DESIGN AND DEVELOPMENT OF COLLABORATION IN LARGE-SCALE ADDITIVE MANUFACTURING

by

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Industrial and Manufacturing Engineering

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May 2022

AUTHOR'S DECLARATION

I, Nyan Linn Htet, declare that the research work carried out for this thesis was in accordance with the regulations of the Asian Institute of Technology. The work presented in it are my own and has been generated by me as the result of my own original research, and if external sources were used, such sources have been cited. It is original and has not been submitted to any other institution to obtain another degree or qualification. This is a true copy of the thesis, including final revisions.

Date:

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Signature: 

ACKNOWLEDGMENTS

First and foremost, I would like to express my deep and sincere gratitude to my thesis supervisor Dr. Pisut Koomsap for giving me the opportunity to do my thesis and providing invaluable guidance and patience throughout my thesis studies. It was a great privilege and honor to work and study under his guidance.

My sincere thanks also go to committee members Dr. Huynh Trung Luong and Dr. Mongkol Ekpanyapong who put a mass interest in my thesis study and guided me with comments and suggestions which inspired and motivated me to continue my studies.

I am eternally grateful to receive financial support from Erasmus and the Programme of the European Union. Without the funding provided by the programme, my completion of this thesis could not have been accomplished. I am deeply overwhelmed with joy by friends in the A-cube research group for their valuable contributions and support to complete this study.

I would also like to acknowledge with much appreciation to Mr. Manh, research specialist who gave me technical support and Mr. Thanit, ISE laboratory supervisor who gave me permission to use the lab equipment, machines and all the necessary tools in the laboratory.

I am extending my heartfelt thanks to my family members especially my parents for their love and support both financially and most important, mentally. None of my achievements would indeed be possible without them.

And last, but definitely not least, I would like to express my special thanks to my girlfriend, Pwint Theingi Maw who is always there to give consistent understanding, encouragement and support during these years.

I can't express more in words how much I value all the support received both physically and mentally, but my heart is still full of favors received from each and every person throughout my thesis journey.

ABSTRACT

Additive manufacturing (AM), commonly known as 3D printing, has been available commercially since the last three decades. The global market for 3D printing has rapidly evolved, and the attention has swapped from hobbyists towards various industries such as aerospace, automotive, electronics, etc. In most large-scaled AM the method employed by Fused Deposition Modeling (FDM) is a slow fabrication procedure because the maximum velocity of the print head is limited to the maximum feed rate of the thermoplastic. There exists an inherent trade off within AM between the layer resolution and the overall scale of printed parts. In order to solve the universal problem of fabrication time, elevating the collaborative 3D printing process in which a swarm of printers work together on a common platform can shorten the fabrication time. According to the previous research, it is found that they can only be used to solve for simple parts by creating the chunks or segments and scheduling the printing job to avoid collision between nozzles. This paper fulfills a gap for the complex parts and situation as a new contribution by fabricating simultaneously and needlessly to set the interference zones or chunks. Moreover, in the mechanism of operating the printers, instead of using robotic arms, the design of the 3D printers is favorably changed. The market offers a fairly large selection of 3D printers with different designs and kinematics. However, the sizes of the commercial 3D printer's design are strictly constrained by the chamber volume of the printer, which can print parts whose sizes are no larger than its volume. This paper presents the design process and the development of a telescopic arm 3D printer which is modular type design. Once planning to fabricate multiple parts at the same time in the common working area, some considerations come into play in the system. Therefore, multiple g-code simulation, collision identification and modification are discussed and implemented in this paper.

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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
BAAM	Big Area Additive Manufacturing
Co-LSAM	Collaborative Large-Scale Additive Manufacturing
DIW	Direct Ink Writing or Robocasting
DLP	Digital Light Processing
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FEF	Freeze-form Extrusion Fabrication
HDPE	High-Density Polyethylene
LENS	Laser Engineered Net Shaping
LSAM	Large-Scale Additive Manufacturing
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
MJM	Multi-Jet Modeling
PPSF	Polyphenylsulfone
RFP	Rapid Freeze Prototyping
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
3DP	Three-Dimensional Printing

