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A cloud-based cyber-physical framework for collaborative manufacturing

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Abstract

This paper discusses a Cyber-Physical framework to support 3D printing based on Next Generation networking principles. While most of the current research has focused on creation and use of existing 3D models on the front-end of these cloud based interactions, there is a need to design and develop user friendly support mechanisms that will allow engineers and non-engineers to create target designs using shape modification techniques and then subsequently manufacture a part. Further, with the advent of the Next Generation networking techniques such as Software Defined Networking (SDN) and continued interest in Future Internet technologies, there is a need to explore the adoption of such networking techniques to support cyber-physical interactions that align with Cyber-Physical Systems (CPS) principles. In this paper, the design of a cloud-based cyber-physical framework for such 3D printing contexts is discussed along with the creation of a 3D Shape Modification App running on the Android platform.

Keywords: Cyber Manufacturing; Internet of Things (IoT); Cyber-Physical Systems (CPS); 3D Printing; Cloud Computing; 3D Printing Monitoring

1. Introduction

3D printing can be described as an additive manufacturing process in which parts or products are built, layer by layer, one cross sectional slice at a time [1]. Some of the benefits of 3D printing includes the ability to build custom products economically, design flexibility without tooling costs, redcued scrap or waste material, among others [1-4]. Cloud computing involves the applications delivered as services over the Internet and the software / hardware used to deliver these services [5]. One of cloud computing is the ability to access the services from anywhere. The other advantages include minimal upfront investment in the computing resources, ability to increase or decrease the level of the use of computing resources as needed and reduced need for maintenance and administration of computing resources [6-9, 46-48].

A Cyber-Physical System (CPS) can be defined as a system of collaborating computational elements interacting with physical entities [10-12]. CPS has also been depicted as a collection of transformative technologies for managing interconnected physical and computational capabilities [13]. CPS technologies have extensive application potential in various fields, including manufacturing, aerospace, automotive, healthcare, and transportation. Another related emerging field involves Internet of Things (IoT) networks, which can be described as a network of software and physical entities embedded within sensors, smart phones, and other devices which have software elements to perform computing or other ompeting activities [14-15]. These entities are the "things" referred to in the term "IoT" which can be capable of collaborating with other similar entities in the Internet at various levels of abstraction and network connectivity [16]. Examples of things are heart monitors, weather sensors, sensors in manufacturing facilities, and software modules providing process feedback, among others [17-20]. Adoption of IoT principles and technologies can also help realize next generation CPSs and cyber manufacturing frameworks which require a higher level of collaboration and autonomy [14].

The development of the Internet, IoT as well as cloud computing technologies are changing the manufacturing landscape [21]. Recent initiatives which have underscored the importance of information centric manufacturing concepts include Industry 4.0, which emphasizes four key design principles including: 1) communication using IoT concepts; 2) information transparency; 3) adoption of CPSs principles; and 4) autonomy in decision making. The general underlying theme is that by linking machines and systems in manufacturing settings, intelligent networks can be developed along the value chain which are capable of autonomous control [22]. The emphasis on such Industry 4.0 concepts is intended to enable manufacturing organizations to potential benefits including cost reducion (through utilizing idle resources or providing manufacturing as a service), and flexibility (enabling customers to adjust to changing customer requirements quickly and effectively) [23].

Researchers have proposed various conceptual platforms and architectures for cloud manufacturing in general [50, 51] as well as applications in more specific domains such as semiconductor or mould industries [52, 53]. Other researchers have proposed the use of cloud computing principles to support 3D printing applications [29-38]. Research and implementation of remote 3D printing applications been discussed in [39, 40]. In [39], the design and implementation of remote monitoring system for 3D printing is outlined. A user can interact with the cloud-based system through a web interface with PCs or thin clients such as tablets and phones. Other services such as those provided NvBots [40] offer online 3D printing solutions through web portals. It includes features such as automated part ejection, full control of print queues. Other researchers have proposed 3D part retrieval techniques where a target part is used as a basis to retrieve similar part designs [54-56].

While cyber manufacturing frameworks employing cloud computing principles have emphasized the ability to 3D print from various locations [29-38], they have not explored the feasibility of adopting next generation networking principles.

