INTEGRATED MONITORING SYSTEM BASED ON SERVICE ORIENTED IOT ARCHITECTURE IN OPEN STEP-NC ENVIRONMENT

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I would like to dedicate this thesis to

Al-Mighty "ALLAH S.W.T"

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My beloved

"Husband, Daughter, Parents and Family"

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ABSTRACT

One of the essential criteria for smart factories specifically the Open CNC machine tool, is bridging the gap between physical machine tool and software applications. The difficulties in this issue were the lack of efficient and sufficient monitoring systems that provide a solution for data acquisition, response, and feedback in real-time. In this study, a methodology to develop an integrated monitoring system to enable data acquisition, response, and feedback-based service-oriented internet of things architecture in STEP-NC based open CNC was proposed. The architecture comprises four main layers, perception, communication, application and CNC machine. The completed system was then tested through two case studies. The first case study is based on STEP-NC Example 1 of Part 21while case study two was based on modified STEP-NC Example 1 of Part 21. Both case studies are tested using a new and worn cutting tool. Based on the conducted case studies, the findings were summarized into four: First, the developed system successfully enabled data flow, from CNC machine tool back to CNC machine, via an integrated monitoring system based service-oriented IoT architecture in STEP-NC Open CNC environment. Secondly, the reading of temperature, vibration and electric current monitoring is higher for the worn cutting tool than the new cutting tool. Third, the percentage different between new and worn cutting tools for temperature is up to 3.38 % and for vibration, it is up to 78.93 %. Fourth, electric current reading is proportional to cutting force as the reading of electric current on cutting insert is higher than reading before cutting tool insert with percentage differences more than 8.33% up to 20%. The case studies summarized that the developed integrated monitoring system is feasible and highly sensitive to any changes, specifically on the cutting tool condition. In the future, this integrated monitoring system could be applied to other Open CNC machine-based plug and play.

ABSTRAK

Salah satu kriteria penting untuk kilang pintar khususnya mesin berbantu komputer terbuka adalah merapatkan jurang antara mesin fizikal dan aplikasi perisian teratas. Kesulitan dalam masalah ini disebabkan oleh kurangnya sistem pemantauan yang efisien dan mencukupi yang memberikan penyelesaian untuk pemerolehan data, respon dan maklum balas pemantauan waktu nyata. Dalam kajian ini, metodologi untuk mengembangkan sistem pemantauan bersepadu untuk membolehkan pemerolehan data, tindak balas dan maklum balas dan perkhidmatan berorientasikan seni bina internet bagi CNC terbuka dalam STEP-NC telah dicadangkan. Seni bina terdiri daripada empat lapisan utama yang meliputi lapisan persepsi, lapisan komunikasi, lapisan aplikasi dan mesin CNC. Sistem yang lengkap kemudian, diuji melalui dua kajian berskala. Kajian kes pertama berdasarkan contoh 1, STEP-NC Part 21 manakala kajian kes kedua berdasarkan contoh 1, STEP-NC Part 21 yang diubahsuai. Kedua-dua kajian kes diuji menggunakan mata alat yang baru dan rosak. Berdasarkan kajian kes yang dilakukan, penemuan ini diringkaskan menjadi empat yang meliputi: Pertama, sistem yang dibangunkan berjaya membenarkan aliran data dari mesin CNC kembali ke mesin CNC melalui sistem pemantauan bersepadu berdasarkan orientasi perkhidmatan arkitaktur IoT ke dalam CNC terbuka berasaskan STEP-NC. Kedua, bacaan pemantauan suhu, getaran dan arus elektrik lebih tinggi untuk mata alat yang rosak berbanding mata alat baru. Ketiga, peratusan perbezaan mata alat baru dan rosak bagi suhu adalah sehingga 3.38% dan bagi getaran adalah sehingga 78.93%. Keempat, bacaan arus elektrik berkadar dengan daya pemotong kerana bacaan arus elektrik pada sisipan pemotong lebih tinggi daripada bacaan sebelum pemotongan dengan perbezaan peratusan lebih daripada 8.33% sehingga 20%. Melalui kajian kes, dapat disimpulkan bahawa sistem pemantauan terpadu yang dibangunkan boleh dilaksanakan dan sangat sensitif terhadap sebarang perubahan, khususnya pada kondisi mata alat. Di masa depan, sistem pemantauan bersepadu ini dapat diterapkan pada mesin Open CNC yang lain berasaskan pasang dan laksanakan.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
3MP	Modern Monitoring Milling Process
AMQP	Advance Message Queuing Protocol
API	Application Programming Interface
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CCD	Charge Couple Device
CNC	Computer Numerical Control
CoAP	Constrained Application Protocol
CORE	Constrained RESTful Environment
CPMT	Cyber Physical Machine Tool
CPPS	Cyber Physical Production System
CPS	Cyber Physical System
DABASA	Design Anywhere, Build Anywhere, and Service Anywhere
DNC	Direct Numerical Control
DMS	Dedicated Manufacturing System
FMS	Flexible Manufacturing System
FMC	Flexible Manufacturing Cell
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
I4.0	Industry 4.0
IBM	International Business Machines
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IoS	Internet of Service
IIoT	Industrial Internet of Things

IoT	Internet of Things
IP	Internet Protocol
ISO	International Standard Organization
ITU	International Telecommunication Union
MITI	Malaysia Tread and Industry
MMFS	Manufacturing Message Format Standard
MMS	Manufacturing Message Specification
MQTT	Message Queuing Telemetry Transport
MT	Machine Tool
NC	Numerical Control
OPC-UA	Open Platform Communication United Architecture
OASIS	Organization for the Advancement of Structure Information Standard
PLC	Programmable Logical Control
PVDF	Polyvinylidene Fluoride
QoS	Quality of Service
RAMI4.0	Reference Architectural Model Industries 4.0
RFID	Radio Frequency Identification
RMC	Reconfigurable Manufacturing Cells
RMS	Reconfigurable Manufacturing System
SME	Small Medium Enterprise
STEP	Standard for Exchange of Product
STEP-NC	Standard for Exchange of Product compliant Numerical Control
TCM	Tool Condition Monitoring
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VDMA	Verband Deutscher Maschinen und Anlagenbau
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Background of research

In this chapter, an overview of the current manufacturing industry of global and Malaysia are introduced. The drawbacks of the conventional Computer Numerical Control (CNC) machine and the future view of the monitoring system integrated with a conventional CNC machine are discussed in the problem statement. Moreover, the objectives, scope and significance of the study are highlighted. Finally, the thesis structure is detailed at the end of this chapter.