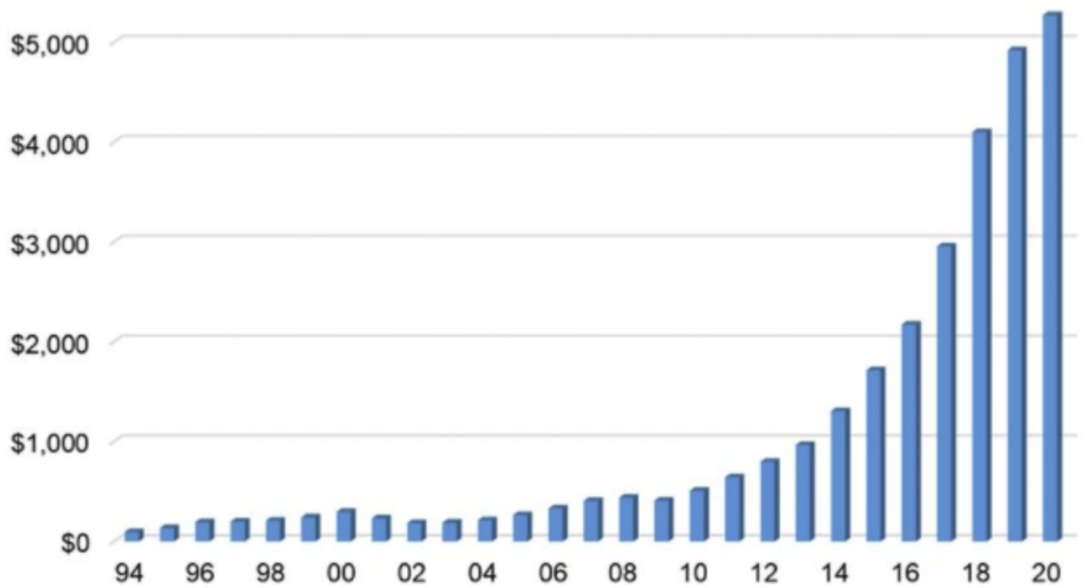
CHAPTER 1
INTRODUCTION

1.1 Background of the Study

Additive manufacturing (AM) technology has become integral to modern prototyping and manufacturing. AM also known as 3D printing has been more than three decades and it is the term used for the technology that builds three dimensional objects by adding layers of materials such as plastic, wood, concrete or metal (Dancel, 2019). AM provides cost and time saving ways to produce low-volume and customized products with complicated geometries and advanced material properties and functionality (Huang et al., 2015). According to the Wohlers Report (2021), there were 5.3 billion dollars of revenues in AM parts production from independent service providers worldwide (see Figure 1.1).

Figure 1.1

Revenues of AM Parts Production (in Millions of Dollars) from Independent Service Providers Worldwide (Source: Wohlers Report, 2021)



Moreover, the application of AM in scientific research shown in Figure 1.2 represents how the research interest for this technology grew over time. It is observed that the number of publications has significantly jumped since 2013 (Durakovic, 2018). Also, applications and impact on Nano-scale to large-scale industries like bio fabrication, electronics, personal products, automotive, architecture/construction and aerospace/defense attract an immense number of researchers (Gao et al., 2015) (see Figure 1.3).

Figure 1.2

AM Application in Scientific Research (Source: Durakovic, 2018)

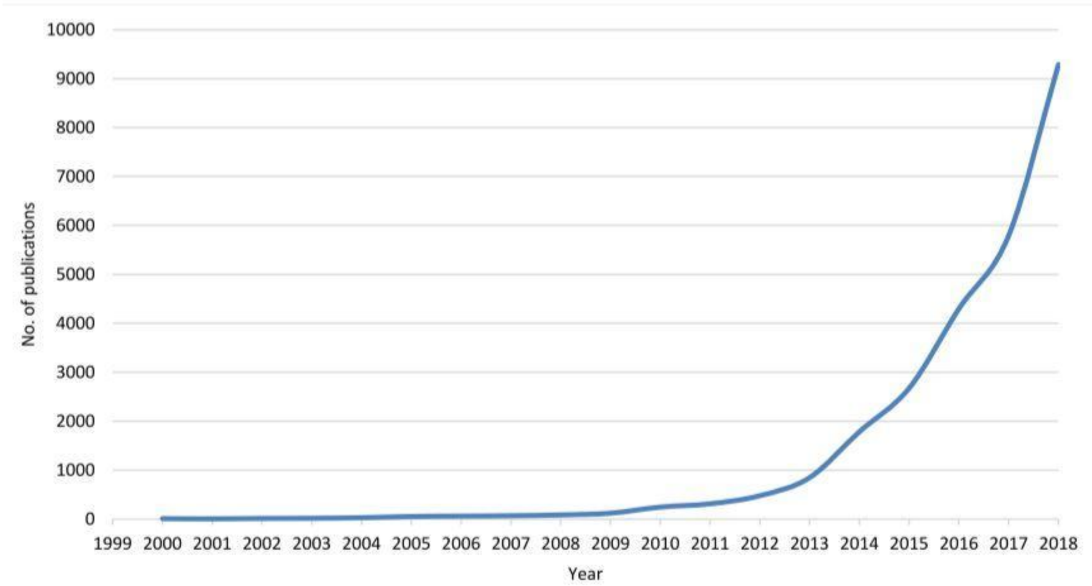
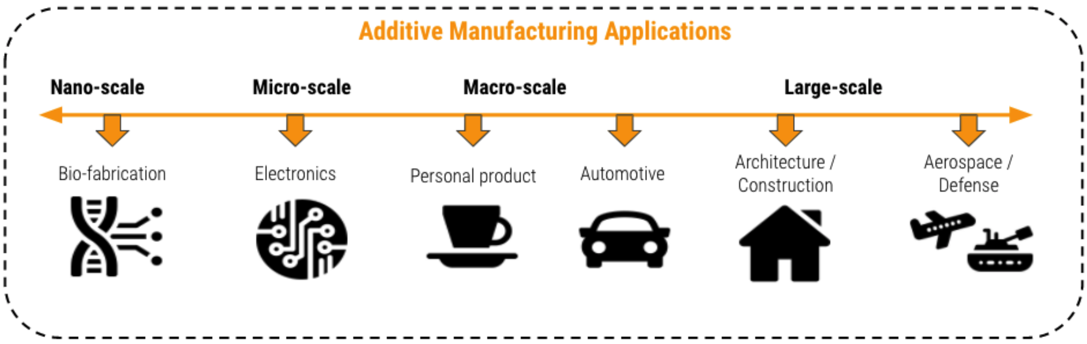


Figure 1.3

Additive Manufacturing Applications and Impacts (Source: Gao Et Al., 2015)



Forecasting of AM adoption rate varies significantly across industries, which is shown in Figure 1.4. Consumer electronics, aerospace and defense, automotive and medical devices are the most mature industries (Durakovic, 2018). These days, people start investing more effort in order to put AM closer to the mass production. AM usually requires a fixed-size printer with a limited printing envelope. The size of the design is strictly constrained by the chamber volume of the 3D printer (Shen, Pan, and Qian, 2019). To overcome the scalability issue, researchers around the world have presented a number of solutions, and these solutions can be divided into two categories. The first category is called large-scale AM (LSAM) (Roschli et al., 2019), in which 3D printers are larger than the printing objects. LSAM is a natural extension of 3D printing technology and several promising studies have been developed. The second category is cooperative 3D printing (Zhang et al., 2018), in which a swarm of printers cooperate with each other on a single printing job.

