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基于MTCONNECT设计和实施信息物理系统云制造

DESIGN AND IMPLEMENTATION OF CYBER-PHYSICAL MANUFACTURING CLOUD USING MTCONNECT

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ABSTRACT

Cyber-physical systems are gaining momentum in the domain of manufacturing. Cloud Manufacturing is also revolutionizing the manufacturing world. However, although there exist numerous physical manufacturing machines which are network-ready, very few of them are operated in a networked environment due to lack of scalability of existing cyber-physical systems. Combining the features offered by cloud manufacturing and cyber-physical systems, we develop a service-oriented architecture of scalable cyber-physical manufacturing cloud with MTConnect. A testbed of cyber-physical manufacturing cloud is being developed based on the above scalable architecture. In this system, manufacturing machines and their capabilities virtualized in a cyber-physical cloud. Manufacturing operations are represented as web services so that they are accessible across the Internet. Performance of the testbed of our cyber-physical manufacturing cloud with MTConnect is evaluated and test results show that our system achieves excellent service performance of manufacturing operations across Internet.

物理信息系统和云制造对制造业有革命性的意义。
虽然说现在很多制造机床已经联网，但由于缺少物理信息系统很少处于网络环境之中。

1 INTRODUCTION

Cloud Manufacturing (CMfg) is globalizing the manufacturing processes by providing remote engagement of intermediary operations to manufacturers and consumers [2]. CMfg extends traditional manufacturing by integrating the following technology stack - cloud computing, Internet of Things (IoT), resource virtualization, service-oriented technologies, artificial systems, and diversified applications stack [10]. CMfg usually transforms manufacturing services into web services that open up the interfaces in the Internet. It also enables sharing of machine resources between factory floors, thus increasing opportunities for start-up businesses to avoid the risk of big initial investments. In addition, CMfg brings diversity of manufacturing resources of a manufacturing system along with its distributed nature. However, the implementation of CMfg is at an early age; we have yet to see a CMfg environment that has complete control on its operations across the Internet. Modern manufacturing machines need more improvements with respect to interconnection capability over the Internet to provide an effective cloud management and control.

云计算 物联网 共享机床资源

On the other hand, cyber-physical systems (CPSs) are being used increasingly in the manufacturing systems to improve the machine connectivity and intelligence. Therefore, CPSs have an important role to play in the Cloud Manufacturing environment. Cyber Physical Systems (CPS) integrate computation, networking, and control with physical processes [27]. Integrating the utilities of CPSs can increase real-time operational capability of manufacturing processes and utilization, configurability and customization of manufacturing resources. However, CMfg and CPS were researched and developed independently from each other in the past. It would be significant to integrate them to develop a Cyber Physical Manufacturing Cloud (CPMC) to provide combined benefits from both of them. Therefore, we construct and present a scalable service oriented architecture of Cyber-Physical Manufacturing Cloud in this paper. In the CPMC architecture,

提高机床连通性和智能性 计算 网络 控制

both characteristics and capabilities of manufacturing machines can be virtualized and made accessible from the Internet. The architecture is highly scalable due to the service-oriented 高扩展性 approach for communication to the manufacturing resources. In our CPMC, we virtualize two types of manufacturing features - characteristics [12] and capabilities [13, 14, and 17]. To maintain high scalability of the CPMC architecture, we develop XML based standard data formats for representing manufacturing characteristics and capability services.

A testbed 试验台 has been implemented based on the architecture of CPMC 物理制造云系统. In the testbed, the characteristics and capabilities of the manufacturing resources are virtualized by RESTful web services and the data format is based on XML. In the implementation, to comply with the manufacturing environment, we use MTConnect, a popular RESTful Internet communication protocol 通信协议, for collecting real-time data 实时采集数据 of manufacturing machines and monitoring them over the Internet in the testbed. MTConnect uses XML for managing and communicating manufacturing data [1]. However, MTConnect is generally used only for monitoring machine status. It doesn't control and execute operations of manufacturing machines. 只能用来监控机床状态，不能用来控制和执行操作 In order to overcome this challenging issue, we create Web services directly based on TCP/IP to execute operations of manufacturing machines. 基于TCP/IP技术 执行机床操作

The next section will present the background and related works. In section 3, an architecture of CPMC with component's interactions will be presented. The testbed implementation will be discussed in the section 4. Use of MTConnect in testbed will be elaborated in the section 5. Section 6 will present use cases of our CPMC. Rest of the sections will discuss about the performance analysis of the implementation, future work, and conclusion of the experiments.

2 LITERATURE SURVEY 文献调研

CMfg 云制造 is a game changer paradigm in the manufacturing field of research. It is leading the manufacturing processes controllable by a cellphone right from our pocket. Several impressive researches have been conducted on the architecture of CMfg. Tao et el [10] proposed a computing and service-oriented manufacturing model describing a ten layer CMfg architecture detailing the traditional manufacturing processes Tao 等人提出了一个计算和服务模型，描述了十层的云制造架构。 and applications. The architecture also gives primary insights on the manufacturing machine virtualization compared to the virtualization techniques on Cloud Computing. The disadvantage with the ten layer architecture is that the delays may harm the real-time performance of the manufacturing 缺点：对实时采集有影响 systems. Another high level four layer architecture of CMfg is proposed by Xu [2]. In addition, several comprehensive researches have been done on the state-of-the-art review of CMfg [3, 4, 5, and 6]. The above research efforts represent preliminary progresses on scalable architecture of CMfg but they do not meet unique needs of CPSs, which integrate internet technology, deeply embedded computing, automatic control and monitoring, and networked manufacturing. Of critical need is to develop a scalable architecture of cyber-physical manufacturing cloud.