1.2 Overview of Research

In recent years, significant advancement has been achieved in the industrial domain with the newest industrial revolution known as Industry 4.0 (I4.0). This new revolution was first initiated in 2011 at Hanover Fair, German, focusing on merged production with information technology and the internet as a higher-technology strategy [1]. The reasons for the emergence are to enhance the current manufacturing system into a higher level of flexibility in-terms of production and services, intelligence and autonomy [2]. Since the introduction, Germany, the United States of America, the United Kingdom, China, and the Republic of Korea are the leading countries embarking on the I4.0 transformation [3]. Their theme and aim for transformation are the same. The theme include data acquisition, data transfer, data analysis and data utilization for real-time information monitoring, response and feedback while developing a smart factory [4]. For a smart factory implementation, the Internet of

Things (IoT) and monitoring technology were adopted to empower the data management and service of the manufacturing information.

Machine tool is one of the most critical resource that facilitate smart factories. The CNC system under the machine tool works as a brain for a machine tool. The CNC system enables the machining process to be executed by allowing machine control movement automatically. The machine tool has possessed much advancement since it was introduced. Today, it has become a modern and highly sophisticated CNC machine tool [5]. Although many advancements have been made, the commercial system is still closed in nature. Users were not able to make any modifications without vendor intervention. As smart factories become fundamental, users' needs CNC technology to be easily integrated with other manufacturing resources such as computers, measurement devices, robots, and cyberspace. To deal with that issue, an Open CNC technology integrate with the internet enables vertical and horizontal integration is an urge [6]. One of the direct methods to support Open CNC technology was replacing the G-code programming standard with a new and powerful standard called STEP-NC. Where in this method, the STEP-NC program is used directly to handle CNC systems [7]. With this method, vertical integration of Open CNC systems that provide a universal and interoperable machining platform would be realized [8]. As smart factories demand intelligent and network manufacturing, sensor information from the monitoring system is important for machine process condition monitoring [9]. The horizontal integration of Open CNC with Internet would be realized by integrating Open CNC with IoT. IoT enable things to be connected to the internet and enable information to be transfer from one platform to the other or back to the platform.

The Open NC system has rapidly developed since the computer-based CNC system was introduced. Open CNC system refers to a software system that is free software or third-party software that offer a modular, reconfigurable and high level of automation to a manufacturing system [10]. This architecture easily handles user-specific functions and is able to cope with complicated parts [11]. A small modification of the code enables software to be reusable and enhance the machining system's performance [12]. The application of the Open CNC system keeps increasing. There are many Open CNC systems available today including Open System Architecture for Control within Automation Systems (OSACA), Open Modular Architecture Controller (OMAC), Open System Environment Consortium (OSEC), Linux NC and Twin CAT [7][13][14][15][16][17].

Under the umbrella of an Open CNC system, there are two approaches to realizing an open CNC system. Fully software-based CNC system and Open CNC system based on PC and motion control card [6]. Open CNC system based on PC and motion control card is a component approach. As per the review, there are machining and interpreter for the Open CNC system based on PC and motion control cards including [18] and [19]. However, there is still limited study applied for the monitoring system. Most monitoring studies applied a completely software-based Open CNC system which includes [4][20][6][14][15]. Only [19] and [21] applied a monitoring approach grounded Open CNC system based on a PC and motion control card. However, their studies only focus on component-based technology which does not support service-oriented IoT technology. Future more, Latif et al., [19] only applied live monitoring of the machining operation, which only visualized the machining process in real-time. While the monitoring system was developed by Adam 2020., [21] was only for drill bit monitoring and thermal monitoring in real-time based on a special device that is isolated and difficult to integrate. Both monitoring approaches were based on component-based technology, available for visualization only and do not offer any solution for service-oriented IoT technology that enable data acquisition, response, and feedback. Adopting service-oriented IoT technology on the current CNC will effectively and efficiently manage information and finally would significantly increase the productivity and savings of up to 50% and 40%, respectively [22], [23]. Therefore, a study on Open CNC system combine with service-oriented IoT technology is urgent.

1.3 Problem Statement

The CNC system plays a critical role in a machine tool. It works as a 'brain' and enables the machining process to be executed by allowing machine movement automatically. As I4.0 has become a massive initiative worldwide, there is a need for future advanced CNC technology to be integrated easily with other manufacturing resources to support smart manufacturing. STEP-NC, for example, was introduced in 1999 to solve the drawback of G-code [24]. As the STEP-NC based machining system becomes the future interest of researcher and academia, the CNC technology becomes more complicated and vendor-dependent. To deal with the close nature of the CNC machine, an Open CNC system is an urge [6].

Open CNC system allow users to freely utilize hardware and software and assemble it to any equipment type [18]. Personal computers for example, offer good open- ness, low cost and high performance to price ratio [19]. Most of the developed Open CNC system was developed completely based on software where each function is linked to each function to enable complete operation which is difficult to modify [7]. Based on the same approaches, several system have been developed using general purpose, object-oriented programming languages such as C, C++, JAVA, VB and others developed for machining, simulation, monitoring, optimization and others solutions [19]. However, the system was based on the indirect STEP-NC programming approach.

As the technology evolves, there is a need to empower the current CNC system with more and more features parallel with I4.0, Open CNC, STEP-NC compliant and equipped with an advanced monitoring system. An advanced monitoring system equipped with IoT enables data acquisition, response and feedback and supports service-oriented technology. The absence of a well develops monitoring system may finally results in undesirable conditions [25]. An undesirable condition such as bad tool condition, excessive tool wear and chatter occurrence may result in poor machining part quality, decreased productivity and decrease production efficiency [26][27][28][29].

