Monika Radaviciute

3D Printing Farm Set-Up: Printers and Software

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Abstract

Author: Monika Radaviciute
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The purpose of this thesis project was to set up a 3D printing farm for Metropolia University of Applied Sciences on Karamalmi campus. The printing farm was to be equipped with multiple 3D printers and management software that would semi-automate its functioning.

In pursuit of this goal, the current selection of 3D printers and management software were examined and evaluated for their suitability in an educationally-oriented 3D printing farm. Considering the requirements as well as the context of the printing farm, Prusa MINI+ 3D printers and open-source management software OctoPrint were selected, set-up, and tested.

These choices provided the 3D printing farm with low-cost reliable printers suitable for entry-level users. The open-source software enables sufficient printer controls without the added and recurrent costs of commercial software options. As the next step, a 3D printer booking system available to students is recommended.

Keywords: 3D printing, 3D printing farm, 3D printer management, additive manufacturing, fused deposition modelling, fused filament fabrication

Contents

List of Abbreviations

3D:	Three-dimensional.
ABS:	Acrylonitrile butadiene styrene. A popular thermoplastic material used in FDM.
AM:	Additive manufacturing.
ASA:	Acrylonitrile styrene acrylate. A thermoplastic material that is considered a successor of ABS.
CAD:	Computer-aided design.
CAM:	Computer-aided manufacturing.
FDM:	Fused deposition modelling.
FFF:	Fused filament fabrication. The term adopted by the RepRap project instead of the trademark FDM process.
PC:	Polycarbonate.
PEI:	Polyetherimide. A temperature-resisted material used in coating the printing surface for FDM.
PETG:	Polyethylene terephthalate glycol. A popular thermoplastic material used in FDM.
PLA:	Polylactic acid. A biodegradable thermoplastic material typically used as FDM filament.
PP:	Polypropylene.

1 Introduction

The interest in 3D printing has been growing worldwide. 3D printing, however, is not a new manufacturing process. Its beginnings can be found in the 1980s when the process was known as rapid prototyping [1, p. 2]. In 2009, the fundamental patents relating to 3D printing technology expired, propelling the development of various commercial and open-source products, and as a result causing 3D printer prices to fall significantly [1, p. 5]. The market for 3D printing has been expanding ever since. Even under the economic pressure of a global pandemic the market experienced growth, amounting to an estimated 12.8 billion USD dollars in 2020 [2]. With this boom, 3D printing has become much more accessible to businesses and home users alike. 3D printing is also finding its place in educational spaces. The technology moved out of the industrial confines of its past.

As the possibilities of 3D printing have captured the attention of technology enthusiasts, so did the providers of 3D printing services start emerging to cater to them. While printers have become more affordable over the years, many potential users only have occasional printing needs and therefore might not be willing to make the investment in a personal machine. Decades ago, internet cafés emerged to provide computer access to the general public. Now, in a similar fashion, 3D printing service providers are appearing to set up 3D printing farms. A 3D printing farm could be defined as a collection of multiple 3D printers intended to function at the same time, in the same space, fulfilling customer orders on demand.

The set-up of 3D printing farms, which is the focus of this thesis, is creating fresh discourse. It brings forth new challenges and the need for specialised multi-printer management solutions for commercial as well as educational contexts. The services segment of the 3D printing market is too small and recent as of now to have gold-standard solutions established.

The objective of this thesis project was to set up a semi-automated 3D printing farm equipped with multiple 3D printers and management software suitable for an educational context. The purpose of this project was to provide 3D printer access to university students to advance their education and to encourage personal interest. The access to 3D printing especially benefits students who are taking 3D modelling courses or whose project work in embedded systems calls for rapid prototypes. The main requirements included reducing the need for physical presence around the printers as well as keeping associated costs low in spirit with the non-commercial purpose of the project. The thesis project was carried out for Metropolia University of Applied Sciences, School of ICT, located on the Karamalmi campus in Espoo.

2 3D printing

Undoubtedly *3D printing* is a widely used term nowadays. However, as the focal point of this thesis, it requires clarification as to its meaning, scope, and implications. As the use of 3D printing shifted throughout its development, this chapter also provides a historical overview of 3D printing. The aim of this chapter is to convey the meaning of the term as well as the developmental context that has shaped 3D printing into how it is known today.

2.1 The concept of 3D printing

Although the term *3D printing* has become part of everyday vocabulary, its interpretation tends to be vague and simplistic. Firstly, *3D printing* in itself implies a process in which a three-dimensional object can be “printed”, as straightforwardly as text on a sheet of paper. It is generally agreed by the experts of the field that it is a “popular culture” or “accessible” term that simplifies the concept [3, p. 58; 1, p. 3]. Moreover, the usage of the term *3D printing* can be very context-dependent and often left unclarified. For instance, bioscientists will associate 3D printing with wildly different materials, processes, and machines from those used by at-home makers. In conclusion, while the popular term is a welcome addition to everyday vocabulary and shows the significance of the technology, it requires a clearer definition.

What 3D printing references is more formally known as *additive manufacturing*. In the broadest sense, additive manufacturing is one of the core processes by which objects can be produced – through *addition* of materials. It stands alongside the oldest manufacturing processes: subtractive manufacturing and moulding [1, p. 1]. However, more specifically, additive manufacturing is often defined as a “process of joining materials to make objects from 3D model data, usually layer upon layer” [4, p. 3]. Such definitions posit additive manufacturing, and consequently 3D printing, as an umbrella term, which covers a number of established manufacturing processes. In fact, in 2010 the American Society for Testing and Materials classified all the AM processes into seven larger categories

[3, p. 58]. These include material extrusion, vat photopolymerization (solidifying a photopolymer with light), powder bed fusion (solidifying a powder with heat), and so on [3 pp. 58-60]. Undeniably these clear-cut categories are much less likely to appear in everyday language.

The first time that the term *3D printing* was established in the 1990s, however, was to refer to a patented AM binder jetting process [1, p. 69]. Nowadays, this AM process is better known by the category it belongs to. The trademarked *3D Printing* (3DP) process remains only the secondary meaning of the widespread term *3D printing*.

Many sources intended for technology enthusiasts have treated the term *3D printing* as a shorthand for material extrusion processes. It can be explained by the fact that this category of 3D printing is the most affordable and the most available one [3, p. 58]. What is often implied with 3D printing in particular is fused deposition modelling (FDM), which is also known as fused filament fabrication (FFF). In this process, filament made of thermoplastic materials is extruded by applying heat and deposited in small layers, which resolidify [1, p. 60].

FDM is not the only popular 3D printing process. Currently gaining ground and becoming more available is stereolithography (SLA), which involves solidifying resin with a beam of ultraviolet light [3, p. 60]. It is commonly referred to as *resin printing* and can be encountered under the *3D printing* umbrella term more often. Another common AM technology is selective laser sintering (SLS), in which lasers combine powder (such as nylon) into solid objects [3, p. 61]. Nevertheless, it is mostly in industrial use, and as such it remains obscure to the average 3D printing enthusiast.

All definition intricacies considered; this thesis uses the familiar term *3D printing* interchangeably with *additive manufacturing*. However, the scope of this project is limited to FDM as the most accessible 3D printing process. Therefore, all the 3D printing hardware and software discussed in this project is meant to relate to FDM only.