虚拟化制造资源 Virtualization of manufacturing resources is important when it comes to cloud-based cyber-physical manufacturing systems. Liu et al [12] proposed an approach of virtualizing manufacturing resources by representing machine characteristics and service encapsulation using XML 使用XML虚拟化制造资源 [18, 19, 20]. Liu et al, Yan et al and Lin et al proposed a multilevel framework [13, 14, and 15], creating layers of representation of functional capabilities of machines using web ontology 本体论 language. Zhao et al [16] developed a system which represents the machine characteristics using RESTful web services. Ameri and Dutta [17] proposed a manufacturing service description language (MSDL). The main issue with the above virtualization approaches is that they consider either machine characteristics or machine capabilities, but not both. Of critical need is to develop an ontology based virtualization method capturing both machine characteristics and capabilities.

Virtualizing manufacturing services requires a uniform data standard. 需要统一的数据格式 In general, RESTful web services are invoked by XML data formats and for manufacturing context, MTConnect is already an XML based machine status monitoring data protocol which is very popular among the manufacturing resource providers. Thereby the use of XML data specified by the MTConnect standard carries tremendous potential for virtualization. Xu [2] proposed the use of MTConnect for the virtualization of the manufacturing units. Vijayaraghavan and Sobel [25] explained the integration of manufacturing system using MTConnect detailing the machine specific relational data. Vijayaraghavan and Sobel [26] described the use of MTConnect enabling process planning and verification in an industrial environment and detailed the relations of MTConnect standard data with the capabilities of manufacturing machines. MTConnect as a communication standard is viable for real-time data operations was shown by standard experiments by Michaloski and Venkatesh at el [24]. An alternative of MTConnect standard has been proposed by Lin et el [23] which is TMTC (Taiwanese Machine Tool Connect) protocol where the integration of different type of Adapters were implemented in a single machine increasing the scalability of the implemented system. Although MTConnect supports only machine monitoring operations, it is yet to become a protocol for operating Cyber-physical systems.

There has not been much effective implementation of CMfg environment due to the lack of service virtualization technologies. To virtualize the machine characteristics, Venkata et al [29] implemented a broker for Cloud Additive Manufacturing Services. Mai et al [28] implemented a testbed of customized production on distributed 3D printing services in CMfg. However, the implementations discuss about the method of virtualizing manufacturing resources but doesn't propose any virtualization data standard. In our implementation of the testbed, we discuss virtualization of both the manufacturing resource characteristics and capabilities. We also demonstrate

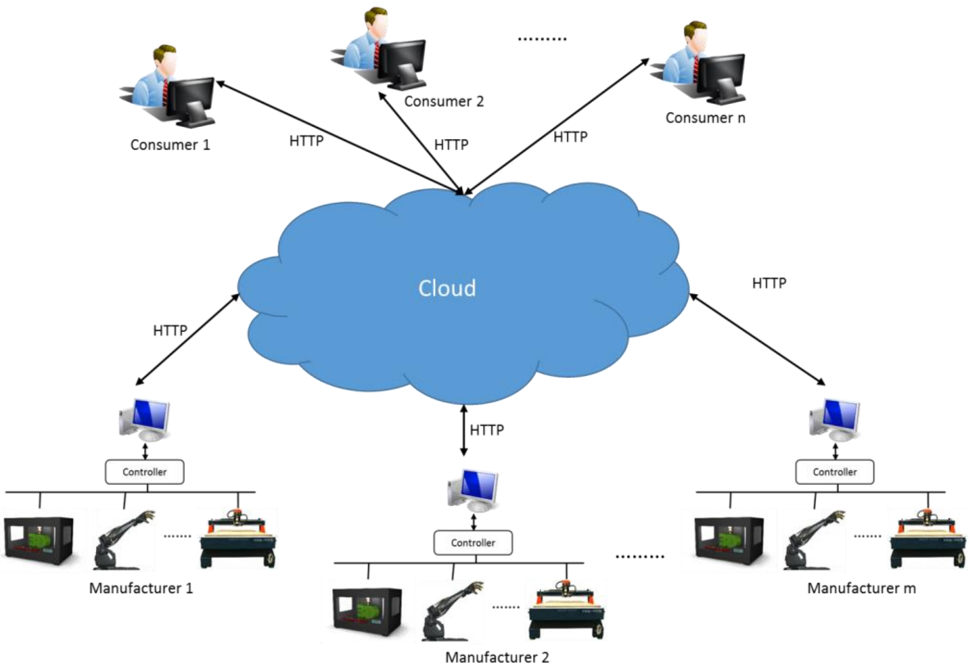

Figure 1: Conceptual framework of CPMC

the implementation of MTConnect as a partial communication standard. The test results show that the testbed implementation is capable of transformation to factory floor standard implementation.