The Monitoring system with data acquisition, response and feedback supporting service-oriented IoT technology enable monitored information to be managed and utilized effectively and efficiently. Open CNC based PC and motion control card compliant with STEP-NC enable interpreted information of the STEP-NC compliant system to be extracted and utilized for machining parameter response and feedback.

Based on the previous study, an Open CNC system based on PC and motion control card compliant with STEP-NC, which is available until now was developed for machining, interpreter and monitoring purpose by Elias et all.,[18], Latif et al.,[19] and Adam [21]. However, their monitoring approach was not focused on service-oriented IoT technology which supports service. It utilized a special monitoring device that is isolated and does not feasible for data acquisition, response, and feedback.

1.4 Objectives of the Study

The objectives of this study include:

i. To develop and implement milling process data acquisition in real-time via wearable devices through service-oriented internet of things architecture.
ii. To develop an integrated response and feedback system based on monitoring information in STEP-NC based Open CNC system.
iii. To validate the performance of the developed integrated monitoring system based on service-oriented internet of things architecture in STEP-NC based Open CNC through two case studies.

1.5 Scopes of the Study

The scope of this study includes:

i. The monitoring system was developed for a conventional Pro-light 1000 milling CNC machine.
ii. The monitoring system integrates the machining system and interpreter compliant STEP-NC (ISO14649) Part 10, 11 and 111 of the milling process from the previous Open CNC system-based PC and motion control card study.
iii. The monitoring system was developed under the Laboratory Virtual Instrument Engineering Workbench using Version 2016.
iv. The monitoring system analyzed cutting tool temperature and alert based on cutting tool softening point for different cutting tool material.
v. The monitoring system analyzed vibration between workpiece and cutting tool interaction under 16mm/s and alert based on vibration severity standard of ISO 10816.
vi. The monitoring system provide electric current utilized by the cutting tool spindle under 10A to prove the electric current utilized by the cutting spindle during machining operation is proportional to cutting force.
vii. The monitoring information is sensed at the specific position as mentioned above during the machining process, send to the cloud, and sent back to the machine based on service-oriented IoT architecture.

viii. The monitoring system enables response and feedback from machining parameters of spindle speed based on initial information extracted from STEP-NC interpreted information.

1.6 Significance of the Study

Innovation is defined as a new or improved production method that creates changes in technique, hardware, and software and enhances production quality, productivity, and efficiency. It was proved that manufacturing process innovation has a significant effect on operational performance [30]. This study intends to develop an integrated monitoring system that combine Service-oriented IoT technology with Open CNC in STEP-NC. The service-oriented architecture enables extendibility, reconfigurability, interoperability and cross-platform portability. These functionalities make the commercial CNC machine tool more flexible, adaptable, versatile, well-connected, widely accessible, smarter, and safer.

1.7 Thesis Structure

The work presented in this thesis deals with developing an integrated monitoring system to enable data acquisition, response, and feedback based service-oriented IoT architecture in STEP-NC based Open CNC, divided into six chapters. In chapter 2, a comprehensive literature review about the concerned technologies, reviews on past research, state of the art of STEP-NC, monitoring system, IoT and the research gap. In Chapter 3, the methodology adopted to address the research gap is presented. In Chapter 4, a detailed explanation of system development is covered. In chapter 5, the implementation and case study of the developed system is demonstrated. Finally, in chapter 6, the conclusion, research contribution, and future work are defined.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Machine tools have gone a lot of advancement since the industrial revolution until now. In the era of industrialization, the need for a future advanced machine tool to the next level to adopt and adapt with the I4.0 concept must be recognized. This chapter presents an overview of I4.0, the cyber-physical machine tool, the challenges and needs for developing cyber-physical machine tools based on vertical and horizontal integration and state of art of STEP-NC research. Besides that, a decade in review on the machine monitoring system, the CNC machine tool data acquisition methodology, the standard for communication and the state of the art of IoT has also been highlighted. At the end of this chapter, the research gap is defined and an approach of integrated monitoring system to enable data acquisition, feedback, and response-based service-oriented internet of things architecture in STEP-NC based open CNC has been proposed.

2.2 Overview of I4.0

In recent years, significant advancement has been achieved in the industrial environment domain by the introduction of I4.0. This new revolution was first initiated in 2011 at Hanover Fair, German, focusing on merging production with Information Technology and the Internet as a high-technology strategy for 2020 [1]. I4.0, also known as “smart manufacturing”, “industrial internet,” or “integrated industry,” which was announced to change the entire industry's ecosystem by changing the way entire systems operates through the combination of production and automation technologies [2], [31-32]. Automation technologies fueled by Information and Communication Technologies (ICT) enable integration between the physical world and virtual space [1], [33–35]. I4.0 is a new term for a new industrial paradigm that concerns Cyber Physical System, IoT, Internet of Services (IoS), Robotics, Big Data, Cloud Manufacturing, and Augmented Reality (AR) technologies for the future industry advancements.

In 2006, Dr. James Truchard introduced the CPS concept by merging the virtual and physical worlds [36]. CPS is the foundation of I4.0. It is the system that collaborates with a computational setup that enables to connect with surrounding, ongoing process, access data and utilized data, provide services based on the processed data through the Internet to accomplished predefine targeting a flexible manner [37]–[39]. In I4.0, CPS technology is utilized to create a Cyber Physical Production System (CPPS). CPS permits resources in the smart factory to become more intelligent and at the same time creates an intelligent production environment. IoT is the foundation of technology utilized to support CPS and the entrance key to realize the new paradigm, I4.0 [40]. IoT transforms physical things into a virtual network to support smart manufacturing. Adopting these technologies into the existing industry enables devices, machines, products, production activities, and other resources to exchange information, trigger actions and control and finally create an intelligent industry environment. This proposition permits enhancement of productivity and efficiency not only to a manufacturing factory but also to the rest of manufacturing factory that adopting and adapting this new paradigm [36], [39]. I4.0 offers vast potentials and opportunities to the economy and societies based on the transformation from classic work organization, business model and production technology into the new paradigm of work organization, business model and production technology [41]. Besides that, I4.0 also promises to tackle global challenges such as sustainability, resource, energy efficiency, and competitiveness [1], [42].

