A Digital Ecosystem for Personal Manufacturing: An Architecture for Cloud-based Distributed Manufacturing Operating Systems

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ABSTRACT

Recently, we have witnessed the advent of personal manufacturing, where home users, small, medium, and Fortune 500 enterprises use devices such as 3D printers, CNC mills, and robotics to manufacture products locally. We have been developing a digital ecosystem of personal manufacturing for the last seven years. This ecosystem is currently used or being tried by 111 Fortune 2000 enterprises. In this paper, we focus on the creation of the cloud-based manufacturing operating system, 3DPrinterOS, to address an evolving critical problem of personal manufacturing. We introduce a novel software ecosystem architecture to sustain a massive communication load of command, control, and telemetry data to and from millions of manufacturing machines and users. Our solution allows users to create and deploy their own applications into 3DPrinterOS cloud operating system. Our long term experiments show that over the last five years, 95,000 users have generated over three million CAD designs and machine codes, and produced more than 1,030,000 physical parts on 32,000 manufacturing machines in 100 countries. Short term experiments showed that, on average, it is five times faster to perform a 3D print using 3DPrinterOS.

CCS CONCEPTS

• **Applied computing** → **Enterprise computing infrastructures**; • **Computer systems organization** → **Cloud computing**; • **General and reference** → *Experimentation*; • **Information systems** → Enterprise applications.

KEYWORDS

3DPrinterOS SECO, personal manufacturing, cloud manufacturing, cloud operating system, cloud manufacturing operating system, digital ecosystem architecture

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1 INTRODUCTION

The impressively fast adoption of automated manufacturing (AM) technologies such as 3D printers, CNC mills, and robotics indicates that this novel approach to manufacturing can become a key enabler for the real-time economy of the future, i.e., represent a possible paradigm shift in manufacturing towards personal manufacturing. In such a paradigm, people will not buy a ready-made product at the factory, but obtain raw material and produce products locally, utilizing their own or publicly available AM machinery.

We have been developing 3DPrinterOS, a digital ecosystem for personal manufacturing, for the last seven years. It is currently deployed or in trials at 111 of the enterprises from the Forbes 2000 list. During this journey, we have faced challenges with interoperability, usability, scalability, and network connection stability, among others while building a self-sufficient AM ecosystem.

In the following, we briefly summarize the main contributions of this paper:

(1) Discuss the motivation behind our creation of a cloud-based manufacturing operating system, 3DPrinterOS, to address an evolving critical problem of personal manufacturing;
(2) Propose the next step in the evolution of user participation in manufacturing—*personal manufacturing*;
(3) Propose a unique and a self-sufficient software ecosystem for *personal manufacturing*. Such a system would support all of the components necessary to produce a physical object from a digital representation of an idea, under either automatic or user control, allowing users to move from an idea to a physical object in one click;
(4) Introduce a novel, cloud-based software ecosystem capable of sustaining a massive communication load of command, control, and telemetry data coming to and from millions of manufacturing machines and users. Our solution allows users to create and deploy their own applications in a cloud operating system.

The remainder of the paper is organized as follows: In Section 2, we discuss the related work and our motivation to create the 3DPrinterOS software ecosystem (SECO). In Section 3, we describe the system overview, which includes the architecture and functions. In Section 4, we discuss a five-year experiment and one short-term experiment. In Section 5, we conclude the paper and suggest directions for future work.

2 RELATED WORK AND MOTIVATION

We have analyzed the most influential and highly cited works published on cloud manufacturing [17], social aspects of advanced manufacturing, and interoperability. This section provides context for our work in the field. We start by focusing on the social aspects of manufacturing.