Figure 1.4

Adoption Rate of AM across Industries 2015-2025 Forecasting (Source: Durakovic, 2018)

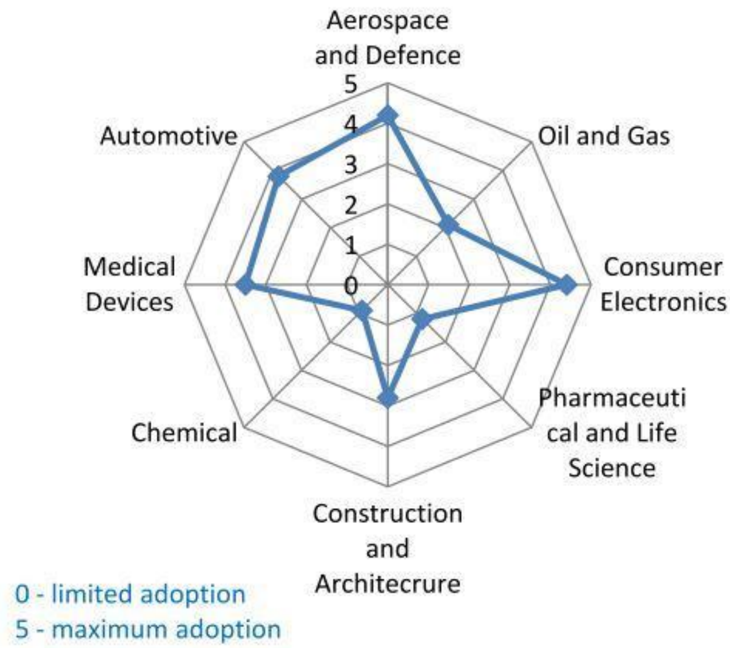
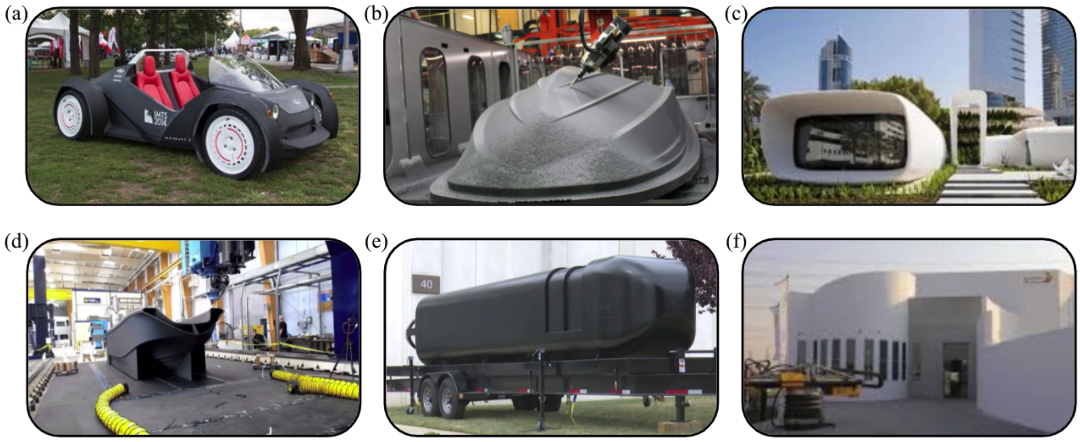


Figure 1.5 illustrates examples of the ability to create or produce large-scale products with unique design capabilities and opportunities that cannot be achieved by other manufacturing processes. Figure 1.5 (a) represents a 3D printed electric car, consisting in the design and development of a 3D printed electric car made out of carbon-fiber-reinforced ABS, with a reduction of the number of parts (Strati, 2014), Figure 1.5 (b) is a 3D printed boat with the combination of additive and subtractive tooling (Thermwood, 2016), Figure 1.5 (c) is an office building printed by Dubai Future

Foundation (WinSun from China, 2016). Figure 1.5 (d) is a world largest 3D printed boat (University of Maine, 2019). Figure 1.5 (e) is a nine-meter submarine hull prototype which is printed in six parts using carbon fiber reinforced ABS, decreasing the costs of this development by 90 per cent and dramatically reducing the production times (Moreno Nieto and Molina 2019). Figure 1.5 (f) is the world's largest 3D printed building in Dubai (Apis Cor, 2019). In addition to that capability to fabricate large-scale products, AM shows great prospect and potential in future.

Figure 1.5

Examples of Large-Scale Products that are Done by AM



Note. (a) 3D printed electric car (Strati, 2014), (b) 3D printed boat (Thermwood, 2016), (c) 3D printed office building (WinSun from China, 2016), (d) World largest 3D printed boat (University of Maine, 2019), (e) 9-m submarine hull prototype (Moreno Nieto and Molina 2019), (f) The world's largest 3D printed building (Apis Cor, 2019)

1.2 Statement of the Problem

AM shows immense potential in the future especially in construction, automotive, aerospace and defense. Most existing LSAM technologies are based on gantry or robotic arm systems, which can print objects whose sizes are limited by the structure of the equipment. Designing a device large enough to fabricate the needed models has been proven to work, but in most cases, scaling up the printer is costly and time-consuming. Though cooperative 3D printing that divides printing tasks among multiple devices seems to be effective, this new technology is currently being investigated by only a few laboratories worldwide (Shen, Pan, and Qian, 2019).

