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Cyber-physical manufacturing cloud: Architecture, virtualization, communication, and testbed

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ABSTRACT

Cyber-physical systems are integrations of computation, networking, and physical processes and they are increasingly finding applications in manufacturing. Cloud manufacturing integrates cloud computing and service-oriented technologies with manufacturing processes and provides manufacturing services in manufacturing clouds. A cyber physical system for manufacturing is not a manufacturing cloud if it does not use virtualization technique in cloud computing and service oriented architecture in service computing. On the other hand, a manufacturing cloud is not cyber physical system if it does not have components for direct interactions with machine tools and other physical devices. In this paper, a new paradigm of Cyber-Physical Manufacturing Cloud (CPMC) is introduced to bridge gaps among cloud computing, cyber physical systems, and manufacturing. A CPMC allows direct operations and monitoring of machine tools in a manufacturing cloud over the Internet. A scalable and service-oriented layered architecture of CPMC is developed. It allows publication and subscription of manufacturing web services and cross-platform applications in CPMC. A virtualization method of manufacturing resources in CPMC is presented. In addition, communication mechanisms between the layers of the CPMC using communication protocols such as MTConnect, TCP/IP, and REST are discussed. A CPMC testbed is developed and implemented based on the proposed architecture. The testbed is fully operational in two geographically distributed sites. The developed testbed is evaluated using several manufacturing scenarios. Its testing results demonstrate that it can monitor and execute manufacturing operations remotely over the Internet efficiently in a manufacturing cloud.

1. Introduction

Cloud manufacturing (CMfg) is an integration of cloud and service computing with manufacturing processes [1,2]. The number of cloud manufacturing systems is increased due to the rapid research and development of CMfg. Cyber Physical Systems (CPS) are another paradigm, which integrates computation, networking, and physical processes and allows directly operating and monitoring physical devices over the Internet and finds applications in manufacturing too [3,4]. Hence, it is necessary to integrate cloud manufacturing and cyber physical systems for providing manufacturing services, which can directly operate and monitor machine tools in a manufacturing cloud. As a result, a new paradigm of Cyber Physical Manufacturing Clouds (CPMC) is introduced. A CPMC is a type of manufacturing clouds where machining tools can be directly monitored and operated over the Internet from clouds. Many existing manufacturing clouds provide manufacturing services and but do not allow their machining tools to be monitored and operated directly from the clouds. For example, Shapeways provide human-in-the-loop cloud manufacturing services [5]. They allow customers to order 3D printing services from a cloud, human operators manually operate 3D machines to perform manufacturing processes. It would be desirable to further automate manufacturing processes in manufacturing clouds by directly operating machining tools and monitoring their manufacturing processes with less human interventions. On the other hand, several cyber physical systems have been developed for manufacturing [6,7]. They allow direct operation and monitoring of machine tools over the Internet. But they are not manufacturing clouds with any virtualization methods and are not based on service-oriented architecture.

Several interesting research issues in CPMC need to be addressed. Firstly, a scalable service oriented architecture needs to be developed for CPMC. Secondly, virtualization of manufacturing resources needs to be investigated. Thirdly, communication mechanisms are needed to enable network communications among

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components of CPMC. There are many network enabled manufacturing tools in the existing manufacturing environments, but very few tools are utilized due to the lack of cyber-physical manufacturing clouds. Application scope of CPMC is widened by the recent developments of Industry 4.0 [8,9]. Therefore, the potential use of CPMC in manufacturing processes can significantly improve the use of underutilized network enabled manufacturing machines.

This paper presents a scalable service-oriented architecture of CPMC. It allows manufacturers to publish and subscribe web services for manufacturing operations and manufacturing applications to monitor and execute manufacturing operations remotely over the Internet. It also creates an open platform for the manufacturers and customers to develop rich Internet applications. Virtualization of manufacturing resources in CPMC is important due to the diversity and complexity of the manufacturing resources. The presented CPMC system virtualizes manufacturing tools by representing functionalities of machining tools using web services and other machining tool characteristics. Communications between layers of the layered architecture are critical due to the diversity of the technical characteristics of each layer. The communication mechanisms are developed using MTConnect, Transmission Control Protocol/Internet Protocol (TCP/IP), and REpresentational State Transfer (REST) protocol.

An operational testbed is implemented based on the layered architecture of CPMC. The testbed consists of two groups of manufacturing machines located in geographically distributed sites – the University of Arkansas (UARK), and the Missouri Institute of Science and Technology (MST). The testbed cloud is hosted in the network of UARK. These manufacturing machines are virtualized as REpresentational State Transfer based (or RESTful) web services and published using the service-publishing center in the cloud. Multiple manufacturing applications are developed using the published web services over platforms such as Web, iOS, and Android. An application center is developed to publish manufacturing applications. These published applications are ready to be subscribed and used for manufacturing. MTConnect protocol is used in the testbed to monitor manufacturing machines remotely over the Internet. MTConnect is a popular RESTful Internet communication protocol for collecting status information of the machine tools. By design, it supports read-only communication of the machines. Consequently, Transmission Control Protocol/Internet Protocol (TCP/IP) is used in order to operate the manufacturing machines.

This paper has four contributions: (1) design of a scalable and service-oriented layered architecture of CPMC; (2) development of a virtualization method of manufacturing resources for CPMC; (3) development of communication mechanisms for components of CPMC; and (4) implementation of a fully operational testbed of CPMC based on the architecture.

The next section in this paper presents related works. Section 3 discusses a scalable service-oriented architecture of the CPMC system. In addition, a virtualization method of the manufacturing resources and the communication mechanisms of the CPMC system are described in Section 3. Section 4 demonstrates the open platform for publishing applications and web services for manufacturing operations. This section also illustrates different workflows based on the roles of the participants in a CPMC system. In Section 5, a testbed of CPMC is presented and its efficiency is evaluated by multiple application scenarios. Section 6 and 7 discusses the results and concludes the research.

2. Literature survey

Cloud manufacturing is an emerging manufacturing paradigm. The concept of cloud manufacturing initially was introduced by Li Bo-hu and his team in 2010 [1]. Several researches have been conducted by them on the architecture of cloud manufacturing [10–13]. According to Esmaeilian et al., research in cloud manufacturing can be classified into three categories: studies focused on designing platform and data-sharing architecture, studies concentrated on resource allocation and management, and studies aimed at describing new business models and cloud manufacturing applications. The first group of studies describes the Information Technology (IT) systems requirement and data integration platforms [14]. Huang et al. [15] discussed an architecture of cloud manufacturing service platforms in small and medium-sized enterprises. Suo and Gao [16] illustrated how simulation software packages can be used to find the optimal configuration for cloud manufacturing service platforms. Zhang et al. [17] demonstrated an application of fiber optic sensing in improving the efficiency of cloud manufacturing service platforms. The paradigm of cloud manufacturing enables companies to expand their capabilities and have flexibility in scale depending on market demand. Helo et al. [18] described a limitation of current IT solutions in distributed manufacturing in a multi-layer supply chain and proposed a new cloud-based centralized software application, where a proper information-sharing infrastructure is provided between suppliers and other supply chain entities. Tao et al. [10] proposed a computing and service-oriented manufacturing model describing a ten-layer cloud-manufacturing architecture incorporating the regular manufacturing processes and applications. The architecture also provided important insights on the manufacturing machine virtualization. However, method of virtualizing the manufacturing machines were not discussed elaborately. In addition, the context of communication between layers were not described in the architecture description. Several other studies on cloud manufacturing were conducted. A high-level four-layer architecture of cloud manufacturing was proposed by Xu [2]. Numerous researchers provided surveys of cloud manufacturing [19–22]. A number of prototypes of cloud manufacturing were developed [23,24]. The above research efforts projects some progresses on scalable architecture of cloud manufacturing. However, the aforementioned researches do not address the unique needs of cyber-physical manufacturing clouds where manufacturing machines are operated and monitored directly from clouds based on an integration of the internet technologies, deeply embedded computing, automatic control and monitoring, and networked manufacturing.