3 CPMC ARCHITECTURE 基于云的物联网系统架构

A conceptual framework of Cyber-physical Manufacturing Cloud (CPMC) is presented in *Figure 1*. CPMC consumers access manufacturing virtual services over the Internet. Manufacturing virtual services are hosted in a local server inside the manufacturing environment and published by the manufacturers to be able to accept secured commands from the cloud. To establish secured and real-time communication between CPMC consumers via applications and manufacturing virtual services, cloud provides necessary infrastructure. For representational purpose, a controller component is added in the framework in between the local server and the machine network. Manufacturing machines inside the factory floor can have any type of network and infrastructure, our conceptual framework only communicates with the manufacturing virtual services. All the communications from the CPMC cloud to the local servers are done by stateless RESTful protocol.

CPMC inherits 继承 the traditional manufacturing processes of CMfg. CPMC extends the direct integration of Cyber-physical Systems into manufacturing. From the conceptual framework of CPMC, the key challenges in the architecture are – 1) The architecture needs to enable Internet access to the 架构需要联网在制造过程中 manufacturing processes and 2) the proposed framework needs to perform real-time 实时操作 operations. In general, CMfg architecture includes a lot of service-oriented layers and each layer adds certain communication delay during the manufacturing processes reducing real-time performance capability. Therefore, a four layer architecture of CPMC is presented in the next subsection.

3.1 Layered architecture overview 架构层次概述

In *Figure 2*, the four layer architecture of CPMC is presented. The number of layers kept low to prevent delays in between cross layer service calls. Although Internet delays occur from different reasons, the primary target is to be able to perform real-time manufacturing operations. The layers of the architecture are as follows –

- **Application Layer:** 应用层 The layer that contains manufacturing applications for multiple operating platforms. Applications of this layer can be hosted in the Cloud or from the user computer or smartphone devices.
- **Core Cloud Layer:** 云核心层 The layer that provides support of CMfg infrastructure and manufacturing resource virtualization database. Services of this layer are hosted in the Cloud.
- **Resource Virtualization Layer:** 资源虚拟化层 Every cyber physical manufacturing resources are virtualized in a service-oriented approach according to the characteristics and capabilities. The services for virtualization can be hosted in a Cloud environment or can be hosted within the manufacturing environment depending on the manufacturing process.
- **Resource Layer:** 资源层 This layer contains the cyber physical manufacturing resources. The networking infrastructure of the cyber physical manufacturing resources depend on the manufacturers and the manufacturing resources are taken as black boxes in the CPMC context.