2.2 The rise of 3D printing

The advances in computer technology gave rise to 3D printing in the 1980s, when a variety of 3D printing processes started emerging simultaneously. The first kind of 3D printing process to appear was stereolithography. Although comparable 3D technology patents were filed in Japan, the USA, and France in the same year of 1984, it was Charles Hull's company 3D Systems that first commercialised the patented 3D process and released the first printer. In 1986, Carl Deckard filed a patent for selective laser sintering, which later led to the establishment of DTM to produce the technology. In 1989, the FDM process was patented by Scott Crump who then founded the Stratasys company. Two years later, the first FDM printer was invented [5, p. 3]. Overall, the first decade of 3D printing was a race from idea to patent and commercialization. [6, p. 37].

When 3D printing came about as a new technology, it became known as *rapid prototyping*. This is how Hull's stereolithography machines were advertised to the industry of product development [6, p. 64]. The term describes the fact that 3D printing was mostly limited to prototype making. However, since the technology quickly advanced in many respects such as precision, it outgrew its original application, and the term gradually became less common. [1, p. 2].

While new 3D printing production processes, machines, and companies were appearing, in the early 2000s there was a key development in another direction. Owing to the climate of what has been called the *maker culture* – the resurgence of interest in making and tinkering – in 2005 the RepRap project was launched. It concerned the open-design of a replicating rapid-prototyper that could produce parts for more printers. The printing process applied was the fused filament fabrication, which was a non-proprietary term equivalent to FDM that the RepRap project adopted [7, p. 177]. The reason for choosing this process for printer development was the option to use numerous materials as well as the low costs [7, p. 181]. Constantly improved by the community of makers, the machine design eventually turned into one that could compete with commercial printers. As various kits were being sold to individuals, online communities such as

Thingiverse.com were also starting to encourage self-made design sharing among the makers. As the original FDM patent expired, the consumer market soon became abundant with more affordable FDM printers made by a number of different manufacturers. Through the RepRap project, the maker community had a formative influence on consumer-accessible 3D printing. [1, p. 80.]

Today, the applications of a great variety of 3D printing processes can be found in virtually every sphere. 3D printing is in demand from the aerospace and automotive industries to numerous manufacturing, medicinal, and pharmaceutical developments [5 pp. viii-x]. The original purpose of prototyping is turning towards *direct digital manufacturing,* the production of end-products [6, p. 41].

3 Overview of FDM 3D printers

Numerous kinds of FDM 3D printers are available nowadays. Despite the fact that the printers may be structured differently, the key hardware components that the FDM process depends on persist in all the configurations.

3.1 Basics of an FDM 3D printer

The main function of an FDM machine is to extrude material layer-upon-layer. The necessary hardware components to fulfil this function are the extruder and the print bed.

The extruder is the component that heats the filament and passes it through the nozzle and onto the printing surface. On the receiving end, there is an extruder drive gear that is driven by a stepper motor, which feeds the filament to the hot-end. The hot-end contains a narrow-diameter nozzle and a heating system. Figure 1 presents a common extruder configuration. Notably, in some configurations the hot-end and the rest of the extruder are arranged as separate elements connected via a Bowden tube. Travelling through the hot-end, the filament is heated and exits the extruder through a nozzle. Temperature is regulated by a heatsink and fans. [8, pp. 26-27].

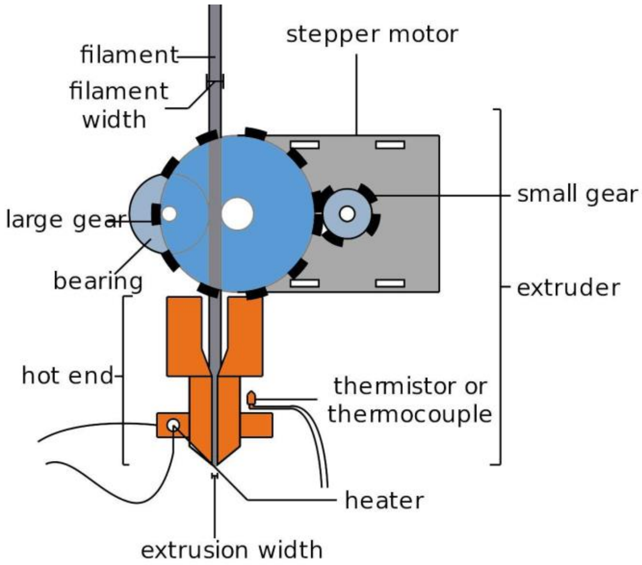


Figure 1. Direct-drive extruder schematic [9]

For the extruded filament to be layered precisely, a smooth printing surface is needed. This element is called a print bed. Most often it contains a heater to maintain temperatures that allow all kinds of filament to remain attached to the printing surface whilst printing. This type of a print bed is also known as a heat bed. A heat bed is usually covered with a PEI sheet, PEI-coated steel, or glass, which becomes the printing surface. [8, p. 26].

In building a three-dimensional object, an FDM 3D printer requires the main components to function in tandem. As there are many configurations to accomplish that, there are also many types of 3D printers developed. Horvath and Cameron categorise FDM 3D printers into *Cartesian* and *non-Cartesian* types [8, p. 20].

3.2 Cartesian printers

The most common type of FDM 3D printer is the Cartesian-coordinate based printer with a square or rectangular build volume [10, p. 6]. Its parts are capable of moving independently along the X, Y, and Z planes to position the extruder and the print bed accordingly. That is, a Cartesian printer is able to reposition itself with dedicated stepping motors on either X, Y, or Z axis without affecting the other axes. This movement can be implemented in a number of ways. Hence, cartesian printers can be further classified into subtypes depending on which components move along which axes. Notably, the naming conventions for such categories are not well-established. The following descriptive category names are used in the RepRap project [11].

3.2.1 Cartesian XZ-head printers

This type of printer is also known as *RepRap style* [12, p. 6] or *moving bed* printer [13, p. 14]. In this configuration, the extruder moves in the X and Z directions. The print bed moves along the Y axis. This type of printer is manufactured by Prusa Research, Creality (Ender-series), LulzBot, among others.

Figure 2. A Cartesian XZ-head printer Prusa i3 MK3S+ [14]

An example of a Cartesian XZ-head printer made by Prusa Research can be observed in figure 2. The configuration of the frame supporting the rods varies in different models.

3.2.2 Cartesian XY-head printers

Another significant type of Cartesian printers is the XY-head type, also known as *MakerBot style* [12, p. 6] or *gantry* printer [13, p. 14]. Its extruder is designed to move along the X and Y axes, while the print bed moves along the Z axis [10, p. 7]. The extruder is fixed to the top of the printer, and the print bed moves downward as the print advances. Often this type of printer is encased, resembling a box (see figure 3). This type of printer is produced by MakerBot, Ultimaker, Creality, Flashforge, and other companies.

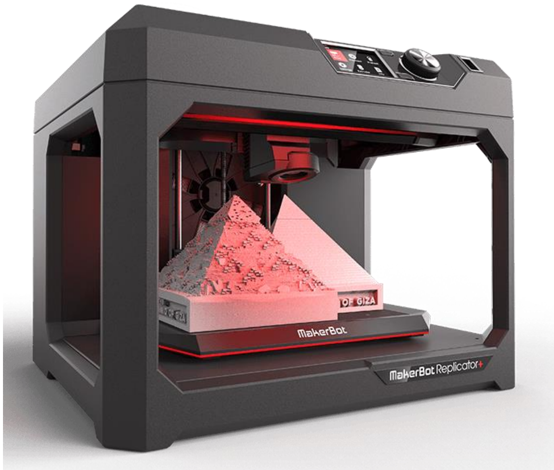


Figure 3. MakerBot Replicator+ [15]

Following the same naming conventions of Cartesian printer types, it is possible to distinguish many more. However, the aforementioned XZ- and XY-head types are the most available nowadays.

