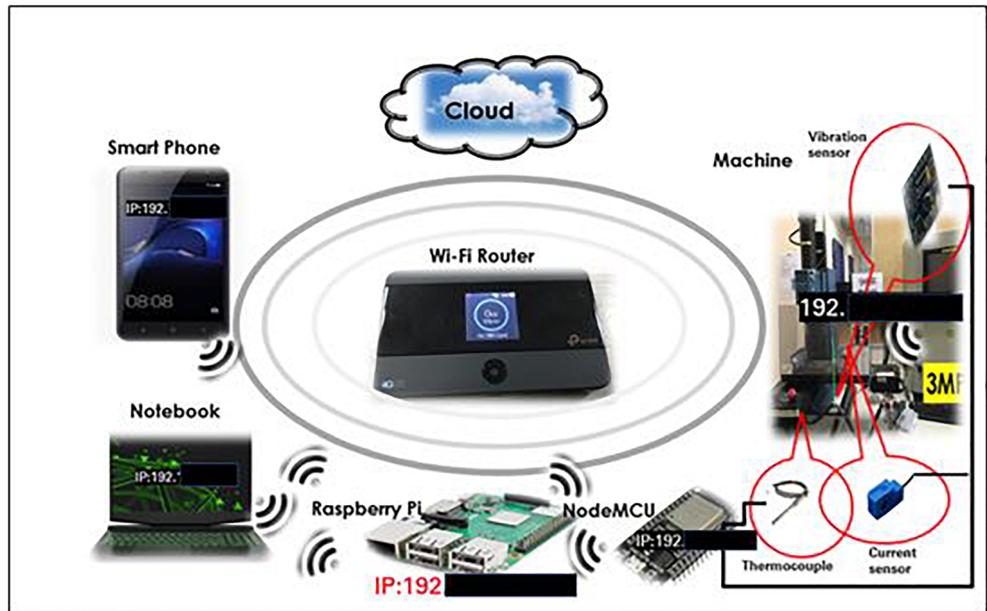


Figure 8: Temperature monitoring interface

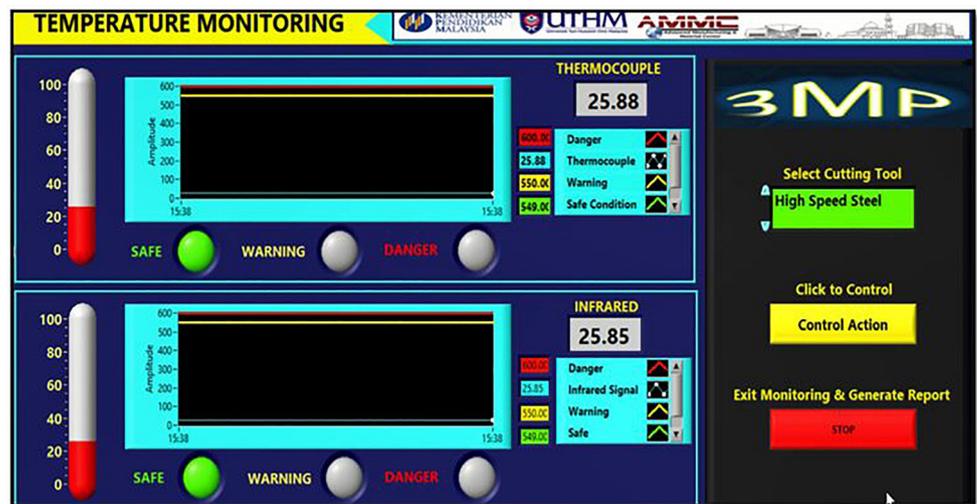
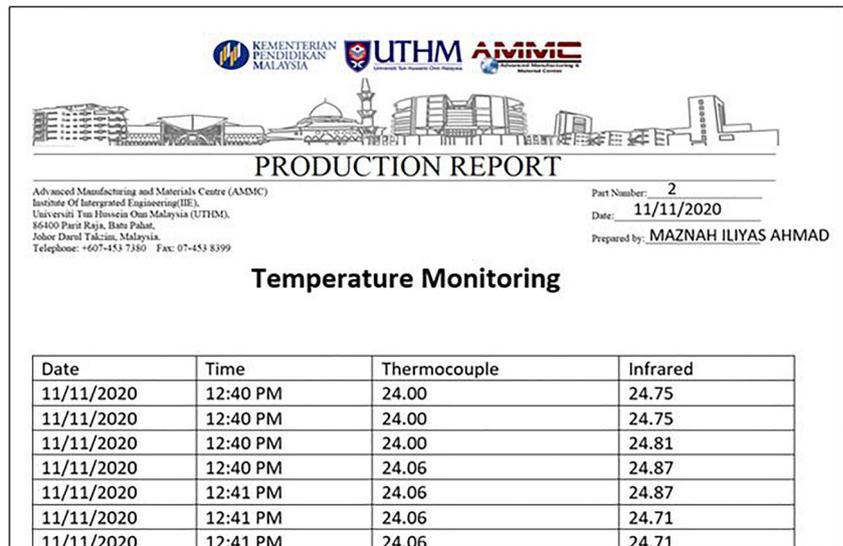


