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From Open CNC Systems to Cyber-Physical Machine Tools: A Case Study

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Abstract

The aim of next-generation Computer Numerical Control (CNC) is shifting from an open architecture, which has better flexibility, adaptability, versatility and expansibility, to a cyber-physical model, which offers real-time monitoring and control of the machining processes. This paper introduces a real case study to demonstrate such tendency from Open CNC systems to Cyber-Physical Machine Tools (CPMT) based on a low-power embedded platform. Firstly, a new open CNC architecture is presented, which is able to achieve high-precision, high-efficiency, and low-power consumption. Secondly, the open CNC architecture is extended to a CPMT by using Wireless Sensor Networks (WSN), where WSN is utilized to enable monitor and control the machining processes, and the integrated development platform is termed as CPMT. Finally, a case of health monitoring system for CPMT is designed and its system testing is carried out.

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1. Introduction

Open computer numerical control (CNC) acts as the core for modern manufacturing industries, because its hardware, software and bus specification are open-designed, and can be upgraded as personal computer (PC) technology evolves [1]. CNC system, as the key component of a CNC machine tool, not only has to meet the needs from different end-users, but also need to automatically adjust the flow of information together with various production processes. End-users can get their own customized functions by secondary development [2]. Therefore, an open CNC system requires better flexibility, adaptability, versatility and expansibility. Meanwhile, with the rapid development of cloud manufacturing, open CNC system

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will no longer be a stand-alone system, but a service-oriented, hyper-connected, and multi-tenant based one [3-4].

There are three existing open CNC system architectures including: number control embedded PC structure, PC embedded number control structure, and PC+real-time communication card [5–7]. PC embedded number control structure and PC+real-time communication card focus on the openness of the Human Machine Interface (HMI), while the core components of the CNC system, such as position control and interpolation calculation are still carried out by a dedicated motion controller. Number control embedded PC structure greatly improves the openness of a CNC system by a dedicated motion controller. However, it has several disadvantages, e.g. relatively high maintenance cost and product complexity. Real-time systems have their own interface specifications, which are detrimental to the portability and openness of CNC system. Some open CNC systems employ PC+real-time communication card to ensure the performance by modifying the real-time system kernel [7].

Cyber-physical Systems (CPS) are rapidly evolving, which bring both the virtual and physical world together to create a truly networked environment, where physical objects can communicate and interact with each other [8-10]. Machines' real-time statuses can be captured by adopting Internet-of-Things (IoT) technologies, such as Radio Frequency Identification (RFID) and wireless communication standards [11]. Such information is visualized through using various data models and cloud-based services over smart phones. As a demonstrative case of CPS, CPMT has been proposed as the next generation of machine tools along with Industry 4.0, which deeply integrate machine tool, machining processes, computation and networking [8]. A CPMT has a Cyber Twin (the digital abstraction of machine tool), that is equipped with computational and networking capabilities, allowing real-time feedback loops to be established, where machining processes and computations form a closed loop, and interact with each other [8]. At the physical level, once the sensor data is gathered from critical components (e.g. slide-ways and spindle), the Cyber Twin of each component analyses the data, which can achieve autonomous functions, such as self-awareness and self-prediction. Furthermore, similarities between the current performance and historical information of a machine tool can be mined to predict its future behaviour. In such way, CPMT becomes intelligent, resilient and self-adaptable.

Real-time status monitoring is a key part inherent in CPMT and it requires monitoring not only the operating status of the servomotor, but also other key components such as spindles, screws and rails. With the rapid development of IoT, Ad Hoc network technology and low-power sensing technology, the new wireless sensor network (WSN), as the core of CPS, can achieve an intelligent monitoring system for machine tools based on data collection [12-15]. The raw data collected by sensors may inevitably be inaccurate. In addition, noise or outliers can be generated in an unstable network. Such noise can be categorized into four types: incomplete, inaccurate, duplicated, and missing [3]. Another key issue is sensor energy consumption. In order to maximize the working life of a sensor to provide a longer reliance, the circuits, architecture, algorithms and network protocols require to be optimized. In the sensor network level, dynamic voltage scaling (DVS) and dynamic power management (DPM) can be used to reduce energy consumption by setting the sensors into a more energy-saving mode depending on the urgency of the event [17]. Consequently, it is necessary to design an algorithm that can provide reliable data, track the changes of a machine tool status, extrapolate the extra knowledge from historical information, and pass the results to the next level.

