SmartMaaS: A Framework for Smart Manufacturing-as-a-Service

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Abstract. With the advancement of information and communication technology, manufacturing organisations are adopting digital manufacturing more than ever before. This gives rise to cloud-based manufacturing through which manufacturers can sell their production capabilities as an on-demand service termed as Manufacturing-as-a-Service (MaaS), instead of selling pre-defined products. Existing MaaS providers (e.g. online 3D printing providers) offer manufacturing customised products. But, customers have more demanding needs, such as rapid turnaround time, quality product, innovative design, etc. To meet such requirements, a Smart Manufacturing-as-a-Service (SmartMaaS) framework has been developed. In order to deliver efficient products at optimal cost, SmartMaaS can take smart actions such as negotiating with manufacturing centres (e.g. 3D printers) with respect to their availability, turnaround time, manufacturing cost, etc. In this paper, SmartMaaS is introduced and demonstrated via a prototype that is capable of accepting customers' product request in the form of "design genes" and manufacturing 3D printed products through an actor-based system.

Keywords. Manufacturing-as-a-Service, Cloud manufacturing, Digital manufacturing, Collaborative manufacturing, Actor-based manufacturing

1. Introduction

Digital manufacturing is growing in a rapid manner and the manufacturing industry is adopting it in a large scale. According to a study by Capgemini [1], the size of the connected products (connected through IoT devices, cloud computing services, etc.) in the global manufacturing market will range between \$519B-\$685B by 2020, and it is predicted that 47% of products will be smart and connected by 2020. This growth has been achieved through the advancement in the information and communication technology (ICT) field in the recent years, specifically, through the evolution of cloud computing, IoT, Machine Learning (ML), and Artificial Intelligence (AI). Overall, digital manufacturing has changed the way products can be manufactured and sold. For example, manufacturers can offer their production capabilities (e.g. 3D printing) on a pay-as-you-go basis over the cloud, instead of selling pre-defined products. In digital manufacturing, such services are termed as Manufacturing-as-a-Service (MaaS). Manufacturing industry has already started adopting the MaaS business model, for example, 3D hubs [2], Shapeways [3], Materialise [4], and Sculpteo [5] offer 3D printing

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services on-demand basis. Using these services, customers can obtain customised 3D printed products at low cost. However, customers continue to become more demanding, they anticipate reduced turnaround time, increased quality, innovative design, etc. To satisfy such customers, a Smart Manufacturing-as-a-Service (SmartMaaS) framework is proposed in this paper. SmartMaaS adopts a Cloud-based design and manufacturing approach, where the customers can submit their product request in the form of some specific parameters (design specifications) and receive the manufactured product after going through a process of design review and feedback.

Researchers in digital manufacturing have already proposed cloud-based design and manufacturing frameworks. The framework in [6] can offer complete manufacturing facility over the cloud by providing the design and manufacturing processes as Software-as-a-Service (SaaS) and Hardware-as-a-Service (HaaS), respectively. Researchers in [7] have proposed a cyber-physical manufacturing cloud architecture, which can enable accessing manufacturing resources through the cloud virtualisation along with the facility to monitor the manufacturing process. They have also demonstrated the architecture using a testbed setup. In [8], a Production-as-a-Service (PaaS) framework has been proposed for small batch manufacturing. PaaS aims to increase the resource utilisation of manufacturers with small facilities by making their resource available for prototyping or small batch production by online users (product developers). The framework uses a back-end cloud service to connect the users with the manufacturers, and implements an optimisation algorithm to find feasible production solutions based on manufacturer production quotes and user preferences. However, these cloud-based manufacturing frameworks do not provide the solutions on how to achieve customers' growing demands as identified above, and this differentiates them from SmartMaaS. Specifically, this paper makes the following **key contributions**: (1) the paper proposes the SmartMaaS framework and demonstrates the SmartMaaS prototype using a simple product manufacturing and (2) the paper discusses how smart manufacturing goals can be achieved using SmartMaaS.