The paradigm of cyber-physical systems has gained momentum in research and development [3,25–27]. Recently cyber-physical systems are finding applications in manufacturing [4,21,28]. A cyber-physical production system was introduced [28]. Wang et al. [29] presented a synopsis of the status of cyber-physical systems in manufacturing systems. In another study, Wang et al. [30] described what the system architecture and data-sharing infrastructure should be for controllability of cyber-physical systems on the cloud. Lee et al. [31] discussed an application of cyber-physical systems and smart algorithms in equipment maintenance. Cooper and Wachter [32] studied the application of cyber-physical systems for thermal modeling in the additive manufacturing processes. Seitz and Nyhuis [33] presented a learning factory idea and discussed the importance of cyber-physical systems for not only monitoring production, but also educating and training the employees in manufacturing. While the overall influence of cyber-physical systems as technological changeovers already has been discussed in the literature, current studies are still in the conceptual level stage [14].

Wang et al. [6] presented an integrated cyber-physical system for cloud manufacturing. It introduced an architecture of cyber physical system for cloud manufacturing with three tiers: control tier, view tier with a web interface, and model tier. Three case studies are provided: the first one is about remote monitoring and control in a mini robotic cell with one serial robot, the second one is a Web-based distributed process planning, and the third one is 3D model-guided remote assembly. Its architecture is clearly for a cyber-physical manufacturing system with a web interface. But it is not a cyber physical manufacturing cloud since it does not provide a common virtualization method of various machining tools, which is essential in a cyber physical manufacturing cloud, and it is not based on a service oriented architecture. In addition, it does not use the RESTful communication protocols and standard web data exchange method, such as XML and JSON, for exchanging manufacturing data over the Internet. Consequently, it is not scalable for cyber physical manufacturing cloud over the Internet. Helu and Hedberg presented an architecture of integrated cyber-physical systems for enabling smart manufacturing across the product lifecycle [7]. Its test bed consists of a Computer-Aided Technologies Lab and a Manufacturing Lab using product models as a basis of information exchange in product lifecycle. It is proposed that MTConnect be used for monitoring a production process. It uses web services to disseminate data and information in testbed. It is a cyber physical system for manufacturing covering many phases in a product life cycle. However, it is not cyber physical manufacturing cloud since it does not provide a common method of virtualization of manufacturing resources and it does not allow direct operation of machine tools over the Internet event though they can be monitored using MTConnect. Several cloud-based commercial manufacturing systems exist. Authentise [34] developed 3DIAX, a cloud based marketplace for 3D modeling services for the manufacturers. Authentise also developed a Manufacturing Execution System to provide human-in-the loop cloud manufacturing services. It allows customers to order 3D printing services. Once orders are received, human operators operate 3D printers for their production. Customers can monitor their production process over the Internet. However, 3D printers cannot be operated over the Internet from the cloud in these systems. As a result, they are not cyber physical manufacturing clouds.

Virtualization of manufacturing resources is important when it comes to CPMC. Liu et al. [35] proposed an approach of virtualizing manufacturing resources by representing machine characteristics and service encapsulation using XML [36–42]. Liu, Yan, and Lin proposed a multilevel framework of manufacturing resource virtualization [43–45] with layers of representation of functional capabilities of machines based on a web ontology language. Zhao et al. [46] represented machine characteristics and functionalities using RESTful web services. Ameri and Dutta [47] proposed a manufacturing service description language (MSDL). One of the major issues with the above virtualization approaches is that they consider either machine characteristics or machine capabilities, but not both.

Communication methods play an important role in CPMC. In general, RESTful web services are invoked by XML data formats. MTConnect is a XML based communication method for machining tools and it can be used for monitoring their status. Thereby, the use of XML data specified by the MTConnect standard has a potential for virtualization. Xu [2] proposed the use of MTConnect for cloud manufacturing. Vijayaraghavan and Sobel [48] explained the integration of manufacturing system using MTConnect detailing the machine specific data. Vijayaraghavan and Dornfeld [49] described the use of MTConnect for enabling process planning and verification in an industrial environment. MTConnect as a communication standard is viable for real-time data operations as shown by research of Michaloski et al. [50]. An alternative of MTConnect standard, TMTC (Taiwanese Machine Tool Connect), has been proposed by Lin et al. [51]. The TMTC is a protocol where an integration of different types of Adapters was implemented in a single machine, increasing the scalability of the implemented system. Although MTConnect supports only machine monitoring operations, it cannot be directly used for operating machining tools in CPMC. MTConnect is being widely accepted commercially as a communication method of machine tools over the Internet. System Insights with ROS-Industrial developed a peer to peer inter machine communication architecture using MTConnect [52,53]. The communication architecture is used for the communication between robotic arms and Computer Numerical Machines (CNC). Another peer-to-peer communication was established by LNS America in collaboration with Mazak Corporation using MTConnect [54,55]. Lately, STEP Tools Incorporated with UI-LABS started a project of O3 to develop a web environment to enable the orchestration of machining and measurement processes from tables and smart phones [56,57]. The O3 project is still seeking for a solution by combining the data of STEP [58], Quality Information Framework (QIF) [59], and MTConnect standards into a unified stream that can be used to evaluate the overall quality of a product. Some other communication mechanisms were also used in several other projects besides MTConnect, such as – Transmission Control Protocol (TCP). Wang et al. [6] used TCP as a primary communication protocol to monitor and control machine tools. ROY-G-BIV developed a machine communication platform called XMC for controlling machine tools over a network [60]. In our CPMC, the communication mechanism from cloud to the manufacturing machines are based on both MTConnect and TCP combined. This paper is another work from a series of researches on cyber-physical manufacturing clouds [61,62].

3. Scalable and service oriented layered architecture of CPMC and manufacturing resource virtualization

A conceptual model of CPMC is presented in Fig. 1. Customers communicate with the CPMC using multiplatform applications from desktops or mobile devices. The multiplatform applications use the secured Hypertext Transfer Protocol (HTTP) based communication protocol. Cloud manufacturing services are hosted in the cloud servers. The cloud services communicate with the manufacturers via local servers to transfer operational commands for monitoring machine tools and operating them. The manufacturers develop and host local servers to connect with the manufacturing tools on the factory floors using communication protocols such as TCP/IP (Transfer Control Protocol/Internet Protocol), RESTful MTConnect. Each manufacturing unit is considered as a CPS. Controllers are used to operate machining tools in each CPS in a local area network. The local servers forward the commands received from the cloud to the controllers for performing manufacturing operations.

3.1. Scalable service-oriented architecture of CPMC

Fig. 2 presents a scalable service-oriented layered architecture of CPMC. The architecture presents a hierarchical view of cloud and communication services. In the diagram, the dotted rounded rectangles are the layers and the solid rectangles inside the layers are the components of a respective layer. The communications between the layers are shown in gray thick doubly pointed arrows. This architecture is discussed from bottom up.