In this paper, we develop a Real-time Monitoring System for Cyber-Physical Machine Tools (RTM-CPMT), and a client application to visualize the monitored data. The proposed RTM-CPMT can ensure a long work-life of the sensors while maintaining low power consumption and also gather reliable real-time manufacturing data for visualization analysis. To achieve this, we introduce a data cleansing algorithm for energy-saving (DCAES) and In-network data cleansing algorithm for energy-saving (IDCAES), which guarantee lightweight computing and energy efficiency in local nodes, for reducing energy consumption without significant performance degradation [15].

The rest of this paper is organized as follows. Section 2 presents an overall architecture of the open CNC, which is a hierarchical system framework including hardware and software platform. Several key modules are illustrated in details. Section 3 describes the basic notions of CPMT and provides a demonstrative case study showing how the proposed approach could be used by typical manufacturing companies. Deployment of various IoT devices as well as designed and developed client applications are based on a laboratory test bed. Finally, the conclusion section highlights our contributions and explores future research to be improved.

2. Open CNC Architecture

2.1. Development of Open CNC architecture

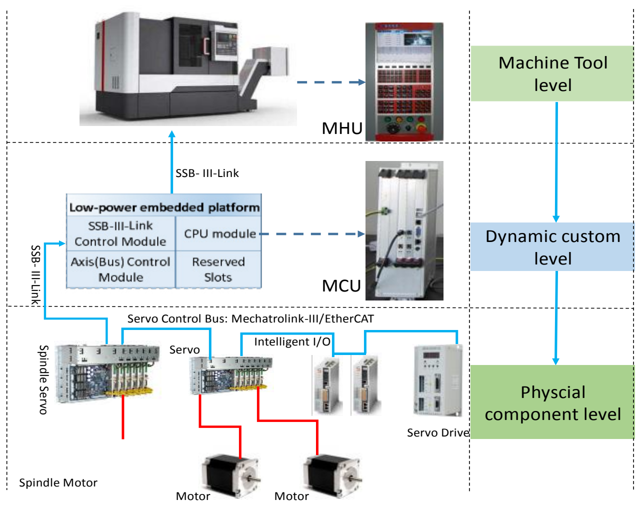

Figure 1. An architecture of Open-CNC based on the low-power embedded platform

This section introduces an open and high-performance CNC system based on a low-power embedded platform, as shown in Figure 1. There are includes four components in the functional block: Human Machine Unit (HMU), Machine Control Unit (MCU), Synchronous serial bus for NCD Link, and Servo control bus. Correspondingly, there are three levels, including Machine Tool level, dynamic custom level, and physical component level. The dynamic custom level includes a numerical control system API and the real-time operating system platform, which can realize different operating system compatibility. End-user or third-party vendors can use this level to expend system function modules such as integration of a new scheduling algorithm. The physical component level enables on-site hardware control and health information sensing such as signal states and servo motor status, which are essential for path planning and decision making.

2.2. *Key modules*

(1) Human Machine Unit

The man-machine interface unit allows to configure the LCD screen and standard machine tool panel that is mainly used for numerical control device command input, interactive programming and machine module design, information management functions, display, online help, as well as Internet interface. HMU is also used for supporting general-purpose processor and real-time operating system.

(2) Machine Control Unit

MCU is a key unit of CNC with Compact Peripheral Component Interface (Compact PCI) box-type multi-slot structure that can be inserted with multiple processor modules and function expansion boards in the low-power embedded platform. There is a bus between the processor module and function expansion board to build a multi-processor hardware platform. MCU chassis can achieve expansion of device function based on hardware platform, and a high-performance, lower-cost and low-power embedded platform is realized to support different processor modules.

