3D Printing Process Pipeline on the Internet

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Abstract. We develop a small and lightweight cloud based service for the utilization of 3D printer resources within an academic context. This service consists of user, artefact and printer management and utilizes existing business process management systems (BPMS) where possible and extends their functionality. It enables scheduling of printing jobs for artefacts and high utilization of 3D printer resources. This cloud based manufacturing (CBM) system enables 3D printers that are non-native networked to be used remotely by providing easily installable low cost networked computers. It focuses on the interface between the physical resources and their representation in software to form a cyber physical system (CPS). This service requires smart 3D printers and representation of technical capabilities of physical resources. We discuss the design and concept of this work in progress service and the distinctions from similar systems.

Keywords: 3D Printing, Additive Manufacturing, Cloud Based Service, Cloud Based Manufacturing, CBM, CPS

1 Introduction

3D Printing or Additive Manufacturing (AM) is the process of creating physical objects from digital models usually layer upon layer [5]. Technologies for AM include Fused Deposition Modelling (FDM, trademark by Stratasys Inc., also Fused Filament Fabrication FFF), Laser Sintering (LS), Electron Beam Melting (EBM), Laminated Object Manufacturing (LOM), Stereolitography (SLA) and Electron Beam Freeform Fabrication (EBF). Every AM technology brings restrictions on the materials possible to process. We focus our research on FFF where thermoplastics like acrylonitrile butadiene styrene (ABS) or polylactid acid (PLA) are fed from a roll in filament form to a heated extruder that heats the plastic to a semi-molten state and extrudes it through a nozzle mounted on the printing head that is moveable in two dimensions (X-Y plane) by electro motors following a pre-programmed path (Toolpath). With this setup it is possible to trace contours and interiors of an object slice-wise. After completion of every layer the printing bed is moved in Z-direction so the following layer can be added on top. For the generation of the toolpath (slicing) it is necessary to segment the original digital model into slices that can be analysed for tool movement along the contours. Various strategies exist for the generation of the toolpath as models

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are mostly created hollow with a specific infill pattern for reduction of weight and processing time. The initial focus on FFF technology does not limit this research to just this technology as the 3D printing process is the same with alterations due to technology used and parameters adapted. It is our understanding that the following reasons mandate the use of printing services over stand-alone 3D printers at the user's workplace:(a) High cost of printer (dependent upon manufacturer and technology) [16] (b) Potential health risks (e.g. fumes, metal dust) [15] (c) Low utilization for non-shared resources [12] (d) Process knowledge necessary for high quality results [10]. The 3D printing process consists of five steps (Fig. 1) that start with the design of the product (also see [5]). For this

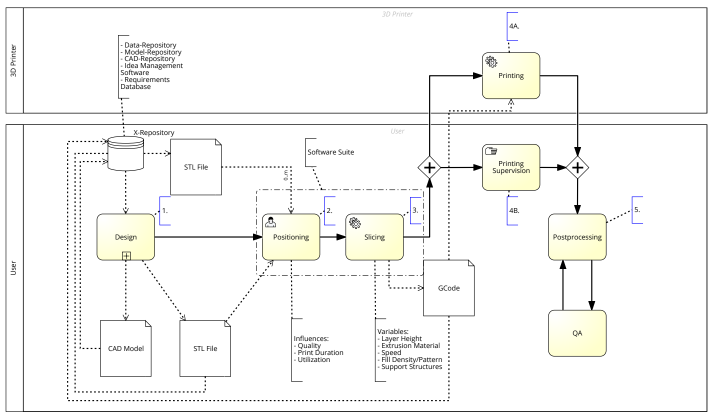

Fig. 1. 3D Printing Process

work we propose two research questions: (a) What requirements are necessary to construct a 3D printing service enabling users utilizing existing 3D printer resources more efficiently (b) How can a 3D printing service be enabled to provide an infrastructure for research.

This article describes current work in progress and outlines the design and implementation considerations and methodology. The design phase can be supported by software using CAD (e.g. Autocad[1] or 3D modelling software[2]). The result of this first step is a CAD model that represents the 3D geometry of the object.

Step two of this process is the positioning of the model in the virtual space that represents the 3D printer and its physical restrictions. Positioning can encompass single objects or multiple objects for increased printer utilization. After the print object is positioned it is sliced using slicer software. A variety of slicing software

[1] http://www.autodesk.com/products/autocad/overview
[2] https://www.rhino3d.com

exists and they differ in aspects like speed, precision, quality and strategies for printing support structures.

The following steps include the upload to the printer if it is a networked device or other means like deployment on memory devices (e.g. SD-Card, USB Stick) and the start of the print which can either require manual interaction or be handled from software. During printing the user is often required to supervise the printing progress as this is error prone especially for consumer grade devices. Post-processing and Quality Assurance (QA) follow when the object has been printed and influence each other. Those steps are not part of our service.