- **Resource Layer:** This layer contains manufacturing resources maintained by the manufacturers. Manufacturing resources have networking and computational capabilities. Manufacturers can offer manufacturing services using these manufacturing resources based on publication-subscription model in service-oriented architecture for the cyber physical manufacturing cloud. These manufacturing services can be used to monitor and operate remotely in the cloud. Manufacturing resources are connected to the servers of the resource virtualization layer. The commu-

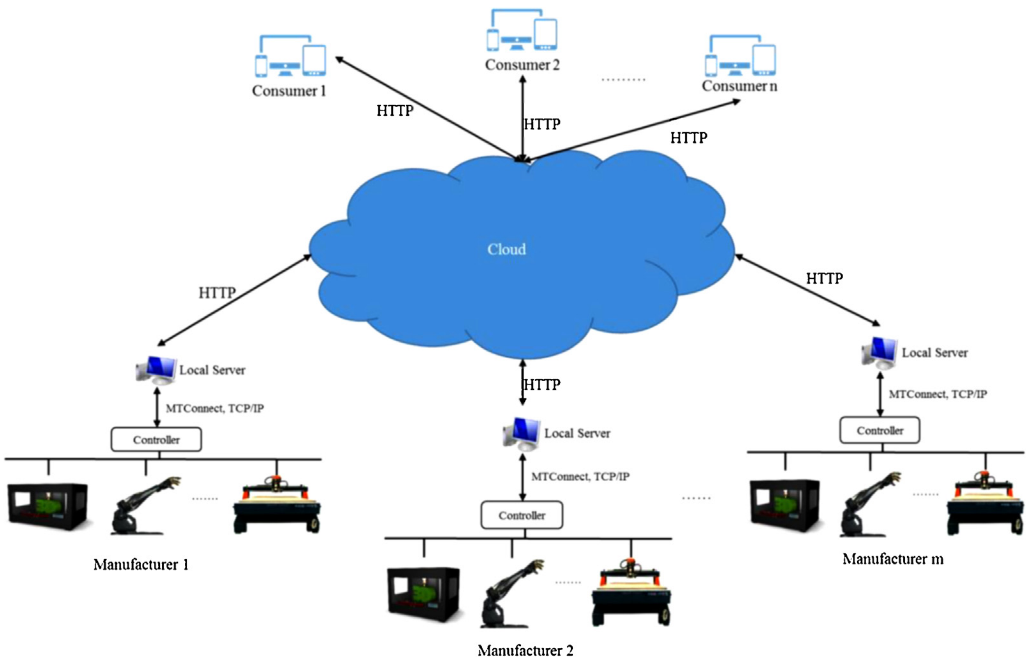

Fig. 1. Conceptual model of CPMC.

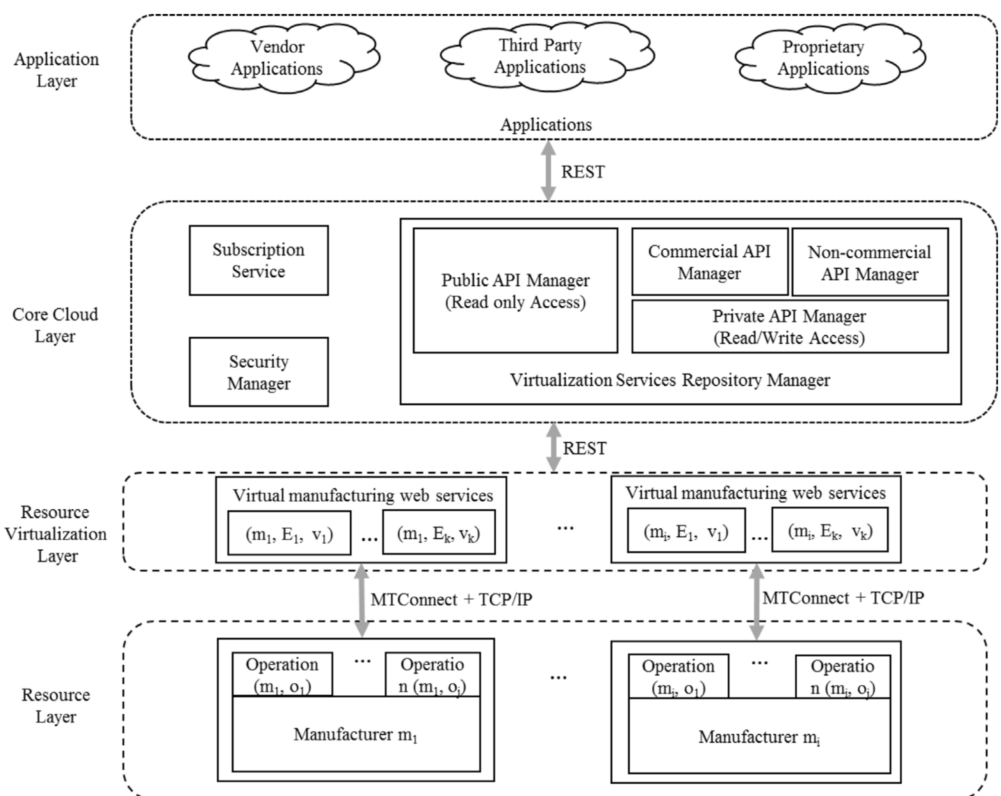

Fig. 2. Four-layer CPMC architecture.

nication mechanism between the resource virtualization layer and resource layer is based on an integration of two communication protocols – MTConnect and TCP/IP. MTConnect is used as the communication method for manufacturing resource data collection and its monitoring. TCP/IP is used as a communication protocol for sending operational requests and receiving their results.

- **Resource Virtualization Layer:** Resource virtualization layer is used to virtualizing manufacturing resources and represent them in CPMC. CPMC virtualizes manufacturing resources by publishing RESTful web services to be accessible over the Internet. In Fig. 2, virtualized manufacturing web services are a set of RESTful web services that are allowed to access over the Internet. The set of RESTful web services for manufacturing operations are developed and deployed by the manufacturers in the servers of the resource virtualization layer. A local server in the conceptual model of CPMC, as shown in Fig. 1, serves as a virtualization server for a manufacturer. There virtualization servers host and run their manufacturing web services. Beside virtualization, resource virtualization layer secures the manufacturing resources by authenticating access requests over the Internet, and validating incoming operation requests from the cloud. The resource virtualization layer communicates with the core cloud layer using HTTP based REST protocol.

- **Core Cloud Layer:** The core cloud layer hosts a set of basic cloud services such as user subscription manager, security manager, and manufacturing operation virtualization services manager. These cloud services are developed as RESTful web services using HTTP based REST protocol for inter-component communications. The core cloud layer also communicates with Application Layer using HTTP based REST protocol. The components of the layer are described as follows.
- Subscription Service: The CPMC users are managed by this component. Users request for an authentication token from this component to operate machining tools over the Internet. Besides, this component has a database of the user's preferences and subscriptions.
- Security Manager: An authentication token is provided to CPMC users by the subscription service component and it is created, monitored, and evaluated by the security manager. The authentication tokens provided by this component are time-based and auto expiring in nature; thus, enhancing system security of the system.
- Virtualization Service Repository Manager: Virtualization service repository manager organizes and stores the applications and virtualization web services data. Each published virtualized RESTful web service of manufacturing resources has a Uniform Resource Locator (URL). URLs of the web services are stored with necessary parameter information in a database. Manufacturers are allowed to configure access of their published web services. These published web services are managed based on their access authorizations as follows.
- Public API Manager: The public API manager provides the information of the published web services by the manufacturers to execute the service from applications. The published web services are open for anyone in the web to use. Due to the open nature of this type of services, it is highly likely that they are used for monitoring.
- Private API Manager: Private API manager manages the use of the published web services by imposing a limited access as specified by the publishing manufacturers. The published services are classified in two categories:
- Commercial API manager: This type of web services are published for commercial use by the application developers based on subscription.
- Non-commercial API manager: This type of web services are published for non-commercial use by the application developers who are given access by the manufacturers to develop applications for internal maintenance purpose of the manufacturing environments.
- **Application Layer:** The application layer manages multiplatform applications for customers to perform manufacturing operations over the Internet. The platforms of the applications can be web browser, embedded systems, desktop operating systems, and mobile operating systems. Positioned at the top of the layered architecture, the applications use cloud services of the core cloud layer to perform manufacturing operations over the Internet. There are three categories of applications published in the application layer, as described below.
- Vendor applications: Vendor applications are generally developed by manufacturers for the public access of consumers of a CPMC.
- Proprietary applications: Proprietary applications are developed by manufacturers for a limited set of consumers, such as paid users.
- Third-party applications: Third-party applications are developed by organizations who subscribe and utilize the application programming interfaces (API) provided in a CPMC by the manufacturers.