(3) Synchronous Serial Bus for NCD Link

NCD link (NC Device) (SSB-III-Link) as a synchronous serial bus is a high-speed fieldbus committed to connecting NC intelligent devices. With SSB-III-Link smart device standard, it can be used to support intelligent devices including single-channel encoder shaft unit, machine control table, intelligent diagnostic unit, and IO unit.

(4) Servo control bus

The fieldbus is dedicated to control the servo motor that is commonly referred to as the servo control bus. Mechatrolink-III and EtherCAT are two kinds of fieldbuses to support in the open architecture [4].

2.3. *Hardware platform*

HMU and MCU are key components in the hardware platform. COM-E module as the processor is adopted by HMU, which can realize some non-real-time functions and system display. Figure 2 depicts the scenario that the processor is used for HMU graphical display with the display interface. Graphical display and non-real-time applications can be implemented in HMU, such as distributed numerical control (DNC) network communication manufacturing execution system (MES), and other functions.

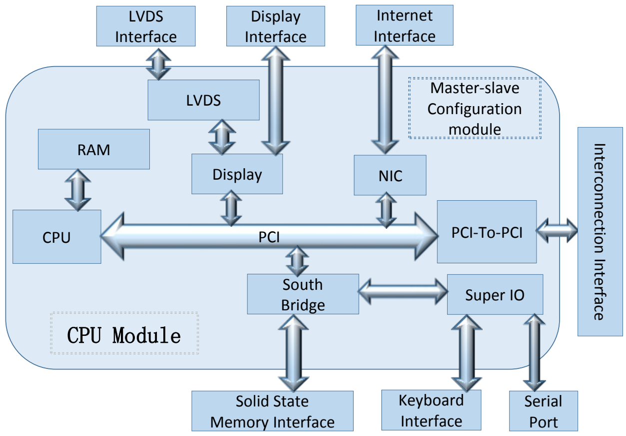

Figure 2. COM-E CNC processor module structure

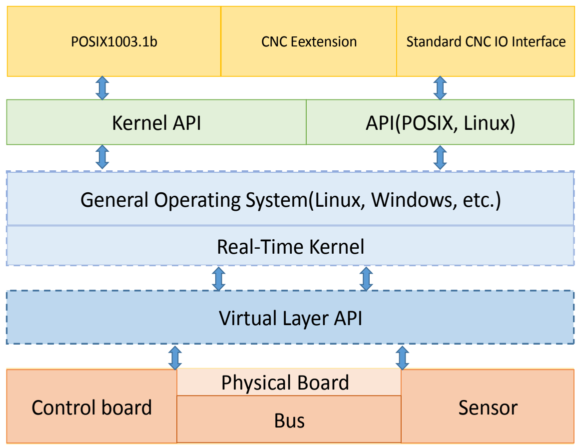

Figure 3. Open-CNC real-time system framework

Figure 3 shows that MCU adopts Compact PCI module to realize CNC real-time control and low-power function, which can achieve multi-processor communication with master-slave mode. The Compact PCI processor module is designed to meet the computational-intensive application (such as spline interpolation) requirements. When the processor module is working in master mode, the on-board PCI bus extends to the global bus through the transparent bridge capabilities of PCI-to-PCI. The slave module is able to connect the global bus through a non-transparent bridge. Based on Compact PCI international standards, CPU is developed to support Multi-core processors interconnected in the CNC hardware platform. The memory window mapping technology and high-speed communication backplane are able to build a high-precision and good scalability CNC system to meet high-precision interpolation.

2.4. Software Platform

In order to make the specification compatible with other real-time operating systems, an API mapping method is developed. With API mapping, CNC software can run on these real-time operating systems using the real-time API specification without modification.