3.3 Non-Cartesian printers

The category of non-Cartesian printers is unified by the fact that no single stepping motor is correlated to a particular axis [8, p. 20]. Printers in this category have a much smaller user base among the maker community in comparison to Cartesian printers. Some of the non-Cartesian types of 3D printers currently in use are pictured in figure 4.

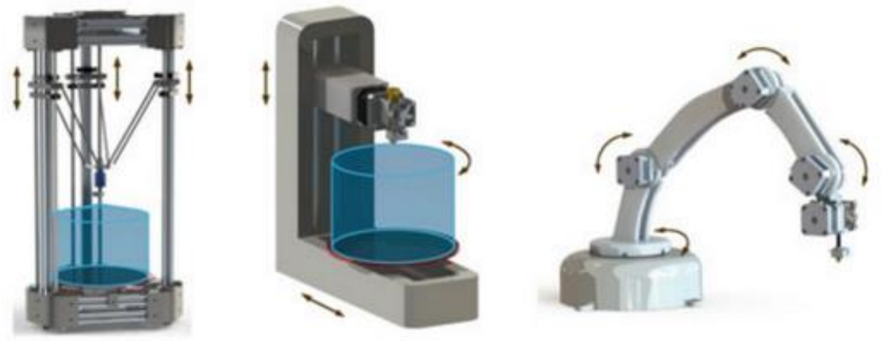


Figure 4. Left to right: delta, polar, and robotic arm 3D printers [10, p. 7]

Delta is the most common type of a non-Cartesian FDM 3D printer [8, p. 21]. The distinguishing feature of delta printers is their vertical construction with three equidistant arms and a suspended extruder. These printers have a cylindrical build volume and are better suited for printing tall items than Cartesian printers. Unlike a Cartesian printer, a delta printer is only capable of moving vertically. In order to reposition itself on a single axis, it moves in all three planes. Since the movement of delta printers is more complex, their assembly is more advanced as well, making these printers less beginner-friendly. Delta printers operate faster than Cartesian printers, although they are not as accurate [10, p. 7]. Some of the delta printer manufacturers include FLSUN, Monoprice, and WASP. [16, p. 27.]

As suggested by their name, polar 3D printers utilise a polar coordinate system. The most distinct feature of polar 3D printers is the rotating print bed. Accordingly, their build volume is cylindrical, just as that of delta printers. As extruder movement is very limited (up-and-down), the rest of positioning is accomplished by the print bed, which could increase the likelihood of adherence issues. Polar printers are among the least common FDM 3D printers. [10, p. 7.]

The last and most complex type of non-Cartesian FDM printers is known as robotic (or multi-axis) arm printers. They are capable of moving in all planes and are not limited to operating on a print bed. This type of 3D printer is drawing more attention due to its speed and ability to reproduce complex shapes accurately. However, robotic arm printers are the least affordable type and are generally unavailable to home users. [12 pp. 6-7; 10, p. 7.]

3.4 Printing materials

There is an abundance of materials that can be used for FDM 3D printing. Amongst the most common printing materials for at-home users are PLA, PETG, and ABS filaments.

Most commonly used filament today is made of polylactic acid (PLA). Its popularity is due to several advantages. PLA is an affordable and biodegradable material. It does not cause excessive adherence issues and can be used on non-heated print beds. PLA filament provides a variety of effects – it can be filled with other materials such as wood or metals. However, PLA filament is brittle and prone to breakage. Additionally, it melts at lower temperatures, therefore items made of this material are likely to warp if exposed to heat or prolonged sunlight. [8 pp. 34-35.]

Another popular filament material is polyethylene terephthalate glycol (PETG). It is often used in prints that require heat-resistance as well as some degree of flexibility. On the other hand, PETG adheres to the print bed strongly, which requires special consideration, as it may damage some surfaces. PETG filament is normally priced higher than regular PLA filament [8, p. 37].

Acrylonitrile butadiene styrene (ABS) is a filament material made out of three polymers in varying proportions. Similarly to PETG, ABS is a durable and heat-resistant material. Nevertheless, the material tends to shrink significantly as it cools, frequently causing it to detach from the printing surface. Another disadvantageous factor is that ABS produces toxic fumes. ABS is gradually being replaced by acrylonitrile styrene acrylate (ASA), which produces less fumes when heated and is not prone to UV-induced discolouration [17]. [8 pp. 37-38.]

In addition to the three major filament materials, many others can be found on the market. Nylon, polycarbonate (PC) blends, polypropylene (PP), polyvinyl chloride (PVC) are among the materials available and affordable to consumers. On the industrial scale, a wider array of expensive, well-performing, and heat-resistant printing materials, such as polysulfones (PSU, PES, PPSU), is used [10, p. 8].

4 Multi-printer management software

FDM 3D printers that are supplied to consumers come equipped with firmware required to operate the printers independently. Normally, 3D printers are controlled via hardware interface elements in conjunction with removable media for file transfer. However, physical interaction with multiple 3D printers is time-consuming. “Local-control, local-management” host software that is traditionally run and operated on a machine physically connected to a single printer is not efficient enough for a 3D printing farm either [12, p. 21]. Cloud services and dedicated hardware capable of supporting multiple printers are better suited for 3D printing farms [12, p. 21]. Although currently the options for multi-printer management are rather limited, there is software available from open-source, freeware, and proprietary domains.

4.1 Open-source software and freeware

During the development of 3D printers within the RepRap community, open-source software played a major role. All 3D printing related software needs could be covered by freely available software, from 3D modelling programs, to slicers that convert models into layers and gcode instructions, and software that transfers gcode instructions to the printer [18, p. 49]. A number of FDM 3D printers available on the market, such as the Creality Ender series, still utilise the open-source firmware developed by the RepRap project [8, p. 25]. It is no surprise that free and open-source developments are expected to answer new printer management demands.

Despite the influence on 3D printing, open-source and freeware options for multiple printer management currently remain limited. Selecting specific software requires careful considerations regarding the available features and the purpose of the 3D printing farm.

4.1.1 OctoPrint

OctoPrint (http://octoprint.org) is open-source software that enables the control of a 3D printer through a web interface on the local network [19, p. 38]. It is a widely known and popular open-source solution. While OctoPrint can run on a Linux, Mac, or Windows machine, installing the specific OctoPi distribution available for Raspberry Pi single-board computers is the easiest approach [12, p. 21].

Among its many advantages, OctoPrint offers access control, precise stepper motor and temperature control, print monitoring and control, webcam support, and file upload via the web interface. In addition to the software itself, users can improve and expand the functionality of OctoPrint via a plugin repository maintained by the maker community. The OctoEverywhere plugin enables remote access from outside the local network, albeit the features of the free-version OctoEverywhere are limited. Although OctoPrint originally was not designed for multi-printer management, the at-home user base has discovered ways to adapt it to that purpose. [12, p. 21.]