The production evolution based on manufacturing advancement resulting from the Industrial Revolution from first to fourth is illustrated in Figure 2.1. In 1999, as globalization began, the landscape of production also changed [43]. Manufacturing field facing unpredictable market changes that require different and complex parts rapidly. This complexity, personalization, and regionalization are not able to be fulfilled by the central production system. To answer these requirements, an advanced manufacturing system that enables Reconfigurable Manufacturing System (RMS), intelligent manufacturing, flexible manufacturing, online manufacturing, agile manufacturing methods is essential [44]. Furthermore, it requires an appropriate technology that allows information exchange among reconfigured industrial devices and systems for production networks toward CPPS. This could be only realized by the implementation of cyber physical concept.

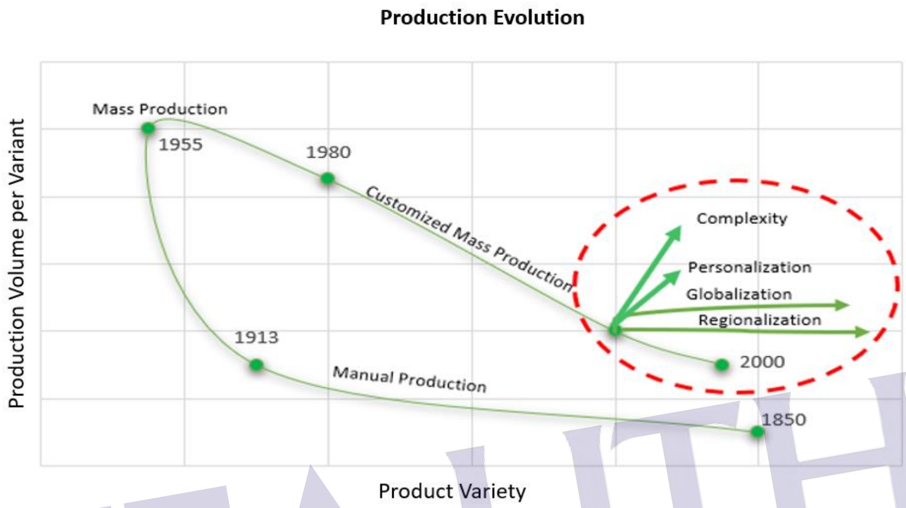

Figure 2.1: Product Revolution [45]

2.3 CNC Machine Tool

I4.0 focuses on creating smart products and processes using smart machines for smart manufacturing systems toward smart factories and finally realizing the cyber-physical production system [41]. The term “Smart” refers to autonomous and independent devices that enable communication in real-time, collaborate with other smart devices, make decisions, and perform an action in a smart environment [46]. CNC Machine tool is one of the main resources under the manufacturing environment that significantly impacted manufacturing productivity and efficiency since the industrial revolution. It is claimed to be a ubiquitous instrument of modern manufacturing [33].

In the dawn of I4.0 and response to the CPPS and smart factories, an effort to create a new generation of machine tools known as MT4.0 or cyber-physical machine tool has become essential. The necessity to cut or shape metal or rigid materials into the desire form in the industrial revolution 1.0 give birth of MT1.0 while the next tool path guided by machine gives birth to MT2.0 and digital revolution resulting from computer application advancement resulted CNC based machine in MT3.0 and now continuously growth MT 4.0. The development of machine tool to a large extent mirrored industrial revolutions and results in the country growth. The evolution of machine tool with the industrial revolution is illustrated in Figure 2.2 [47]. Under the evolution of MT1.0 to MT3.0, today machine tool becomes more economical, resource-efficient, provide more function, flexible, adaptable and equipped with a high technological component such as bearing, drive motor and others [48]–[53]. However, the commercial CNC machine is still isolated [33] and the architecture become more and more complex.

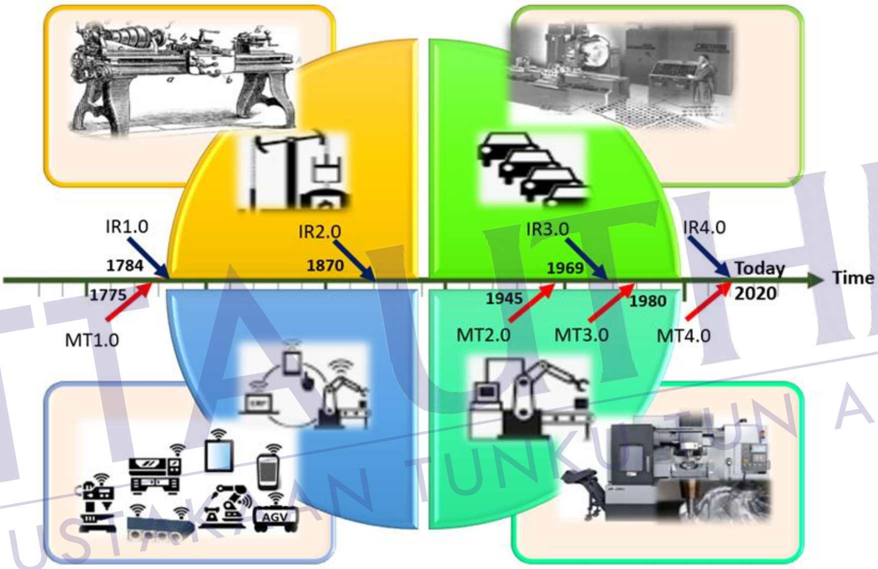

Figure 2.2: Industrial revolution versus machine tool revolution [47]

2.4 Cyber Physical Machine Tool (CPMT)

CPMT is the new term of MT4.0, which was inspired by CPS's recent advancement. CPS is generally defined as technology innovation that manages the interconnected systems via physical and computational environment integration [41]. Xu [47] defines CPMT as integrating machine tools, machining processes, computation, and networks that permit machining process monitoring and control. Liu et al. [54] describe CPMT as the integration of machine tool with machining processes in cyberspace through computation and networking ability to create CPS. CPMT has a clear-cut advantage compared to the conventional machine tool. Embedded computation facilitates real-time information, and decision-making support endows CPMT with advanced intelligence and autonomy. Connectivity and ubiquitous networking create product-service CPMT systems. With the CPMT system, machining performance and efficiency would be significantly improved. Development of CPMT system focuses the integration of machine tool vertically and horizontally [27]. The implementation of vertical and horizontal integrations allows machine tool to be more flexible, more adaptable, versatile, well connected, smarter, and safer.