Figure 3 depicts the scenario where operating system interface framework provides a five-tier interface. The top level is the application-oriented operating system interface, and the real-time API specification adds the API for CNC systems to facilitate realization of CNC software and improve portability with real-time system interface standard Portable Operating System Interface X (POSIX) 1003.1b. In order to unify the operation of CNC hardware (e.g. control boards, buses, sensors, etc.), the real-time API specification also includes the standard CNC IO interface. Users or third-party vendors can use this interface to extend functional modules. The second is the real-time API specification and general operating system API. The third is the real-time operating system kernel interface and real-time kernel interface. The forth layer is provided by virtual level development interface, which allows to migrate operating system to a virtual level. The bottom layer is physical board including control board, bus, and sensor.

3. Cyber-Physical Machine Tools

The open CNC architecture can be extended to a CPMT by using Wireless Sensor Networks (WSN), where WSN is utilized to enable monitor and control the machining processes, and the integrated development platform is termed as CPMT. As a typical example of CPS, we designed a Cyber-Physical Machine Tools (CPMT) based on open CNC architectures. The framework of the real-time monitoring system for Cyber-physical machine tools is presented in Figure 4. Correspondingly, the model of the proposed RTM-CPMT based on wireless sensors can be divided into four levels: physical components level, sensor network level, cyber space level and cloud services level. In the physical components level, there are including machine tools and its components. In the sensor network level, the acquisition nodes are attached to the spindle and the ball screw to obtain vibration or temperature data. The acquisition nodes clean the received data, remove the noise information, and then send the data to the sink node; In the cyber space level, cyber-twins can not only make an open CNC machine tool to a smart machine with optimal decision support analytics but also to be provisioned as a cloud service in support of cloud manufacturing. The information models and knowledge base are two key elements in a machine tool. The information model represents the relationships among the physical elements and the real-time status of the critical elements. CPMT can make use of the information models and knowledge base to represent machine performance and degradation behaviour in the physical world [8]. MTConnect as an international data standard is used for data integration, which strives to strengthen the data acquisition capabilities of devices and towards developing a plug-and-play component to reduce the cost of integration [15]. The data is encapsulated into MTConnect format and sent to database by the data fusion.

In the cloud application level, RTM-CPMT is designed to fulfil such a task that is using learning and data mining algorithms in the cloud services level, such a knowledge base can be automatically populated. The knowledge base increases its loyalty and reliability with the continuous collection of new data. Finally, a client application is developed in the cloud application level, which can visualize data and structure from the device with the information of the cyber space level.