4.1.2 Repetier

Overall, Repetier (https://repetier.com) offers a few free and flexible software solutions for 3D printing: Repetier-Firmware, Repetier-Host, and Repetier-Server. Repetier-Host is local-management host software with integrated slicers that connects to a printer via a serial or TCP/IP connection, or a Repetier-Server. Repetier-Server freeware enables remote access and management of multiple 3D printers via a web browser. Repetier-Server is compatible with the major operating systems, and can be set up on a device such as a Raspberry Pi. Contrary to OctoPrint, Repetier offers a single interface for multiple printers. [20.]

Although the rest of Repetier software only encourages donations, Repetier-Server is offered in free and pro (priced at 59.99 euro single payment) versions. While remote printer management along with the basic control features is included in the free version, a number of useful features, for instance webcam support and print statistics, are not available. Yet, Repetier freeware offers price calculation that is based on filament usage, time, and a definable handling fee. Considering its features, Repetier freeware could suit small-scale commercial services with an on-site supervisor. [21.]

4.2 Commercially available software

3D printing farms are more likely to be set up by various organisations for educational or for-profit purposes rather than by technology enthusiasts for personal use. Accordingly, the management software for FDM 3D printers is more abundant in the commercial sphere. Notably, some of the commercial software providers offer free limited versions of their products. Nevertheless, they tend to be too limiting for 3D printing farms to warrant consideration as freeware.

4.2.1 AstroPrint

AstroPrint (https://astroprint.com), which originated as a fork of OctoPrint, was fully developed to manage multiple printers operated by multiple users [12, p. 22]. It is a subscription-based service that boasts a 240 000 user base [22]. In addition to the basic features, AstroPrint offers print queue management, cloud-based print file storage and slicing [22]. To manage printers wirelessly, a self-made or directly purchased Raspberry Pi based product (AstroBox Gateway or AstroBox Touch) is required. 3D printers can thus be operated via a web browser as well as desktop and mobile apps. AstroPrint emphasises cloud ecosystems and accessibility to the “general (non-technical) consumer”, which distinguishes the software from its OctoPrint roots and “technically savvy” user base [23]. Nevertheless, AstroPrint is also available to OctoPrint users through a plugin.

The free AstroPrint plan is intended for a single user operating maximum two 3D printers. Beyond that, minimum AstroPrint monthly costs consist of 9.90 USD dollars [24].

4.2.2 3DPrinterOS

Reaching a smaller user base than AstroPrint, 3DPrinterOS (https://3dprinteros.com) caters to educational institutions, various enterprises, as well as 3D printer manufacturers [25]. 3DPrinterOS offers fully cloud-based 3D printer management services. 3D printer connection to the cloud is possible via software, devices such as a Raspberry Pi, or it can be embedded directly in the printer [26]. As expected, 3DPrinterOS management software is compatible with a great number of desktop and industrial 3D printers [25]. The platform is capable of accepting input from CAD and CAM software, augmented reality, and 3D scanners [27, p. 2]. Depending on the subscription plan, the service can include extensive access control, cloud-based slicing, unlimited file storage, a single interface for managing multiple printers, tracking filament usage and other in-depth statistics [28]. An exceptional feature of the 3DPrinterOS platform is the *magic fix*, which analyses print files and fixes common modelling mistakes [12, p. 22]. Undoubtedly, 3DPrinterOS offers advanced solutions uniquely suitable to enterprises and manufacturers. Nevertheless, as Griffey [12, p. 22] points out, complete reliance on cloud services may not be the best choice for non-commercial spaces with low bandwidth or connectivity issues.

With a storage of 5 Mb and a bandwidth of 25 Mbps, 3DPrinterOS allows free limited-feature accounts through the company’s website (https://cloud.3dprinteros.com/). The company, however, does not publicly disclose prices for other subscriptions.

4.2.3 Polar Cloud

Polar Cloud (https://polar3d.com) is a cloud-based 3D printer management platform geared especially towards educational institutions. Polar Cloud users are able to create 3D models in-browser, join their educational groups, and send print requests to their participating institutions. The educational institution subscription plans, which start at 500 US dollars per year, include such uncommon features as the option to sell student designs as well as fundraising. It also includes specific access controls, allowing to distinguish advanced users and printer operators. Polar Cloud also offers a free account option for at-home makers, which includes cloud slicing, print monitoring and queuing for a single user. In addition to these features, the subscription plan for entrepreneurs also provides unlimited cloud storage and a notification system. This service is among the most affordable on the market at 5 US dollars per month and it could suit a commercial 3D printing farm. A number of printers can be connected to Polar Cloud through an OctoPrint plugin. [29.]

Certainly, the printer management service market is not limited to the aforementioned options. In addition, there are newer and lesser-used solutions such as SimplyPrint or Simplify3D. New multi-printer management options are also being developed by printer manufacturers. For instance, 3D printer management software Prusa Connect is currently being developed by Prusa Research [30]. Since commercial management software is on the rise, a variety of specific requirements and 3D printing farm environments can be accommodated.

5 3D printer selection and set-up process

In the fulfilment of the thesis project, the selection of four FDM 3D printers for a university 3D printing farm was guided by a few main criteria. It was essential that the printers were reliable, low-cost, and accessible to new users. Since a university-funded 3D printing farm would not have an on-site supervisor to assist the students, printers that have a large user base and plenty of available information were preferable. Moreover, using 3D printers for introductory educational purposes does not place demands on specific build volume or speed. Due to all of the factors, a Cartesian 3D printer was the clear choice.

A great selection of Cartesian 3D printers is available nowadays. The enclosed XY-head type of 3D printers is a common choice for educational spaces, especially with a young user base. However, these printers are bulkier and heavier, which may be disadvantageous for limited-space 3D printing farms. Additionally, the XY-head printers cost more on average. Thus, the 3D printer selection was limited to XZ-head type printers. And while there is no shortage of affordable XZ-head printers, there are not as many that are known for their reliability and high manufacturer quality.

Prusa Research, an award-winning 3D printer manufacturer based in the Czech Republic, is known for producing 3D printer parts in their own printing farm consisting of 500 and more of their well-tested Prusa i3 MK3S+ printers [8, p. 248]. In fact, in 2019, 1096 of these printers broke the Guiness World Record for most 3D printers operated simultaneously in a single location [8, p. 248]. Although the i3 MK3S+ model is less affordable, Prusa launched a more compact but otherwise similarly-featured Prusa MINI model in the same year [31]. Its successor Prusa MINI+ was promptly recognised and heralded as the best 3D printer for hobbyists [32]. Due to its reliability, cost, and many other advantageous features, Prusa MINI+ was selected for the 3D printing farm located in the campus of Metropolia.

5.1 Prusa MINI+ features

Prusa MINI+ printers (pictured in figure 5) are compact, affordable, and well-equipped machines. Prusa Research recommends this model for “for beginners, companies looking to build a printing farm and 3D printing enthusiasts” [33].

Figure 5. Assembled Prusa MINI+ printers

Prusa MINI+ can print 3D objects up to 180 millimetres in length, width, and height. Although its build volume is smaller than of average 3D printers, the printer shows advantages over other lower-cost 3D printers. It is equipped with a Bowden-type extruder and a standard 0.4 mm nozzle that extrudes filament in finer than regular (0.05–0.25 mm) layers. The extruder and heatbed of Prusa MINI+ can reach high temperatures (280 °C and 100 °C respectively), therefore the printer is capable of printing with an exceptionally wide range of filament materials, such as PLA, PETG, ABS, ASA, PC, PP, nylon, and so on. Printer temperatures are regulated with three thermistors. Such high extruder temperatures are more commonly a feature of higher-end 3D printers. [33].