Today's Internet is supporting unforeseen yet useful and popular applications. These applications have steered the use of the Internet into directions which were not initially anticipated. This has resulted in demanding technological and policy challenges in security, mobility, heterogeneity, complexity, etc. The solutions so far to address these concerns are seen by some observers as short term 'patches'. A more concerted and well planned set of initiatives are needed to design the Next Generation of Internet(s). Projects such as GENI [24], FIRE [25] and other Future Internet initiatives are attempting to address this need. In today's existing Internet, users cannot program the network or the routers. The next generation networking techniques Software-Defined Networking aim at addressing these drawbacks. Software-Defined Networking (SDN) is dynamic, manageable, cost-effective, and adaptable, which is capable of supporting the high-bandwidth, dynamic nature of a myriad of engineering and other applications [26-28]. It decouples the network control and forwarding functions which allows the network control to become directly programmable along with abstracting the underlying infrastructure for applications and network services. The OpenFlow™ protocol is an implementation of SDN. The SDN architecture is:

- Directly programmable: Network control is directly programmable as it is decoupled from forwarding functions.
- Agile: Abstracting control from forwarding allows administrators to dynamically adjust network-wide traffic flow to meet changing requirements and needs.
- Programmatically configured: It allows network managers to configure, manage, secure, and optimize network resources through automated SDN programs.
- Centrally managed: Network intelligence is centralized in software-based SDN controllers which appears to applications as a single, logical switch.
- Open standards-based and vendor-neutral: SDN simplifies network design and operation because instructions are provided by SDN controllers instead of multiple, vendor-specific devices and protocols.

In this context, there is a need to explore the adoption of Next Generation networking principles such as Software Defined Networking (SDN) to support cyber-physical interactions in advanced manufacturing [22]. There is also a need to design user friendly tools which will allow engineers and non-engineers from the 'maker' communities to modify existing part designs and then manufacture these designs using 3D printing. This paper focuses on addressing these two elements that have not been addressed by researchers.

2. Design of the IoT based Cyber-Physical Activities

Information centric models (termed as information intensive process models IIPMs) can play a key role in the design of collaborative approaches as well as broader frameworks which depend on a combination of cyber and physical resources to achieve distributed collaboration [22]. Other research efforts have explored the role of information models to design computer aided fixture design systems [61, 62] as well as virtual prototyping environments [63, 64]. The creation of such models can provide a unique and structure foundation from an information centric viewpoint that seeks to develop both a functional and temporal understanding of the various complex interactions in the life-cycle of a manufacturing enterprise. This foundation can also be viewed as a blueprint to design a cohesive set of IoT based interactions, which in turn enable collaborating partners to effectively integrate their distributed cyber-physical activities. The complex interactions among a diverse group of engineering and manufacturing enterprises (or partners) can be modeled as a process roadmap, which when implemented, will enable the automation and integration of both cyber and physical activities involving distributed resources. With the help of modeling languages (such as the engineering Enterprise Modeling Languages eEML [60]), these interactions can be modeled taking into consideration the functional and temporal relationships involving the various cyber and physical activities.

The life-cycle of the IoT based collaborative activities can be represented as a universal set comprising of 5 distinctive sets of entities including *process units (PU), driving inputs(DI), constraints or controlling factors (CF), performing agents (PA) and decision outcomes (DO)* as shown in Figure 1. *Driving inputs (DI)* can be categorized into *cyber inputs (CI) and physical inputs (PI); performing agents (PA)* can be categorized into *human agents (HA), software agents (SA) and physical resources (PR).* Each activity can be represented as a process unit; the IoT based collaboration can be reflected in an information intensive process model (IIPM). Such an information model based approach can serve as a state chart representing the functional and temporal relationships among process units and can provide a structured basis to propose and compare alternate plans for collaboration, help identify and emphasize data/information exchange requirements, as well as provide a starting point for conducting simulation activities at various levels of abstraction. Figure 1 shows one such state chart where the various entities are represented using the functional relationships and temporal precedence constraints; the junction boxes as in Figure 1 can be used to represent both asynchronous and synchronous cyber and physical activities.