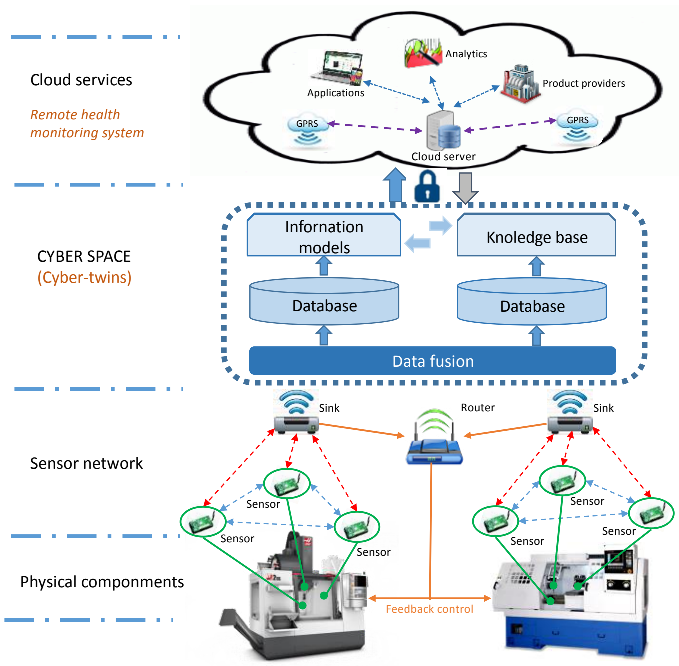

Figure 4. An architecture of RTM-CPMT based on IoT-enabled real-time monitoring

3.1. International Standards Organization: MTConnect

Nowadays, manufacturing systems usually integrate manufacturing devices from different provider companies who use their dedicated communication protocol. Hence there is a challenge in standardization of the meaning, wording, units and values of the data from a manufacturing system that usually vary from machine to machine. This makes the integration, data exchange and management in the CPMT a challenging issue, prompting an urgent need for a unified data exchange standard for the field-level manufacturing devices. MTConnect, as an open, lightweight, and extensible data protocol designed for the exchange of data between shop floor equipment and software applications, is a viable option for this task [15]. MTConnect is built upon the most prevalent standards in the software and manufacturing industry including eXtensible Markup Language (XML) and Hypertext Transport Protocol (HTTP), which maximizes the number of tools available for their implementation. Therefore, MTConnect can share data seamlessly in a common format which allows for integrated disparate entities in a manufacturing system along with their associated devices.

MTConnect standard defines a hierarchical information model for machine tools based on a machine-readable XML schema. This information model allows the key components as well as their data items of the machine tool to be logically, clearly and comprehensively represented. Hierarchical structure such that the data relating to the same components can be bound and grouped together to the component. For example, the speed data and vibration acceleration data of a spindle collected from different sensors can be grouped together. All relevant data items for such spindle can be retrieved by a single command without having to query each data item separately. Figure 5 depicts the scenario where the spindle motor of a machine tool can be built an information model with the MTConnect. In addition, it is easily and effectively implemented into existing models for their related data items and additional sensors via the extensibility of MTConnect standard.

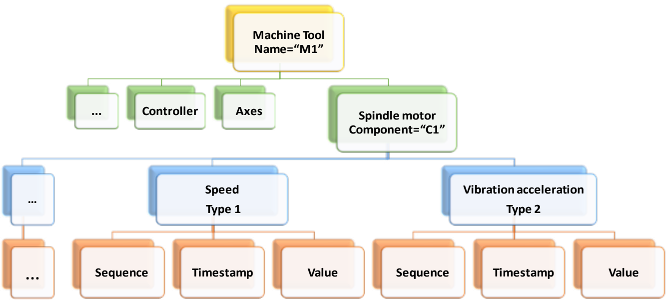

Figure 5. A paradigm hierarchy for RTM-CPMT with MTConnect

3.2. Cyber-Physical Machine Tools

With smarter machine tools development, some functionalities including self-awareness, self-maintenance and self-optimization can be fulfill. CPMT's health and degradation can assess via a self-aware and self-maintained, and further use the fusion information to optimize the follow-up operations meanwhile make timely maintenance feedback and decisions. Real-time Monitoring System for health analytics can be realized at individual machine tools. As health records of each machine tool increases, a data-driven algorithms can be used to update and analyze the data collected from the machine. The health conditions of the machine tool are fed back to the data center and the machine controller uses optimization algorithms for adaptive control and optimized decision.

3.3. A Case of Client for RTS-CPMT

In the cloud application level, we developed a new client application as shown in Figure 6. It is divided into the four main areas that are highlighted in the form. To start communicating with an MTConnect agent, its address must be typed into the address bar in Figure 6. After clicking the "Go!"-button, the device explorer is populated with the agent's devices information and their structure. Selecting one of the data items within the device explorer will then load the appropriate data into the visualization area. Available data will be listed in the table at the bottom of the window and numerical values will also be drawn in the chart area. For analyzing purposes, these numerical data streams can be correlated with each other by clicking the "Correlations" button, which opens a new window, the correlation view.

