https://doi.org/10.1016/j.rcim.2021.102256

3D Printing in the Context of Cloud Manufacturing

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Abstract

3D printing has drawn tremendous attention in Industry 4.0. Nowadays, with the ever-increasing consumers' request for 3D printing services, there lies a big challenge to eliminate the unbalanced demands and supplies of 3D printing resources in a geographically distributed environment. Cloud manufacturing, as a newly emerged service-oriented manufacturing paradigm, provides a promising way to overcome the challenge by integrating 3D printing into the cloud-based context, which may flourish the development of smart networks of virtual 3D printing cloud and also promote a novel 3D printing service business model to achieve mass customization. This paper presents a comprehensive study of 3D printing in cloud manufacturing environment. Two typical models of 3D printing, i.e. primary 3D printing cloud model and advanced 3D printing cloud model are presented and compared. The system architecture design of a 3D printing cloud platform is proposed to support the latter model. Furthermore, a series of key enabling technologies are presented based on the proposed system architecture. Finally, a prototype of 3D printing cloud platform is deployed with a case study of an aircraft engine part. The

research will provide valuable theoretical and practical reference to the future development of 3D printing clouds.

Keywords

3D Printing, Cloud Manufacturing, Cyber Physical Systems, Industry 4.0

1 INTRODUCTION

3D printing , also known as Additive Manufacturing (AM), is envisioned as the starting point of ‘a third industrial revolution’ [1]. In a 3D printing process, the physical object is created from a geometrical representation by adding successive layers of material under the control of a computer. Unlike the traditional complicated processes of subtractive manufacturing, it prevails in its unique capabilities of complex geometry production, integrated assembly and elimination of many manufacturing constraints, thus promoting the realization of rapid prototyping/manufacturing [2, 3]. Moreover, 3D printing is superior in one-of-a-kind or small batch production with cost-efficiency, which provides a potential and profitable solution for today’s manufacturing industries based on their economies of scale . Nowadays, 3D printing has been widely utilized in industrial applications with a broad range, e.g. firearms, medical devices, construction, aircraft, and robots [4].

Meanwhile, owing to the rapid development and dramatically decreasing cost of 3D printers in the last five years, they have provided not merely industry-level manufacturing solutions, but increasingly filled the market of consumer-level solutions [5]. This tendency makes 3D printers, especially those small desktop ones, more accessible to normal consumers, and in turn, allows them to create personalized 3D printed items readily. As a result, the prosperity of consumer-level 3D printers provides a promising way to enable the achievement of mass customization.

Nevertheless, despite the prevailing attention from industry and academia, only a relatively small amount of people, mostly consisting of engineers from large enterprises and researchers from universities, have real access to the specifically required 3D printers and know how to exploit them. However, the 3D printing industry is developing rapidly. The 2018 Wohlers Report [6] shows that overall the 3D printing industry grew by 21% in the 2017/18 reporting period [7]. The Frost & Sullivan's Global 360° Research Team [8] also forecasts that additive manufacturing is poised to grow at a rate of 15.0% during 2015-2025. The ever-increasing demands of both industry-level and consumer-level 3D printers urge the openness and accessibility of them in a user-friendly manner. Therefore, one of the key challenges lies in how to eliminate the unbalanced demands and supplies of 3D printing resources in a geographically distributed environment by means of Internet and advanced IT techniques.

Cloud manufacturing was defined as *'a computing and service-oriented manufacturing model developed from existing advanced manufacturing models and information technologies'* [9] to enable service-oriented, knowledge-based, highly collaborative and flexible manufacturing [10-13]. With the convergence and adoption of advanced information technologies, such as Cloud Computing [14], Cyber Physical Systems (CPS) [15], and Internet-of-Things (IoT) , manufacturing industries have been transformed rapidly into a smart, connected environment [16]. Meanwhile, the distributed manufacturing resources and capabilities are *servitized* , i.e. virtualized into a shared resource pool, so that each user can obtain customized services in the cloud upon request all along the product lifecycle [17]. In this sense, 3D printing, as one type of advanced manufacturing technologies, can be regarded as a manufacturing capability service, and correspondingly, 3D printers are the manufacturing resources, following the definitions of cloud manufacturing [18, 19]. Hence, the integration of 3D printers into a cloud manufacturing environment can somehow flourish the development of smart networks of virtual 3D printing cloud in the near future [20, 21], and also promote a novel 3D printing business model in a service-oriented manner to achieve mass customization [22-24].

Aiming to address these issues, this research presents a comprehensive model, technology, platform and application to facilitate 3D printing in a cloud manufacturing environment. The rest of the paper is organized as follows: Section 2 proposes two types of 3D printing cloud models, i.e. primarily 3D printing cloud model, and advanced 3D printing cloud model. Then, section 3 proposes a platform architecture design supporting an advanced 3D printing cloud. Section 4 presents key enabling technologies, i.e., cloud terminalization of 3D printer, cloud servitization of 3D printing, and parallel 3D printing service composition optimization. A 3D printing cloud platform prototype and applications are given in section 5. Section 6 concludes the paper.

2 MODELS OF 3D PRINTING CLOUD

2.1 Primary 3D printing cloud model

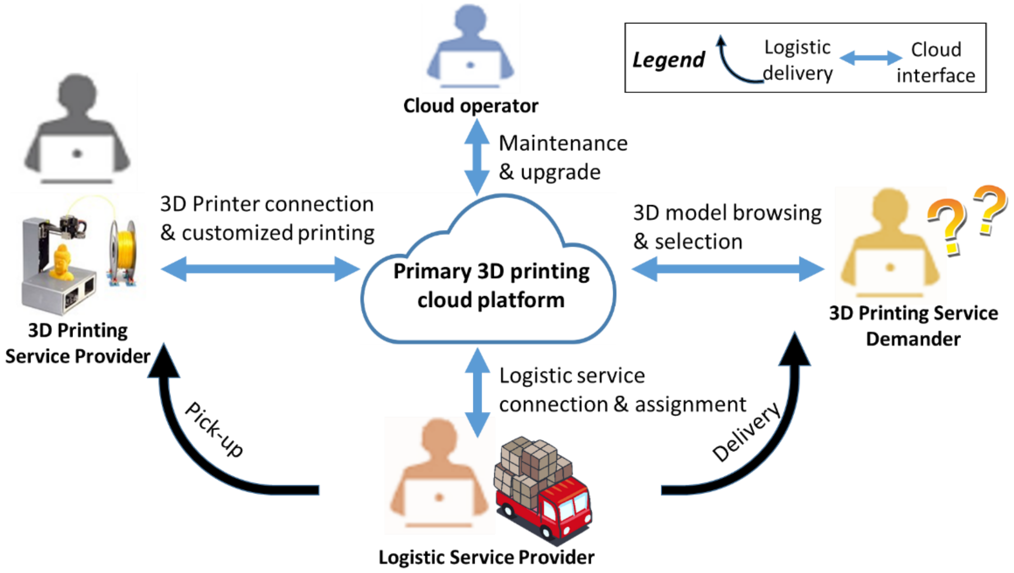


Fig. 1. Primary 3D printing cloud model.