Although, AM has various kinds of techniques (Singh et al, 2020) such as stereolithography (SLA) (Su et al, 2018), selective laser sintering (SLS) (Schmid et al, 2015), this paper will primarily focus on large-scale AM devices utilizing fused filament fabrication (FFF) (Singh et al, 2020) as an operating principle because the fundamental design of FFF extrusion device is substantially simpler and more robust than other alternatives, thereby reducing the machine cost when building on a larger scale. Moreover, material extrusion allows fabricating products with a wide range of thermoplastic materials such as polycarbonate (PC), acrylonitrile butadiene styrene (ABS), Nylon and polylactic acid (PLA) and other types of materials (Shah et al., 2019).

However, the method employed by FFF is a slow fabrication procedure because the large mass composing the print head has to travel all the deposition paths. The print head has to accelerate at the path start, reach the maximum velocity and decelerate near the end of the tool path. Moreover, the maximum velocity of the print head is also limited to the maximum feed rate of the thermoplastic (Go et al., 2017). Furthermore, there exists an inherent trade off within AM between the layer resolution and the overall scale of printed parts (Gao et al., 2015).

Many researchers have been studying this subject and important enhancements on the increased fabrication speed and finishing quality have been achieved, mainly through deposition process optimization at the software level, for which the tool-path generation is the key aspect among the optimization. Using multiple AM units might benefit in elimination of the assembly process, minimize the working space, be capable of managing multiple tasks simultaneously and reduce fabrication cycle time, etc.

A very few studies approached this topic. The first one is “Multiple Deposition Heads System" by Project Escher, Titan robotic in 2017. Using multiple print heads printing approach can lead to collision between print heads. So, they need to create the boundary of each print head and manage the tool-path in the slicing process to avoid collision between them. In another research that is “Large-scale 3D Printing by a Team of Mobile Robots” (Zhang et al., 2018), they conduct the multi robot replacement optimization, platform navigation and localization and nozzle trajectory planning, but they did not mention the collision between nozzles. The next one “Research on Large-scale Additive Manufacturing Based on Multi-robot Collaboration Technology” (Shen, Pan and Qian, 2019) is that they separate as interference area and safe area for each robot and let them print sequentially to avoid collision between them, however this research cannot fulfill the complex parts.

According to the previous research mentioned above, it is found that they can only be used to solve for simple parts by creating the chunks or segments and scheduling the printing job to avoid collision between nozzles. There is still a gap to fulfill for the complex parts and situation as a new contribution by fabricating simultaneously and needless to set the interference zones or chunks.

1.3 Objectives of the Study

The objective of this study is to design and develop a large-scale additive manufacturing system for collaboration to reduce fabrication time.

1.4 Limitations and Scopes

1. Since additive manufacturing has various techniques to deposit the materials, this study focuses on Fused Filament Fabrication (FFF).
2. In this study, print parts partition, positioning and orientation are needed to be considered by the operator.
3. Only two AM units will be developed in this study because of the limited budget.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the technologies used in AM are explained as AM process chain and process overview. As LSAM is a natural extension of 3D printing technology, the current issues such as layer resolution, fabrication speed and cycle time are presented in this chapter. Moreover, how collaboration comes into play in AM and current state of collaborative AM are discussed for managing the multiple AM units to reduce the fabrication time.

2.1 Additive Manufacturing (AM)

Additive manufacturing (AM) refers to the group of methods or technologies for the production of three-dimensional products directly from a digital 3D model, by successively adding material and this kind of technology has been used for more than three decades. These processes start with an empty build platform in which the object will be created. The object is made by deposition of successive layers forming the desired object (Singh, 2016). The majority of process chain and process overview in AM are summarized and discussed in next section 2.1.1 and 2.1.2.

2.1.1 Additive Manufacturing Process Chain

The generic AM process includes the eight steps as shown in Figure 2.1.

Step 1: Conceptualization and Computer-aided design (CAD)

The generic AM process starts with 3D CAD design and information. There are many ways to create 3D models or CAD files by using Autodesk AutoCAD, Sketch, Fusion360, Solidworks, Siemens NX, etc. Products developed through AM are created beginning with a software model containing the exterior geometry. Another viable option is to reverse engineer an item or part using a laser or scanning device.

Step 2: Conversion to STereoLithography (STL)

This step requires converting files to STL (Hu, 2017), which is the current standard and can be produced by a majority of CAD systems. The process of converting to STL is automatic within most CAD systems, some are already described in step 1. The STL file is required because it contains the dimensions of the closed exterior surface and is necessary to calculate the layers.

Step 3: STL File Manipulation and Upload to AM Machines
The generated STL file is uploaded to the AM machine. Necessary manipulation of the file may be performed at this time to ensure details such as size, position, and angle.

Step 4: 3D Printer/Machine Setup
All AM machines will have at least some setup parameters that are specific to that machine or process (Yang et al., 2017). Configure the AM machine setting to ensure it accounts for restrictions, power source, layer width, precision degrees, timing, and other configurations.

Step 5: Build
The AM machine builds the object via an automated process similar to paper printers. Limited oversight needs are required to make sure the printer has adequate material and to address possible software malfunctions.