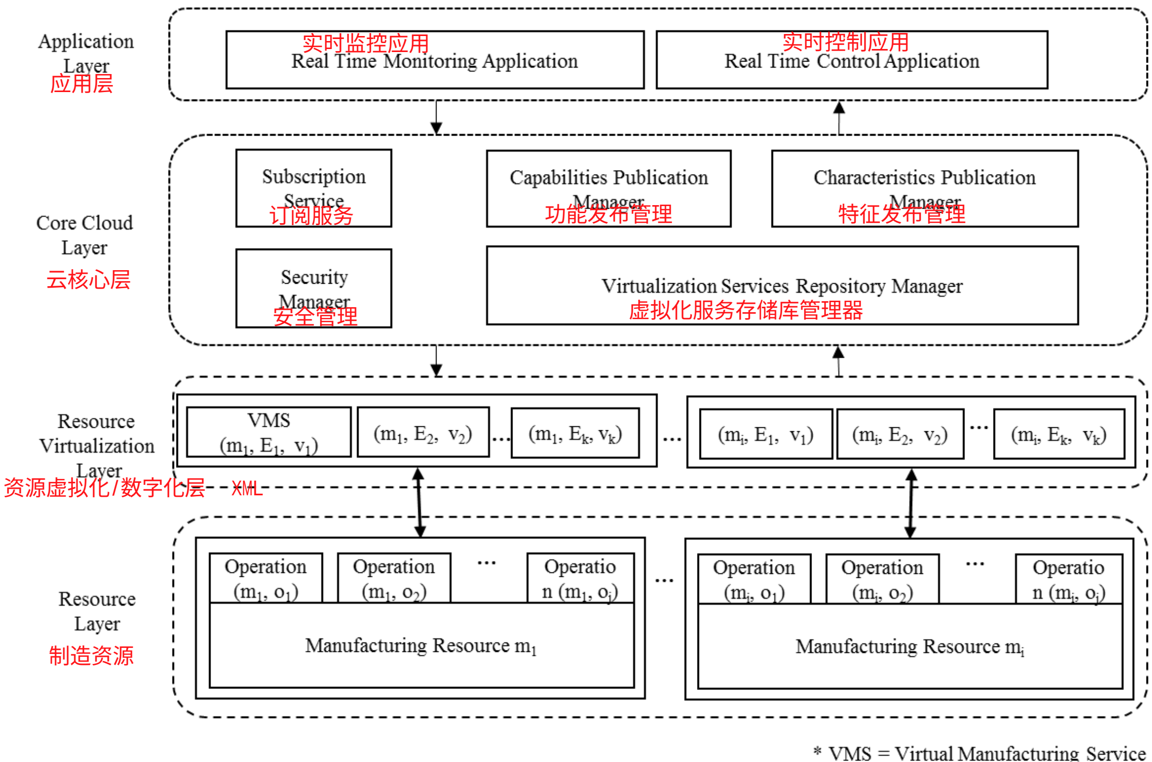

Figure 2: Layered Architecture of CPMC

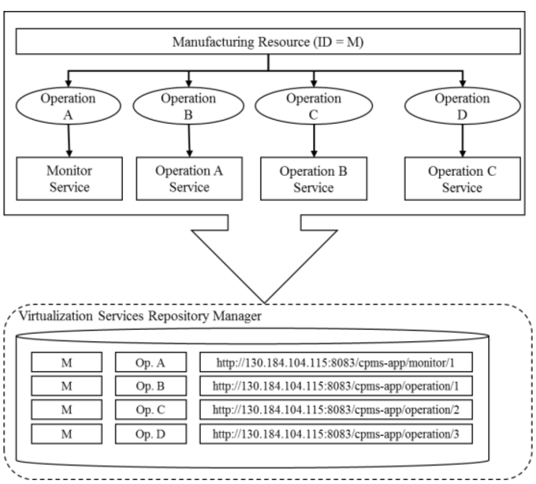

Figure 3: Manufacturing virtual service record in VSRM

3.2 Architectural details 架构细节

The relation in between the Resource Virtualization Layer and Resource Layer can be explained mathematically where, where N is the set of natural numbers, M is the set of manufacturing resources, O is the set of operations that a manufacturing resource m_i can accomplish, E is the set of operations that are accessible from the cloud, and V is the set of virtual manufacturing services from a manufacturing resource. The following equations explains the relations of Resource virtualization layer and Resource Layer –

$$M = \{m_i \mid i \in N\}$$
$$O = \{(m_i, o_j) \mid m_i \in M \text{ and } j \in N\}$$
$$V = \{(m_i, E_k, v_k) \mid m_i \in M, E_k \in E, E \subseteq O, \text{ and } j \in N\}$$

According to the equations, a virtual manufacturing service can accomplish a set of operations that a manufacturing resource can offer.

Virtual Manufacturing Services (VMS) are the primary interfaces for the CPMC architecture. VMS contains two types of services – manufacturing characteristics and capabilities services. However, to make the services accessible from the Internet, the service locations (URL) are stored in the Virtual Service Repository Manager. The structure of manufacturing virtualization services data storage is shown in *Figure 3*. A primitive VSRM data record contains Id of the manufacturing resource, type of operation the service accomplishes, and the manufacturing service URL to access over the Internet.

In *Figure 4*, a service-level sequence diagram drawn to describe the monitor/control operation of the CPMC implementation. Subscription Service component authorizes every service oriented communication in between the components. To perform monitor/control operation from the Internet, the application has to get the virtual manufacturing service URL from the Virtualization Service Repository Manager.

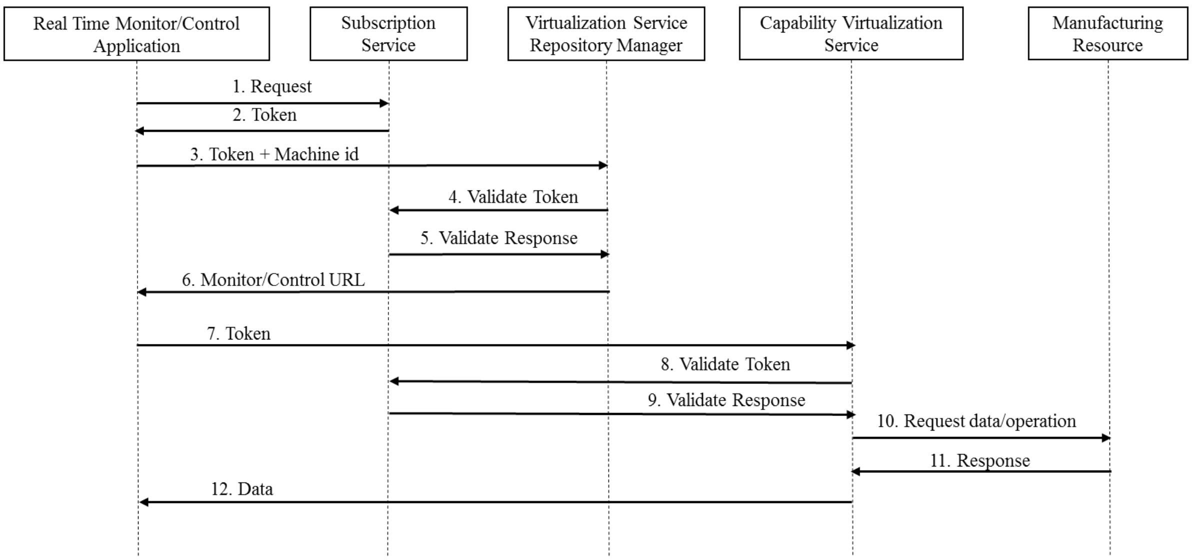

Figure 4: Sequence Diagram of Real-time Monitor/Control operations flow for cyber physical manufacturing resource

安全控制

3.3 Security Management of CPMC

The CPMC architecture is protected by a token 令牌 based authorization system empowered by the Subscription Service component. Every access from the Internet is verified by the Subscription Service whether the request carries valid authentication token. To have a valid authentication token, the requestor has to be a CPMC user. The three types of users in the system are –

1) Consumers 用户, who subscribe published virtual manufacturing services of the manufacturers;
2) CPMC administrators 管理员, who publish virtual manufacturing services in the Cloud and also have the ability to reconfigure those services;
3) Cloud administrators, who are accountable to maintain the manufacturing cloud environment.