Figure 9: Temperature monitoring report generation



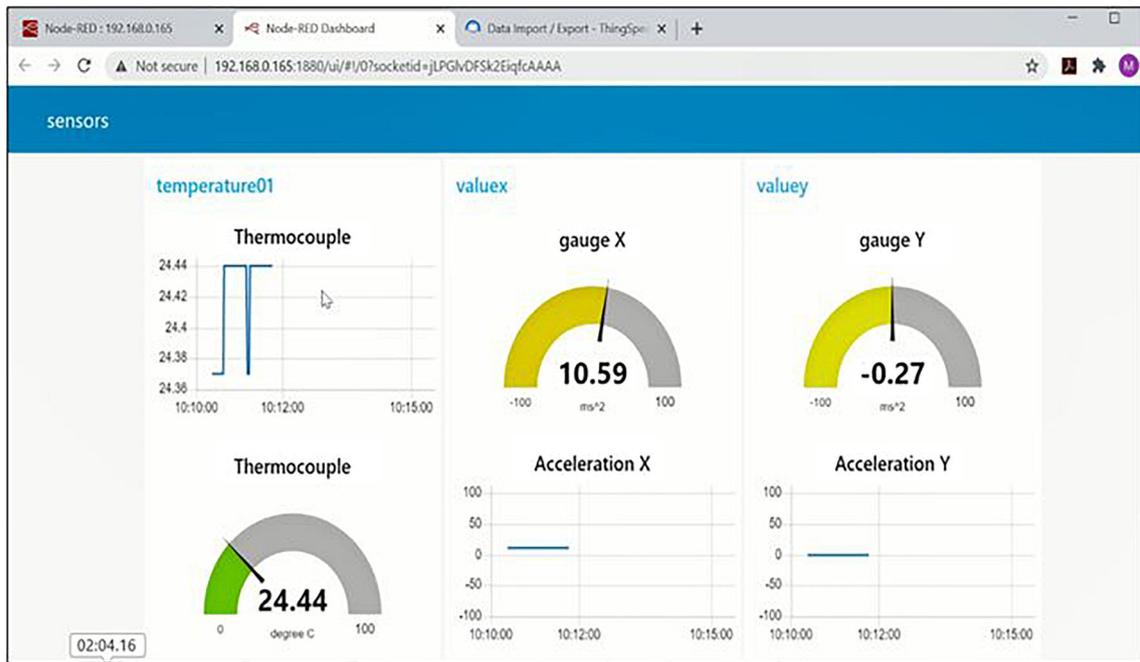


Figure 10: IoT-based monitoring platform

sensor and integrated with the CNC machine controller. IoT-based protocols utilized a single IP address to make everything connected to the Internet. The machining information collection was realized based on the implementation of MQTT IoT-based application protocol over the different operating systems. The interpreted STEP-NC data on the

machine motion control interface could be called directly to monitoring control interface for machining information update if any undesirable condition occurs using Global Function. Based on the monitoring capability testing and result, the monitoring system based on IoT with SOA architecture enables to provide a critical machining process