Additionally, Prusa 3D printers are equipped with SuperPINDA sensors for automatic mesh bed levelling. Prusa MINI+ 3D printer maintains network connectivity via an ethernet port. It is also equipped with an LCD screen that allows the user to easily control the printer and to preview prints. Prusa printer components are open-source, rendering them more readily replaceable if damaged. Optionally, Prusa MINI+ can be upgraded with a filament sensor which pauses printing in case of filament ending. Moreover, Prusa Research provides

24/7 customer support. All of the described features make up a compact, yet versatile 3D printer suitable for a university 3D printing farm. [33.]

5.2 Printer set-up and maintenance

The main difficulty factor in setting up a Prusa MINI+ is whether the 3D printer is ordered as semi-assembled or as an assembly kit. Although a Prusa MINI+ assembly kit is more affordable than its semi-assembled counterpart (priced at 379 euros and 419 euros respectively at the time of writing), the lead time for the kits can be a few times longer, up to 3 to 4 months. Additionally, assembling a kit is time-consuming (starting with 6 hours per printer) and leaves room for user error in assembly. A larger 3D printing farm ordering all of the equipment at once would benefit from opting for semi-assembled 3D printers. [34.]

Otherwise, Prusa Research provides a corresponding detailed assembly manual and 3D printing handbook with each 3D printer or kit. The semi-assembled Prusa MINI+ arrives with pre-assembled XZ-axis as well Y-axis. The provided instructions lead the user through over 30 steps to join the axes together, to connect the LCD screen, and to construct the filament spool holder. Optionally, the filament sensor is also installed. [35 pp. 3-22.]

After printer assembly is done and all the components are in place, the printer needs to be powered on for calibration with Prusa’s calibration wizard. The calibration process consists of a self-test, mesh bed levelling, and first layer calibration. The self-test is carried out after assembly to reveal any errors in wiring, component failure, or hindrances in axial movement. Before any further calibration is carried out, filament must be loaded. This is accomplished by cutting the filament at an angle and feeding it into the Bowden tube after the extruder has been heated. The last step of calibration is taken to ensure the quality of the first layer and to help the print remain attached to the print bed. Before first layer calibration, as before any printing takes place, the 3D printer automatically carries out mesh bed levelling. In the process, the SuperPINDA probe measures the distances to the print bed at multiple points in a grid-like manner. When any warping of the print bed is accounted for, printing can take place. The first layer calibration is used to determine the optimal distance of the nozzle from the print bed, so that layers of filament are deposited in a manner that creates an even and consistent surface. A comparison of first layer calibration quality can be observed in figure 6. Although other steps of set up and calibration are taken only once, the first layer calibration is recommended every time filament or print sheet is changed. [36, pp. 17-24.]

Figure 6. First layer configured well (below) and nozzle too high (above)

Outside of set up, the maintenance of a Prusa MINI+ 3D printer is low-cost and low-effort. To ensure print adhesion, wiping the printing surface with 90% isopropyl alcohol solution is a choice suitable for all types of print sheets. The smooth PEI sheet normally supplied with a Prusa MINI+ can also be cleaned with water and dish soap, although running water could be less commonly accessible in a printing farm setting. The print sheet should be cleaned every time the print sheet appears stained, which could be as often as every time the print sheet is handled. [36 pp. 39-42.]

As for other types of maintenance, they need to be carried out less frequently. On rare occasions that the printer nozzle does not dispense filament correctly, it may be cleaned with a needle provided with the printer. Every 200 hours of printing, the smooth rods of Y and Z axes require cleaning and lubrication. Printer fans should also be cleaned at the same interval. The groves of extruder gears as well as the Bowden tube can become clogged with filament particles. These issues can be alleviated with a can of compressed air. [36 pp. 43-47.]

In setting up a Prusa MINI+, printer assembly is undoubtedly the most time-consuming step, albeit well-described in the materials provided by the manufacturer. Aside from that, maintaining a printer is fairly straightforward and does not require considerable investment or constant professional supervision.

6 Management software selection and deployment

In regard to management software, a 3D printing farm arranged for educational reasons calls for uniquely distinct features. While a commercial printing farm operator would benefit from complete printer control locally as well as remotely, it may prove to be dangerous to grant hundreds of users lacking expertise and accountability the same access. Thus, a university printing farm relies upon maintaining at least two access groups: regular users and administrators. Moreover, an educational printing farm, being not a commercial endeavour and not self-funding, requires limiting expenses as much as possible. As freeware does not guarantee to keep its status in the future, an open-source option was highly preferred. Moreover, an open-source solution leaves the opportunity for various customization and integration projects, if needed. Considering these factors, the management option that was left in the selection pool for Metropolia’s printing farm was OctoPrint.

6.1 OctoPrint

In addition to being an open-source venture, OctoPrint provides plenty of useful features that benefit a not-for-profit printing farm. OctoPrint is not resource-intensive and can support multiple printers on a single Raspberry Pi. Unlike Repetier freeware, OctoPrint enables web camera feed, which is especially beneficial for tracking filament or printing progress in an environment without a designated attendant. OctoPrint allows administrators to create multiple user groups with customised access. Another important aspect of OctoPrint is that extra features are easily managed through OctoPrint dashboard and plugin repository. Anyone can take part in improving the software.

Although the exact numbers are not known, OctoPrint has a large user base that is a great source for gathering additional information or troubleshooting arising issues. A great variety of FDM 3D printers are compatible with OctoPrint, including Prusa MINI+. In fact, perhaps due to common open-source roots, Prusa Research endorses OctoPrint use with their printers [36, p. 25].

6.2 OctoPrint deployment on a Raspberry Pi

Although currently OctoPrint does not support multiple printers out-of-the-box, the process of adapting it is not complex nor uncommon. To start, OctoPrint deployment on a Raspberry Pi requires a single microcomputer and its power supply, a microSD card along with an adapter, a microUSB cable for each 3D printer, network access, and optionally a web camera. In this project, a Raspberry Pi 3B+ model with a 2.5 A power supply and a 16 GB microSD card were provided. This model of Raspberry Pi is equipped with four USB ports, and it was intended to support four 3D printers and a web camera. Therefore, a USB hub was required as well.

Deploying OctoPrint on a Raspberry Pi is made easy by installing OctoPi, a Raspbian-based image that contains OctoPrint, its dependencies, and an application for camera support [36]. The installation can be carried out with Raspberry Pi Imager, an application that flashes a selected Raspberry Pi image onto an SD card with minimal user effort. The latest available OctoPi 0.18.0 version was installed.

After the image installation, basic configuration is completed. The user password is changed, SSH connections enabled, and network access is configured by adding a network block in the *octopi-wpa-supplicant.txt* file located in the *boot* directory:

```
network= {
      ssid="eduroam"
      key_mgmt=WPA-EAP
      eap=PEAP
      phase2="auth=MSCHAPV2"
      identity="user@metropolia.fi"
      password="password"
}
```

Listing 1. Example of WPA-Enterprise network configuration block

The location of the file allows it to be edited before the card is transferred into a Raspberry Pi. Attention needs to be paid that the symbolic link to */etc/wpa_supplicant/wpa_supplicant.conf* file is preserved. At the time of carrying out the project, OctoPi 0.18.0 was based on Debian version 10, also known as Buster. This particular version exhibited an issue that prevented the Raspberry Pi from connecting to WPA-Enterprise networks, such as eduroam [38; 39]. The issue was noted in Raspberry Pi acquiring an IP address from within the automatic IP addressing range (169.254.0.1-169.254.255.254). In order to connect to the expected network, the wpa_supplicant was downgraded to the 2.4 version available from Debian 9 (Stretch) repository. Network connectivity can be verified within the local network by navigating to *octopi.local* in a browser. Then OctoPrint can be set up with an administrator account and default printer profile.