3.2. Virtualization of manufacturing resources using RESTful web services

Virtualization of manufacturing resources in the CPMC is done by developing and publishing manufacturing web services. These web services provide functionalities of the manufacturing resources. Each manufacturing web service is available through a Uniform Resource Locator (URL) accessible in the cloud. For example, a web service can be developed and made available for a 3D printer to display printing progress over the Internet. The virtualization method provided in this layered architecture of CPMC stores URLs of the web services with other Meta data about the manufacturing resources and functionalities. In our CPMC, a manufacturing resource has an ID. Each manufacturing resource can perform one or more operations through web service over the Internet. Fig. 3 shows a workflow of the virtualization. A manufacturing resource M has n number of operations. Each operation is transformed into web services and each web service has an URL. A database of the web services is developed to manage virtualized manufacturing resources. A database server storing the web services is hosted in the cloud and is called Service Repository. In the layered architecture, Virtual Service Repository Manager (VSRM) component inside the Core Cloud Layer manages the service publishing. Manufacturing web services in Service Repository may have parameters and they are stored in the database. Security of the web services are maintained through an auto expiring encrypted security token-based mechanism. To access published web services stored in Service Repository, cloud-based applications must request for an authorization to the VSRM. The VSRM then provides the URL of the requested web services with the information of the parameters in JSON data format.

Fig. 4 presents a simple example of virtualization of a manufacturing resource using a web service for 3D printing in JSON format. Each web service in Service Repository is stored with an ID, URL, some other metadata, and security configurations. The example in Fig. 4 shows how the parameters of the web service is managed. Each parameter has a name, type of data, and value. In this example, this web service needs a 3D model file to start a 3D printing operation. It has a parameter for the 3D object file and its type is FILE. When an application requests for this operation, the application must provide a CAD file as a 3D model, name of the material, and color of the object.

3.3. Communication methods in the CPMC

The communication methods across the layers are crucial due to the requirements for manufacturing data exchange with speedy transmission. Fig. 5 illustrates communication mechanisms of our CPMC. The HTTP based REST protocol is used to perform the communication from the application layer to the core cloud layer. The components in the core cloud layer are developed to provide RESTful web services in our CPMC layered service oriented architecture. The applications from the application layer communicates with the components from the core cloud layer by making REST calls and get

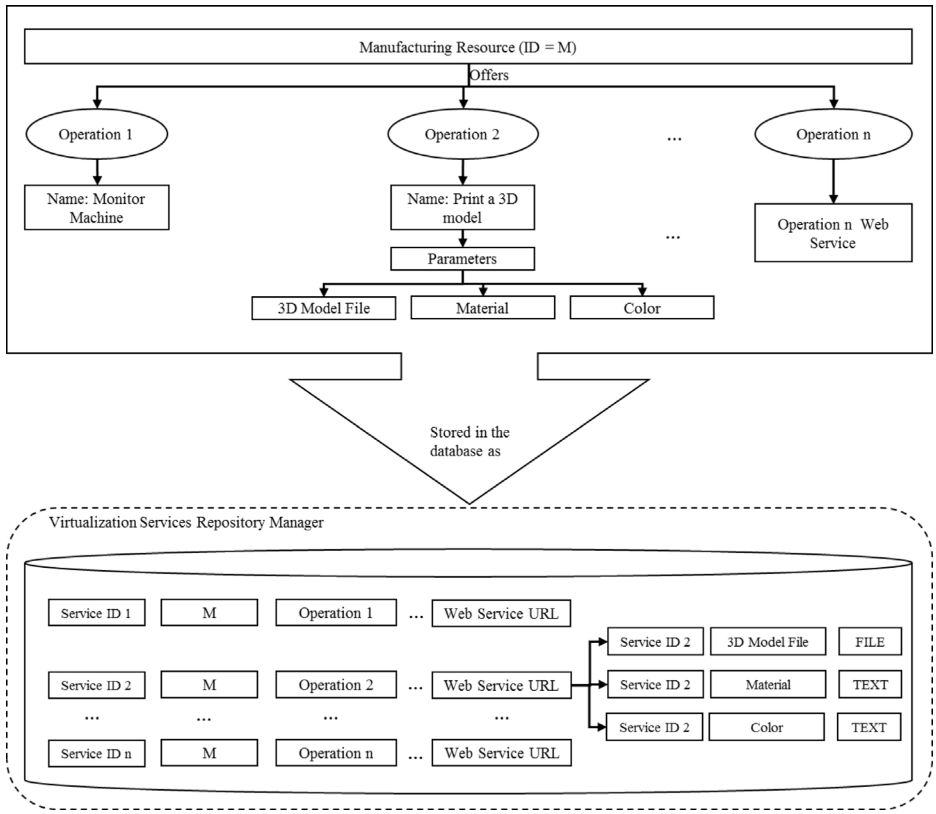

Fig. 3. Workflow of Virtualization method in CPMC.


```
{
   "service_id":"1054265",
   "service_url":"http://local-server-ip:port/virtualization/ultimaker/control/print",
   "primary_category":"3D Printing",
   "secondary_categories":"Prototyping",
   "provider":"University of Arkansas",
   "ssl_support":"YES",
   "authentication_model":"API KEY",
   "params":[
      {
         "param_name":"cad_file",
         "param_value_type":"FILE"
```


(Continued from left)


```
      },
      {
         "param_name":"material",
         "param_value_type":"TEXT"
      },
      {
         "param_name":"color",
         "param_value_type":"TEXT"
      }
   ]
}
```


Fig. 4. Virtualization data of a manufacturing resource using web service for 3D printing in JSON.

a HTTP response in return. The request-response data is in JSON, which is an XML based cloud friendly data format.

The Core Cloud Layer communicates with the Resource Virtualization Layer via RESTful web services. The resource virtualization layer is hosted in the local servers of manufacturers. In the CPMC context, the components from both layers, communicate each other interactively using HTTP based REST calls. The data exchange is based on XML based JSON format, which is one of common web data exchange methods. The reason behind keeping the REST protocol as the communication standard between these two layers is also the cloud-friendly data format.

Multiple protocols are used, such as – RESTful MTConnect and TCP/IP, for communications between resource virtualization layer and resource layer. There are two types of communications between the resource virtualization layer and resource layer: sending machine operation requests and acquiring machine status information for monitoring. Machining operation commands are sent using TCP/IP. The RESTful MTConnect web services are used for gathering monitoring data of the manufacturing tools in XML format. The data from an MTConnect response is then parsed and converted to JSON format for the use of the requesting components from the core cloud layer.

4. Publication and subscription of manufacturing applications and web services

The service-oriented architecture of CPMC enables an integration of cloud-based applications with services in manufacturing environments. Additionally, the architecture provides a platform to develop Internet scale manufacturing application software and web services, and make them available over the Internet.