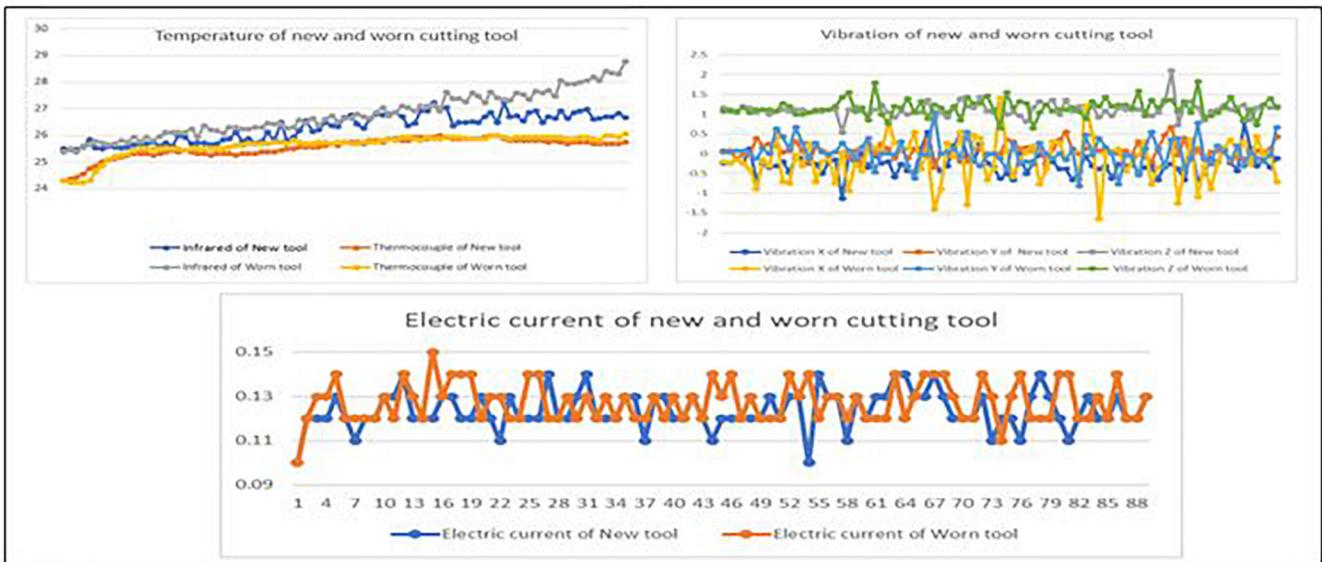


Figure 11: Temperature, vibration and electric current monitoring information

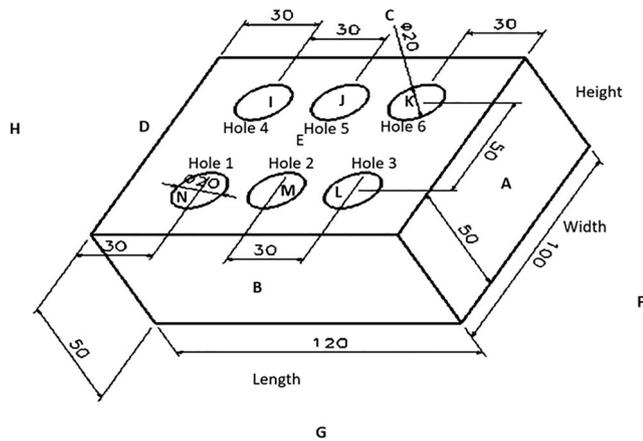


Figure 12: Machined part

information, increase machining performance and prolong tool life utilization. MQTT-based protocol has been proven to enable horizontal integration of CNC machine toward CPMT, which is interoperability and connectivity while interpreted STEP-NC information utilization enables the monitoring and machining integration and enables extendable for control activity. Based on the analysis of the monitoring information generated in real time during the machining process, it was found that there is a different trend for information generated for the new and worn tool. The worn tool gave a higher reading as compared to a new cutting tool based on temperature, vibration and electric current reading. Based on the analysis that appears for the case study, the average error between the normal model with measurement on the CAD system and the measurement based on the CMM is 0.2854.