2.5 Vertical Integration of Machine Tool

Vertical integration of machine tool is termed by the end-to-end digital integration. The end-to-end digital integration integrates engineering, including design, process planning, manufacturing, assembly, and others. As a matter for the machining process, the term end-to-end integration referred to the integration from design to manufacturing, including part design, part design model, detail process planning, path process planning, and manufacturing process. The integration is successfully realized when all the information from design to manufacturing is available without any data losses. Unfortunately, the current CNC machine, MT3.0, as illustrated in Figure 2.3, is still predominantly using G-Code programming language since the 1950s [47], [55], [56]. G-code only delivers minimum information to the CNC on how-to-do information. It breaks the information to be flown between the CAx chain, unable to access the internal code, limited bandwidth. It does not offer shop floor modification [28], [57], making the MT3.0 less flexible, less intelligent, and unbearable.

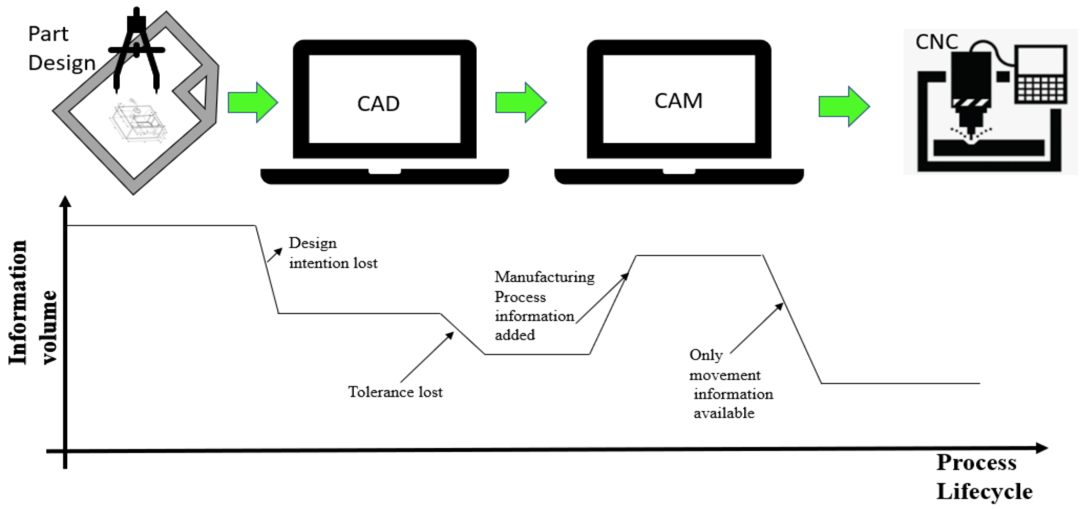

Figure 2.3: Information flow in existing machine tool, MT3.0 [47]

STEP-NC namely call as Standard for the Exchange of Product model data compliant with Numerical Control, guarantees to resolve G-code drawback and enable integration from design to manufacturing without data losses as it is compliant with STEP [47]. Furthermore, STEP-NC provides detailed information on what-to-do information. To sum up, these facilities provide an enormous interoperability platform and are vertically integrated into the manufacturing system [58]. Figure 2.4 illustrates the information flown capability via STEP-NC to realize MT4.0 as STEP-NC provides vertical integration capability, CAM and CAPP as consolidated with the CNC machine. Such capabilities enable CNC machines directly to interact with design model CAD. To do so, Open CNC compliant STEP-NC can provide smarter decisions dynamically and adaptively. Some previous study that had been done for open CNC system are [18], [19], [59]–[64].

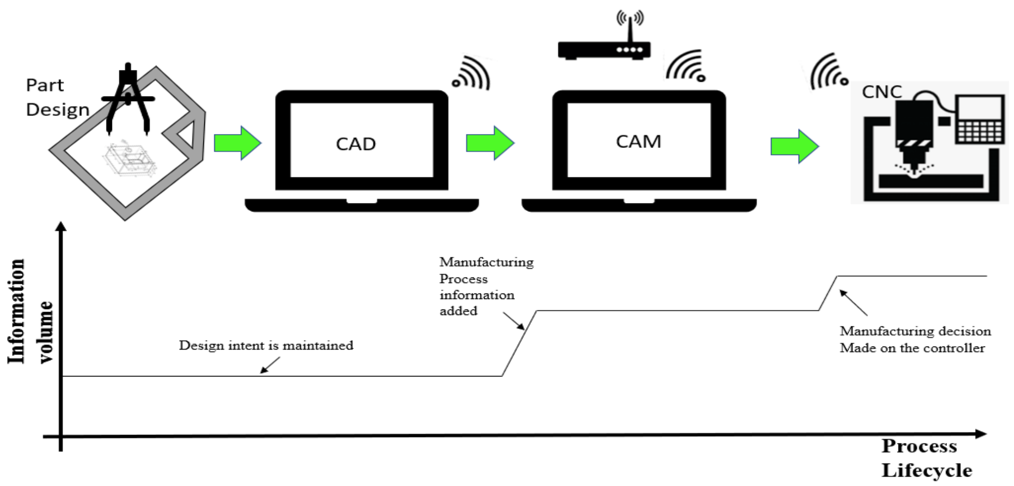

Figure 2.4: Information flow in MT4.0 [47]

STEP-NC includes several parts, as listed in Table 2.1. The arrangement of the part is based on the hierarchy-tree method. Start with general process data Part 10, followed by process data for milling or turning Part 11 or Part 12, respectively, and finally followed by a description on Tool data for milling or Tool data for turning known Part 111 or Part 121, respectively. The STEP-NC file-based object-oriented data model structure is illustrated in Figure 2.5 [57], [65].