The primary 3D printing cloud model is depicted in Fig. 1, including four different types of roles, namely *cloud operator, 3D printing service provider, 3D printing service demander, and logistic service provider.* The interactions among different roles are conducted in a *cloud platform*, which is the fundamental basis in connecting all the roles, offering search engines, managing 3D model classification, and recording all the essential information. *Cloud operator* is responsible for cloud platform maintenance and plays as an intermediary between demand and supply. *3D printing service providers*, as the manufacturing service providers, normally have their own 3D printers, and publish available 3D printing service information on the cloud platform. Conversely, *3D printing service demanders*, or consumers, can access the cloud platform, and browse the published 3D models and service information online within the pre-defined selection scope. They can make secure online transactions after the required 3D printing service is ordered and service agreement signed, and the transaction information will be recorded by the cloud platform. Once the 3D model is accomplished, the third-party *logistic service provider* will deliver the end-product to the consumer. The primary 3D printing cloud model can be seen as the initial stage of prospective 3D printing cloud, and is widely adopted by many websites to promote their cloud-based 3D printing services.

2.2 Advanced 3D printing cloud model

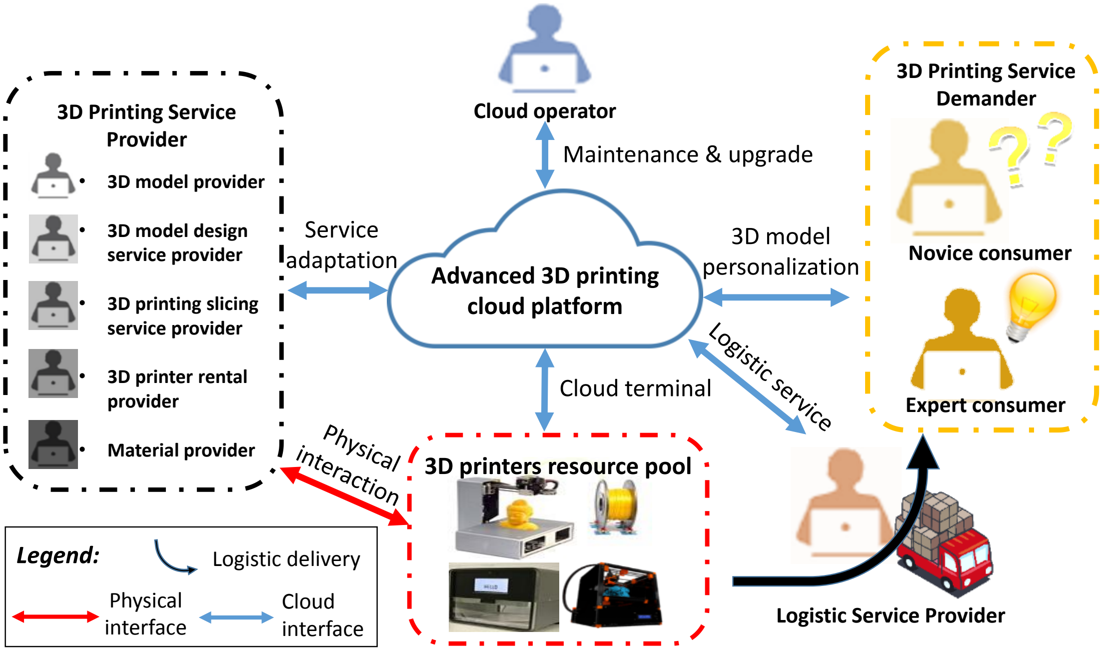


Fig. 2. Advanced 3D printing cloud model.

The advanced 3D printing cloud model is shown in Fig. 2. In comparison with the prior model, it is much more complex, including various roles, specialized 3D printing services, and types of networked 3D printers, to meet the various individual customer requirements. *3D printing Service demanders* are further categorized into two types, *novice consumer* and *expert consumer*. A *novice consumer* lacks in-depth knowledge of 3D printing process, and can somehow only select pre-defined 3D models and recommended printers provided by the *3D printing service providers* or claim a design request to the service providers for their design solutions, based on their requirements. In contrast, an *expert consumer* often has the capability to utilize CAD software to create 3D models, and also to manage the configuration of various 3D printing parameters of a specific 3D printer. Therefore, the service demands from an expert consumer can be quite complex and more specific information should be provided, e.g., personalized 3D model design, model slicing, and 3D printer control.

For *3D printing service providers,* they can be further classified into *3D model provider*, *3D model design service provider*, *3D printing slicing service provider*, *3D printer rental provider*, and *material provider*. *3D model provider*, publishes existing 3D models for service demander's selection*; 3D model design service provider* can offer personalized CAD model design service to the consumers without specific design background or provide a user-friendly co-creation toolkit for customers who have CAD skills*; 3D printing slicing service provider* will offer online model slicing interfaces with various slicing engine algorithms*; 3D printer rental provider* will share his/her available 3D printers for 3D printing services in a pay-per-use manner; *and material provider* offers the various printing materials for consumer's different printing purposes. These different roles of service providers act in a cooperative manner by following the guidelines and agreement established in the advanced cloud platform.

In this advanced 3D printing cloud model, various types of distributed 3D printers are all connected into cloud networks under the control of the cloud platform. Hence, a 3D printer can be remotely utilized as a cloud terminal. It runs a shared business model, where dispersed, spare 3D printing resources of the 3D printer owners can be utilized effectively in a pay-per-use manner. Also, it largely reduces the upfront investment of 3D printers or IT infrastructure for the service demander, especially for those who have great knowledge in 3D printing while without any ownerships. Moreover, the intellectual property of customized 3D models is protected, and all the essential design information will be stored in the cloud platform with unique access for the specific users. Table 1 presents a thorough comparison of the primary 3D printing cloud model and the advanced 3D printing cloud model from three different perspectives.