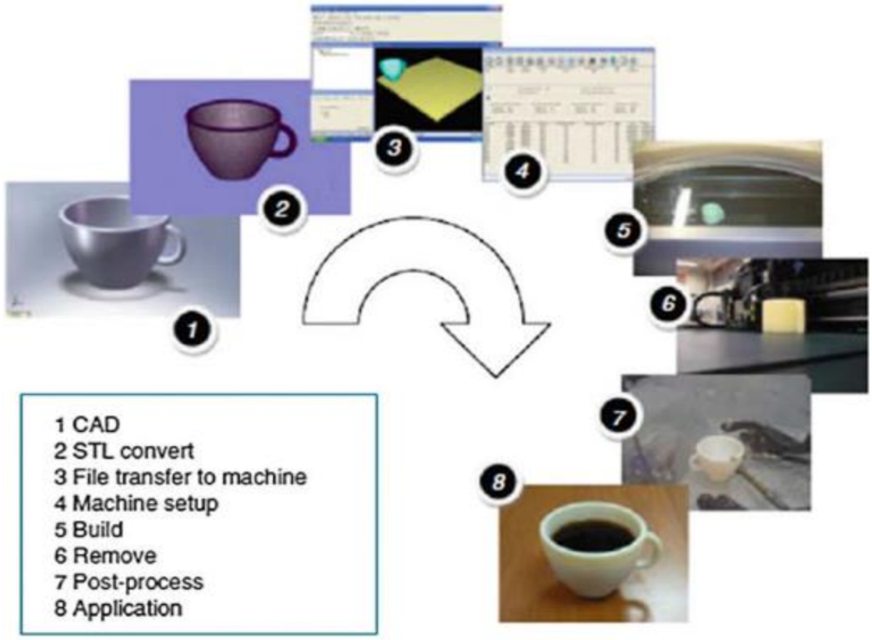
Step 6: Removal
The printed object must be removed upon completion of build. Aside from simply removing it, safety interlocks in place to prevent the printer from overheating or from moving parts.

Step 7: Post Processing
More often the parts still require a significant amount of manual finishing before they are ready for use. Depending on the removal of the printed object from the printer, it may need to be cleaned, subjected or unbraced to final manual touch-ups.

Step 8: Application
The 3D-printed object may now be functional. In some cases, it may require additional manipulation such as priming, painting, texturing or finishing necessary to realize the final intended end use state (Dizon et al., 2021). At this point, it can be used or assembled into the component of which it is a part for complete functionality.

Figure 2.1

The Generic AM Process

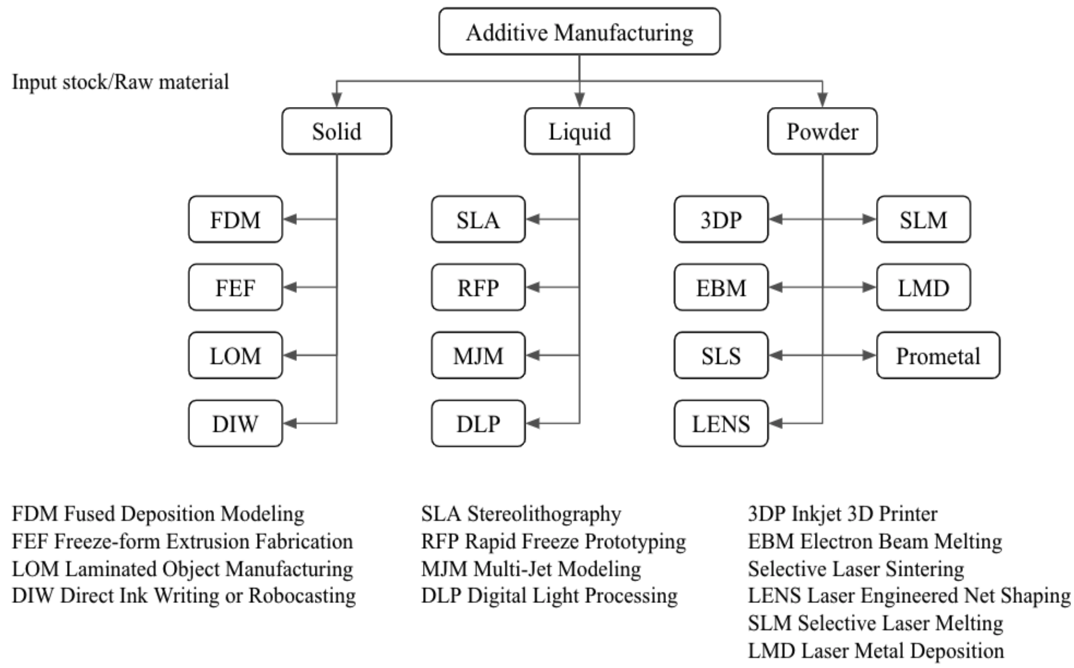


2.1.2 Additive Manufacturing Processes Overview

The techniques under the AM umbrella are diverse. There is not an ideal or standard category but a common approach is to classify the AM techniques according to the fabrication method used (depositing, sintering, curing, etc.) or according to the type state of raw material (solid, powder or liquid) as represented in Figure 2.2. In a Liquid based rapid prototyping (RP) system, liquid state is the initial form of the material. Through a curing process, the liquid is transformed into the solid state, for example, 3D Systems' Stereolithography Apparatus (SLA) (Su et al, 2018), Cubital's Solid Ground Curing (SGC). Solid-based RP systems are meant to encompass all forms of material in the solid state except for powder. In this condition, the solid form can include the shape in the form of a wire, a roll, laminates and pellets, for instance, Cubic Technologies' Laminated Object Manufacturing (LOM), Stratasys' Fused Deposition Modeling (FDM). In a strict sense, powder is somehow created to be in solid state. However, it is intentionally made as a category outside the solid-based RP systems, for example, 3D System's Selective Laser Sintering (SLS) (Schmid et al, 2015), Z Corporation's Three-Dimensional Printing (3DP) (Pérez et al., 2017). This work focuses on FDM technology, for this reason the other AM techniques are presented but not explained here.