The Subscription Service automatically renews the authentication token for a user accessing manufacturing virtual services. Although auto expiring authentication token increases the rate of failed virtual manufacturing operations, it adds an extra layer of security in the system. As manufacturing devices are in generally expensive and sensitive, extra security protects the system better than non-expiring authorization token system. Additionally, the Subscription Service component registers and manages all users of the system according to their roles to provide better access control into the system.

3.4 Virtualization of Cyber Physical Systems and MTConnect 虚拟化 物理信息系统和MTConnect

Virtualization method of cyber manufacturing resources is directly influential to the scalability 可扩展性 of the CPMC. In addition to that, a uniform standard data format for all type of virtual manufacturing services is required to develop a virtualization standard. The cyber physical manufacturing resources can be made highly scalable if virtualized as RESTful web services and a uniform data format can be designed for the application developers. In cloud computing paradigm, RESTful architectures use XML or JSON data format for virtualizing computing resources. For CMfg paradigm, MTConnect is a XML based RESTful communication protocol for manufacturing tools. A high number of manufacturing machine providers have adapted MTConnect standard with their machines to enable machine status monitoring over the Internet. Usability of MTConnect as a communication and data protocol for manufacturing resources is highly potential, although it has certain limitations. Additionally, MTConnect standard is capable of real-time machine monitoring. Therefore, the current capabilities and popularity of MTConnect leads it to become a game changing protocol for manufacturing processes that performs real-time operations on manufacturing machines iver the Internet. We used MTConnect in our testbed to check the feasibility of it in the CPMC framework.

4 USE OF MTCONNECT IN THE TESTBED FOR CPMC

MTConnect works in an Agent-Adapter 代理器-适配器 paradigm in between the Cloud Applications 在云和机床之间 and the manufacturing machines. A brief study on how MTConnect works is presented in the next subsection.

RESTFUL 架构

4.1 RESTFUL ARCHITECTURE

REST stands for Representational State Transfer. REST is an architectural approach for network based applications, and it is generally used for web services. RESTful web services are light, and highly scalable 轻量级 可扩展性. An architecture is called RESTful when it is service-oriented. A service-oriented architecture provides operations as services. In the case of manufacturing, a service-oriented architecture offers manufacturing operations as services. For example, the developed CPMC architecture is a RESTful architecture that offers interfaces in the cloud to operate manufacturing machines remotely. MTConnect works in an Agent-Adapter paradigm in between the Cloud Applications and the manufacturing machines. A brief study on how MTConnect works is presented in the next subsection.

4.2 MTCONNECT

MTConnect is designed as a RESTful architecture offering manufacturing status information as web services. *Figure 5* [1] gives a general idea on how MTConnect services are offered. The three standard web services by MTConnect standard responds to HTTP GET requests. Here the web services are like interfaces on top of the Agent server. Cloud applications have to make HTTP calls to the web services to get MTConnect standard XML data response. MTConnect standard XML is predefined in a namespace providing complete control on the response data.

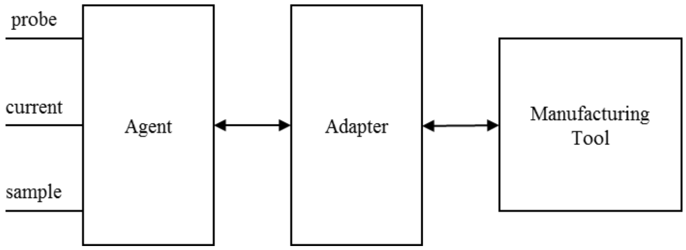

Figure 5: RESTful architecture of MTConnect

MTConnect 适配器

The MTConnect Adapter is the driver module that collects and buffers manufacturing tools data as dictionary which is a key-value based data structure. Depending on the implementation, the Agent gets data as dictionary from the Adapter, converts it to MTConnect standard XML, and responds back to the Cloud. The block component – Manufacturing Tool can consisting of only one manufacturing tool or several manufacturing tools depending on the Adapter implementation.

MTConnect在试验台中的应用

4.3 MTConnect implementation in testbed

In the CPMC, the virtualization of manufacturing services are explained in *Figure 6*. An MTConnect Agent is a RESTful web server hosting the capability virtualization services accessible across the Internet. The Adapter is responsible to connect and fetch data from the cyber physical manufacturing resources. As the Agent is a web server that can be hosted in the cloud depending on the manufacturing environment. Adapter is tightly bound with the cyber physical manufacturing resources and the implementation of it is hardware specific.

In the reformed workflow of the capabilities virtualization services, all the requests for action coming from the upper layer in the architecture (i.e. Application Layer or Core Cloud Layer) will be HTTP requests. Upon getting the request, the Agent will translate the HTTP parameters to a dictionary format for the Adapter to proceed further. The Adapter then communicates with the manufacturing resource by the available media. The available media from Adapter to cyber physical manufacturing resource can be accomplished by TCP/IP network or by Universal Serial/Parallel Bus or any other standard medium. When the Adapter receives the request from the Agent, it fetches appropriate data from the machine, creates a dictionary with all available data and then send the dictionary back to the Agent. The Agent then converts the data dictionary into an MTConnect Standard XML format and publishes that XML.