Table 1. Comparison of the primary 3D printing cloud model and the advanced 3D printing cloud model

Perspective	Primary 3D printing cloud model	Advanced 3D printing cloud model
Perspective of resource/service	■ 3D Printing service ■ Logistic service ■ 3D model library service	■ 3D printing service ■ Logistic service ■ Advanced 3D model library service ■ 3D model personalized design service ■ Supporting-structure optimization service ■ Online slicing service ■ Virtual printing service ■ 3D printer maintenance service ■ 3D printing material supply service

		Knowledge service and creative service
Perspective of user	■ With knowledge background in 3D printing technology ■ 3D printer owner and professional 3D printing service demander	■ Lower the professional knowledge threshold for potential user to utilize the 3D printing technology ■ Reduce the cost of benefiting from 3D printing technology ■ 3D printer owner and 3D printer renter ■ 3D printing service demander and 3D model designer ■ 3D printing material supplier ■ 3D printer maintenance service provider **Expand the users' range, promote the collaborative development of 3D printing related industries**
Perspective of cloud platform	■ Information sharing platform	■ Information sharing and knowledge creation ■ Task packaging or decomposition ■ Supply and demand matching ■ Unbalance demand dynamic scheduling ■ Transaction monitoring and service evaluation ■ Intellectual property protection **Fundamental basis of the 3D printing community**

3 ARCHITECTURE OF 3D PRINTING CLOUD PLATFORM

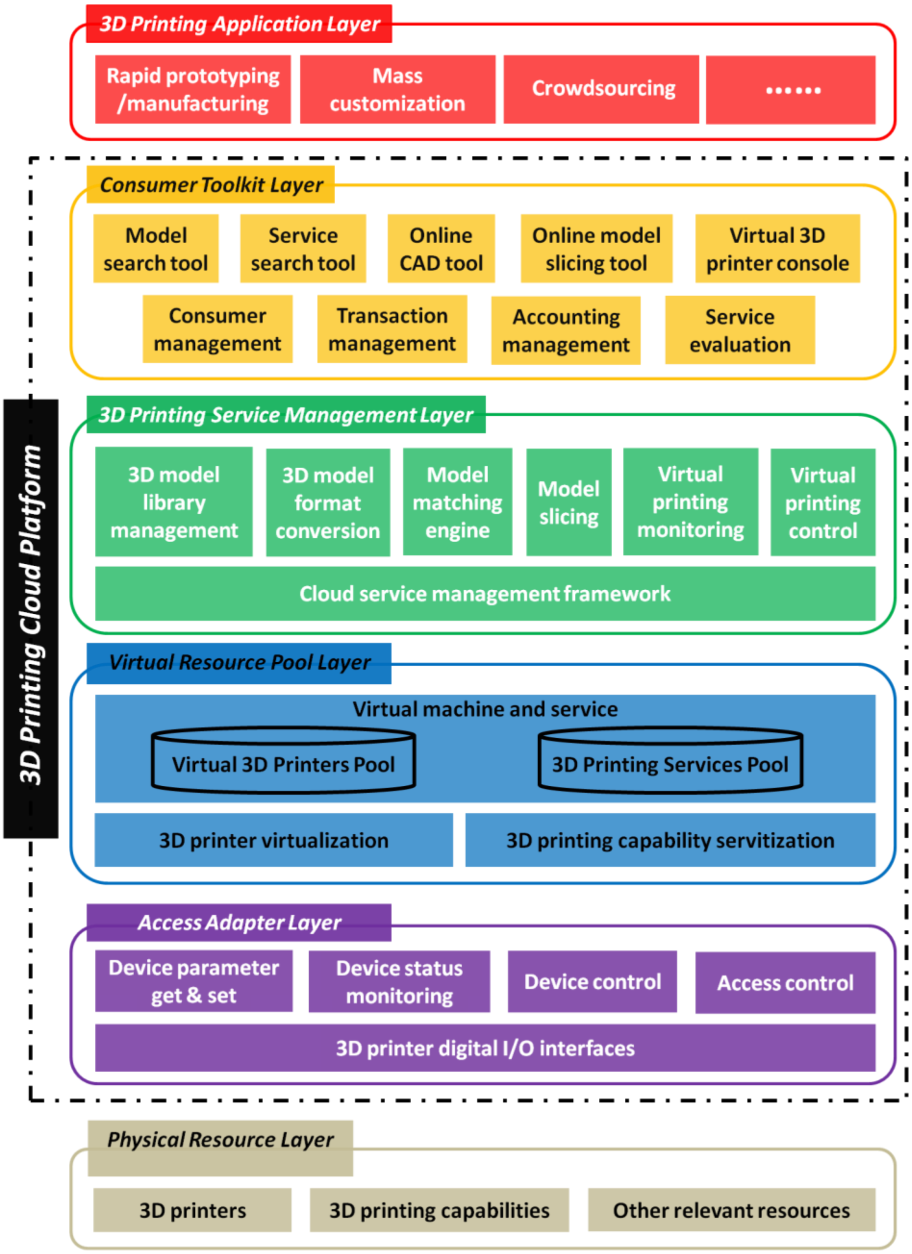


Fig. 3. Architecture of 3D printing cloud platform.

Fig. 3 shows the proposed architecture design of a 3D printing cloud platform, mainly to support the aforementioned advanced 3D printing cloud model. One can find that the cloud platform consists of four layers, i.e. *access adapter layer*, *virtual pool layer, 3D printing service management layer, and user toolkit layer*, in a bottom-up manner. Meanwhile, the overall architecture also contains the *physical resource layer*, and *3D printing application layer*, to realize the implementation of the 3D printing cloud platform. The detail information of each layer is described below.

（1） Physical resource layer

The *physical resource layer* is composed by multiple geographically distributed 3D printing resources, e.g. 3D printers, 3D printing capabilities, and etc. Based on the pre-defined set of communication protocols, various 3D printers can be connected to the Internet and accessed by individual service demanders [4]. 3D printing capabilities stand for the professional services that the 3D printing service providers can offer. They will be virtualized into a standard information structure, which can be parsed as different cloud services provided.

（2） Access adapter layer

The *access adapter layer* serves to enable the adaptive access to a variety of 3D printers and also unify I/O interfaces. A set of abstract 3D printer digital I/O interfaces should be pre-defined as the standard ones in the cloud platform, so as to be adopted by all the devices connected to the cloud. Generally, these standard interfaces should include the functions of parameter get and set, status monitoring, device control and access control [25]. When a new device connected, it should follow all the definitions of the predefined set of abstract interfaces so as to be implemented.