2.1 Social aspects of manufacturing

In their work "Advanced manufacturing systems: socialization characteristics and trends," F. Tao et al. [20] analyze the degree and scope of resource sharing since the 1960s. Then, they describe four phases in the evolution of manufacturing resource sharing, which they say happens: a) within an enterprise; b) among enterprises; c) among industries and across regions; d) in society as a whole. Moreover, they [20] describe the degree of user participation in the manufacturing of a product: 1) Buy—the role of the user is minimal; the user buys a ready-made mass produced product. There is no interaction between the consumer and the manufacturer. A good example is the Ford Model T. 2) Buy and choose—the user has a chance to choose a more satisfying product from among a greater variety of products that are "mass customized" [18]. The manufacturer performs market research to segment their customers, and provides each segment with a product customized to match their preferences. For example, a car manufacturer such as Toyota produces different models for each customer segment. Within each segment, customers can select interior and exterior colors, engine power, and optional equipment. 3) Buy, choose, and design—in addition to the above, the consumer participates in the design of the product. The manufacturer produces a customized product for each user; for example, personalized 3D-printed insoles for shoes manufactured based on 3D scans of the consumer's feet. 4) Full customization—in addition to the above, the user can monitor the manufacturing process online and select and arrange the delivery method and date.

In our work, we seek to contribute the next logical step of the evolution of consumer participation in manufacturing by creating a new model: 5) *Personal manufacturing*—beyond full customization, the consumer is involved not just in monitoring production, but in the actual manufacturing process. The consumer either owns the equipment for automated manufacturing or has easy access to such. The user can select the quality, price, speed, material, production technology, and location of manufacturing; this may include choosing a popular solution, or designing a custom one.

2.2 Cloud manufacturing

In their work, Tao et al. [21], define and compare cloud manufacturing to cloud computing, and name the key advantages of cloud manufacturing as: a) reducing the idle time of manufacturing machinery and increasing utilization; b) greatly reducing the cost of entry for home users, small, medium, and even Fortune 500 enterprises, as it provides immediate access to high-value manufacturing resources (e.g. expensive automated manufacturing machinery) without up-front capital investments.; c) similarly, reducing the cost of ownership via savings on manufacturing infrastructure maintenance and administrative costs and reduced energy use; d) making it easier to scale production and business in line with client demand; e) generating new types of business models and ways to deliver products [26], for example, MyStemKits [11], RESA [14]; f) allowing enterprises and people to focus only on their core business and service rather than the entire manufacturing life cycle.

2.3 Interoperability

In their respective works, Tao et al. [20], Ray et al. [13], Tibaut et al. [22], Wang et al. [25], Panetto et al. [12], and Figay et al. [6] name the interoperability of manufacturing systems and components as one of the most compelling challenges in the evolution of cloud manufacturing resource sharing.

Interoperability requirements affect the architecture of manufacturing cloud operating systems. In this work, we seek to quickly adjust and keep up with new manufacturing machines as they become available. There are currently thousands of different types and modifications of manufacturing machines, and this number continues to increase.

3 SYSTEM OVERVIEW

3.1 Architecture

3DPrinterOS connects users to manufacturing machines (Figure 1). Users have web browsers installed on the devices they use to access the cloud OS. Manufacturing machines, which are industrial IoT devices in this case, are connected to the cloud through firmware or a *cloud client*. Ideally, the 3DPrinterOS firmware is deployed within a manufacturing machine and controls the low-level operations involved in producing parts. If a manufacturing machine does not have enough computing power to connect to the cloud over the network and provide the implementation of the 3DPrinterOS protocol with command and control and telemetry data, then it is connected to external hardware (Linux, Windows or Mac) connected to the cloud with the *cloud client* installed. Both the 3DPrinterOS firmware and cloud client can receive printer profiles, material profiles and slicing profiles, lists of manufacturing files, and projects, and cache these data locally.