The remainder of the paper is organised as follows. Section 2 introduces the SmartMaaS framework and discusses its key components. Section 3 demonstrates the SmartMaaS prototype. Section 4 discusses the goals that SmartMaaS can achieve for its customers. Finally, Section 5 concludes the paper.

2. SmartMaaS Framework

The SmartMaaS framework is depicted in Figure 1. SmartMaaS orchestrator is the main element of SmartMaaS. The orchestrator receives customers' product request, runs necessary algorithms (e.g. genetic/evolutionary algorithms for innovative design, ML/AI algorithms for decision making, etc.), and manages all the design and manufacturing resources. SmartMaaS accepts the product request in the form of some specific parameters (design specifications) instead of predefined design model, which is the case with the existing MaaS providers, specifically 3D printing service providers like 3D hubs [2], Shapeways [3], Materialise [4], Sculpteo [5], etc. SmartMaaS takes these parameters and prepares the design of the product using specialised algorithms such as the genetic or evolutionary algorithms in order to bring innovation to the design. To achieve such a design approach SmartMaaS uses a specific module, which is "Designing". This module integrates with a distributed computing framework to achieve faster processing of the designing algorithms and to deal with the heavy-weight computation that is required for running the design simulations.

After finalising the design, the orchestrator employs its "Modelling" and "Manufacturing" modules to accomplish the manufacturing of the product by allocating optimal design and manufacturing resources. As SmartMaaS uses cloud-based design and manufacturing, it gets access to a number of modelling tools (e.g. CAD tools) and manufacturers (e.g. 3D printers), which are made available via cloud services, Sofware-as-a-Service (SaaS) and Hardware-as-a-Service (HaaS), respectively. The orchestrator uses its "Decision Making" module to make the selections of the CAD tool and the manufacturer, based on their availability, cost, turnaround time, etc. Importantly, the module can receive customer feedback and capture emergent behavior (during the design process), which can help evaluate and update the design to meet the customer goals (we discuss this in detail in our companion papers [12], [16]).