（3） Virtual resource pool layer

The *virtual resource pool layer* is a virtual pool of abstracted logical resources from their underlying physical resources, i.e. 3D printers and 3D printing capabilities. The information of physical resources is accumulated and managed in this layer following a centralized manner. For example, a 3D printer will be virtualized into a virtual model. Its machine parameters will be described by a structured information model, and its functional interfaces can be virtualized by adopting software virtualization methods. Therefore, such a virtual-twin between the physical 3D printer and virtual one is established. With ever increasing 3D printers connected, a virtual resource pool is formed [20]. Meanwhile, for 3D printing capabilities, such as model optimization and model slicing, can be virtualized into cloud services with certain service specifications as well. Hence, this virtual resource pool serves as the core assets of the cloud platform.

（4） 3D printing service management layer

Upon the *virtual resource pool layer*, the *3D printing management layer* manages all the 3D printing services. Cloud service management framework, as the fundamental basis of this layer, offers common functional service interfaces, including service modeling template, service registration, service publishing, service search, service invoke, service composition, and etc. Major 3D printing services can be derived from the framework, namely, 3D model library management [26], model format conversion, model matching engine [27, 28], model slicing, virtual printer monitoring, and virtual printer control. Various 3D model data (e.g. STL files and CAD source files) are managed and recorded in the library, and converted into a standard format for 3D printing process. Model matching engine provides a personalized graph-based search engine to enable customized searching. Moreover, it is important to be aware of the availability and capability of manufacturing resources in a geographically distributed cloud manufacturing environment [29]. The virtual printer monitoring and control services are implemented relying on the digital interfaces through the virtual resource pool and access adapter layers. Also, cloud computing techniques, e.g. cloud storage, can be utilized to manage the big data obtained from various services.

（5） Consumer toolkit layer

The *consumer toolkit layer*, offers customized online tools for service demanders' own usage in the cloud platform. It mainly contains two categories, i.e. general-purpose tools and 3D printing-related tools. The prior one includes the tools for user management, transaction management, accounting management, and service evaluation [20, 30]. Meanwhile, the latter one consists of 3D model search tool, service search tool, online CAD tool, online model slicing tool, and virtual 3D printer consoler. The consumers will benefit from these plugins to customize their services.

（6） 3D printing application layer

The *3D printing application layer* consists of various 3D printing manufacturing mode applications based on the support of 3D printing cloud platform. These 3D printing manufacturing mode applications including rapid prototyping/manufacturing, mass customization, crowdsourcing and so on. Benefit from the shared business model of the 3D printing cloud platform as well as its advantage in promoting the reduction of upfront investment, various manufacturing modes with 3D printing technology involved may change and flourish in a service-oriented manner.

The advanced 3D printing cloud model is a combination of 3D printing technology with cloud manufacturing paradigm. Furthermore, the advanced 3D printing cloud model-based 3D printing cloud platform is characterized by service-oriented architecture, personalized customization technology, and scalable service platform. The advanced 3D printing cloud model is expected to promote a novel 3D printing business model in a service-oriented manner to achieve mass customization in Industry 4.0. Instead of an independent information sharing platform, the 3D printing cloud platform is an open, shared, and scalable platform that provides both 3D printing service and other types of high value-added knowledge services. The 3D printing cloud platform can lead to a group innovation-based 3D printing community and promote the development of 3D printing related industrials.

4 KEY ENABLING TECHNOLOGIES

Generally, there are two classes of core scientific problems in design and implementation of the 3D printing cloud platform. At the platform level, the most critical scientific problem is the service management, including accurate service matching, flexible service composition, dynamic service scheduling, and comprehensive service evaluation. In addition, collective intelligence emerging from the collaboration and competition of users of the 3D printing cloud platform is also an important scientific problem. At the specific technical level, especially in the computer graphics domain, one scientific problem is the supporting-structure design and optimization, while the other is the 3D model design with printability constraints. Apart from the scientific problems, there are also several core technical issues for the implementation and operation of the 3D printing cloud platform, including six categories: (1) perception and access of 3D printing resources/capabilities; (2) virtualization and servitization of 3D printing resources/capabilities; (3) construction, management, running, and evaluation of service environment on 3D printing cloud platform; (4) pervasive human–computer interaction technology for 3D printing cloud platform; (5) safety and security of 3D printing cloud platform; and (6) development and integration of the functional modules. Cloud terminalization technology for 3D printer, virtualization and servitization technology for 3D printer as well as the heuristic strategy for parallel 3D printing service composition optimization problem are presented is this section.

4.1 Cloud terminalization of 3D printer

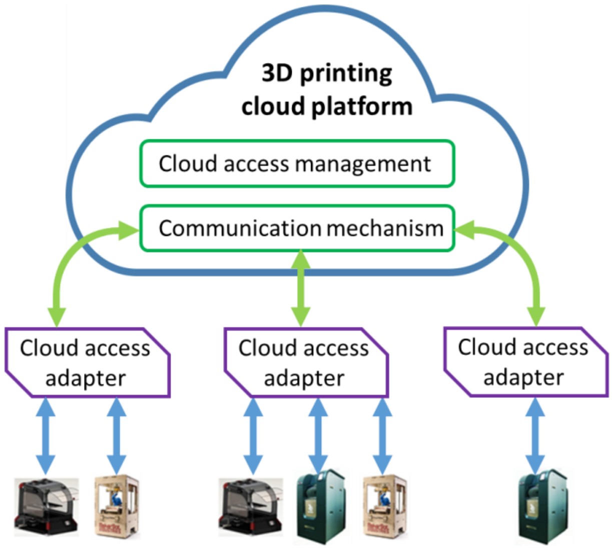


Fig. 4. 3D printer cloud access mechanism.

Cloud terminalization of 3D printer means that an independent 3D printer is connected to networks as a cloud terminal, which can be used online and provide remote 3D printing services for multiple users over networks. Fig. 4 illustrates the cloud access mechanism of 3D printers that can support cloud terminalization of 3D printer. To realize cloud access, three main components should be involved, i.e., *cloud access adapter*, *communication mechanism*, and *cloud access management*.