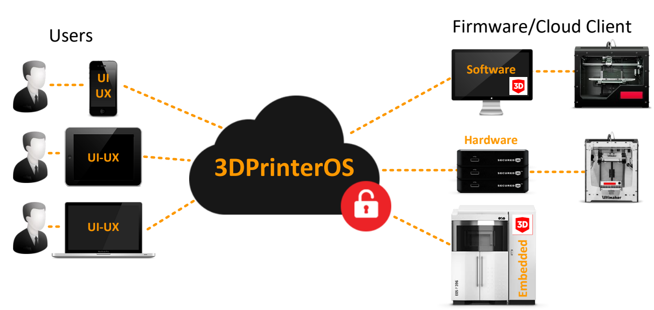

Figure 1: High-level conceptual diagramm of cloud-based distributed manufacturing operating system 3DPrinterOS

The architecture of a cloud operating system consists of three layers: application, libraries, and cloud kernel (Figure 2).

The *application layer* is where 3DPrinterOS provides basic functionality for end users, like file uploads and storage, toolpath visualization, an end-user dashboard, management for print jobs, real-time updates for the user interface (UI), storage manager, authentication of the user, user manager, notification manager, printer

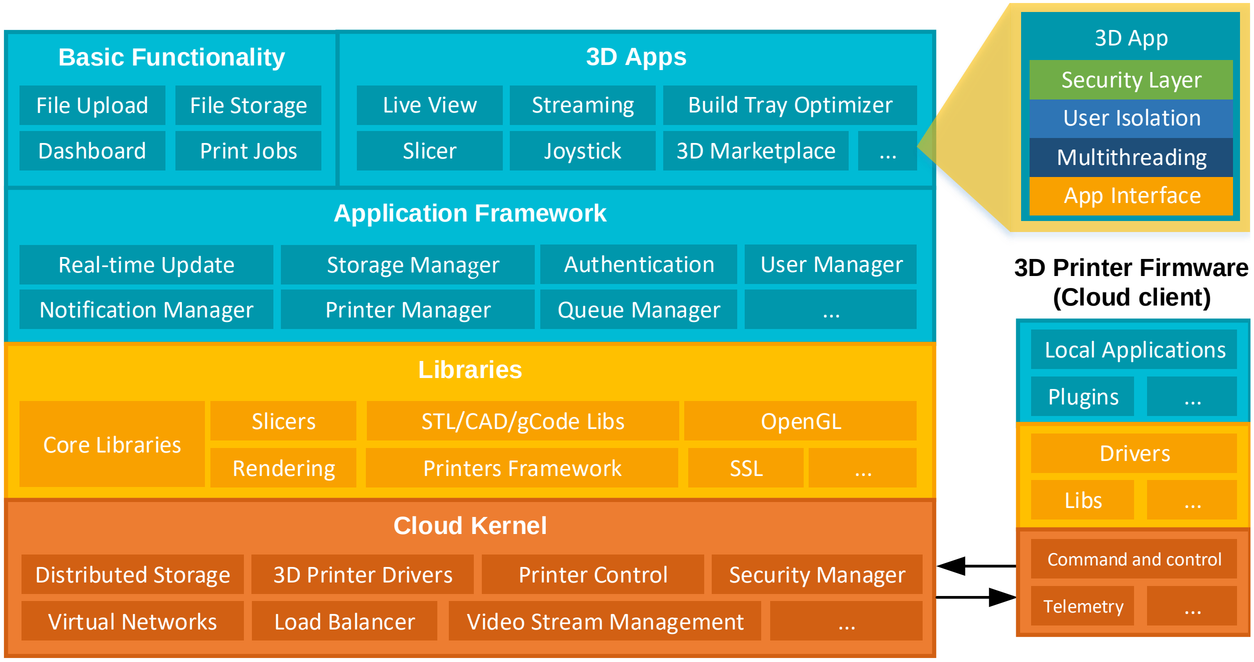

Figure 2: Architecture diagram of cloud-based distributed manufacturing operating system