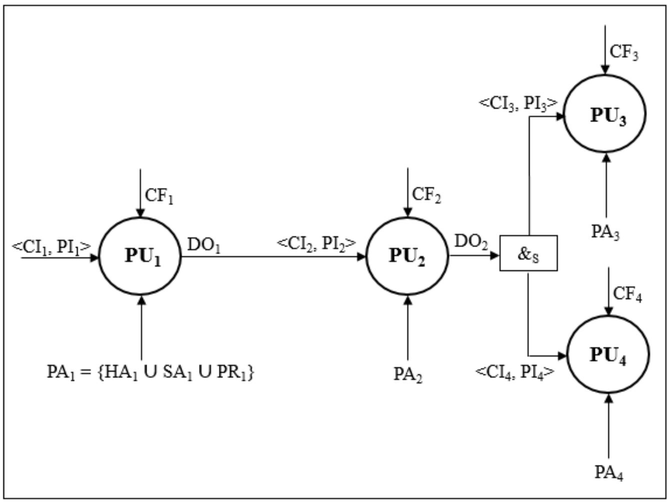

Fig. 1. An Information Intensive Process Model

3. Cyber-Physical components of the cloud-based framework

The key components of the cyber-physical framework supported by SDN includes several cyber components (Shape Modification App, Shape Retrieval Module, Virtual Assembly Module and 3D Cyber-Physical Interface) and physical components (the 3D Printing Resources and Monitoring Module). Next Generation Networking is additional component which supports the communication and interaction between the cyber and the physical components. These key components are shown in Figure 2.

One highlight of such shape modification apps linked to cyber manufacturing frameworks (such as the one discussed in this paper) is that it removes the need to use other expensive CAD tools such as SolidWorks or ProE. Rather than create a completely new model, with the help of a such shape modification app, a user (from a maker community) or engineer can first build a conceptual (or starting) model with some of the target features and then retrieve a similar CAD model using a Shape Retrieval Tool (SRT) [57, 58]. The societal benefit of using such shape modification apps lies in its ability to introduce manufacturing to a wider population instead of just being limited to professionals who are skilled at using CAD tools. It will also be beneficial to users active in the Maker Movement, which is an umbrella term for independent designers, inventors, and tinkerers [59].

A brief discussion of each of the key components of the cloud-based framework follows.