Cloud access adapter [25] is the most critical component that is responsible for connecting various 3D printers into networks. The core functions of this access device include: multiple 3D printer access, collecting real time operating data, gathering progress information of printing tasks, managing device security and user access, controlling communication between access adapter and 3D printing device, and 3D printing device online operation. Based on embedded system hardware and Linux operating system, cloud access adapter can connect multiple 3D printing devices by a plurality of USB interfaces and run a variety of functional modules. The adapter can provide support for receiving processing files sent from cloud 3D printing platform to the corresponding 3D printer, and offering necessary functions to control 3D printing tasks execution remotely, e.g., begin, pause, stop and adjust.

The main modules constituting a *cloud access adapter* are shown in Fig. 5, including device interface, monitor interface, network interface, and core function modules. *Device interface module* is used for connecting multiple 3D printers by universal serial bus interfaces, series communication interfaces, and wireless IoT interfaces. *Monitor interface module* targets at implementing real time monitoring of 3D printing device status by using remote camera. *Network interface module* is responsible for establishing connection between the core function module and Internet through cable Internet interface or wireless Internet interface.

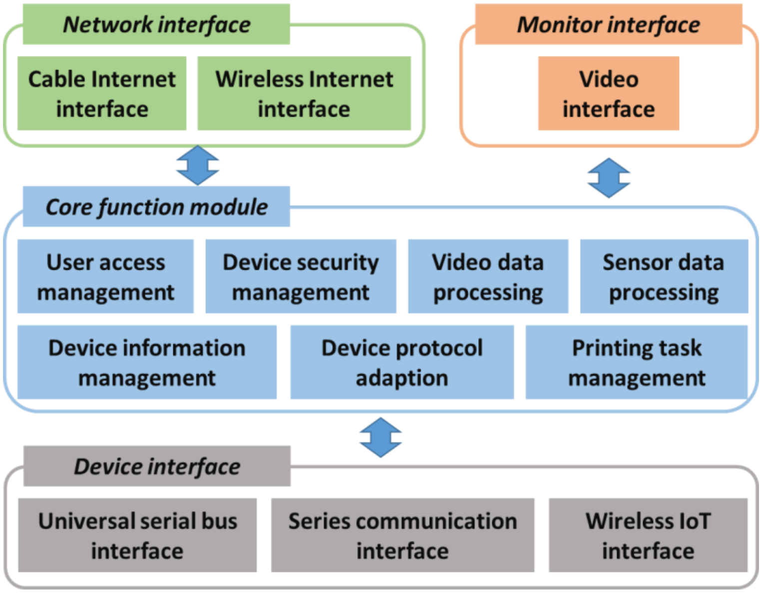


Fig. 5. The modules of cloud access adapter.

The core function module runs programs of multiple modules, including device protocol adaptation module, device information management module, sensor data processing module, video data processing module, printing task management module, user access control module, and security management module. Their main functions are depicted as follows:

- *Device protocol adaptation module* is capable to automatically select the corresponding communication protocol to communicate with 3D printing device, according to the device model. Also, it is responsible for receiving and processing the real time online remote operation instructions issued from cloud 3D printing platform, including operations such as connecting, disconnecting, nozzle movement, and nozzle temperature settings.
- *Sensor data processing module* is adopted for collecting dynamic data of 3D printing devices such as sensor data, e.g. temperature, and uploading it to the cloud 3D printing platform.
- *Video data processing module* is used to gather real time video information and upload it to the cloud 3D printing platform.

- *Device information management module* is in charge of managing the basic information, e.g., device model, precision and size limitation of multiple 3D printing devices that were connected to this cloud access adapter.
- *Printing task management module* is exploited to get a set of printing tasks from cloud 3D printing platform and generating processing tasks queue [31].
- *User access control module* is to manage the authority of remote users over networks. The security management module ensures device security based on real time data analysis.

4.2 Cloud virtualization and servitization of 3D printer

By utilizing the technology of cloud terminalization of 3D printer, 3D printing devices can be connected into cloud platform networks through cloud access adapter. Hence, in order to achieve transformation from various independent devices to standard remote online 3D printing service, 3D printer and printing capabilities should be virtualized and encapsulated to standard cloud services [20].

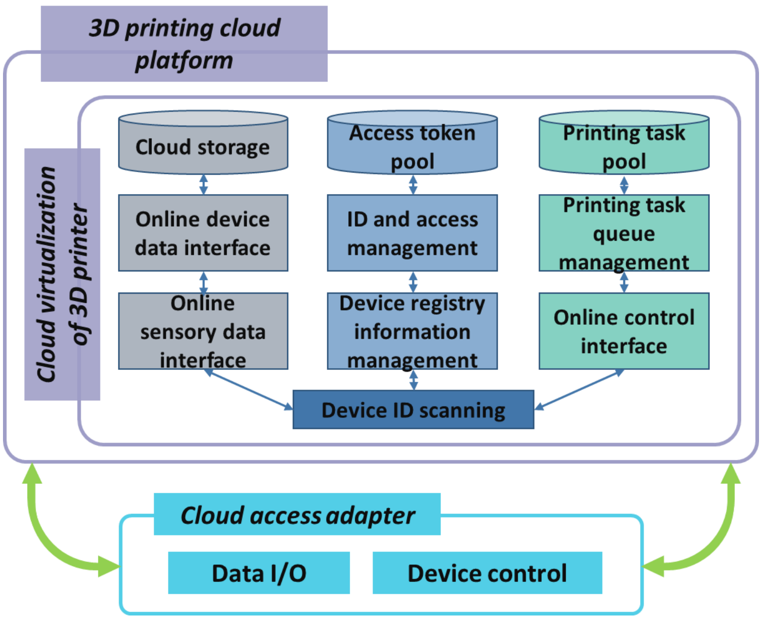


Fig. 6. Cloud virtualization of 3D printers.

Fig. 6 shows the main principle and mechanism of cloud virtualization of 3D printers. The *device ID scanning module* is responsible for parsing the device information scanned from the interfaces of cloud access adapter. The parsed results include a serial port names and numbers that can be utilized to connect devices and access adapters. This is the crucial parameters used for distinguishing multiple different 3D printers connected to an identical access adapter. The *device registry and information management module* is in charge of 3D printer registration management as well as device information management. Its basic information includes an URI (Uniform Resource Identifier), device name, device model, device status, serial port name and number, and communication baud rate. The *ID and access management module* is used for device access authorization by using dynamic tokens. The request token is a string of encrypted data used to establish trusted registration for devices. At its first registration, the URI of device should be verified before a temporary token is issued, and the token will be registered in the cloud access token pool to accomplish.