manager, queue manager, default slicers. An important part of the 3DPrinterOS cloud platform is its *app engine and marketplace*, which allows the deployment of applications developed by third parties—*3D Apps*. Such apps allow users of the platform to perform a very specific niche action. Each *3D App* has a common interface (Figure 2) with a security layer, user isolation, multithreading, and standardized UI. A *3D App* is an encapsulated application, wrapped in a Linux container (e.g. a Docker container [9]). Through encapsulation, we achieve a high level of security [3, 8]: *3D Apps* cannot access the memory space and data of other apps. User isolation guarantees that a separate instance of the application will process each user's data, and after processing, will return the result and be destroyed. Multithreading allows faster performance of operations. The app interface allows *3D App* developers to create a unique experience for the end user.

The *libraries layer* of 3DPrinterOS cloud platform provides numerous core libraries as virtual resources for the application layer including *3D Apps*. Core libraries are: 3D rendering engine, libraries for STL, CAD and gCodes, OpenGL, cryptography frameworks (e.g. key-less, byte-less encryption), and other 3D printer frameworks.

The *cloud kernel layer* is responsible for the most low-level operations in the cloud, such as distributed storage, 3D printer drivers, printer command and control, security manager, virtual networks, load balancer, content distribution network (CDN), and video stream management.

The *3D printer firmware*, which we call the cloud client, also has three layers. Although our cloud OS is not intended to provide extensive functionality on the printer side (as the cloud does), it has minimized versions of some *3D Apps*. It also can receive printer profiles, material profiles and slicing profiles, lists of manufacturing files, and projects, and cache these data locally.

Taken together, the user interface, cloud, and industrial IoT components form a cloud-based distributed manufacturing operating system.

3.2 Roles, Artifacts, Relations

To describe the 3DPrinterOS ecosystem in our work, we have used the Software Ecosystem (SECO) approach formulated by Manicas et al. [7], where "a software ecosystem is the interaction of a set of actors on top of a common technological platform that results in a number of software solutions or services. Each actor is motivated by a set of interests or business models and connected to the rest of the actors and the ecosystem as a whole with symbiotic relationships, while, the technological platform is structured in a way that allows the involvement and contribution of the different actors". The proposed ecosystem in this paper belongs to the web operating system-centric ecosystem class according to the software ecosystem taxonomy proposed by Bosch [2].

The roles, artifacts and relations of the 3DPrinterOS SECO are shown in Figure 3. Actors, actor types, actors' contribution to the 3DPrinterOS SECO, and the benefits they receive are described as follows:

Orchestrator is 3DPrinterOS. The orchectrator is neutral to all other actors and responsible for the well-functioning of the ecosystem. The orchestrator develops and manages the cloud platform and other parts of the system, mediates relationships and the value flow among other actors of the ecosystem by settings the rules, processes, business procedures, setting and monitoring quality standards. The orchestrator sustains a base service layer by developing and providing simple high-level applications for end users. In this case, the orchestrator could be compared to the Android [4] operating