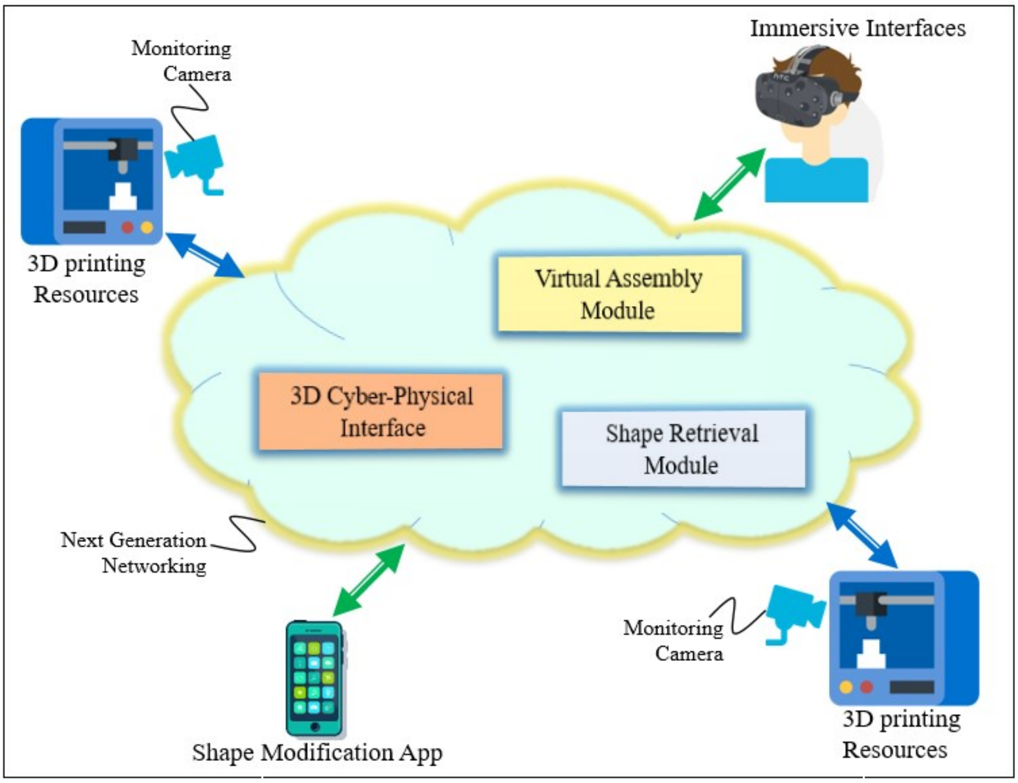

Fig. 2. Architecture of the cloud-based framework

3.1. Shape Retrieval Module

Shape Retrieval Module is a service that performs searches for 3D models through different 3D databases and returns the best matched shapes to the query. A user can search for a 3D object through various parameters such as name, color, or material. Alternatively, they can utilize the Shape Modification App to create a conceptual CAD model by the users which can be used to retrieve similar 3D models through the Shape Retrieval module.

3.2. Shape Modification App (SMA)

A user can propose an initial or conceptual design using the Shape Modification App. Based on this initial design, similar part designs can be retrieved using Shape Retrieval Tools (SRT). The retrieved files can be further modified if necessary by the user and can serve the final part design. This final design can be manufactured by 3D printing resources with the help of cyber-physical interfaces. Further discussion of the shape modification app is presented in section 4.

3.3. 3D Cyber-Physical Interfaces

The 3D Cyber-Physical Interface is another component of the cyber-physical framework. A web-based portal processes a user's 3D model input and initiates, as well as monitors, the 3D printing process. Once a user has finalized their design, the relevant instructions can be sent to a physical 3D printer (at a remote location or at a partner site). Other components that support IoT principles are a camera based monitoring module which relays the progress of the 3D printing process to other users at different locations using SDN.

3.4. Virtual Assembly Module

Another key component in this cyber-physical framework is a collaborative Virtual Reality based assembly simulation environment (Figure 3) which allows users to study assembly alternatives involving individual parts that can be manufactured by 3D printing. This will allow users to build more complex designs involving individual 3D printed parts. The creation of immersive interfaces can enable users to also interact with the Virtual Reality based Assembly Module (termed Virtual Assembly Module in Figure 2). Such interfaces enable users to propose and compare assembly alternatives involving the parts or components which are manufactured by 3D printing process. The VR interfaces can also facilitate users to interact with the shape modification module using controllers and 3D VR platforms (using the Vive and other platforms). Users can propose their own assembly plans or sequences or use the automate sequence generator to assemble a target design; the automated generators use a Genetic Algorithm based approach to determine a near optimal assembly sequence; the objective function is the assembly time involved. Genetic operators play a key role in this assembly planning approach.

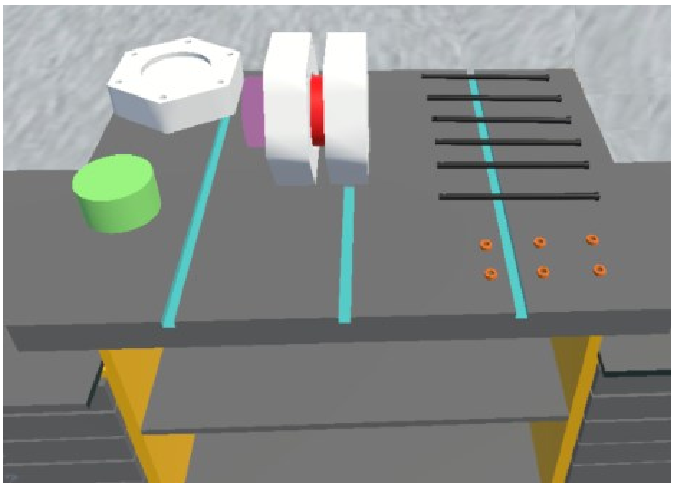

Fig. 3. Virtual Assembly Environment for studying assembly alternatives

3.5. Monitoring Module

The physical activities in such a cyber-physical framework can be monitored using cameras and other sensors; this enables distributed and remote users to be updated of the Work in Progress (WIP) relating to the manufacturing activities. As part of the preliminary implementation, a monitoring module has been implemented which is discussed in section 5.

3.6. Next Generation Networking

The next generation networking component supports the interactions between the cyber and physical components of the cloud-based framework. The component utilizes Software Defined Networking (SDN) based principles which supports network virtualization. Further discussion of the SDN based networking approach is provided in section 6.