8 Conclusion

In Industry 4.0, Cyber-Physical Machine Tools (CPMT) is known as a new generation machine tools with a smart, well-connected, advanced accessibility and more adaptive and autonomous facility. The core development of CPMT lies in the vertical and horizontal integration of machine tool, and it is a critical yet challenging task. Due to the lack of previous research, this article proposes a CPMT platform to bridge the research gaps of horizontal integration. This research’s main contribution is a case study on the development of monitoring based on IoT architecture using interpreted STEP-NC information to enable interoperable information flow and communication between various machines, monitoring devices and software platforms. Through the case study, it was found that the developed system bridges the gap of interoperability and efficiency of information communication which provide a great outcome for CPMT. With this development, the conventional machine could also be retrofitted to be MT4.0.

Furthermore, with this monitoring system, issues to get information were solved, and the future work of this research is to use the big data by implementing Artificial Intelligence system for decision-making. On the other hand, the CMM was conducted; and for the measurement of the workpiece features, which have been validated, the model’s reliability was 99.97%. Even though the inspection part is done separately, inspection part could also be able to be integrated with monitoring to enable modification on X, Y and Z axis by applying the same method as explain in the monitoring part. However, this study can be a foundation for the full utilization of the configuration system. The task can also be designed to support the other manufacturing process stages such as inspecting, assembling, sizing, etc.

Table 3: The measurement of the case study based on CMM

| Feature description | Target measurement | Number of point | Point | Original reading | CMM reading (mm) | Error |
|---------------------|--------------------|-----------------|----------|------------------|------------------|--------|
| Reference | 000 | 3 | F-G-H | 0 | 0 | 0 |
| Height | Height | 2 | E-F | 50 | 50.5515 | 0.5515 |
| Length | Length | 3 | A1-A2-D | 120 | 120.5570 | 0.5570 |
| Width | Width | 3 | B1-B2-C | 100 | 100.9185 | 0.9185 |
| Hole | Hole 1 | 3 | N1-N2-N3 | 20 | 20.4010 | 0.4010 |
| Hole | Hole 2 | 3 | M1-M2-M3 | 20 | 20.0992 | 0.0992 |
| Hole | Hole 3 | 3 | L1-L2-L3 | 20 | 20.0988 | 0.0988 |
| Hole | Hole 4 | 3 | I1-I2-I3 | 20 | 20.1480 | 0.1480 |
| Hole | Hole 5 | 3 | J1-J2-J3 | 20 | 20.0355 | 0.0355 |
| Hole | Hole 6 | 3 | K1-K2-K3 | 20 | 20.0440 | 0.0440 |
| Average error | | | | | | 0.2854 |

Acknowledgements This work was jointly sponsored by the Centre for Graduate Studies UTHM, Prototype Development Research Grant (grant code: G011), Ministry of Higher Education, the Malaysian Government under Ministry of Education Malaysia (MOE), Universiti Tun Hussein Onn Malaysia (UTHM), Universiti Teknikal Malaysia Melaka (UTEM), Universiti Teknologi Malaysia (UTM) and Jabatan Pendidikan Politeknik dan Kolej Komuniti (JPPKK).

Code availability The code availability (software application or custom code) is not applicable.

Author contribution Maznah Iliyas Ahmad—writing original draft preparation for monitoring part, conceptual and validation

Yazid Saif—writing original draft preparation for inspection part, conceptual and validation

Yusri Yusof—supervision and methodology

Md Elias Daud—reviewing and editing

Kamran Latif—reviewing and editing

Aini Zuhra Abdul Kadir—reviewing and editing

Funding This article was partly sponsored by the Centre for Graduate Studies UTHM and supported by the research project grant (grant code: G011), Prototype Development Research Grant (grant code: G011), Ministry of Higher Education, the Malaysian Government under Ministry of Education Malaysia (MOE), Universiti Tun Hussein Onn Malaysia and Politeknik Sultan Azlan Shah, Jabatan Pendidikan Politeknik dan Kolej Komuniti (JPPKK).

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval Ethics approval (include approvals or waivers) is not applicable. Additional declarations for article (in life science journals that report the results of studies involving humans and/or animals) are not applicable.

Consent to participate The authors voluntarily agree to participate in this research study.

Consent for publication The authors sign for and accept responsibility for releasing this material on behalf of all co-authors.

Conflict of interest The authors declare no competing interests.

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