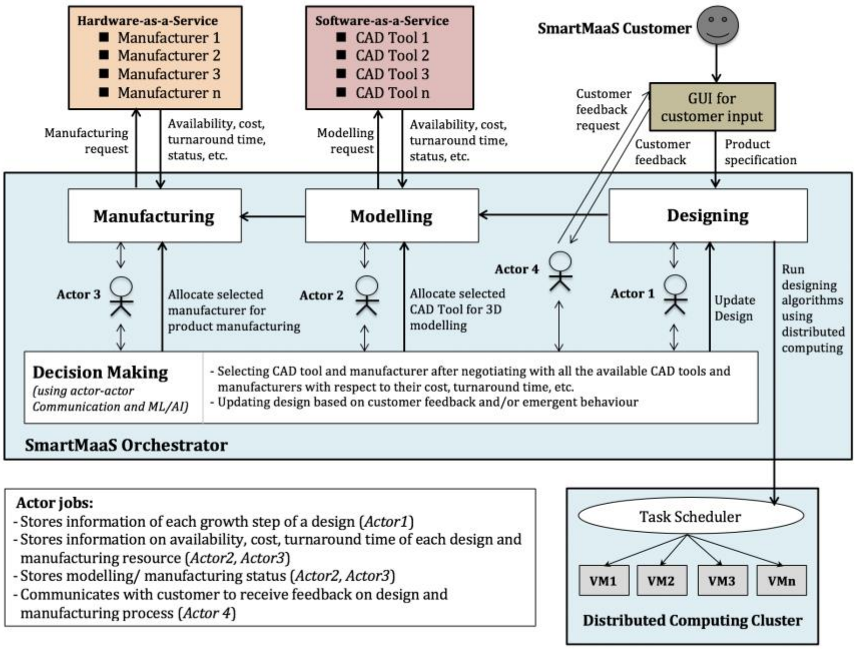

Figure 1. SmartMaaS framework

The orchestrator uses an actor model in order to implement efficient communication between the customer, the design process, and the design and manufacturing resources. The actor model is a conceptual model to perform concurrent computation, where the actors are the basic units of computation [9]. Specifically, the orchestrator uses actors to check and store the status of the design process, modelling, and manufacturing at regular interval (please see Figure 1 for more details on the jobs done by the actors). This actor-based communication and storage approach keeps the SmartMaaS alive throughout the design and manufacturing process, which subsequently helps in making smart decisions (using the "Decision Making" module) to meet customers' goals.

Both the orchestrator and the distributed computing framework can be deployed in a cluster of virtual machines (VMs) allocated through public cloud (e.g. Amazon EC2, Microsoft Azure, Google Compute Engine, etc.) or private cloud (e.g. in-house cloud set-up using OpenStack [10] software).

3. SmartMaaS Prototype

The SmartMaaS prototype (Figure 2) has been developed with the following basic functionalities:

- **Actor-based state storage:** the SmartMaaS orchestrator has been deployed by using Microsoft Azure Service Fabric (SF) [11]. SF provides the actor model (Reliable Actors) which allows actor-based storage of the design process and manufacturing state. SF actors are isolated, independent units which can store states and run small logics. Importantly, SF actors are reliable, they have replicas which can store a copy of the state of the actors so that the state is never lost. Also, SF provides the messaging service for the actor-client, actor-actor communication. SF clusters can be deployed in both private and public clouds. This functionality of the prototype demonstrates the ability of SmartMaaS to keep the design and manufacturing process alive.
- **Gene-based design growth:** a design growth algorithm (taken from our companion paper [12]) has been implemented inside the SmartMaaS orchestrator. The algorithm uses a set of "design genes" to trigger and control the design growth through mechanisms such as branching and stretching. The algorithm can produce unpredicted-but-valuable designs. This design growth approach demonstrates that SmartMaaS can run genetic/evolutionary kind of algorithm for innovative design.

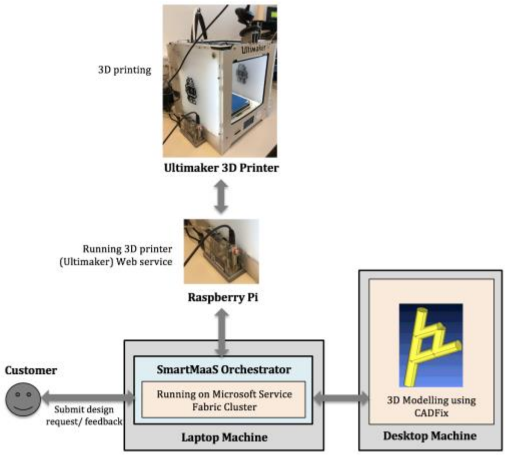

Figure 2. SmartMaaS prototype

- **Remote CAD modelling:** remote CAD modelling has been performed by integrating the SmartMaaS orchestrator with CADfix [13], a CAD modelling tool that is running on a remote desktop. CADfix provides an API for Python code that helps to perform the integration. This remote modelling demonstrates the ability of SmartMaaS to access any modelling tools that are made available as SaaS.
- **Remote 3D printing:** remote 3D printing has been performed by integrating the SmartMaaS orchestrator with an Ultimaker 3D printer [14]. The integration is achieved through a Raspbery Pi which hosts a web service provided by OctoPrint [15] (3D print controller application) to make the 3D printer accessible via internet. This remote 3D printing demonstrates the concept of SmartMaaS accessing manufacturing facilities that are made available as HaaS.

3.1. An example of manufacturing a cylinder structure

In order to showcase the SmartMaaS prototype, manufacturing a simple cylinder structure (Figure 3-A) is considered. This structure has seven design growth steps. The request for manufacturing this structure is submitted in the form of “design genes” (concept taken from our companion paper [12]), where each gene consists of a number of parameters (Figure 3-B).