4. Creation of the Shape Modification App (SMA)

The SMA is a part of the proposed cyber-physical system that provides users the ability to import and modify various features of a 3D CAD model (e.g. vertices, faces, and edges). In the framework proposed, the Shape Modification app interfaces with the 3D Shape Finder and Print Job Controller. The user can build a CAD model with some of the target or desired features and then utilize a 3D Shape Finder to retrieve similar objects. If necessary, after this retrieval, other design modifications can also be undertaken.

The Shape Modification App for the Android platform was built using the Unity3D Engine. This Unity3D Engine is a cross-platform game engine that can also be used to create an assortment of engineering simulation environments [41-44].

In Unity, each 3D object contains different components that comprise the object (Figure 4). The two components of interest are the Mesh Filter and the Mesh Renderer. The Mesh Filter consists of an array of various sub-components that define the shape of the object while the Mesh Renderer actually renders the object into the Unity space.

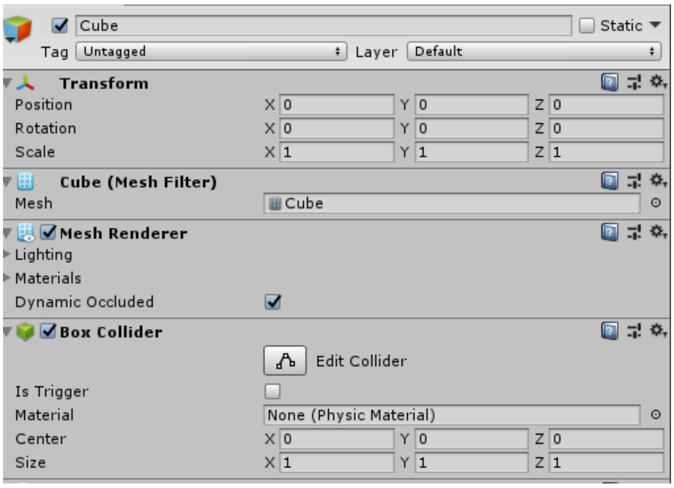

Fig. 4. Components of a Unity 3D object

In the Mesh Filter, there are many attributes, such as lighting and texturing, that control the appearance of objects. However, the two most important sub-components are vertices and triangles. These sub-components contain the underlying data structure that Unity uses for building its 3D objects. An indexed triangle mesh is another way to describe the mechanism Unity engine applies. A triangle consists of 3 points (vertices) in the 3D space and multiple combined triangles form a 3D mesh.

Vertices are an array of 3D vectors that store the positions of each vertex in the triangles to form a mesh. Triangles are an array of integers in groups of three that correspond to the indices of the vertices array (Figure 5). As shown in Figure 5, Unity uses triangle and vertices arrays to represent triangles, and the combination of multiple triangles forms a 3D shape or design.

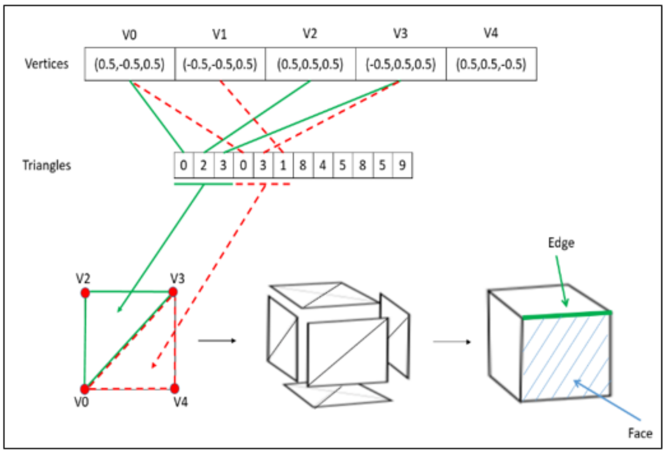

Fig. 5. Structure of the 3D mesh

This Shape Modification App facilitates users to quickly conceptualize ideas as well as modify designs. Users (such as hobbyists, inventors, maker users, etc.) may not have the skills needed to use industry standard 3D modeling software such as SolidWorks or ProE or they may not have access to such expensive design tools.

In the current stage of the prototype presented in this paper, our Shape Modification App is limited to manipulating the following features: vertices, edges, faces, extruding/insetting a face, and creating a new face. The Shape Modification App provides a list of each available feature for quick selection as well as buttons that assist camera movement.