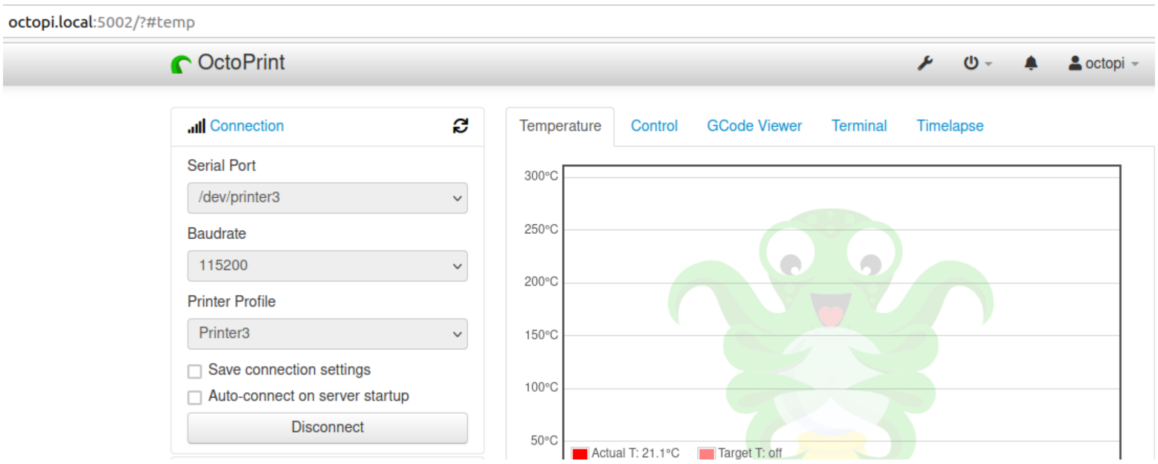
After configuration and verification that OctoPrint is reachable, additional instances for each 3D printer can be created. Many sources are available to guide an administrator through this process. Essentially, the original *octoprint* directory is copied and renamed as *octoprint2*, *octoprint3*, and so on until there is one copy for each printer. The octoprint service file available in the */etc/systemd/system/* directory is also copied and renamed in the same manner. In the subsequently created service files the base directory as well as the port used should be updated. Normally, OctoPrint binds to port 5000, therefore the following instances can be ascribed to subsequent ports 5001, 5002, and so on. This way, the new OctoPrint instances will be reachable through the browser by adding the port, for instance, as *octopi.local:5001*. When the new services are enabled, they will be started on Raspberry Pi's start up. The service names need to be updated through the newly created dashboards as well so that the correct instance is affected when action such as restarting is taken. [40.]

When the additional OctoPrint instances are functioning, an issue caused by dynamic USB addresses arises. Since devices can be assigned different addresses every time they are plugged into a Raspberry Pi, being able to connect to a particular printer out of multiple would require frequent tedious verification. Ideally, the order or specific port to which a 3D printer is plugged should be irrelevant. For that reason, a few static rules that create a persistent device-associated address are defined. In */etc/udev/rules.d* directory a file *99.usb-serial.rules* was created with a line for each printer in the following manner:

```
SUBSYSTEM=="tty", ATTRS{idVendor}=="2c99", ATTRS{idProduct}=="000c",
ATTRS{serial}=="serial number", SYMLINK+="unique printer name"
```

Listing 2. Example of a *udev* rule for a Prusa MINI+ printer

The information necessary for these rules can be found in the logs after connecting a printer to the Raspberry Pi. Fortunately, Prusa MINI+ printers are provided with unique serial numbers. It may not be the case with all 3D printers available on the market, which entails that each printer may need to be mapped to a specific port. Symbolic links are given descriptive names (such as *printer1*, *printer2*), as they will be visible on the OctoPrint dashboard (see figure 7). Lastly, on each OctoPrint instance the addresses not associated with it can be easily blacklisted through the dashboard. This is meant to prevent connections to wrong printers. [40.]



octopi.local:5002/?#temp

Serial Port: /dev/printer3

Baudrate: 115200

Printer Profile: Printer3

☐ Save connection settings

☐ Auto-connect on server startup

Actual T: 21.1°C

Target T: off

Figure 7. OctoPrint dashboard of a fully configured instance

These key steps complete the process of configuring multiple functional OctoPrint instances. Additionally, a web camera was enabled as well as accounts with restricted access permissions. After sufficient testing, the capabilities of OctoPrint can be further expanded.

6.3 Utilising the plugin repository

The OctoPrint repository (https://plugins.octoprint.org/) contains over 300 plugins that can be easily installed from the OctoPrint dashboard. When OctoPrint is used with multiple 3D printers as described above, plugins only require to be installed on a single instance in order to appear on all.

Plugins are developed to provide existing feature improvement or additional features. For instance, the remaining printing time that OctoPrint estimates can be wildly inaccurate. For this reason, the **PrintTimeGenius** plugin that analyses gcode instructions before printing and provides more accurate estimates is amongst the most popular plugins in the community [41].

An extra feature that is beneficial for any type of printing farm is filament tracking. The **FilamentManager** plugin allows a user to keep a database of all available filament, adjust nozzle temperatures for specific spools, and track filament usage in grams with each print [42]. The plugin does, however, rely on users consistently printing through OctoPrint instead of directly operating the printers.

What is additionally beneficial in an educationally-oriented printing farm is the ability to notify users of various printing events, such as errors or print completion. The **OctoPrint-Telegram** plugin enables communication between 3D printers and users through Telegram messenger. It is intended to enable full-scale printer operation through commands sent to a printer-associated Telegram bot. Which commands are permitted is customizable to each chat or group. [43.]

Notably, this plugin does not anticipate the use of multiple printers or numerous users, as every chat is required to be confirmed manually by the administrator through the OctoPrint dashboard. To simplify the process, a group containing four printer-associated bots was created. To avoid unauthorised use, the group was set up to be joined through a link or QR code only, and the user commands were limited to informational ones, such as status updates that include photos from the web camera. Interestingly, this plugin is made to be compatible with previously described FilamentManager, therefore users are able to receive filament information through commands as well.

Another widely used plugin is **OctoEverywhere**. This plugin enables control of printers outside of the local network. Such a feature was not expected to be provided to printing farm users, however, remote access for an administrator of a largely self-run printing farm is very useful. An administrator would be able to monitor and troubleshoot some issues arising in the 3D printing farm off-site. OctoEverywhere also provides more forms of notification and supports camera access as well as multiple 3D printers [44]. Sharing printer access with more users remains a paid service at the moment.

The plugins reviewed in this subchapter were applied in the project. A great number of plugins is available in the OctoPrint repository to suit the needs of different printing farms.