Figure 2.2

Classification of AM Processes Depending on the State of Raw Material

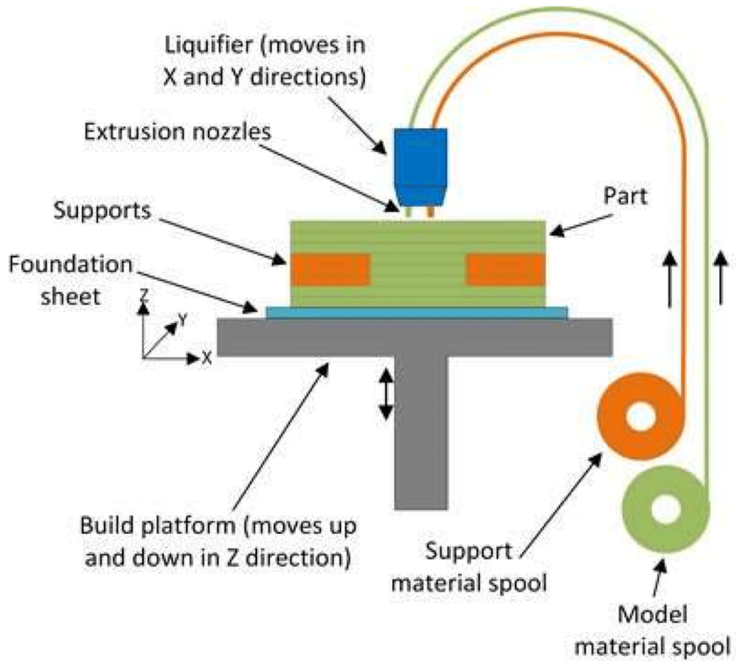


2.1.3 Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF)

Fused Deposition Modeling (FDM) is an AM technique suitable for RP of plastic parts, concept model's development, functional prototypes and end-use parts fabrication, with high mechanical and thermal strength. FDM is a trademark of Stratasys company (Koprnický et al., 2017) and, for this reason, the technique is sometimes called Fused Filament Fabrication (FFF). Stratasys has developed a range of proprietary industrial grade materials for its FDM process that are suitable for some production applications. At the entry-level end of the market, materials are more limited, but the range is growing. The most common materials for entry-level FFF 3D printers are ABS and PLA. For example, in Figure 2.3, the FDM/FFF processes require support structures for any applications with overhanging geometries. Support structures have generally been a limitation of the entry level FFF 3D printers (Singh, 2016). However, the FDM machines are now able to extrude a variety of strong plastics, waxes and other polymers with low melting point such as ABS (Acrylonitrile Butadiene Styrene) and PLA (Poly Lactic Acid), PC (Polycarbonate), Nylon, PPSF (Polyphenylsulfone), HDPE (High-density polyethylene), among others, available in different colors.

Figure 2.3

Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF)



A common FDM machine usually requires a fixed-size printer with a limited printing envelope. The size of the design is strictly constrained by the chamber volume of the 3D printer, which can print parts whose sizes are no larger than its volume. The reason behind this small size is the amount of time required to print parts with a large cross-sectional area, because the print head needs to travel longer distances to lay down the material, increasing the amount of time required to fabricate a layer. As a consequence, a larger machine that takes too much time to fabricate a part will be unfeasible to use and not commercially competitive. In fact, the deposition speed of a print head is limited to its maximum extrusion feed rate and motion velocity. Therefore, improving them could require a more powerful extruder (probably heavier) or have a larger nozzle (reduce the mechanical accuracy). Increasing the motion would require the improvement of the machine stability due to the large mass of the moving parts during acceleration and deceleration. A more stable structure will certainly be more expensive, increasing the machine's cost.

2.1.4 Large-Scale Additive Manufacturing (LSAM)

Large-scale additive manufacturing (LSAM) is a natural extension of 3D printing technology and several promising studies have been developed. The first one "Big Area

Additive Manufacturing (BAAM)", developed by the Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF), is a large-scale 3D printer for thermoplastics and composite materials (Chesser et al., 2019). The BAAM utilizes a pellet-based extruder versus a filament fed extrusion. This allows the printed material to include longer fiber reinforcement strands, and to output nearly 100 pounds of material every hour. LSAM has rapidly developed in the Building and Construction (B&C) industry (Delgado Camacho et al., 2018b). Several architectural fabricators such as Brach Technology and Apis Cor specialize in construction-scale 3D printing and various technologies like Contour Crafting and D-Shape have been developed for large-scale AM architectural projects. Table 2.1 summarizes the largest 3D printers currently available in the market and all prices are in USD (March 25, 2018). While these printers offer increased build volumes, they are quite expensive for smaller companies and education institute budgets (Shah et al., 2019).

Table 2. 1

Summary of Largest Available Material Extrusion 3D Printers

3D printer	Price (MSRP) ($)	Build volume (mm^3)	Build size (mm)
BAAM-Cincinnati labs	-	35.3	6096 × 3186 x 1829
BigRep ONE	50,000	1.02	1005 x 1005 x 1005
Fouche 3D Printing Cheetah Pro	10,400	1.00	1000 x 1000 x 1000
CoLiDo Mega	26,000	1.50	1000 x 1000 x 1500
Titan Robotics Atlas 2.0	26,200	1.02	915 x 915 x 1220
3D Platform 400 Series	36,999	1.05	1000 × 1500 x 700
HORIZ1000	40,000	1.00	1000 × 1000 × 1000
Erector EB 2076 LX	46,425	23.78	6096 × 2133 x 1829
German RepRap X1000	65,500	0.48	1000 x 800 x 600

3D printer	Price (MSRP) ($)	Build volume (mm^3)	Build size (mm)
Zilla3D Deltazilla	7,995	0.69	750 × 750 x 1220
THE BOX	< 250,000	2.48	1500 × 1100 × 1500
Moebyus Machines M3	18,516	1.00	1000 × 1000 × 1000
Extreme Builder 2000	23,456	0.89	700 x 700 x 1820
DeltaWASP 3MT	27,660	1.20	3000 × 3000 x 3000
Leapfrog XceL	27,783	0.59	510 × 500 x 2300
Tractus3D T3500	42,602	2.00	1000 × 1000 x 2000