Under the Vertex Mode, the app will automatically detect vertices of the object and create a handle on each vertex. This allows users to modify the vertices individually by moving the handles in a chosen direction (Figure 6). The main steps involved in the manipulation of the vertices is shown in Figure 7.

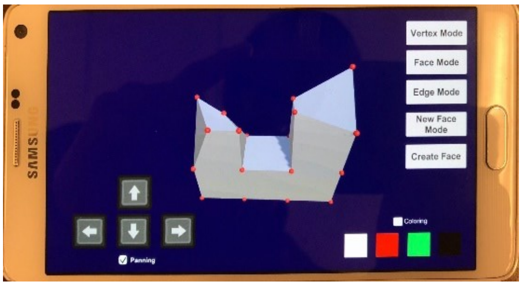

Fig. 6. Modifying vertices in a conceptual model

```
vertexList ← MeshFilter.mesh.vertices
for each vertexHandler in vertexHandlerList array do
    update corresponding vertex 'position with handle's
    position
MeshFilter.mesh ← vertexList
recalculate normals
recalculate bounds
```

Fig. 7. Overview of steps involved in modifying vertices

Similar to the Vertex Mode, Edge Mode gives users the ability to modify the edges of a shape. A user will first have to select two vertices on a target object in order to create a 'handle' that will modify the chosen edge (Figure 8). The handle can then be moved to adjust the edge according to the steps in Figure 9.

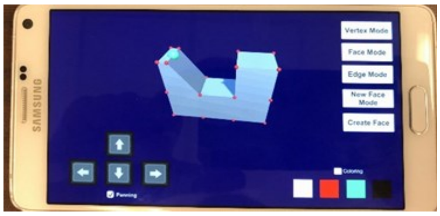

Fig. 8. Modifying Edges

```
create a handle at the mid-point of 2 selected vertices
apply displacement of the handle to 2 selected vertices
for each vertex in vertexList do
    if vertex is selected vertex then
        for each selectedVertex in selectedVertices do
            vertex ← selectedVertex
MeshFilter.mesh.vertices ← vertexList
recalculate normals
recalculate bounds
```

Fig. 9. Steps involved in modifying edges

Extruding and inserting the face of an object is another feature in the current stage of the Shape Modification App. After selecting the Extrude Mode from the menu, green handles will appear on each face of the object. The user can then move these handles to extrude or inset a face (Figure 10). An overview of the main steps for extruding operations can be seen in Figure 11.

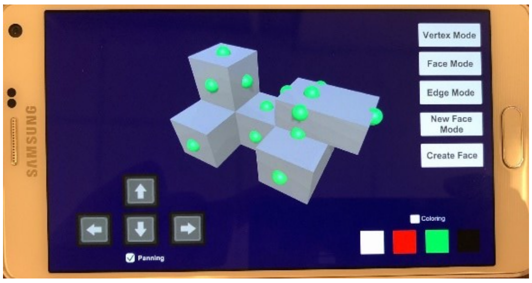

Fig. 10. Modifying faces in a conceptual model

```
for each face in faces
    create handle at the mid-point of the face
for each face in faces
    for each vertex in face
        apply corresponding handle's displacement to vertex
MeshFilter.mesh.vertices ← vertexList
Recalculate Normals
Recalculate Bounds
```

Fig. 11. Process of extruding faces

5. The Monitoring Module

Monitoring of the WIP of manufacturing activities is an important aspect of the proposed IoT based Cyber Physical System. The progress of various 3D printing processes and tasks can be monitored using cameras in the 3D printing work cells; the SDN based framework supports the exchange of such IoT data to users in distributed or remote locations. Continuous monitoring enables feedback and routine status updates. A monitoring module was created as a part of the proposed cloud-based framework (Figure 12 and 13). The design of the IoT interactions was based on the creation of an information intensive process model (IIPM) using the engineering Enterprise Modeling Language (eEML) [60]. This is similar to the approach discussed in [60], where eEML was also used to track and monitor the IoT activities for a different collaborative manufacturing context involving the domain of micro assembly. The discussion of this IIPM based approach is beyond the scope of this paper.