Table 2.1: ISO 14649 Parts [66]

ISO14649 Part	Specification	Details
Part 1	Overview and Fundamental Principles	Provides an introduction and overview of a data model for CNCs, basic principles and advantages.
Part 10	General Process Data	Provides basic capabilities for machining parts process planning.
Part 11	Process Data for milling	Provides specific process planning capabilities for milling machine
Part 111	Tools for Milling	Provide description on Tool data for milling
Part 12	Process data for turning	Provides specific process planning capabilities for turning machine
Part 121	Tools for Turning	Provides description on Tool data for turning

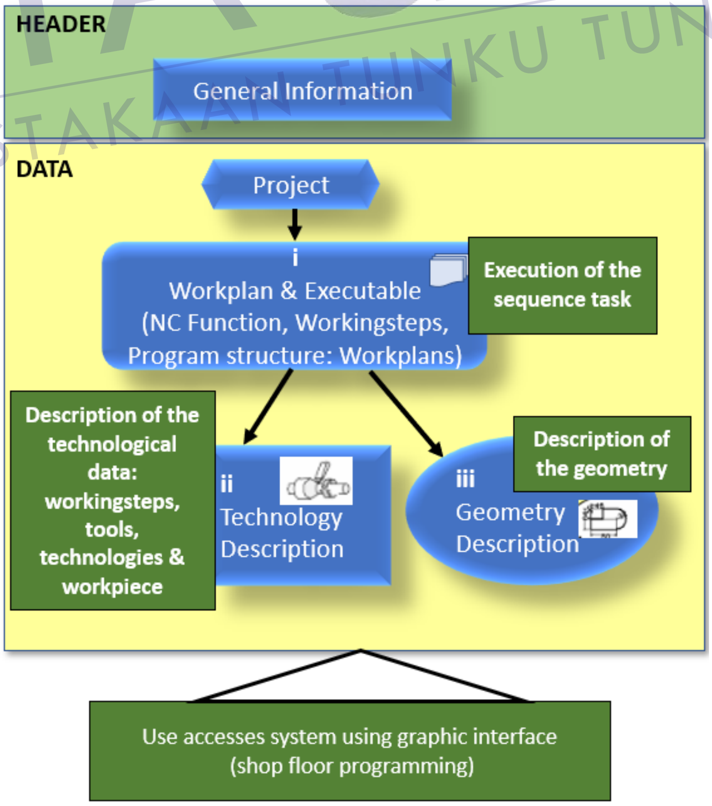

Figure 2.5: STEP-NC file based object-oriented Data model structure [67]

ISO released the physical representation of STEP-NC Example 1 for research activities is illustrated in Figure 2.6. Example 1 consists of three features, which include a planar face, round_ hole and pocket. The code programming for the implementation of Example 1 is as in APPENDIX A.

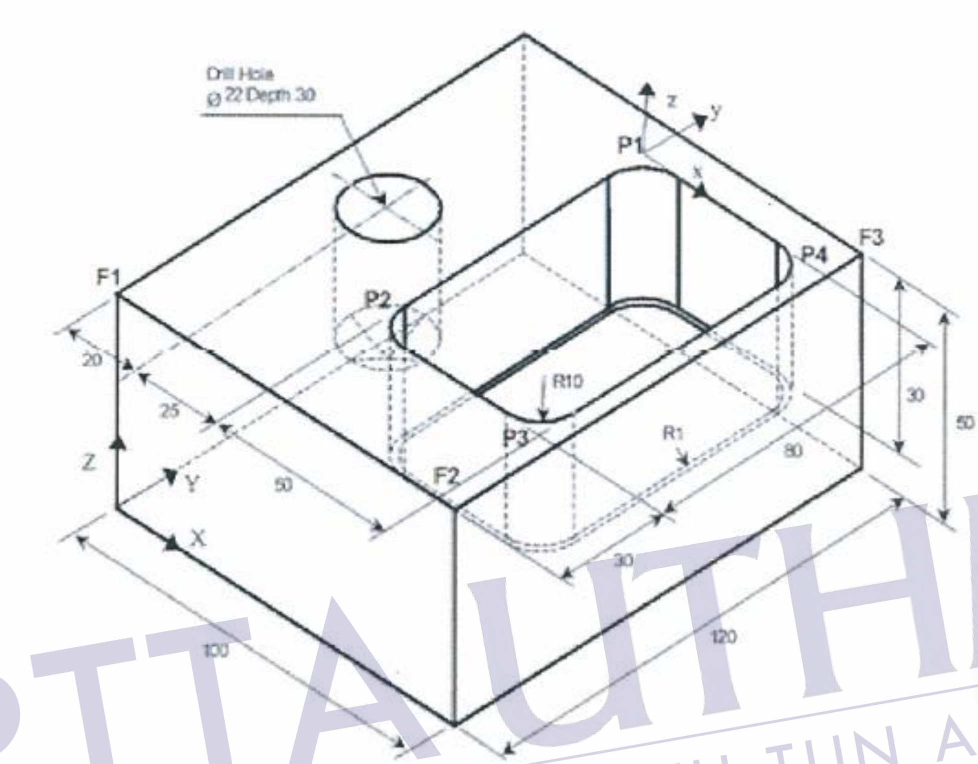

Figure 2.6: Physical representation of STEP-NC Example 1

2.6 Horizontal Integration of Machine Tool

Horizontal integration of machine tools integrates machine tools with other manufacturing facilities and resources that include robots, conveyors, measurement devices, and others to realize collaborative production [27]. The key requirement of horizontal integration of machine tool with other manufacturing facilities and resources is divided into two: acquire accurate and reliable information, data integration and communication capability through feedback and response facility.

2.6.1 Acquire Accurate and Reliable Information

CNC machine tools are composed of different components and utilized different peripheral devices with different brands and capabilities. CNC machine tools generate a large amount of information during machining, influencing product quality, productivity, and production efficiency. Furthermore, the CNC controller provides some useful information such as axis position, speed, feed rate and others, but lacks critical information that directly influences the machining operation such as workpiece or tool or machine vibration, cutting force, temperature and other information [33], [68]. In the direction to realized MT4.0, a comprehensive representation of machine tools in a cyber world is essential. A standard information model together with real-time information of machine tool critical components must be established.