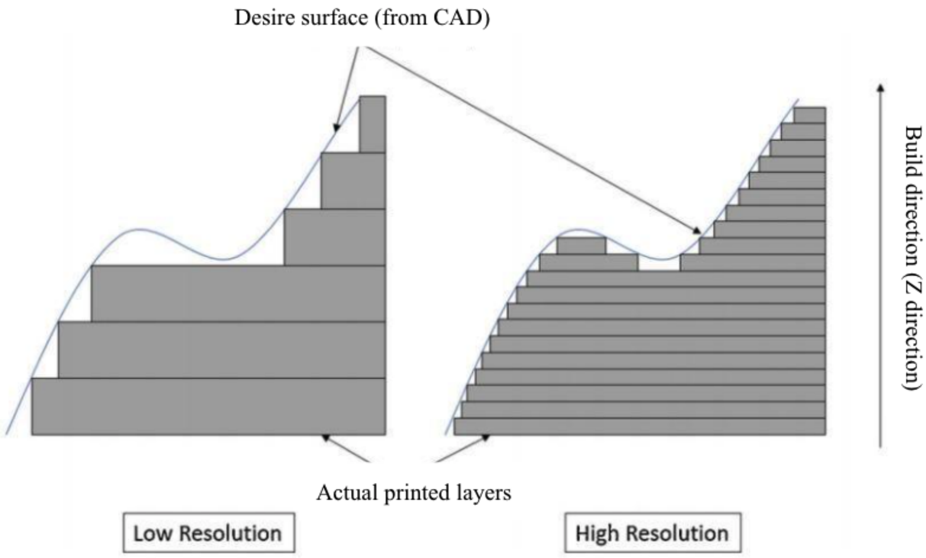
2.1.5 Challenges of Upsizing in Machine Volume and Accuracy

When a material extrusion 3D printer is scaled up, there are issues that arise with the mechanisms inherent to the process. Therefore, some design changes are necessary as the machine gets above 500 × 500 mm in horizontal build area. It is beyond this size that limitations in the methods of extrusion 3D printing become problematic. Most existing LSAM technologies are based on gantry or robotic arm systems, which can print objects whose sizes are limited by the structure of the equipment. Designing a device large enough to fabricate the needed models has been proven to work, but in most cases, scaling up the printer is costly and time-consuming.

The primary issue affecting geometric fidelity and surface finish on LSAM is layer height or layer resolution. AM is the process of laying down material layer by layer to create a final part. This layering process introduces a generally unavoidable deviation from the intended surface. Figure 2.4 demonstrates how this layered approach limits the ability to follow a desired surface, and how decreasing the layer height increases the resolution. Decreasing the layer height also improves the surface finish because it decreases the waviness, or stair-stepped nature of the surface (Chesser et al., 2019).

Figure 2.4

Effect of Layer Height on Resolution

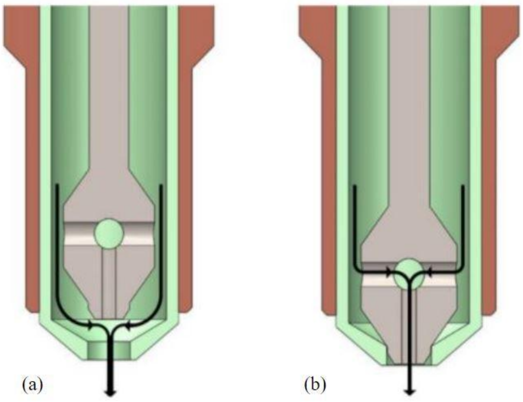


Decreasing the nozzle size improves the geometric fidelity by decreasing layer height, but it also reduces the deposition rate. Thus, when the layer height is decreased, the print time increases. This inverse relationship between build resolution and build rate is a fundamental tradeoff in many AM systems. This tradeoff also has important cost implications. At lower resolutions, higher throughput leads to shorter build times and lower costs, making a more cost-efficient process. Higher resolution with reduced throughput leads to longer build times, higher costs, and lower cost efficiency. Owing to the large build volumes of the parts that can be processed, the use of filaments involves increased printing time. This is the reason why LSAM generally incorporates a pellet-based feedstock system that melts the polymeric pellets and extrudes them "on the go," producing a fused filament with a diameter normally bigger than 2.5 mm. Using polymeric pellets as feedstock material can improve production times by up to 200 times and reduce costs by a factor of 10, since a prior additional filament-extruding step is not required during the pellet-based AM process. In addition, polymer filaments are limited in the variety of materials, whereas all industrial polymers can be found as pellets, thus encouraging the use of pellets (Moreno Nieto and Molina, 2019).

To achieve multi-resolution printing, multiple extruders with different nozzles could be used. However, this increases the complexity of the system. The offset between the extruders also must be accurately known, and the gantry must have the capability to move around the mass of multiple extruders. Furthermore, the addition of multiple extruders reduces the workspace of a given machine. These problems can be resolved by having one extruder with a nozzle that can change orifice diameter. ORNL developed a nozzle that can print with two orifice diameters by adding a poppet near the tip of the deposition nozzle. This poppet is coaxial to the nozzle. Figure 2.5 shows the poppet (gray) inside of the nozzle (green) in the up position (a) and in the down position (b). In the up position, melted polymer flows around the poppet and out of the larger orifice in the nozzle's tip. When the poppet is in the down position, it blocks flow in the tip. Melted polymer is then forced through cross drilled holes in the poppet and out a smaller diameter hole in the center of the poppet, which forms the orifice for fine resolution deposition. This design allows for nozzle diameters to be selected mid-print from one extruder.