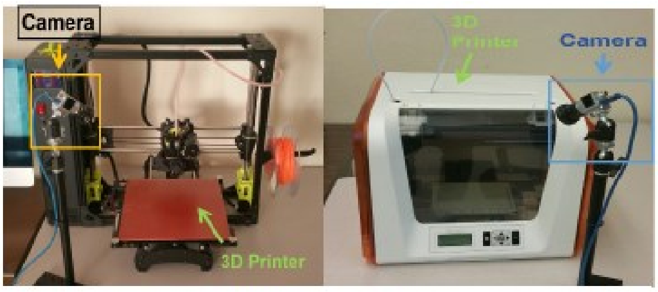

Fig. 12. 3D printers in the cyber-physical framework implemented

Fig. 13. View of the 3D printing task in progress seen through a webpage (supported by the cloud based framework)

6. Next Generation SDN based Networking

SDN provides significant advantages in that it supports virtualization and allows the network to become programmable. SDN principles do not only reduce the complexity seen in today's networks but also help Cloud service providers host millions of virtual networks without the need for common separation/isolation methods. An overview of the next generation SDN based architecture and approach is provided in this section.

Figure 14 shows the multi-user architecture for this IoT based cyber-physical framework. As the Unity based architecture can experience a single point failure of the PASS (Printing & Assembly Simulation Server), the entire system can fail if the PASS fails or if the network connection to the PASS fails and all PASCs (Printing Clients) are deregistered and disconnected.

In this IoT based cloud based framework for 3D printing, the users or participants (who can be viewed as Simulation Clients PASCs) can be engineers and manufacturers situated at different locations. For the shape modification or assembly simulation tasks, multiple users can interact though this IoT based cyber-physical framework. The key activities in the networking architecture include:

1. Only one client has a ``token'' at any given time that gives him/her the right to modify the state (e.g., make changes in the design, initiate the 3D printing process, propose assembly plans) to maintain the consistency; the other printing clients can observe the changes being made by the "client with the token."
2. A command interface allows a client with the token to 'pass the token' to any other client.

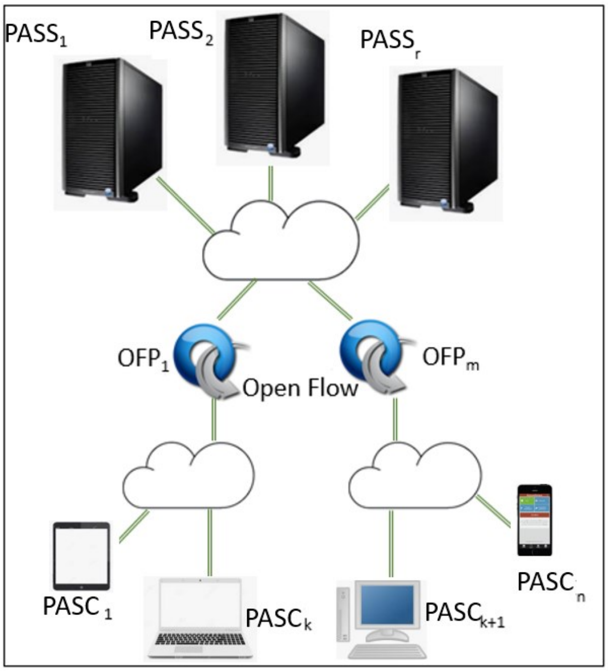

Fig. 14. SDN based Network Architecture

Since Unity is not an open-source platform, it is not possible to modify its libraries to support resiliency against connection failures to the Printing & Assembly Simulation server (PASS).

In the SDN based architecture shown in Figure 14, the clients do not directly connect to the PASS. Each client connects to the PASS via proxies implemented by SDN switches (which are OpenFlow Proxies or OFPs) (realized through OpenFlow). If there are ‘m’ OFPs, then the clients are partitioned into m groups; using one of the OFPs, each group connects to the PASS. The OFPs play a crucial role in providing failure resiliency without introducing much latency. Using SDN helps increase the resiliency to PASS failures.

7. Conclusion

In this paper, a discussion of a Next Generation Networking based cyber-physical framework to support 3D printing has been provided. The focus is on creation of a framework and an app which allows engineers and non-engineers to modify existing CAD models and then subsequently manufacture the part using 3D printers. SDN based technologies have been utilized in the development of the cloud based IoT framework for 3D printing.

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