2.6.2 Data Acquisition Technology

Despite different data acquisition technologies available today, the most critical issue is how to match the information from one machine to another machine and device to device to enable data integration and communication for feedback and response [47]. It may vary by the meaning, wording, units, values, and others. As mentioned earlier, CNC system provided some real-time information, however not all CNC system was available to be accessed. For example, Linux CNC can be accessed through the Application Programming Interface (APIs). Nonetheless, some CNC system are vendor-specific, such as FANUC, Siemens, and Haas, requiring specific adapters to enable access [47], [69]. MT Connect and Open Platform Communications United Architecture (OPC-UA) are currently open-source standards that allow solving data integration and communication issue for feedback and response, however, both adapters have their limitation. Therefore, to enable data integration and communication between machine to machine or device to device, an open, consolidated, and standard communication platform enables data flow to be implemented.

2.7 State of the Art of STEP-NC Research

With over 60 years of CNC development, the CNC system has become more powerful, reliable, and secure. On the other perspective, the CNC system has become exclusive all the time. The exclusivity refers to the unstandardized of both hardware and software on CNC system [7]. To be more specific, the CNC software made of vendor-specific CNC domain logic includes traditional machining, additive machining and hybrid additive and subtractive machining [70]. With this proprietary software, the user unable to do any modification to adapt with new or other features. Furthermore, this proprietary software is also tightly integrated with a vendor specified hardware platform which offers limited capabilities such as limited memory capacity, limited CPU performance and others. Besides that, users cannot migrate the CNC software to seamlessly to a more powerful platform [7]. In a nutshell, commercial CNC systems are proprietary and stand-alone. All this complexity made available CNC system unsuitable for today's manufacturing environment as it may cause [19], and [4]:

i. Difficulties in modifying its functionality with freedom.
ii. Unable to distribute or migrate the software application to another platform seamlessly.
iii. Increase the cost of installation, commissioning, training, and maintenance and increase the value of the CNC system.

Therefore, to deal with those issues, the development and implementation of Open CNC was motivated and became the hottest topic in the last three decades. According to IEEE, *an open system provides capabilities that enable properly implemented applications to run on various of platforms from multiple vendors, interoperate with other system applications and present a consistent interaction style with the user* [6][71]. It is broadly accepted that open CNC should be vendor-neutral and standard-based software that is independent and allows function extendable and reconfigurable and enables software system to be interoperable and portable so its usefulness could be customized for users [4][10].

In the development of Open CNC applications, Component-based software development (CBSD) is widely utilized. It is referred as an Open CNC application approach built by composing a set of components. Each component is implementing specific CNC sub-domain logic that enable extendibility and reconfigurability. Service Oriented Architecture (SOA) is the evolution of CBSD. SOA composed of more domain logic, enabling extendibility, reconfigurability, interoperability and cross-platform portability [7]. Both service and component support independent deployment and reuse. However, service is not constrained by a specific component model and is independent of the infrastructure platform. An SOA is a set of components that can be invoked and whose interface descriptions can be published and discovered. SOA has been introduced to address the Dynamic Link Library (DLL Hell) issues of CBSD[72]. “DLL Hell” issues happened due to an incompatible version of the component on which the component was compiled. SOA enables to cover the emergence of varying platforms, varying protocols, various devices, the internet and others by enabling information to be subscribed by other independent software via RESTful HTTP APIs or lightweight messaging [73].

In the era of I4.0, rapid advancement in computer application, information and communication, the internet and smart devices gave birth to multi approach automation such as smart manufacturing [74], cloud manufacturing [75] , industrial internet of things (IIoT) [14], and cyber-physical concepts [27]. The core of all the automation approaches is the integrating manufacturing resources and their information vertically and horizontally. In this way, the manufacturing systems are digitized and interconnected. Physical machine tool are developed in cyber space by using sensors, cameras, RFID tags and readers, signal processing devices, and so forth [47]. Various CNC resources and information are collected, maintained, and shared in a powerful platform. With all the resource and information available on the cloud platform, different CNC functions would be loosely executed, for example monitoring, inspection, optimization and others [76]. Thus, SOA architecture is suitable for CNC platforms instead of CBSD to cope with diversity and infrastructure platform [7].

Based on the review made for in the last five years, from 2017 to 2021 in the field of STEP-NC, a total of 74 articles were reviewed and summarized as shown in Table 2.2. The study conducted includes review work, framework development and system development and implementation. Throughout the review on the past five years, the research trend was on adapting and adopting the I4.0 concept to the CNC system. The research conducted not only emphasis on Open CNC machining system implementation, but also monitoring, optimization, inspection, and others. In 2020, Jovanović [6] summarized the Open CNC system into two: first, an Open CNC system based on a Personal computer (PC) and motion control card and the second, completely software-based CNC system. Both approaches functionality is proficient by the utilization of software on PC. Good openness, low cost and high performance to price ratio made PC a preferred hardware platform for open CNC systems [77]. The software-based CNC system utilized software for overall system development, while the Open CNC system based on PC and motion control cards integrates the reusability of software with a redesigned hardware platform for more interoperability, portability, adaptability, and open system [18].