The *online sensory data interface* is utilized for processing data from the sensor data interface [32] of the access adapter. The *video data interface* monitors real time video of 3D printing scenario through the video interface of the access adapter. The temporal big data generated from the interfaces would be stored in cloud storage for further data analysis. The *online control interface* is in charge of online monitoring and remote operation of 3D printing devices. It gives instructions to activate camera, take snapshots of 3D printing scenario, and return real-time video streaming data. In addition, the interface is responsible for issuing remote operation requests, such as actuator movement, material feeding, and nozzle heating. These operation commands would be executed once the access authorized.

The *printing task queue management module* manages multiple printing tasks on various 3D printers from multiple users [33]. When a printing task queue initialized, the operation limitation should be configured, including NOT OPEN level, OPEN level, and AUDIT level. The NOT OPEN level means that only the device owner has the access authorization. The OPEN level sets no limitations for user access. The AUDIT level represents that the device is limited only to the authorized users. In addition, the module is responsible for creating new printing tasks, cancelling printing tasks, and processing task failures.

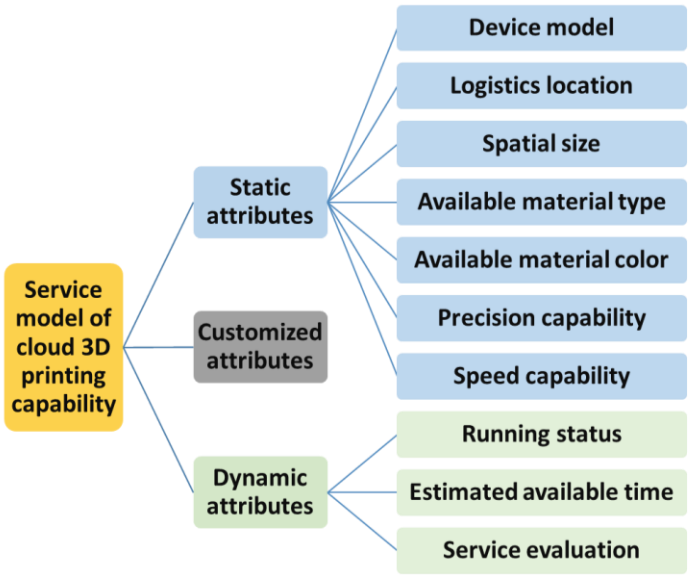


Fig. 7. Service model of cloud 3D printing capability.

Based on the virtualization of 3D printers, 3D printing capabilities should also be encapsulated into standard cloud services. The key approach of cloud servitization is named 3D printing capability modeling. The service model of cloud 3D printing capability with different categories of attributes is shown in Fig. 7. The attributes of the model are classified into three categories, i.e., *static attributes, dynamic attributes*, and *customized attributes*. The *static attributes* consist of device model, logistics location, spatial size (length, width and height), available material type, available material color, precision capability, and speed capability. The *dynamic attributes* include running status, expected available time, and service evaluation. *Customized attributes* are the unique ones defined by each individual consumers thereafter.

4.3 Parallel 3D printing service composition optimization

To achieve product mass customization by exploiting cloud 3D printing services, the key technology lies in parallel cloud 3D printing service composition [34]. It allows complex composite product models to be decomposed into parts that can be processed by multiple 3D printing services in parallel. To achieve this, a 3D printing service composition optimization method is the key, which can provide support for optimal selection of a vast number of distributed cloud services [35]. The service composition optimization process is given as follows.

（1） **Complex composite 3D printing task modeling**

Task node refers to a single printing process of a component model.

TaskNode=<*NodeID, NodeName, MaterialType, MaterialColor, ModelSize, ModelPrecision, FileInfo, ProcessTo*>

MaterialType, MaterialColor, ModelSize, and ModelPrecision are basic parameters set by task publisher. FileInfo refers to 3D printing processing file associated with the task node. ProcessTo refers to ID for next task node.

Task flow refers to order of the task nodes on one 3D printer.

Printing subtask refers to the task nodes and corresponding task flow to be printed on one 3D printer.

PrintingSubtask=<*SubtaskID, SubtaskName, NodeList, MaterialType, MaterialColor, ModelSize, ModelPrecision, Speed, DeviceType, Position*>

NodeList refers to the task nodes included in the printing task. Other attributes are either subtask tag information or basic parameters set by task publisher.

One complex synthesis 3D printing task can be described as a whole that contains multiple printing subtasks. Each printing subtask consists of multiple task nodes and corresponding task flow. Further, the printing subtasks are matched to multiple 3D printers in order to achieve distributed parallel printing processing.

PrintingTask=<*TaskID, TaskName, NodeAll, SubtaskAll*>

NodeAll and SubtaskAll refer to all the nodes and all the printing subtasks that are included by the complex synthesis 3D printing task, respectively.

（2） **Mathematical description of cloud 3D printing service**

Attributes of online 3D printing services can be divided into static and dynamic parts in general. Static attributes mainly describe the basic information of the online 3D printing service while dynamic attributes are used to characterize the status of the equipment.

Online3DPrintingService=<*TagInfo, StaticAttribute, DynamicAttribute, CustomizedAttribute*>

TagInfo refers to the basic identification information of a online 3D printing service, like ID and name.

StaticAttribute=< *DeviceModel, Position, SpatialSize, MaterialType, MaterialColor, ProcessingPrecision, ProcessingSpeed* >

SpatialSize refers to limit size of the product printed by the corresponding online 3D printing service. MaterialType, MaterialColor, ProcessingPrecision, and

ProcessingSpeed refer to the material and processing capability that can be provided by the printing service.

DynamicAttribute=<*RunningStatus, EstimatedAvailableTime, ServiceEvaluation*>

RunningStatus of an online 3D printing service can be idle, busy, pause, stop, off, empty, and fail. EstimatedAvailableTime can be obtained using the probability model that constructed based on the statistical data of equipment working condition as well as equipment work load. ServiceEvaluation rating approach is an integrated method by combining system assessment with user evaluation.

(3) Optimal composition model for parallel cloud 3D printing service

$\boldsymbol{T} = (T_1, T_2, \dots, T_n)$ represents a complex synthesis 3D printing task, parallel subtask T_i is the ith component element for the complex synthesis task.

$\boldsymbol{C_i} = (S_i^1, S_i^2, \dots, S_i^{N_i})$ refers to a finite set of candidate services for parallel subtask T_i. Thus, family of sets $\boldsymbol{C} = (\boldsymbol{C_1}, \boldsymbol{C_2}, \dots, \boldsymbol{C_n})$ is a set of parallel subtask candidate service sets.