We provide support for all steps but the design, post-processing and QA step within our service. These are omitted for the following reasons 1) The design process is supported by specialized software and integration is not compatible with our lightweight approach 2) Post-processing and QA is not reasonable supportable by soft- or hardware as these steps require intensive human interaction.

The remainder of this article is organized as follows: We display current research in this area in [Sect. 2] and derive implementation requirements from established approaches. Then a introduction of the implementation guidelines [Sect. 3] for the service is given. Following is a summary of requirements [Sect. 3.1] for our research. Then we introduce an example and discuss problems encountered with the implementation [Sect. 3.2]. In [Sect. 4] we discuss our approach, its application and benefits.

2 Related Work

Similar systems or services already exist in form of closed source commercial services where we will name two of: a) 3D Hubs[3]b) 3D Printer OS[4]. As commercial entities their focus is on financial viability. These services allow adding ones own 3D printer and manage it from within the service with a varying degree of granularity. They lack an extension mechanism or plug-in architecture. In contrast to our approach they are not intended as open services. The software octoprint[5] offers remote printing and object management capabilities but does not provide an interface to a BPMS, user-selectable slicing solutions or support for consolidated information on printing information. Further research provides proposals from [18] for CBM systems but our system differs from those approaches as our focus is the tight integration of business process management (BPM) and 3D printing as well as the sensory upgrade of this technology. From Dong et al. [3] we will implement the video supervision approach for the printing process and its remote error detection. Extensions of CBM in the form of Cloud Based Design and Manufacturing [19] provide further insight into the concept of Hardware-as-a-Service (HaaS) and the connection to the broader concept of flexible manufacturing spanning every phase of product development and involvement of different stakeholders. While the availability of affordable

[3] https://www.3dhubs.com
[4] https://www.3dprinteros.com
[5] http://octoprint.org

consumer grade 3D printers certainly has helped the progression of research in and distribution of 3D printers the scenario where every individual will own a digital fabricator [9] is debatable as the general direction is to offer and consume services [2]. Van Moergestel et al. [8] proved the concept of Manufacturing-as-a-Service (MaaS) on cheap, distributed and reconfigurable production machines (equiplets) with a focus on interaction in a multi-agent system. Lan [6] names STL viewers as Java applets or other visualization tools as one of the key issues in his review. We employ JavaScript embeddable visualization into the service as to alleviate the dependency on thick clients. Further key issues e.g. a) Remote control and monitoring b) Job planning and scheduling and c) RP data pre-planning are addressed in our service.

3 Implementation

Our service follows the software framework proposed by Schulte et al. [14] with a focus on the action executioner. It acts as the connector between the printing resources and the printing service in our proposal in contrast to the proposed functionality by Schulte et al. Further foci are the service registry for keeping information on production capabilities and the monitoring data manager that connects the real execution in the 3D printer with the virtual representation. From CloudMan [11] we incorporate the layered service approach but restrict our focus to 3D printers and not manufacturing infrastructure in general. See Fig. 2 for overview of the intended architecture with BPMS supporting the main service controller.

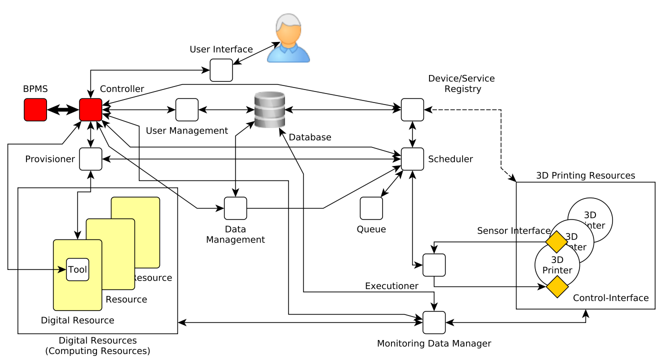

Fig. 2. Abstract Architecture for 3D Printing Service

As per the definition of NIST (SP 800-145) [7] of cloud computing the system is set up to provide a user management system by incorporating available libraries. Besides standard user management information the user is able to store appropriate files[6] in his account. For this we define an interchange format for printing related information consisting of original CAD file(s), resulting STL and GCode [4] files, conversion and printing protocols as well as imagery (for quality assessment). The service is accessible in a standard compliant web browser that supports HTML 5[7] and JavaScript, both are necessary for rendering purposes for the phase of positioning. The resources necessary for slicing and preparation of the models are shared amongst the users based on a scheduling scheme that reflects first-come first-serve. As the 3D printer is the limiting resource at present the pooling of the computing resources not regarded as critical. In anticipation of multiple 3D printers controlled by the system the distribution of computing resources for the preparatory tasks is becoming queue based with data stored in associated cloud service storage (e.g. Amazon S3[8]). Users will be informed if the capacity of the 3D printers is depleted and the projected processing time for an object exceeds a defined threshold. The requirement for "rapid elasticity" is severely impaired by the physical restrictions set by the geometry of the object to be printed and the limitations in the speed vs. quality trade-off of a 3D printer. Basic measurements are intended where the user can track the number and nature of printed objects as well as associated information and a full audit trail for research purposes. Utilization of machines and computing resources is measured and associated with respective user accounts. The systems control layer resides in the cloud and is expandable by utilizing proven technology (e.g. Docker[9]) as means of deployment. The interfacing layer consists of gateway computers that interface directly with 3D printers if they do not support network access natively. These interface solutions depend on rapidly deployable, cost sensitive and reliable computer systems. In the first phase these interfaces will allow direct manipulation of 3D printers via the Internet and limited control information backflow. Further iterations extend this system to a broader sensorial back channel ultimately leading to closed loop printing systems.