4.1. Application and web service publishing center of the CPMC

Web service and application publishing center provides manufacturing operations as either web services or standalone software applications. The published manufacturing web services are accessible over the Internet based on their access privilege. Three

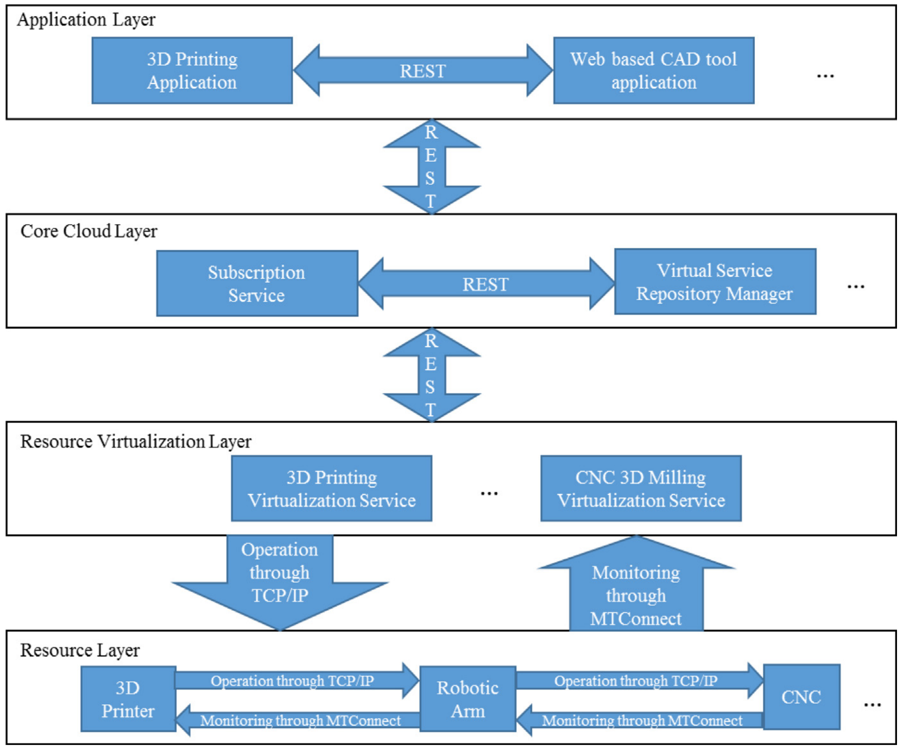

Fig. 5. Contextualization of communications between layers and between components.

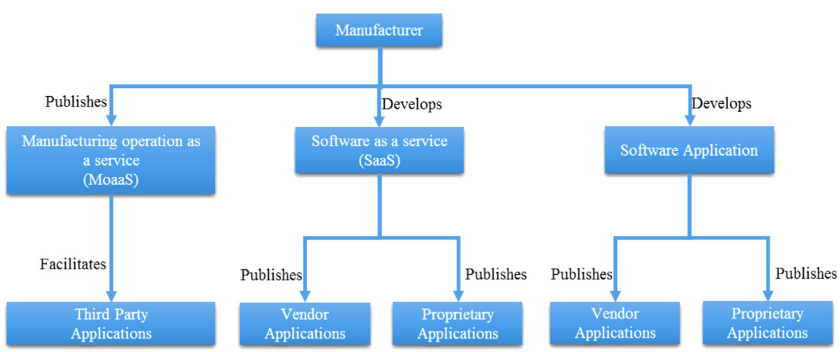

Fig. 6. Application and services for manufacturing operations development hierarchy.

kinds of access privileges are provided: public, commercial, and non-commercial web services. Fig. 6 shows a classification of manufacturing services and applications over the Internet. An application and service publishing center is designed and developed in the testbed manage these types of services.

4.2. *Workflow: manufacturers, application developers, and consumers*

The roles of the participants in the CPMC include manufacturers, application developers, and consumers. Fig. 7 shows a workflow from perspectives of these three participants. In the top portion of Fig. 7, manufacturers develop manufacturing web services. The next step is that the manufacturers publish these services in the cloud. Once the services are available over the Internet, they are used to develop manufacturing applications over multiple platforms. Upon applications are developed, they may or may not be published in the application center. A workflow for CPMC consumers is described in the middle portion of Fig. 7. In the bottom portion of Fig. 7, third party software developers can develop manufacturing applications by subscribing the published manufacturing web services and using the web services in their applications.

5. Testbed implementation

We developed a testbed based on the architecture of CPMC in Section 3. The testbed is developed as an operational prototype.

5.1. *Testbed implementation*

We developed a testbed based on the presented architecture of CPMC in Section 3. The testbed is developed as a full-scale operational prototype of the proposed model of CPMC. A structure of the testbed in presented in Fig. 7. It has two manufacturing sites connected to the cloud over the Internet. Each site has a local area network of machining tools. The first one is in the University of Arkansas and the other is in the Missouri Institute of Science and Technology. The site in the University of Arkansas has five manufacturing machines, including one CNC, two 3-D printers, and two robotic arms, and three controllers, and one local server. The site

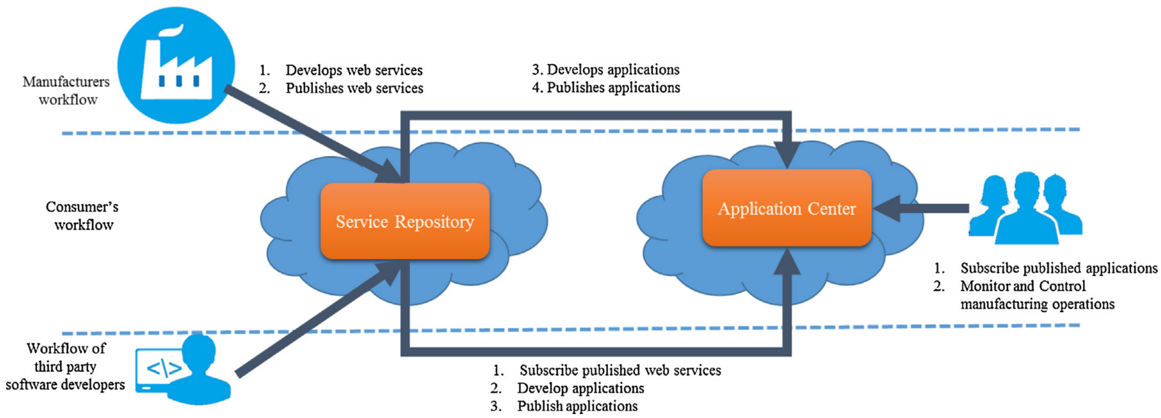

Fig. 7. Workflow of the participants in the CPMC system.