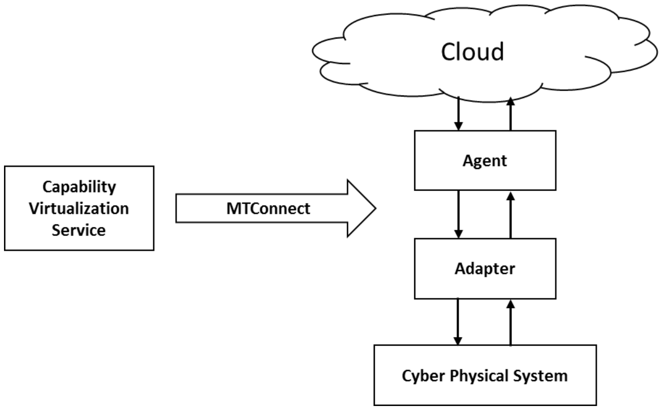

Figure 6: Virtualization Service component representation on MTConnect

The process described above is a standard MTConnect data monitoring procedure. In our proposed CPMC architecture, the functionality of both the Agent and the Adapter is extended in such a way that those also provide some control of the machine alongside data monitoring. For that purpose, more web services is added in the Agent beside the three monitoring requests, one for each available control. For example, whenever the Agent receives a request named 'commence', it sends an appropriate command to the Adapter. After verifying the request the Adapter instructs the machine to start the particular job. If the Agent receives a request 'cancel', it will instruct the Adapter to stop the current job and return to default state.

The type and number of such services vary depending on what kind of control is provided for a particular machine. Some services may require additional parameters, i.e. the model file to be executed, material type for the job, temperature to be maintained etc. For these cases the services are designed accordingly so that they can receive those parameters and send to the Adapter. To ensure safety for the machine, all incoming requests are checked and verified by both Agent and Adapter. The machine and the Adapter works like 'Black Box' where none can have direct access preventing harmful attempt to damage the machine by the malicious attackers. The Adapter will only instruct the machine when it has a verified and validated request.

试验台施行

5 TESTBED IMPLEMENTATION

A testbed is being developed to explore the challenges associated with the implementation of CPMC. The implementation has two basic parts, Cloud part 云平台 and the manufacturing hardware resource part 制造硬件平台. In the cloud part, all the basic block components that are mentioned in the layered architecture and the sequence diagram are implemented as web applications in Java and Spring MVC. The web applications are hosted in an Ubuntu 14.04 virtual machine with 4 gigabytes of RAM, 20 gigabytes of hard disk and 2 processors. Jetty 6.1.10 is used as the web server to run the web applications. MySql 6.0

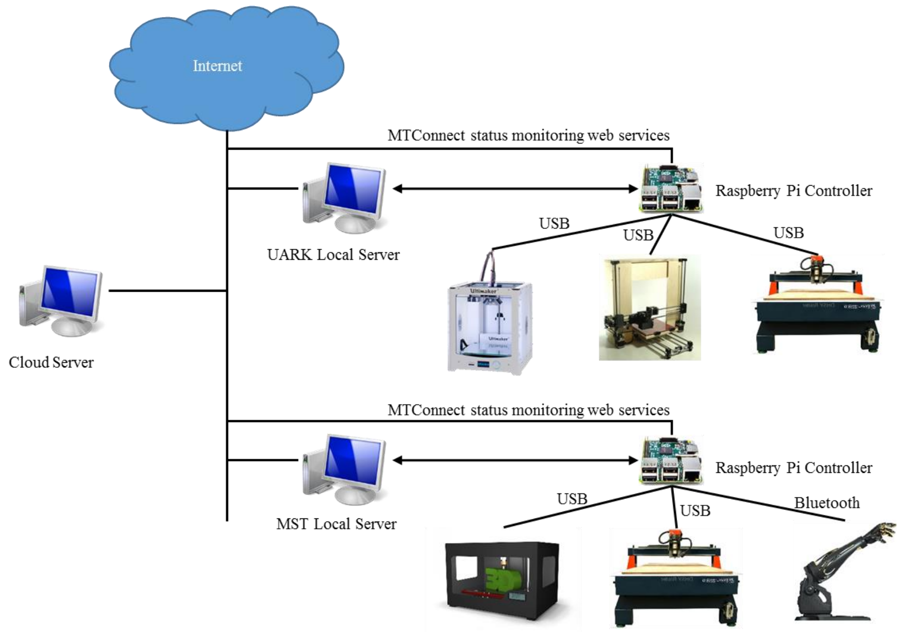

Figure 7: Testbed implementation of CPMC

is used as the database for the Virtualization Service Repository Manager, and Subscription Manager Components.

On the manufacturing hardware resource part, a testbed is being implemented in two different locations 两个地方进行测试 – University of Arkansas and Missouri Institute of Science and Technology. In the testbed, we are using three 3D printers, two CNC machines, and one robotic arm. In future, the number of machines are going to increase according to the plan. *Figure 7* presents the current testbed implementation networking architecture. One of the 3D printer for experiment is a complete open-source Ultimaker 2 machine. 3D打印机品牌 We implemented the MTConnect Adapter for the Ultimaker 2 in a Raspberry pi 2 Model B using Python programming language. The adapter was based on the open-source software called Printrun [21] that is designed for monitoring and controlling 3D printers. It is written in Python and is compatible with most of the open-source 3D printers. It communicated with the 3D printer via a USB cord. It both fetches and feeds machine data to the MTConnect Agent and instructs the machine to execute appropriate commands. The Agent is based on the open-source MTConnect project titled 'makerbot_agent' [22]. The project was designed as an agent-adapter combo for Makerbot 3D printers. The Agent in the testbed has been designed to handle more requests alongside the three standard requests (probe, current and sample).