3.1 Requirements

The requirements for a CBM provided by Wu et al. [17] "(R1) [...] (R2) Should provide cloud-based distributed file systems that allow users to have ubiquitous access to manufacturing-related data (R3) Should have an open-source programming framework that manufacturing systems can process and analyse big data stored in the cloud (R4) Should provide a multi-tenancy environment where a single software instance can serve multiple tenants (R5) Should be able to collect real-time data from manufacturing resources (e.g., machines, robots, and assembly lines), store these data in the cloud, remotely monitor and control these manufacturing resources (R6) Should provide IaaS, PaaS, HaaS, and SaaS applications to users (R7) [...] (R8) [...]" are considered in the design of our system.

[6] CAD files, STL files, Printing Log files
[7] http://www.w3.org/TR/html5
[8] http://aws.amazon.com/s3
[9] https://www.docker.com

Due to the design goal of developing a lightweight system the requirements R1, R7 and the focus on academic settings requirement R8 are not incorporated in our service. We further define the requirements a) Capability to use BPMN extension for 3D printers (which is proposed separately) and integration of a BPMS b) Modular integration of tools for the 3D printing process and c) Modular and dynamic integration of 3D printing resources.

3.2 Example and Problems

We encounter the problem of defining capabilities of various 3D printers for use in this service. To our knowledge such a description format or language does currently not exist. Resource Description Language (RDL [13]) is a proposition for this issue for the domain of network embedded resources. Capabilities required for interaction with tools includes a) GCode dialect b) Quality settings c) Processing speed and d) Material capabilities. This information is also required for utilization planning and optimization strategies. As a solution for this problem we propose a derivative RDL tailored towards additive manufacturing for subsequent publication. Further problems arise from the firmware of our research printer that limits the transmission speed (ca. 3.5 KiB/s) over the USB serial connection to the device storage resulting in long transmission times. Solutions include flashing a different firmware and utilizing WiFi enabled SD cards.

To clarify the flow of information (see Fig. 2) and data within our proposed service we discuss this by an example of a user printing an object. The first process steps of designing and modelling the object with a CAD or modelling tool are not discussed and we assume the user, which already has an account within the service, logs in and has an AutoCAD DXF[10] file stored on his computer. As a first action the file is uploaded through the web-interface to the controller that instructs the data management service to store the file in the database, then the file is transformed into STL and AMF [1] format for future use and stored in the database. The user then selects a printer for printing. This information is provided by the device/service registry. Future implementations can suggest an appropriate printer to the user. After selecting the printer the user is able to select slicing parameters and position the object in the virtual build environment. Future implementations can suggest appropriate parameters based on analysis of the model file and positioning on optimization criteria to the user. The user is able to add other tool steps to the processing of the object file which are orchestrated by the provisioner and associated virtual computing resources. After the model file is sliced the printing job is instantiated with the scheduler that checks if the requested printer resource is available and if so sends it to the executioner. If not a queue is used to store the job until the resource becomes available. The executioner communicates with the control interface of the 3D printer in order to transfer and start the print. Sensor data is transmitted back to the executioner from the sensor interface. Sensor data is then stored in the database via the scheduler and the controller. BPMS support is intended as to

[10] Drawing Interchange Format

externalise the logic of the controller to a BPMS that orchestrates the other services. During the print the user is informed on the progress and possible failure of the print via web interface. After completion of the print the user is informed through a notification. Data acquired during the print is stored in the database for later analysis.

4 Future Work

To the best of our knowledge no open source 3D printing service is published yet. There are existing solutions that focus on separate parts and provide solutions to different aspects of the 3D printing process. Our approach is characterized and differs from other approaches by: a) Focus on 3D printer b) Focus on communication with manufacturing device c) Interface to BPMS d) Platform for testing BPMN extension e) Smartifying 3D printer f) Platform for testing sensor array and g) Interchange format for print related information. This software service is designed as an open research platform for academic users to embed experiments and utilize distributed resources. Further projects are aimed at 1. providing means of control of 3D printers from within process models as we are writing an BPMN extension, based on the work of [20] tailored for 3D printers, 2. utilize sensors for print status observation and as a means for quality research into 3D printing (see ICRM 2016[11]). Those projects are to be incorporated in the umbrella project described in this work. As a related project we develop a BPMN extension for 3D printer integration into BPMN where the hardware resources and data flows can be modelled using the extension. This extension is out of scope of this work and published separately.

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