7 Conclusions and next steps

The aim of this thesis project was to arrange a 3D printing farm equipped with four FDM 3D printers and management software for Metropolia University of Applied Sciences. In the pursuit of that goal, currently available printer and software options for 3D printing farms were examined and evaluated for their suitability for an educationally-oriented 3D printing farm.

In FDM 3D printer selection, ease of use, reliability, and relatively low cost were the main requirements. The chosen Prusa MINI+ 3D printer fulfils these criteria well. It is a Cartesian XZ-head type of 3D printer, which is prevalent for personal and business uses. Prusa MINI+ 3D printers are produced by Prusa Research, which has a reputation for affordable printers that do not compromise on quality.

Since Metropolia's 3D printing farm was expected to have only minimal recurring costs relating to material use and maintenance, paid management software options were eliminated. The selected OctoPrint option is open-source, without the risk of unexpected current or future expenses. Although OctoPrint may be more complex to deploy than commercial software that is already suited to multi-printer management, it suits the basic needs of a university 3D printing farm. With its functionality expanded through the OctoPrint plugin repository, OctoPrint has proved capable of multiple printer management, access control, camera support, notifications, remote administrator access, and so on.

While these solutions set an education 3D printing farm for a good start, the overall management of a 3D printing farm could be improved. In the next steps, a booking system that allows students to reserve 3D printing time slots should be arranged. Since a system for booking classrooms is already in place at Metropolia, 3D printer booking could be integrated with it. It would provide the advantage of allowing bookings only when no lectures are taking place in the same space.

It would also be advisable to keep track of future software developments as well. For instance, Prusa Connect, which is management software currently in beta testing by Prusa Research, could be evaluated for its suitability for the 3D printing farm once the software is available.

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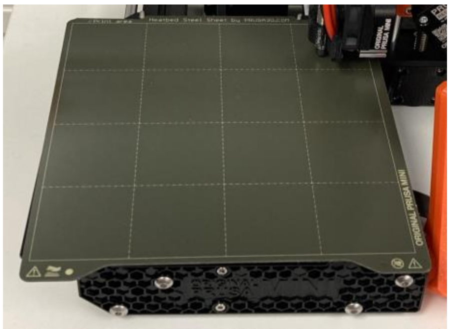
User instructions

Prusa Mini+ and OctoPrint
User Instructions

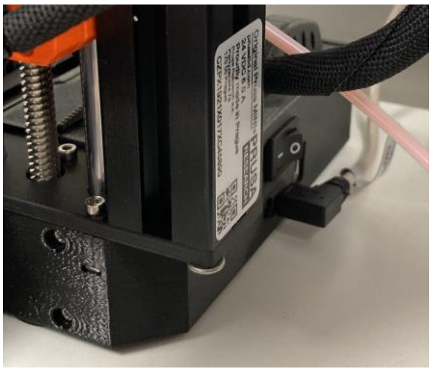
Before you print

1. **Make sure that the printing surface** of the printer **is empty –** there is no plastic or leftover prints from a previous user.



2. Clean the sheet with isopropyl alcohol spray and cloth provided in the cabinet under the table. Try not to touch it after cleaning. This is an important step, as any trace of residue can make your print fail by detaching from the surface.

3. Check that the printer is on: that it is plugged into the socket, and the button on the right side of the base is flipped on.



4. See that the filament roll is not empty. **Only PLA material is allowed on these printers**. If you need to print with other materials, please contact Antti Piironen for further instructions.

Accessing the software

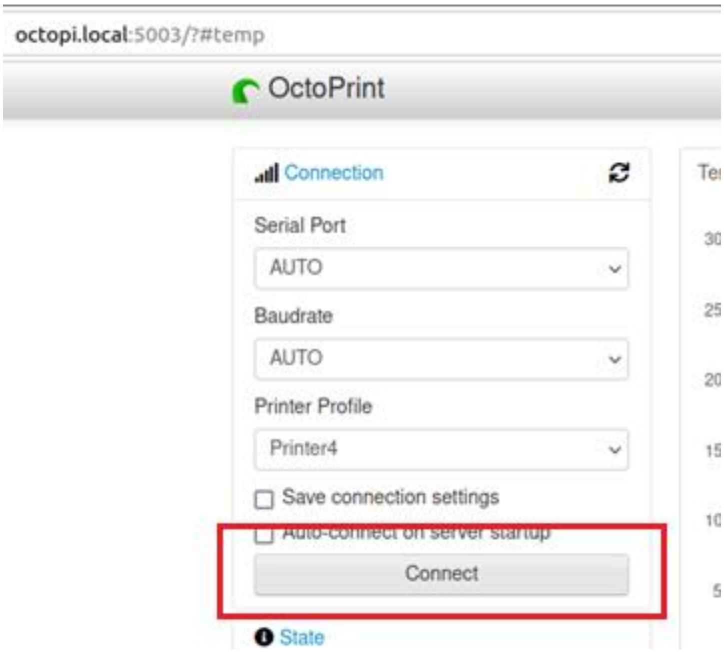
1. When connected to **eduroam** network, navigate to the address of the selected printer on your web browser:

   For printer 1: octopi.local or octopi.local:5000
   For printer 2: octopi.local:5001
   For printer 3: octopi.local:5002
   For printer 4: octopi.local:5003

   Make sure to type the correct address: you can connect to a printer only from one designated address.

2. Find the login information in the classroom next to the printers. This account works for all printers.

3. Once you have logged in, connect to the printer by simply pressing “connect”.



octopi.local:5003/?#temp

Serial Port: AUTO

Baudrate: AUTO

Printer Profile: Printer4

☐ Save connection settings

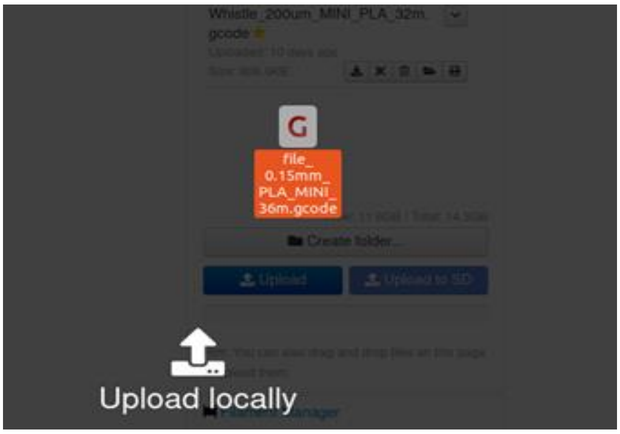
☐ Auto-connect on server startup

Once connected you will see it on the *Connection* tab, as well as the printer: the screen will display the OctoPrint logo as below.

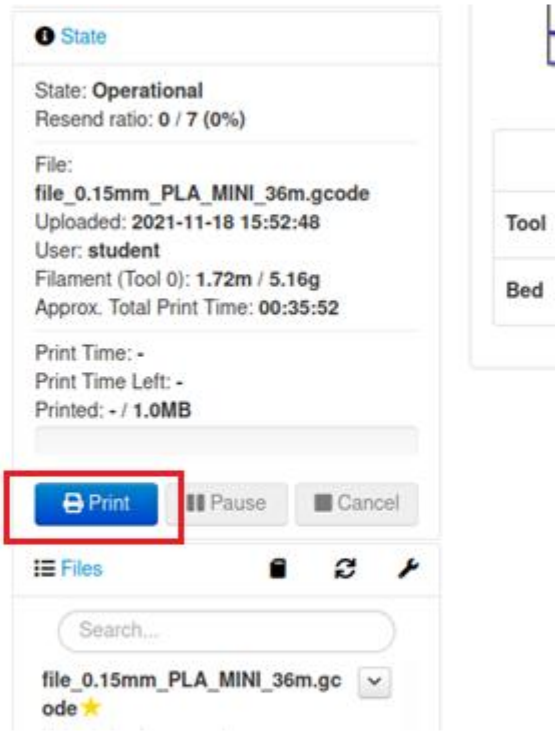
4. To print, you need to upload a sliced file with extensions **.g, .gco, or .gcode**. Make sure it is sliced for a 0.4 mm nozzle and PLA filament (Prusa Slicer

recommended).