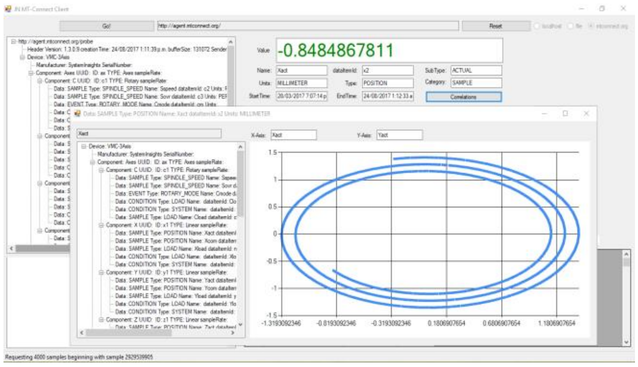

Figure 6. A visualization platform of RTS-CPMT for the correlation view

3.3.1 MTConnect agent configuration

The agent configuration for providing the probe response, which is defined in the file devices.xml. For implementing the new data streams, a new XML node must be created for each new data stream and component.

For example, to add the speed stream for the X axis, the following new child node is added to the component.

<Linear name="X" id="id1001">:

<DataItem category="SAMPLE" id="id01" name="Speed" type="Speed" units="MILLIMETER/SECOND" Sub-type="ACTUAL" >

</DataItem>

This defines a new sample stream, whose values are coming from the adapter stream named Speed. The other data items are added in the same way.

3.3.2 Data processing

After a first connection to the agent has been established, the client has only received information about the structure of the machine and data, but no values. To get actual data, the client requests an initial set of up-to-date values using the current-request. With the information about the number of available samples provided by the response, it uses a sample-request to download a predefined number of past data samples, until the most recent data sample is downloaded. These requests are performed by the *MtAgent.LoadSampleValues*().

To save the data locally for further processing, the client uses a class structure. The samples (instances of class Data) for each data item are stored in an instance of the class DataSequence. This class provides methods for addition and removal of data samples, as well as methods to request the stored data in a specified format. The DataSequence instances are then stored in a list within the Device class's DataCon member, an instance of DataContainer, which contains all data streams of the device.

3.3.3 Data visualization

To maintain a high level of flexibility for future developments or alterations, the greatest part of the client's functionality is realized in a class file separated from the main view implementation, similar to the model-view-controller (MVC) concept.

The client can be used as a platform for further analysis. As an example for using the client data to find simple correlations between two data items, the correlation viewer was implemented. It can be activated for every numerical data item by clicking the "Correlations"-button. A new window opens and on the left side the user can choose the other numerical data item for the correlation view. Figure 6 shows the machining process information for two data items correlation at the same time point in time. After selecting the second data item, the values for both items are linearly interpolated to a common timescale. The timescale list is then iterated and the interpolated data item value pairs are plotted into the point-diagram on the right side of the window. The real-time processing path can be drawn according to the value of x-axis and y-axis, which is easy to observe the working status of the tool and health prediction.

4. Conclusion

This paper introduced the trend from Open CNC system to Cyber-Physical Machine Tools based on the low-power embedded platform. Firstly, an open CNC architecture was described based on the low-power embedded platform, which is able to achieve high-precision and more extensible by making use of international standards, and open components such as hardware and software. Secondly, the open architecture is extended to reusable data communication components with WSN, which can monitor and control the machining processes. Combined with all useful information mentioned above, the new integrated development platform is known as CPMT. Finally, a real-time monitoring system was developed for CPMT with WSN, and taking data cleaning into consideration, which strives to achieve a low-power and reliable monitoring system for Cyber-physical machine tools.

There also lie some shortcomings in the RTM-CPMT, for example, the system requires a lot of data before the accurate diagnosis. Also, the relevant eigenvalue extraction and data mining algorithm remain to be studied. The system information model and knowledge base also need to be improved in order to include various errors.

Further research will be conducted in the industrial related mining algorithms and big data analysis based on RTM-CPMT. With the data visualization platform, the data volume keeps gathering. Intelligent analysis based on industrial big data is possible, and the data can be modeled using the powerful computing of cloud data centers. A mature and reliable data model can be trained for deployment in a local NC system, which can achieve cloud-local collaborative computing so as to make the system more intelligent and green.

Acknowledgments

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