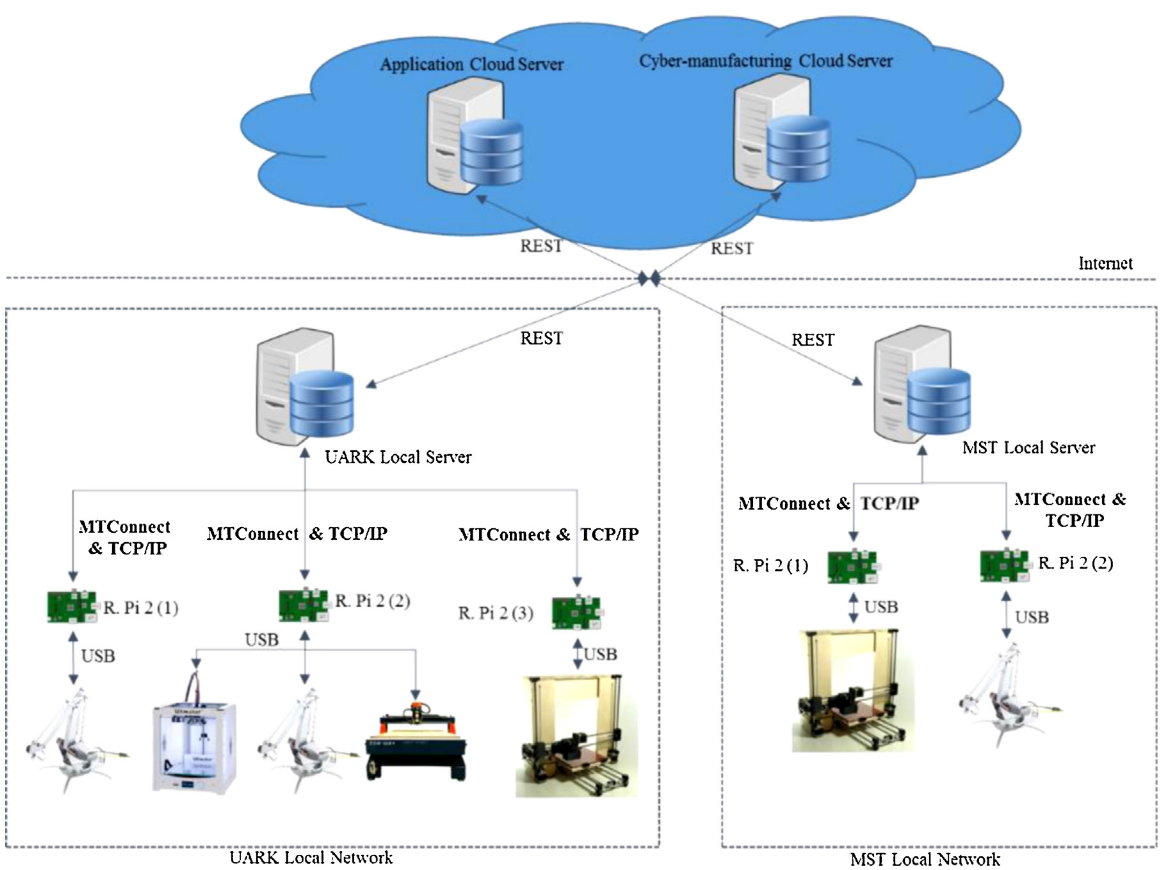

Fig. 8. Testbed implementation of CPMC.

in the Missouri University of Science and Technology has one 3-D printer, one robotic arm, two controllers, and one local server. Machining tools are connected to a controller and all the controllers are connected to the local server where the virtualized manufacturing web services are hosted. The local server is a communication focal point from the cloud. The communication from the local server to the controllers are implemented using MTConnect and TCP/IP protocol. The testbed uses MTConnect for monitoring manufacturing operations and TCP/IP for communicating manufacturing operations (Fig. 8).

As explained in the conceptual model, the local servers host manufacturing web services. They receive and process incoming requests for manufacturing operations from the cloud. There are two cloud servers for hosting cloud-based applications and manufacturing cloud services respectively. The server for the manufacturing cloud services hosts the components of core cloud layer in the layered architecture. The application cloud server hosts an application center and several other cloud-based applications. The application center, which is a web application hosted in the cloud, is a marketplace of all the published applications. Users can sign into the application center and subscribe cloud-based applications. A screenshot of the application subscription page is shown in Fig. 9. In Fig. 10, a screenshot of the application center dashboard is presented. The dashboard contains access links of the subscribed applications of users. A mobile application developed for both iOS and Android operating system was developed as an example of the open framework for the third-party application developers. This vision behind the open framework of applications is to allow any-

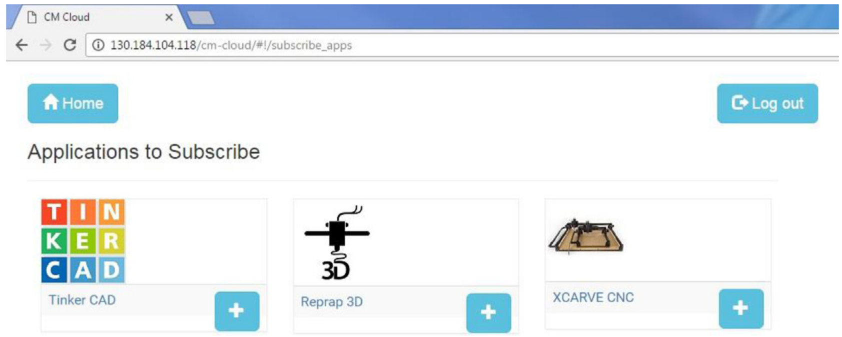

Fig. 9. Subscribe applications in the Application Center.

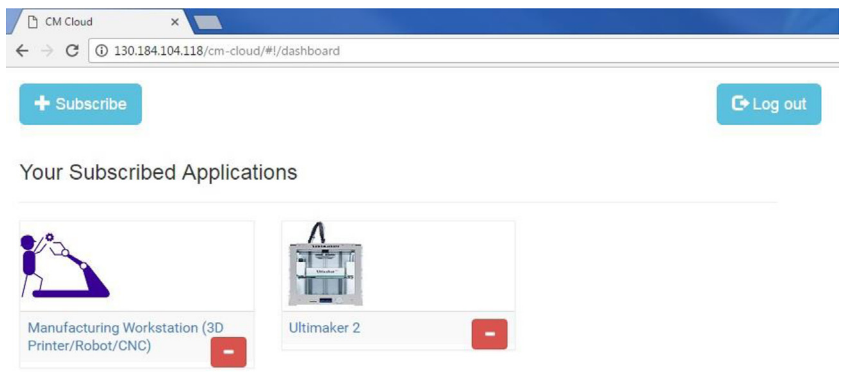

Fig. 10. Application Center dashboard showing subscribed applications.

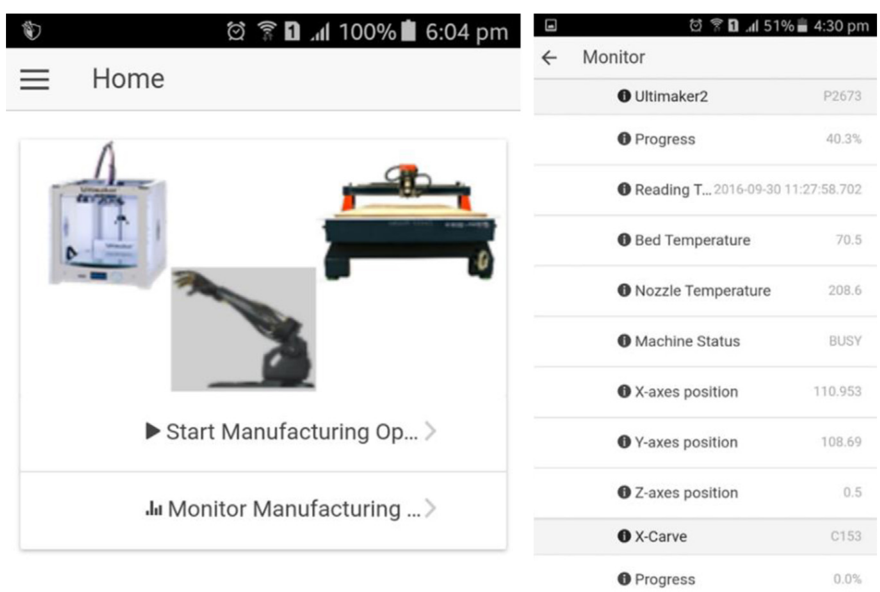

Fig. 11. Dashboard and Monitoring Operation view of a third-party smartphone application.

one to develop cloud-based applications for manufacturing and they can be hosted in the cloud. A screenshot of a smartphone manufacturing application developed for the testbed of CPMC is presented in Fig. 11. The mobile application can be used to monitor a manufacturing tool and perform manufacturing operations over the Internet. To facilitate publishing web services by the manufacturers, a web-based application named Web Service-Publishing Center is developed. Manufacturers can publish their web services as illustrated in Fig. 12. The published web services then appear on the list of services as shown in Fig. 13 in the Service-Publishing Center search web page. Users can search for web services by functionalities and other search criteria.