$\boldsymbol{S} = (S_1, S_2, \dots, S_n)$ is a feasible candidate solution for synthesis 3D printing task $\boldsymbol{T}$.

The general composition optimization objective function is given as follows:

$$\begin{cases} min\,(f(\boldsymbol{S})) \\ s.t.\ S_i \epsilon \boldsymbol{C_i}, i = 1,2,\dots,n \end{cases} \tag{1}$$

For a specific purpose of minimize the 3D printing service time or coat, then

$$f(\boldsymbol{S}) = max(f_T(S_i)) \tag{2}$$

or

$$f(\boldsymbol{S}) = \sum_{i=1}^{n} f_C(S_i) \tag{3}$$

where $f_T(S_i)$ represents the 3D printing service time evaluation function and $f_C(S_i)$ refers to the service cost evaluation function.

(4) Heuristic strategy for composition optimization model solving

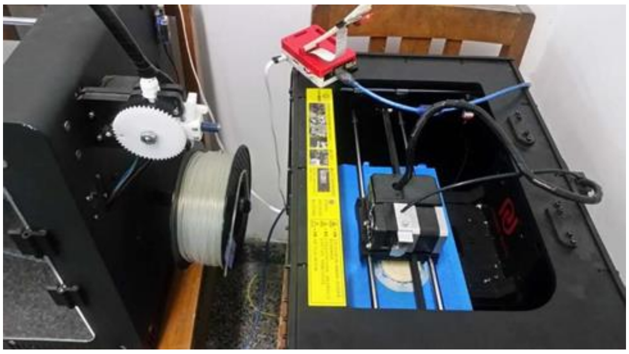
Numerous online 3D printing services are integrated in 3D printing cloud service platform, efficient solving method for the online 3D printing service composition optimal selection model become increasing critical. In order to obtain the optimal feasible solution for the proposed model, this section presents a heuristic strategy for the solving algorithm.

After getting a feasible solution from the candidate solution space randomly, cross-subtask online 3D printing service search strategy provides effective information to avoid falling into the local optimal solution. The core idea is, (a) identifying the subtasks corresponding to the worst feasible service and the second poor performance service, (b) updating the service pairs corresponding to the subtasks and evaluate performance of the updated feasible solution, (c) iterating until reach the terminate condition. This strategy can therefore benefit the solving process of the proposed parallel processing task oriented online 3D printing service composition optimal selection model [36].

5 PROTOTYPE AND APPLICATION

We have developed a prototype of cloud 3D printing platform. Fig. 8 (a) shows the cloud access adapter developed for fused deposition modeling (FDM) 3D printers. With the support of this access adapter, a variety of FDM 3D printers are connected to the cloud 3D printing platform through USB ports, wireless or cable Internet ports (Fig. 8 (b)). It enables remote monitoring of 3D printing scenario as well as online control of 3D printing operations, as shown in Fig. 9.

(a) A cloud access adapter for FDM 3D printers.



(b) Connecting 3D printer to cloud platform through the cloud access adapter.

Fig. 8. Hardware Part.

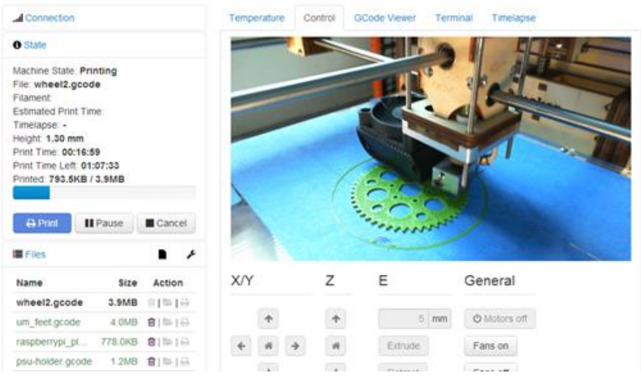


Fig. 9. Remote online monitoring and control of cloud 3D printers.

Based on the access adapter shown in Fig. 8(a), 3D printers are connected to the cloud service platform. On the one hand, connected printers are able to receive printing tasks from the cloud service platform through the access adapter. On the other hand, with the access adapter, the cloud platform can achieve run-time information collection and real-time monitoring of the connected printers. This part mainly corresponds to the access adapter layer and the physical resource layer of the 3D printing cloud platform architecture.

On the cloud 3D printing platform, users can customize desired models by searching the model library, as shown in Fig. 10. To achieve better efficiency of model query, we developed sketching-based model search tool as shown in Fig. 11. To efficiently support online design of relatively simple models, online design tools are also developed, as shown in Fig. 12. In this platform, we also provide model format conversion tool used for transforming different file formats of a model. This part mainly corresponds to the consumer toolkit layer and the 3D printing service management layer of the 3D printing cloud platform architecture.

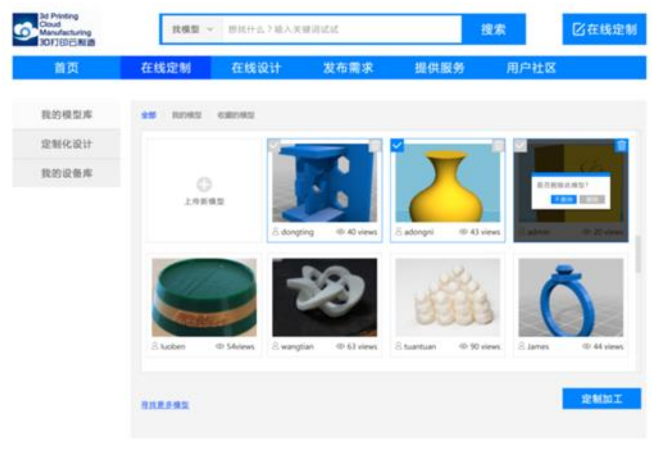


Fig. 10. User customization by searching in cloud model library.

Fig. 11. Sketching-based model searching.

Fig. 12. Online model design tool.

Fig. 13, Fig. 14(a), Fig. 14(b), and Fig. 15 show the example of printing an aircraft engine model in a distributed environment with the support of our prototype 3D printing cloud platform. Fig. 13 shows the printing task demand of an aircraft engine prototype model. It consists of 12 sub-models. These sub-models can be further classified into three groups according to the printing accuracy constraint, printing material constraint, and printing color constraint. Detailed information of the printing task demand of the aircraft engine prototype model is shown in Table 2.