The orchestrator runs the design growth algorithm [12] based on the submitted “design genes” and generates geometry points for building the model for the design. The orchestrator sends these geometry points to the remote desktop machine that uses CADFix tool to produce the design model (as STL file) and sends the STL file to the orchestrator. The orchestrator then calls OctoPrint web service (hosted by the Raspberry Pi) to print the model in 3D. The OctoPrint first performs a “slicing” operation which converts the STL file to the GCODE (which contains line by line code for printing the model in the Ultimaker 3D printer), and then, prints the 3D model (Figure 3-C).

SF actors store the state of the design growth and the 3D printing. In Figure 3-D, we can see how an actor returns the state of a particular design growth step, and in Figure 3-E, we can see that an actor is returning the status of the 3D printing.

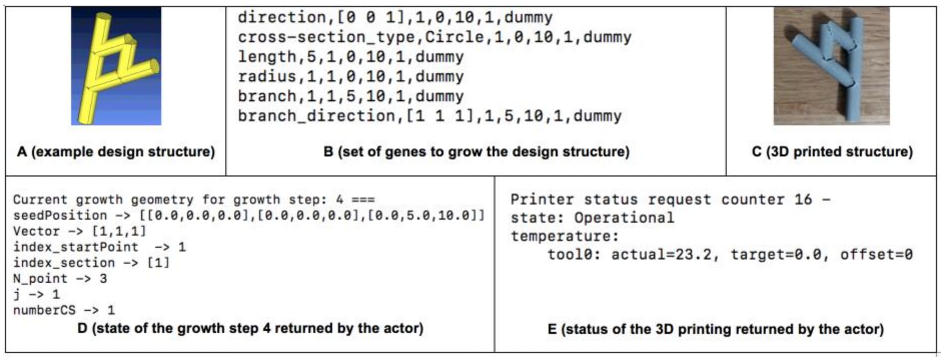

Figure 3. Example of manufacturing a cylinder structure

4. Smart Manufacturing Using SmartMaaS

Based on the prototype as demonstrated above, the following smart manufacturing goals can be achieved:

- **Rapid turnaround time:** SmartMaaS can manufacture a product in a quick time due to the following reasons: (i) using cloud services can allow multiple user requests to be processed at the same time, (ii) using distributed computing framework can allow faster processing of the design growth steps, (iii) choosing optimal modelling and manufacturing option (using SmartMaaS orchestrator) with respect to their turnaround time, and (iv) using AI/ML to detect anomalies in the manufacturing process or to forecast machine malfunction, etc. can help to escape unwanted delay in manufacturing
- **Product quality:** during the manufacturing process, SmartMaaS can redesign and manufacture part of the product or the product as a whole differently based on the

customers' feedback or emergent behavior (e.g. load bearing capability of the design is not meeting the customer requirement). This ensures the product quality. Detailed discussion on this concept is available in our companion paper [16]. Additionally, co-operative decision making through SmartMaaS orchestrator and actors can also improve the product quality.

- **Innovative design:** SmartMaaS customers can submit the product requests with minimal predefined parameters, based on which SmartMaaS can grow an innovative design. Specifically, the customers can submit a product request as a set of "design genes", where each gene consists of a number of parameters.

5. Conclusion

This paper introduces SmartMaaS, a Smart Manufacturing-as-a-Service framework, which uses Cloud-based design and manufacturing, and an actor model. Also, the paper presents a SmartMaaS prototype which demonstrates that SmartMaaS can achieve many of the smart manufacturing goals for its customers. The future work includes achieving the goals that are set for SmartMaaS. As a next step, the SmartMaaS framework will be deployed in a public cloud, and decision making algorithms will be proposed to choose optimal manufacturing (3D printing) options.

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