Due to the fact that MTConnect is read-only protocol, for controlling the machine the communication from the components hosted in the cloud to the testbed Raspberry Pi 2 was established by TCP/IP via virtual web services as in the architecture. In another implementation, both the monitoring and control operations of the machines were implemented using TCP/IP communication which was difficult to implement, specifically for the handling of concurrent requests. Using MTConnect standard solved the issue partially for machine data monitoring. However, communication for control operations are still done by TCP/IP based communication.

An MTConnect Agent is a web server that can handle the difficulty of concurrent requests for manufacturing operations. For example, the performance of monitoring a 3D printer machine gained significant performance boost after the MTConnect adaptation in the testbed. In *Figure 10*, a screenshot of the machine monitoring web application is presented. On the other hand, for control operations, sending command to print a CAD model file to the Ultimaker 2 3D printer, a capability virtualization service is developed that is working efficiently. Instead of sending the CAD file to the MTConnect Agent, the model file is being sent to the Raspberry Pi 2 directly by file streaming through TCP/IP network protocol. In the MTConnect implementation for machine status monitoring, three standard services (*probe*, *current* and *sample*) are implemented. The three services and the capability virtualization services are accessible securely from the cloud.

6 TESTBED USE CASES

To have a better understanding on the testbed implementation, two test cases are elaborated with Use case and Sequence diagrams. The two test cases are – 1) Monitor 3D printing progress 监控3D打印机 and 2) Print a 3D model file. 输出3D模型文件 The testbed implementation is under construction and the Use Cases explained are very basic Use Cases.

6.1 Use Case: Monitor 3D printing progress

In this use case, a CPMC user wants to monitor the progress report of the printing process running on a 3D printer. In the testbed implementation, the user commands the printer to fetch progress report by a web application hosted in the Cloud. Figure 8 presents the Use Case Diagram.

In response to the command from the user, the web application sends a HTTP GET request to fetch all status report of the 3D printer. The GET request is sent to a RESTful MTConnect Agent server. The web service that is called for the status information is current. Following MTConnect standard, the Adapter fetches data from the manufacturing machines and the responses back as an MTConnect standard XML document. The whole process is presented in a sequence diagram in *Figure 9*. Security Management details has been presented in 3.2, the following sequence diagram doesn't include the security steps due to avoid redundancy.

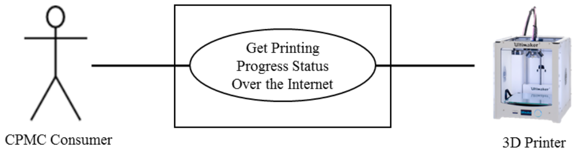

Figure 8: Use Case Diagram - Monitor 3D printing progress

6.2 Use Case: Print a 3D model file

This Use Case gives a better idea on the controlling part of the testbed implementation. By MTConnect standard, there is no standard RESTful web services to operate the machines remotely. Therefore we implemented RESTful web services to send operational commands to the manufacturing machines from the User. In Figure 11, a Use Case diagram is presented.