5.2. MTConnect implementation in the testbed

MTConnect can be used to acquiring manufacturing status information of machining tools over the Internet. Fig. 14 contains a structure of MTConnect communication method. The three web

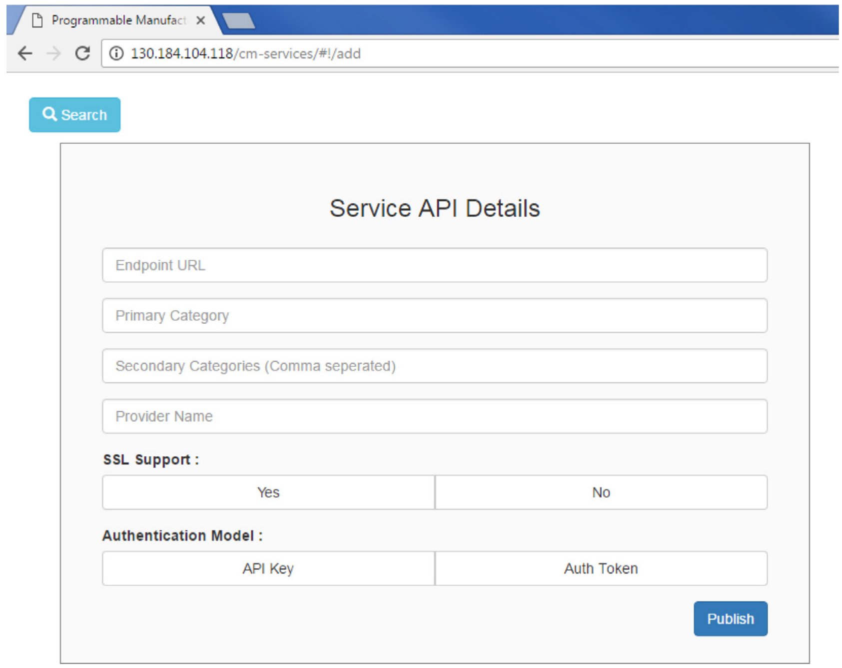

Fig. 12. Service-Publishing Center – publish a web service.

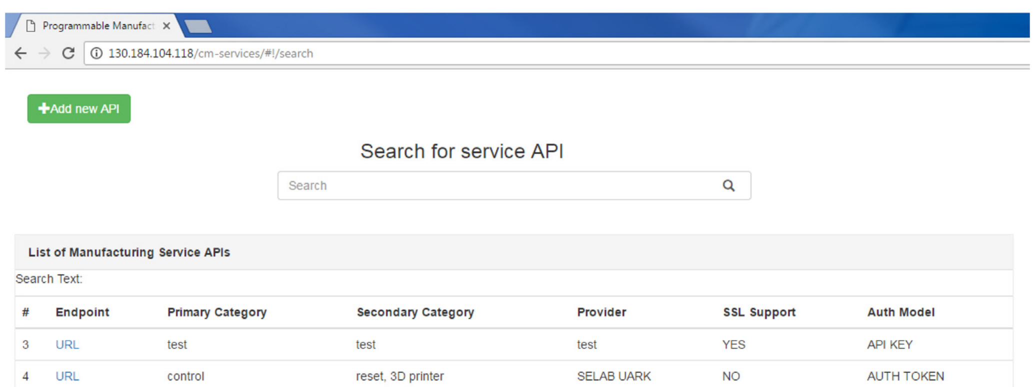

Fig. 13. Search Engine of published web services.

services are provided by MTConnect: Probe, Current, and Sample. Cloud applications make HTTP calls to these web services to acquire data in XML format. In our testbed, the adapter is a driver module that collects and buffers data of the manufacturing tools in using key-value based data structure. The agent obtain data from the adapter; converts it into XML format; and then sends back to the Cloud.

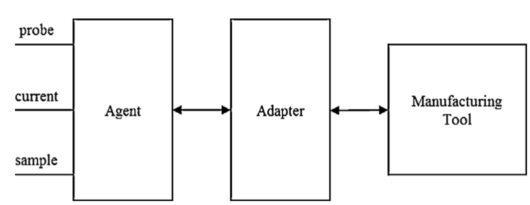

Fig. 14. RESTful architecture of MTConnect [63].

5.3. Evaluation of the testbed in manufacturing application scenarios

The testbed is evaluated using many manufacturing application scenarios. Two of the evaluated manufacturing scenarios are presented here to demonstrate capability and performance of our CPMC testbed.

5.3.1. Manufacturing application scenario 1: directly operate a 3-D printer from cloud over the Internet

In this manufacturing scenario, a smartphone manufacturing application implemented in the testbed is used to perform a manufacturing operation using a 3D printer from cloud over the Internet. This manufacturing application scenario described as a Use Case in Fig. 15, shows a customer can use smartphone to operate a 3-D printer from our CPMC over the Internet. Fig. 16 contains a sequence diagram to show how components in our CPMC work together to implement this manufacturing operation over the Internet. The 3D printer is actively operated in the University of Arkansas (UARK) from our cloud. Clearly, this operation requires streaming a 3D CAD model file to the UARK 3D printer. The smartphone application in the CPMC sends the file along the print operation request to the local server. The local server validates the request and forwards it to the controller of the machine. The controller then parses the request and instructs the machine to perform the operation accordingly.

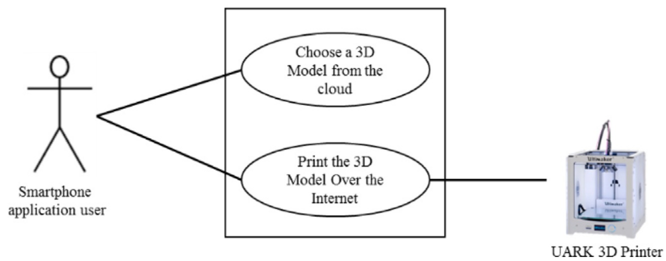

Fig. 15. Use Case diagram for manufacturing application scenario 1.

5.3.2. Manufacturing application scenario 2: monitoring operations of 3D printer from the cloud over the Internet

When the printing job is in progress, a user can use our CPMC to monitor the printing progress of the 3-D printer. This manufacturing application scenario is represented as a Use Case in Fig. 17. A sequence diagram in Fig. 18 shows how components in our CPMC testbed work together to monitor progress of a printing job performed by a 3-D printer on a real-time basis. The user sends a request for monitoring the 3D printer using a smartphone manufacturing application implemented in our CPMC testbed. Upon authorization from the Subscription service of the CPMC, the smartphone manufacturing application requests the local server to provide status information using MTConnect protocol. Upon a validated incoming request from the local server, an MTConnect agent gathers data from the 3D printer through an MTConnect adapter and returns it to the local server in XML format using MTConnect for further processing. The local server then transmits the data to JSON format and returns to the smartphone application to display to the user.

6. Discussion and future work

The proposed architecture of CPMC provides a strong support to the scalability of manufacturing. Manufacturing resources can be virtualized and added to the CPMC. They even can be reconfigured dynamically. A manufacturer can develop web services to enable accessing manufacturing services over the Internet and publish them in the cloud. To remove manufacturing resources, all a manufacturer needs to do is to remove their web services from the web service publish center in our CPMC. Although the CPMC architecture and testbed show feasibility of integration of manufacturing cloud and cyber physical systems to enable directly operation and monitoring of machining tools from a cyber physical manufacturing cloud over the Internet, we still need to perform additional researches and experiments on large-scale cyber physical manufacturing clouds before achieving its potential in the industry. The layered service-oriented architecture for CPMC is the first step toward an open-architecture of cloud-based manufacturing systems. Many challenging issues need to be investigated in this direction. Few of the issues are – security of CPMC based on an open architecture, production process planning, dynamic configurability of the manufacturing resources, and big data analytics of manufacturing.