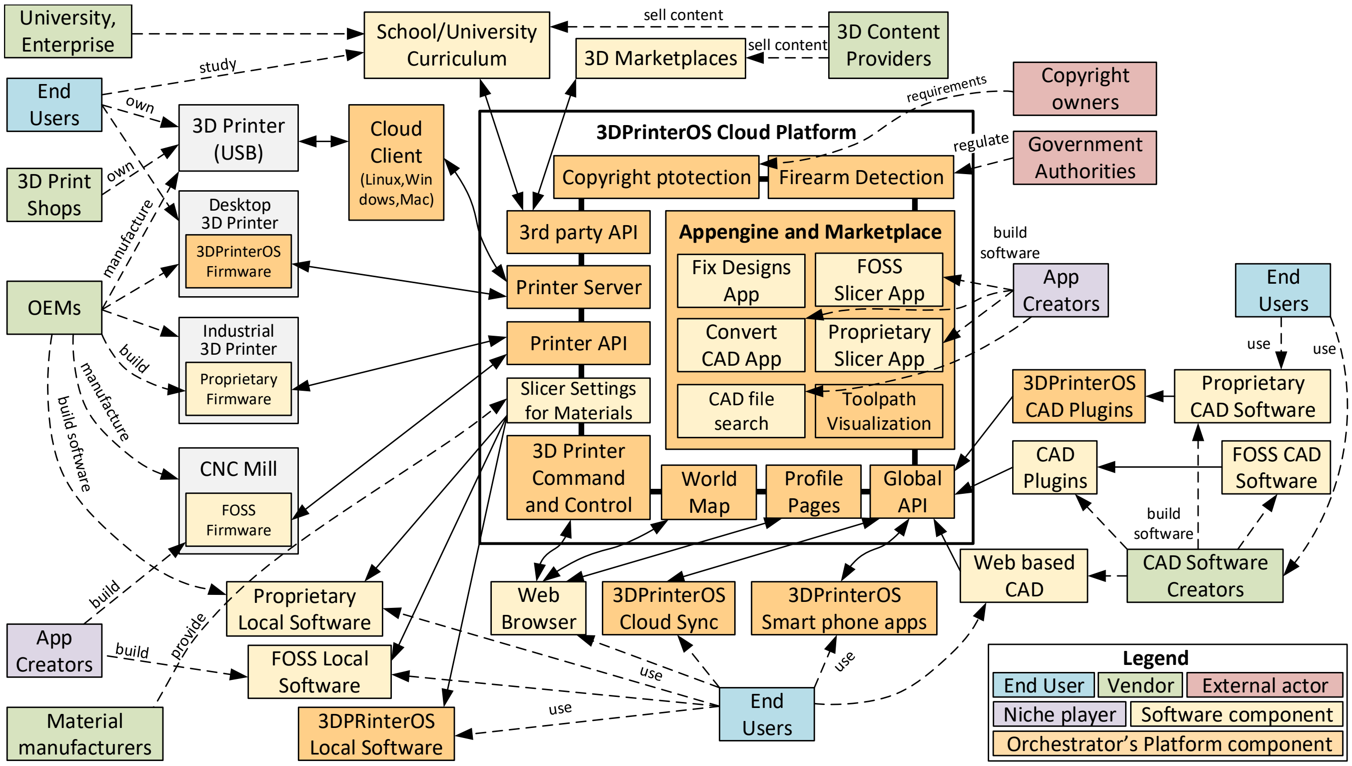

Figure 3: Overview of 3DPrinterOS SECO

system, which provides some simple default apps for end users. However, if the end user needs a more specific application, they can obtain it from the app marketplace.

Niche players are *3D Apps* creators; they contribute to the ecosystem by creating very specific niche applications. For instance, they override the default basic applications on the platform, e.g., 3DPrinterOS has developed the MagicFix application, which checks CAD files for inconsistencies and address them. There are multiple niche players who have developed more specific applications to detect and fix issues in CAD files. These applications provide additional value to the end users by publishing their *3D Apps* on the 3DPrinterOS platform. In other settings, niche players provide the main value, e.g., slicer software for 3D printers. The orchestrator does not have a public version of the slicer, and all the slicer *3D Apps* on the public platform are developed by niche players.

External actors perform activities that are limited to the actor's interest and provide indirect value to the ecosystem by observing the evolution of the ecosystem. For example, government authorities want to make sure that no illegal parts are 3D printed, e.g. firearm parts. Copyright owners want to ensure that parts produced with the means of automated manufacturing (AM) are according with the copyright contracts, and does not infringe creators' rights.