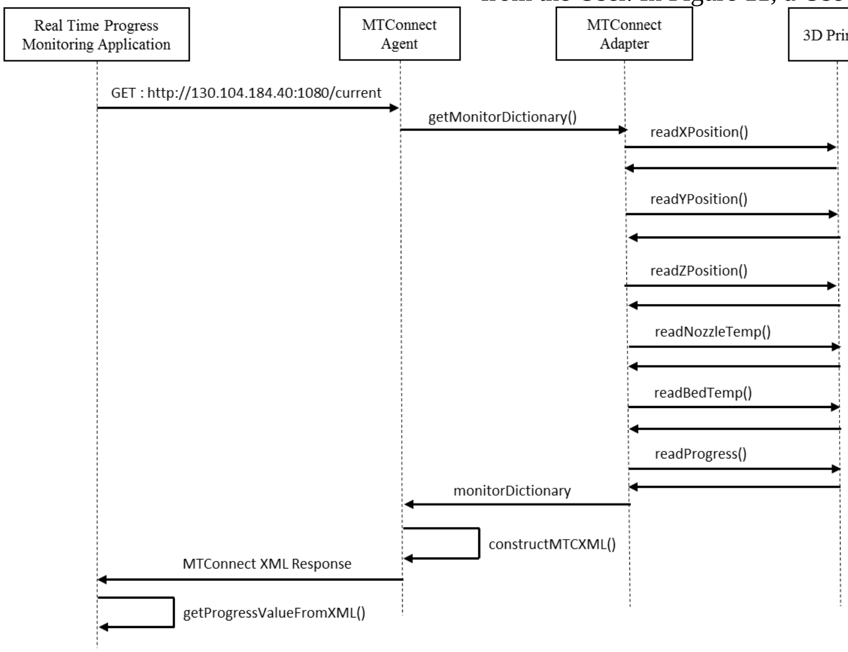

Figure 9: Sequence Diagram - Monitor 3D Printing Progress

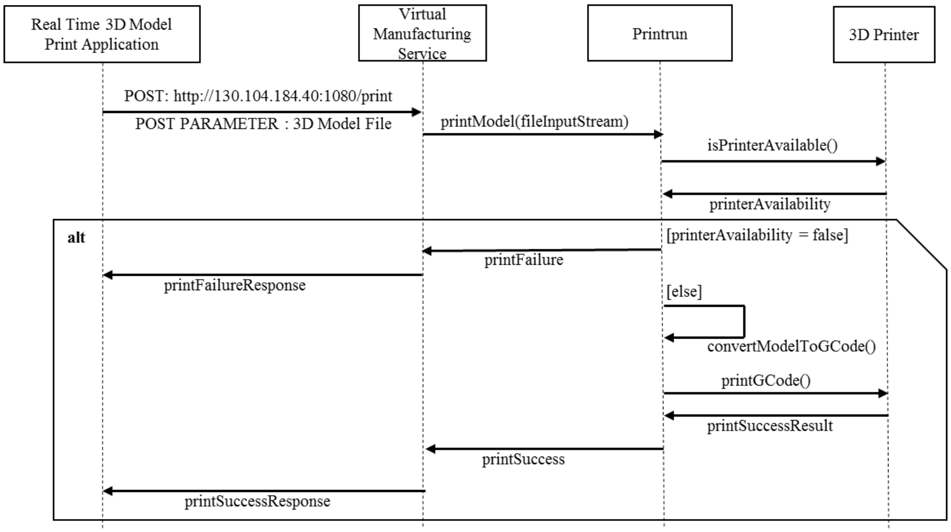

Figure 10: Sequence Diagram - Print a 3D model file

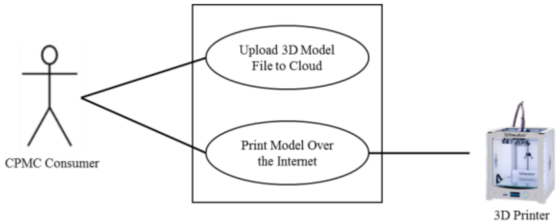

Figure 11: Use Case Diagram - Print a 3D model file

The user uploads the 3D model file (i.e. any type of CAD files) to a web application hosted in the Cloud. Upon the print request, the web application sends a HTTP POST request to the RESTful web service hosted in a local server of the testbed implementation. The web service takes the model file as an input parameter and forwards the file to a Python program running in the Raspberry Pi 2 controller that works on top of printrun. The program converts the model file to gcode file and streams into the printer for further processing. *Figure 10* presents the detail steps by a sequence diagram. Security Management is not included in the sequence diagram.

7 PERFORMANCE ANALYSIS

The most viable bottleneck of the CPMC architecture is the response delays from the cloud to the cyber physical manufacturing resources. Performance of the developed system was measured from two prospects of manufacturing – monitoring and control.

7.1 Machine monitoring performance

In our implementation, the MTConnect Agent that runs in a Raspberry pi 2 machine, is a tiny RESTful server and it collects machine status information from the manufacturing resources. The response time of the Agent over the Internet was tested for performance evaluation. We tested the response time of the Agent web services using Apache Benchmark which is a renowned test framework for web services response time. The results are mentioned in *Table 1*. The performance analysis shows that the web services offered by the Agent has ~5.5 milliseconds of average response time, which proves the real-time capability of machine status monitoring operations presented in the architecture.

Service name	Time taken for tests (seconds)	Complete requests	Failed requests	Total transferred (bytes)	Requests per second (mean)	Time per request (mean in ms)
Probe	5.452	1000	0	115000	183.43	5.452
Current	5.714	1000	0	115000	175.00	5.714
Sample	5.379	1000	0	115000	185.92	5.379

Figure 1: Response time of MTConnect services for monitoring operations

7.2 Machine control performance

In the implementation, the operational commands are sent as data bytes in a TCP/IP networked communication. Although the communication for control commands is in a preliminary stage, bytes communication for commands and file streaming for CAD models are done efficiently. From an experiment, a sample 3.89 MB sized CAD file sent to the Ultimaker 3D printer across University of Arkansas local network via the Raspberrry Pi 2 Controller in 1585.33 milliseconds resulting in a file transfer rate of 2.45 megabytes per seconds (MBps). Rest of the control commands are in generally 4-10 character bytes in size that takes very small amount of time. The total time to complete the operations depend on the manufacturing machines.

8 CONCLUSIONS

This paper presents a scalable and service-oriented architecture of Cyber Physical Manufacturing Cloud using MTConnect. A testbed of the architecture was implemented. Performance of the testbed was evaluated and the performance analysis shows that the architecture is capable of overcoming the shortcomings of the current cloud manufacturing systems by enabling real-time collection of information of manufacturing machines and monitoring of them as well as control and execution of operations of manufacturing machines over the Internet. From the study of the proposed architecture and the testbed implementation, we can summarize the contributions of this paper are as follows -

- Developed a Cyber Physical Manufacturing Cloud by integrating paradigms of cloud manufacturing and cyber physical systems;
- Create scalable service oriented architecture of Cyber Physical Manufacturing Cloud;
- Develop a method of virtualization of manufacturing characteristics and capabilities;
- Adopt the RESTful Internet protocol MTConnect for real-time collection of data of manufacturing machines and monitoring them over the Internet in the Cyber Physical Manufacturing Cloud;
- Developed TCP/IP based Web services for controlling and executing operations of manufacturing machines;
- Demonstrate feasibility of real-time manufacturing operations and processes over the Internet through Cyber Physical Manufacturing Cloud.

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