Table 2.2: Research on Open CNC system (from 2017-2021)

Author, Year, Country	**Title**	**Machining Type**	**CNC Domain (Function)**			**ISO Standard**	**Software & Type**	**Research Focus**	**Method**	**Parameter**	**Limitation**
Basharat-Foumani et al, [78], 2021, Finland	Fundamentals and new achievements in feature-based modeling, a review	-			-	-	-	Review Work	-	-	-
Liu et al., [12], 2021, China	An efficient machine tool control instruction compression method for networked numerical control systems,	Milling			Controller	-	-	Development and Implementation of machine tool control instruction compression method	Applied Different Algorithm to enable data transmission for network		-
Liu et al., [4] 2020, China	A method of NC machine tools intelligent monitoring system in smart factories	Milling	NCK	PLC	HMI	-	SOA	Framework and implementation of monitoring system	Data acquisition and integration through OPC-UA between machine and upper application	Multimachine monitoring, spindle speed, motor temperature	Complex data acquisition methodology

Table 2.2: Research on Open CNC system (continue)

Author, Year, Country	**Title**	**Machining Type**	**CNC Domain (Function)**			**ISO Standard**	**Software & Type**	**Research Focus**	**Method**	**Parameter**	**Limitation**
Mourad et al, [76], 2020, UK	Assessment of interoperability in cloud manufacturing							Focusing on six drivers of big data applications in manufacturing	Investigation on financial matter toward interoperability		
Cui et al., [79], 2020, Australia	Manufacturing big data ecosystem: A systematic literature review									Monitoring, prediction, ICT framework and data analytics are the four most frequently used big-data applications in manufacturing.	
Liu et al., [20], 2020, China	Development of a novel component-based open CNC software system	Milling	NCK	PLC	HMI	G-Code	CBSD and DIP	Development of Open CNC system with through Component and decomposition method	CBSD	-	G-code based
Saif et al.,[80], 2020, Malaysia	Systematic review of STEP-NC-based inspection					STEP STEP-NC: ISO14649, STEP-NC: AP 238		Research was focus on STEP-NC implementation CNC system and inspection			

Table 2.2: Research on Open CNC system (continue)

Author, Year, Country	Title	Machining Type	CNC Domain (Function)	ISO Standard	Software & Type	Research Focus	Method	Parameter	Limitation
Saif et al., [81], 2020, Malaysia	A Framework to develop intelligent system for measuring product features using Open-CV technique	Milling	NCK, PLC, HMI	ISO 14649	SOA	Inspection	Vision system inspection via Open-CV	Machining feature hole, pocket, planar face	
Tengku Mohd Sharir et al.,[82], 2020, Malaysia	File and PC-Based CNC Controller using Integrated Interface System (I2S)	Milling	NCK, HMI	G-Code STEP STEP-NC	CBSD	PC-based CNC controller through integrated interface	The system read and extract machining information from STEP file as an output from G-code		G-code
Srivastava & Komma [83], 2020, India	Systematic development of an interface for automatic generation of STEP-NC (AP238) code for milled feature	Milling	Interface	AP203 AP 244 STEP-NC AP 238	JSDAI for EXPRESS compiler and Java for interface	Extract data from AP203 & AP 244, feature recognition, process parameter selector and generate STEP-NC AP238 code in Part 21 format	Convert AP 203 and AP244 to AP238 in Part 21 format file for	Systematic development of an interface for automatic generation of CC3 level of STEP-NC AP238 code using JSDAITM	

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Table 2.2: Research on Open CNC system (continue)

Author, Year, Country	Title	Machining Type	CNC Domain (Function)	ISO Standard	Software & Type	Research Focus	Method	Parameter	Limitation
Othman et al.,[84], 2020, Malaysia	Design and development of a 3-Axis vertical milling machine control logic architecture	Milling	NCK		HMI	IEC 61499 function		Motion control subsystem	motion control subsystem using IEC 61499 function block
Kubota et al., [85], 2020, New Zealand	STEP-NC enabled machine tool digital twin	Milling		STEP-NC ISO 14649		Machine tool digital twin	Data transfer using OPC-UA	Knowledge based and Machining parameter Optimization	
Adam., [21], 2020, Malaysia	Development of sustainable platform controller for STEP-NC compliant open CNC system	Milling	HMI	STEP-NC: ISO 14649	LabVIEW Version 2016, CBSD	PC-based CNC controller	CBSD	Thermal monitoring, machining monitoring, Argument Reality	The system does not include service-oriented architecture
Jeon et al.,[86], 2020, South Korea	The architecture development of Industry 4.0 compliant smart machine tool system					Provide architecture for the development of I4.0 compliant smart machine tool	Intelligent CNC system, AI, machine learning		

Table 2.2: Research on Open CNC system (continue)

Author, Year, Country	Title	Machining Type	CNC Domain (Function)	ISO Standard	Software & Type	Research Focus	Method	Parameter	Limitation
Martinov et al., [75], 2020, Russia	From classic CNC systems to cloud-based technology and back	Milling		NCK	Cloud based terminal (HMI, PLC, and others)	G-code		Pc based CNC controller	Cloud based CNC system
Jokkanovi., [6], 2020, Bosnia and Herzegovina	Towards an Open CNC	Turning			PC based open system: Completely software-based CNC control.	G-code	VS2013	Software based controller	Open CNC architecture based on modest servo drive, common communication devices and open-source microcontrollers
Gua and Sun ., [17], 2020, China	Research and development of monitoring system and data monitoring system and data acquisition of CNC machine tool	Turning	PC based open system: Completely software-based CNC control.	G-code		Software based controller	Open CNC interface MT connect. Established hierarchical object-oriented Petri net model of machining tasks	Numerical control machining task modeling, machining task prediction, and processing task progress monitoring	G-code Read data only

Table 2.2: Research on Open CNC system (continue)

Author, Year, Country	Title	Machining Type	CNC Domain (Function)	ISO Standard	Software & Type	Research Focus	Method	Parameter	Limitation
Cao et al, [87], 2020, China	Digital Twin–oriented real-time cutting simulation for intelligent CNC machining	Milling			HMI	STEP-NC		Software based simulation	Open CNC interface MT Connect and OPC-UA for data communication and integration
Lu et al., [74], 2020, New Zealand	A critical review of the standards and envisioned scenarios	-				ISO14649 ISO AP238		Focus on different type of standard for smart manufacturing process and system	MT Connect for monitoring standard
Liu et al, [7], 2020, China	A review of the application of CBSD in open CNC systems						Highlight component based open CNC		
Latif et al., [28], 2019, Malaysia	The Importance of STEP-NC in the IR 4.0 Manufacturin g Systems					highlighting the history and concept of IR4.0 in manufacturing system, limitation of G-code, advantage of STEP-NC			

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