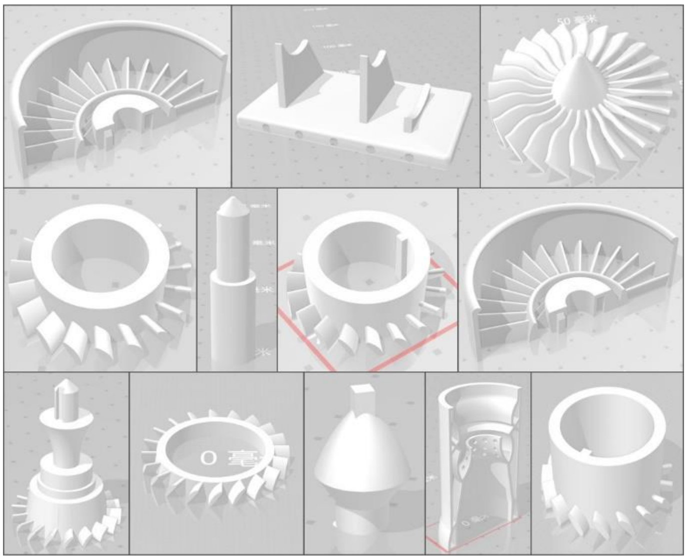


Fig. 13. Parts of an aircraft engine prototype model in a cloud 3D printing application.

Table 2. Printing task demand of the aircraft engine prototype model

Group No.	Sub-model No.	Sub-model Name	Printing Accuracy	Printing Material	Printing Color
Group 1	(1)	Supporting base	0.2 mm	ABS	White
	(2)	Upper guard			
Group 2	(3)	Exhaust turbine	0.1 mm	PLA	White
	(4)	Front axle			
	(5)	Housing			
	(6)	Primary compression			
	(7)	Rear axle			
	(8)	Second level compression			
	(9)	Shaft			
	(10)	Third level compression			
Group 3	(11)	Lower guard	0.2 mm	ABS	White
	(12)	Turbofan			

The prototype 3D printing cloud platform decomposed the printing task into three different subtasks and defined the sub-model printing order for each subtask (as shown in Fig. 14 (a)). The cloud platform supported decision-making process is a complex procedure with both domain knowledge and practical constraints are considered. In this example, the individualized printing demand and the aircraft engine mode assembly sequence are the most important influencing factors for the task decomposition procedure and the sub-model printing order definition procedure, respectively.

Then, the prototype 3D printing cloud platform matched an optimal cloud service for each subtask according to the available 3D printing cloud services and the printing task demand constraints. Both functional attributes and non-functional attributes of the candidate cloud 3D printing services are considered in the service matching and optimal selection procedure. Two phases are included in this procedure. Firstly, the cloud platform selects a set of 3D printing services from all the available cloud 3D printing services according to the service functional attributes. The selected cloud 3D printing services are able to satisfy the basic functional demand of the printing task. Secondly, the cloud platform selects the most suitable cloud 3D printing service for the printing task demand from the candidate service set which acquired from the previous step. In this process, the non-functional attributes of candidate cloud 3D printing service, like service quality and service price, are considered. In this example, the optimal composition result of distributed parallel 3D cloud printing services that can realize the printing task demand of the aircraft engine prototype model is shown in Fig. 14 (b).

(a) Decomposed printing tasks.

(b) Optimal composition results of distributed parallel 3D cloud printing services.

Fig. 14. 3D printing service composition optimization.

After the slicing process, the G-code files which correspond to the 3D models are sent to the corresponding selected cloud 3D printing services. Finally, the task is finished by different 3D printing cloud services collaboratively and the printed sub-models are shown in Fig. 15. In this process, the selected cloud 3D printing services might be mapped to geographically distributed 3D printer resources.

3D printing cloud platform not only makes it possible to improve the utilization of 3D printing resources/capabilities, but also serves as a means to create and maintain a 3D printing community. 3D printing cloud platform expands the range of user and candidate service, it is a promising method to meet the challenge of mass customization.

Fig. 15. Printed parts.

However, at present, there are two aspects to be further addressed in the implementation process of a 3D printing cloud platform based on the advanced 3D printing cloud model. The first is the adoption of artificial intelligence. The advanced 3D printing cloud model based cloud platform serves as a platform of knowledge creation and application. Knowledge is the core element for service matching, composition, scheduling, and evaluation on the cloud platform. Characterized by deep integration of the Internet and the manufacturing industry, smart cloud manufacturing is a typical application of artificial intelligence. Smart cloud manufacturing can provide reference for the development and implementation of the advanced 3D printing cloud model. The second is the safety and security issue. Safety and security issue in the advanced 3D printing cloud model includes safety in physical space, security in cyberspace, safety and security problems of mutual effect between physical and cyberspace. As much concerned by the customers, they represent the biggest obstacle to promote the 3D printing cloud platform for commercialization.

6 CONCLUSION

3D printing, as a prevailing advanced manufacturing technology in Industry 4.0, is facing new opportunities and challenges in a cyber-physical integrated manufacturing environment exploiting the technologies such as CPS, IoT and cloud computing. Cloud manufacturing, as a newly emerged service-oriented smart manufacturing paradigm, provides a promising way to overcome the challenges by integrating 3D printing into the cloud-based context and flourish the development of smart networks of virtual 3D printing cloud. This paper presents a comprehensive study of the model, technology, platform and application of 3D printing in a cloud manufacturing environment. The paper presents two typical models of 3D printing towards cloud manufacturing, i.e. *primary 3D printing cloud model* and *advanced 3D printing cloud model*. Then, the system architecture design of a 3D printing cloud platform is proposed to support the latter model. Furthermore, a series of key enabling technologies are presented based on the proposed system architecture. Finally, a prototype of 3D printing cloud platform is deployed with a case study of an aircraft engine part. The research will provide valuable theoretical and practical reference to the future development and deployment of 3D printing clouds, and promote a novel 3D printing business model in a service-oriented manner to achieve mass customization in Industry 4.0.

In future work, we will put the emphasis on data security for 3D printing clouds, because a large number of 3D models in trading usually involve business secrets as well as intellectual property rights.

Acknowledgements

The research is supported by the National Key Research and Development Program of China [grant No. 2019YFB1705502 and 2018YFB1004001], and the National Natural Science Foundation of China [grant No. 61572057 and 61836001].

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