This research on CPMC provides valuable insights on the development of an Internet-scale manufacturing communication protocol. MTConnect standard and TCP/IP protocol are used to connect manufacturing tools over the Internet. However, by design,

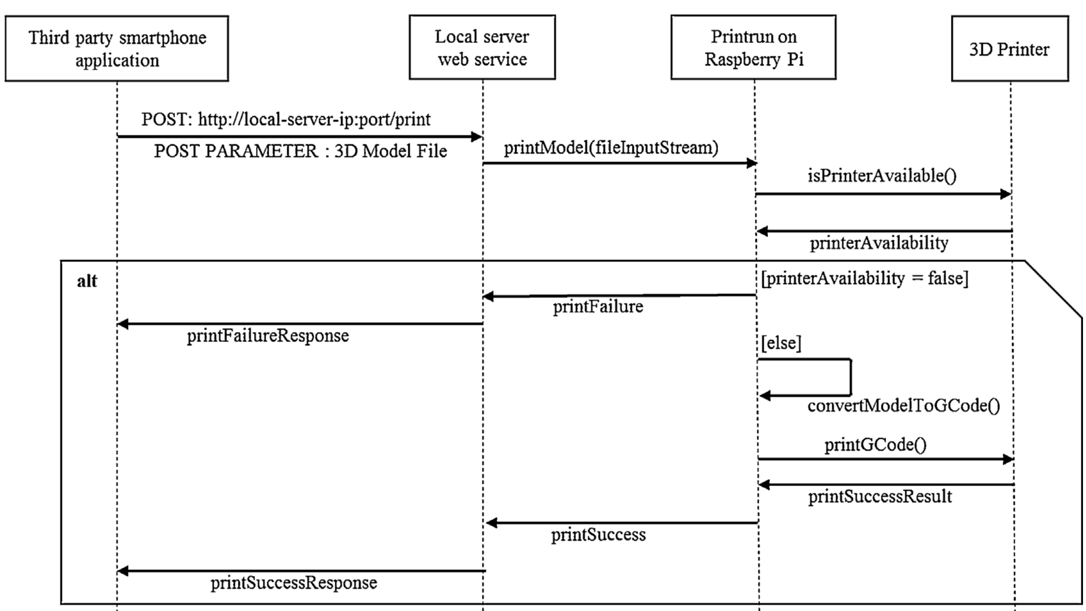

Fig. 16. Sequence Diagram for manufacturing application scenario 1.

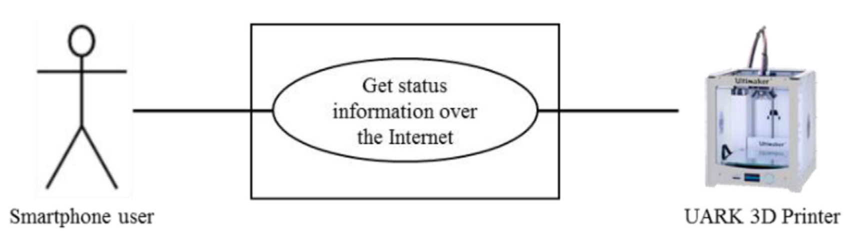

Fig. 17. Use Case diagram of manufacturing application scenario 2.

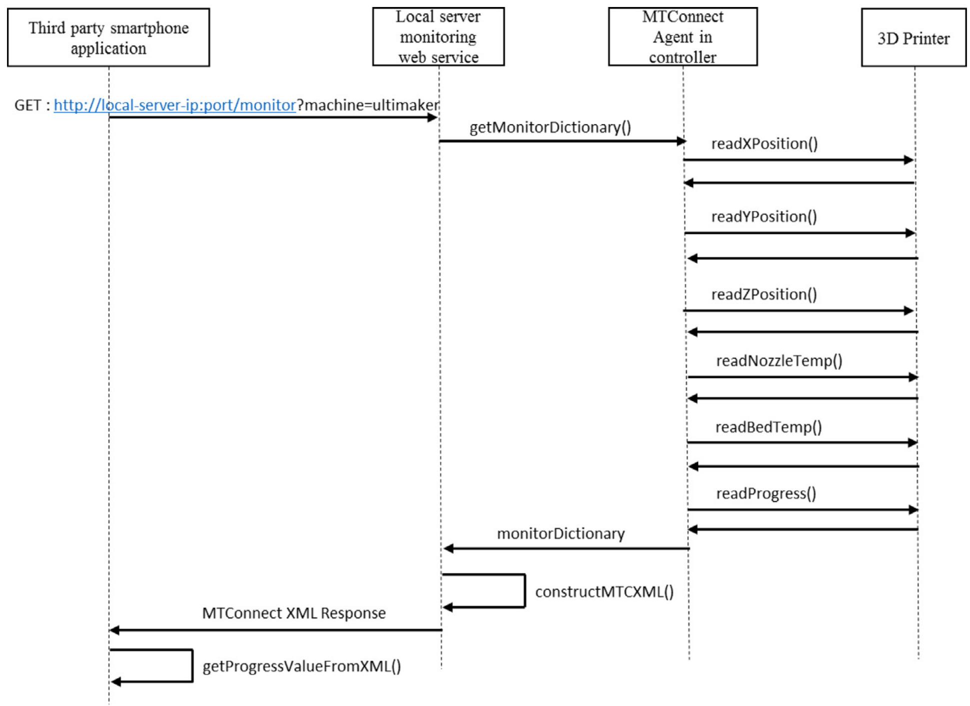

Fig. 18. Sequence Diagram for manufacturing application scenario 2.

MTConnect cannot be used for direct communication of manufacturing services over the Internet due to its focus on data acquisition for monitoring from machining tools. Instead, TCP/IP is utilized as a workaround for communication of manufacturing services in the testbed. However, it does not satisfy several requirements of Internet scale manufacturing communication methods for easy and efficient exchange of manufacturing services over the Internet. More researches need to be done on Internet scale manufacturing communication method.

Speedy transmission of manufacturing data exchange across layers is crucial for a successful implementation of a CPMC. Not all existing industrial machine tools are capable of computation and networking. Besides, many existing machine tools are operated by outdated operating systems. Although addition of those machines to a CPMC is challenging, we had a preliminary success with several types of those in the development of the testbed of CPMC. In the testbed of CPMC, several machine tools, such as one CNC, two 3D printers, two robotic arms did not have the networking capabilities except the USB interface. We added low-cost Raspberry Pi 2 controllers with MTConnect to connect them through USB interfaces to the network. Respective driver programs are also installed in the controllers to monitor and operate these machines. However, for large industrial machine tools, small Raspberry Pi 2 controllers may not be sufficient. Therefore, more researches need to be conducted to develop networking and middleware technologies that enable machine tools with outdated operating systems and hardware to be networked and their services can be provided in a CPMC.

7. Conclusions

This paper presents a scalable service-oriented architecture, virtualization technique, and communication methods of a cyber physical manufacturing cloud. It integrates paradigms of cloud manufacturing and cyber physical systems to enable direct operation of machining tools from a manufacturing cloud over the Internet. It has a web-based application for publishing web services for manufacturing operations and an application center to publish software applications for manufacturing operations. It utilizes the RESTful Internet protocol MTConnect for acquiring status data of machining tools to monitor their operations over the Internet. It provides a TCP/IP based solution for communicating operational manufacturing services in the cyber physical manufacturing cloud. The implemented operational CPMC testbed demonstrates feasibility of monitoring machining operations and performing manufacturing operations and processes directly from a manufacturing cloud over the Internet.

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