Click *upload* in the *Files* section, or drag a file straight into the file area:



5. Once your file appears on the list, click on it to select. You will be able to see how much filament is needed and how long it will take. Simply press print and wait for the print to finish. You should not need to do any calibrations yourself.

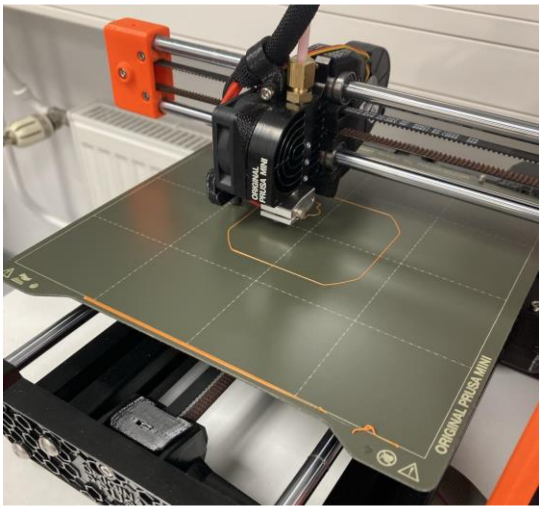

State

State: **Operational**
Resend ratio: **0 / 7 (0%)**

File: **file_0.15mm_PLA_MINI_36m.gcode**
Uploaded: **2021-11-18 15:52:48**
User: **student**
Filament (Tool 0): **1.72m / 5.16g**
Approx. Total Print Time: **00:35:52**

Print Time: **-**
Print Time Left: **-**
Printed: **- / 1.0MB**

The printer will preheat the heat bed and the nozzle. After that it will move in a grid-like pattern to measure the distance to the print sheet, make a line at the front of the sheet, and make an outline for your print, before starting to print your design. All of this happens automatically.

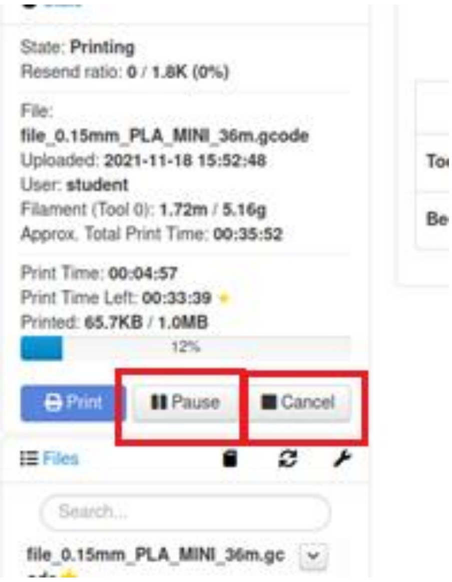


6. After the printer has finished, **wait for the heat bed to cool** - by default it will reach 60 degrees during printing. Prints come off the bed much easier once it is cool as well.

   Remove your print. In case it is not coming off easily, take off the green magnetic print sheet and very carefully bend both sides downwards to loosen the print. Put it back on, aligning back to its original place. Always try to avoid excessive touching and leaving fingerprints.
   Remove any excess plastic (outlines and lines at the front).

Pausing and cancelling the print

If anything goes wrong during the printing process, be ready to **pause** or **cancel** it:



State: **Printing**
Resend ratio: **0 / 1.8K (0%)**

File:
file_0.15mm_PLA_MINI_36m.gcode
Uploaded: **2021-11-18 15:52:48**
User: **student**
Filament (Tool 0): **1.72m / 5.16g**
Approx. Total Print Time: **00:35:52**

Print Time: **00:04:57**
Print Time Left: **00:33:39**
Printed: **65.7KB / 1.0MB**

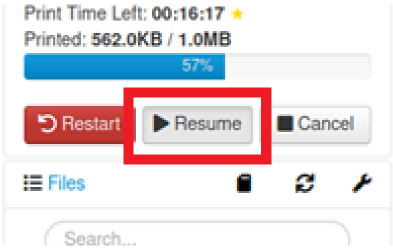
The process can be paused on the printer as well:

Pausing

You may want to pause the print for minor issues, for instance, if there is **filament build-up** on the nozzle after making the initial line (usually the nozzle oozes some filament during heating, but it comes off before the outline).

Pause the print, and very carefully remove it with a tool (not with hands – the nozzle will reach over 200°C).

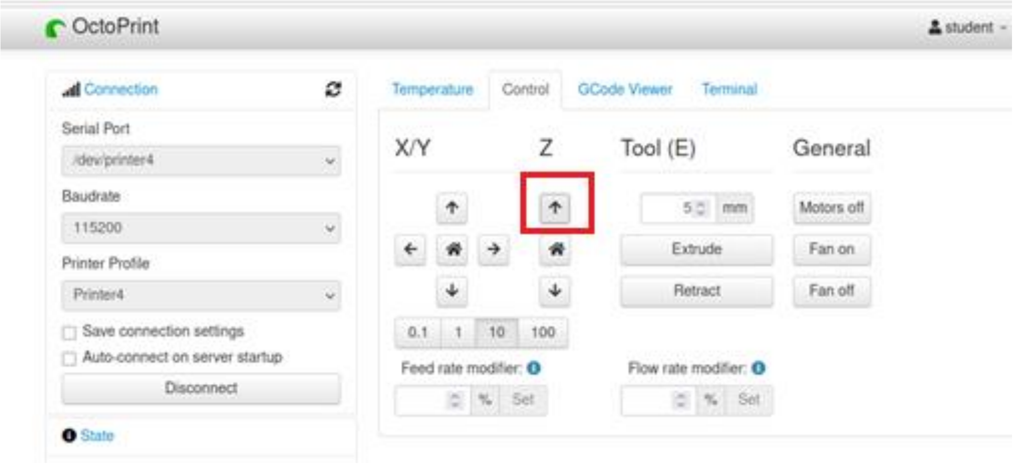
Resume printing through OctoPrint.



Print Time Left: 00:16:17
Printed: 562.0KB / 1.0MB

Cancelling

If any part of your print detaches from its place or fails otherwise, **cancel** the print. When you cancel, the printer will stop in its tracks. Next, on the OctoPrint tab *Control* press the upwards arrow on the Z-axis until the printer extruder is out of the way to reach the failed print.



Serial Port: /dev/printer4
Baudrate: 115200
Printer Profile: Printer4
Tool (E): 5 mm

Wait for the print sheet to cool and remove all plastic. Clean the sheet again if restarting.

Notifications

If you wish to receive notifications about your prints (finished prints, errors, or status updates), you can join a Telegram group **3D printing farm (KME662)** through a link or QR code that are available in the classroom.