Vendors distribute the products of the ecosystem to end-users or other vendors. The products are bundles of AM hardware and software, vendors' own software bundled with the ecosystem components, complete integration or separate components. In case of the ecosystem presented in this paper vendors are original hardware manufacturers (OEM), AM machine manufacturers and 3D printer manufacturers particularly. Vendors manufacture hardware, integrate their machines with 3DPrinterOS, and benefit from increased sales and number of end users. The other representatives of vendors of the ecosystem are 3D print shops, who own AM machines and connect those to the platform to increase utilization and make more money. Material manufacturers provide precise slicer settings to the platform to improve manufacturing quality, and increase material sales though increased popularity and credibility.

End users or customers are the persons, companies, and other entities that either purchase or obtain a complete or partial SECO [7]. In our case, there are four types of end users:

a) the do-it-yourself community, who benefit from ease of use, and single interface to any AM machine;
b) small and medium businesses, who save time and money managing their fleet of 3D printers, reduce prototyping turnover time, and reduce time to market;
c) educational institutions, who provide fully self-service access to AM machines, reducing the costs to minimum, utilizing the power of data analytics to improve the service and more efficiently procure materials from material manufacturers;
d) Fortune 2000 enterprises, who save at least one human resource per every 10 AM machines, stay IT compliant, and have a full overview of who is manufacturing what in their enterprise on AM machines.

All types of users benefit from utilizing the 3DPrinterOS SECO, regardless of whether they manufacture using their own machinery, or machinery selected from among their organization's machinery, or that of their organization's partners or subcontractors.

Users can create virtual factories from 3DPrinterOS SECO artifacts, e.g. a full process flow, starting from searching for a CAD design and ending with delivery of a manufactured and assembled product without actually owning AM equipment or CAD software.

4 EXPERIMENTS

3DPrinterOS SECO is an experiment by itself. The project was started in 2014 as an experiment to see whether the idea of AM and 3D printing SECO would work. The last five years have showed the success of the SECO; as of today, the 3DPrinterOS cloud platform [1] has more than 95, 000 end users who have generated over three million CAD designs and machine codes. 3DPrinterOS end users have produced more than 1, 030, 000 physical parts on 32, 000 3D printers and other AM machines in 100 countries. These statistics double every six months. 3DPrinterOS SECO components are licensed to vendors including Microsoft [5], Bosch [10], Kodak [16], Robo3D [15] and other popular desktop 3D printer manufacturers, and distributed to their end users.

Moreover, the 3DPrinterOS SECO is implemented by top US universities: Duke, MIT, Purdue, Harvard, Yale, Caltech, and Texas A&M. Students use 3DPrinterOS as a self-service way to manufacture parts for their projects, with access to hundreds of manufacturing machines. All universities involved have reported a large reduction in costs (instead of 1 AM lab technician per 5 to 10 manufacturing machines, on average, to just one person in the lab), an average of 10x higher utilization of manufacturing machines, 100x more student involvement, and a reduction in waste.

An experiment that was carried out at TalTech [19] as a part of 3D-printing classes for university students.For the first experiment, we selected 74 people, aged 21 to 55 years, 49 men and 25 women. 22 of the experimental group had previously used a 3D printer (Group A). The other 52 had not used a 3D printer before (Group B). Half (Group 1) of each group (A and B) were asked to 3D-print a part using the 3D printing software, Cura [23], native to the 3D printer used— the Ultimaker 2 [24]. The other half (Group 2) were asked to perform the same task using 3DPrinterOS digital ecosystem. For people in groups A1,A2,B1 and B2, it took an average of 10, 2, 42, and 8 min, respectively, to 3D print a design. The results showed, that on average, it was five times faster for members of both groups to print a 3D part using 3DPrinterOS.

5 CONCLUSION

In this paper, we have described 3DPrinterOS SECO—a digital ecosystem for personal manufacturing, which allows users to move from an idea to a physical object in one click. We have proposed and explained the architecture for a self-sufficient cloud-based distributed manufacturing operating system which would allow the user to perform all necessary steps to produce a product at the point and time of need, with zero latency. We have described the most important functions of the system and presented the results of an ease-of-use experiment.

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