Figure 2.5

Dual Port Poppet Orifice Showing Material Flow Paths

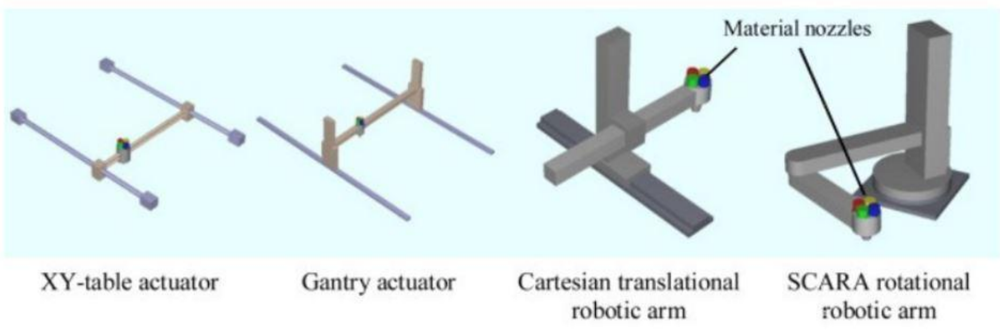


A nozzle that can change orifice size in the manner described above has been termed a dual-port nozzle. This system has been successfully implemented on the BAAM, and parts have successfully been printed using this methodology. Two of the most remarkable product developments accomplished with LSAM polymer-based techniques have been produced by using the BAAM equipment. In 2014, the "Strati" 3D-printed electric car as shown in Figure 1.5 (a) was presented, consisting in the design and development of a 3D printed electric car made out of carbon-fiber-reinforced ABS, with a reduction of the number of parts. This research also focused on quantifying the mechanical strength of the materials and the integration of fasteners into the structures. Another interesting development was accomplished in July 2017 by ORNL together with the US Navy research departments. The development of a 9-m submarine hull prototype was printed in six parts using carbon fiber reinforced ABS presented in Figure 1.5 (b), decreasing the costs of this development by 90 per cent and dramatically reduced the production times. This submarine was not functional, but they are committed to developing a functional and water-tight prototype by 2019 (Moreno Nieto and Molina, 2019). The other successful products in both industry and construction are already presented in introduction.

Moreover, according to (Choi and Cheung, 2005) a virtual prototyping system in which the actuators are reconfigurable was developed, as a way to mitigate the problems on fabrication materials, deposition speed and build volume. Based on the most common types of actuators, the end-effectors, geometrical dimensions and layout configurations can be designed, visualized and validated presented in Figure 2.6. However, the size of a design is constrained by the chamber volume of the 3D printer, and large-scale additive manufacturing technology with flexible equipment is still unproven. Few developments and researches in collaborative additive manufacturing are discussed in session 2.2.

Figure 2.6

Four Common Actuators Configurations



2.2 Collaboration in Additive Manufacturing (Co-AM)

Collaboration is a vital feature of today's manufacturing industry and AM, which can be declared the future of manufacturing, shows immense potential to combine these two key technologies. There are two methods in AM to fabricate large-scale products.

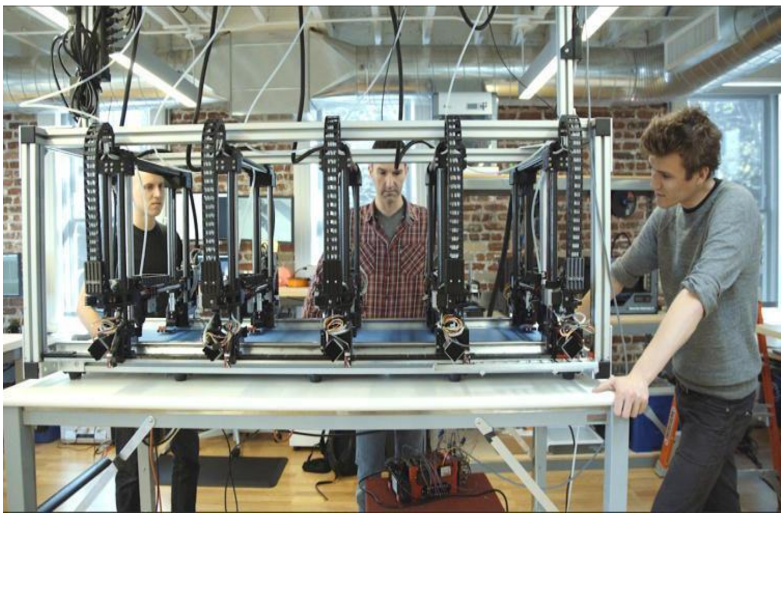
The first method is creating components in pieces and assembling them last. It is suitable for prototyping, but it is difficult to meet some requirements such as part quality, strength, etc. and it is necessary to assemble at the end. Apart from this first approach, the second method is building everything in one place with multiple AM units. It might benefit in elimination of the assembly process, minimize the working space, be capable of managing multiple tasks simultaneously and reduce fabrication cycle time, etc.

2.2.1 Current State of Collaboration in Additive Manufacturing

The developments of collaboration in AM are not suitable for collaborative fabrication, where a lack of studies still remains. A solution to this problem has to solve both mechanical and software challenges. A very few studies approached this topic. A machine was implemented as a conceptual FDM machine. It belongs to a project called "Multiple Deposition Heads System" by Project Escher, see Figure 2.7, supported by the Autodesk company. Using multiple print heads printing approach can lead to collision between print heads. So, they need to create the boundary of each print head and manage the tool-path in the slicing process to avoid collision between them. However, the project claims that it did not develop nor release the machine, but only developed the parallel processing system instead (Frutuoso, 2017).

Figure 2.7

Multiple Deposition Heads System (by The Project Escher,2017)



The previous research shows that some researchers have accidentally touched collaboration in AM in order to achieve certain applications, because there are few attempts to use both additive and subtractive manufacturing technologies together to achieve a finished product. Nevertheless, these systems are operated in a manual fashion which seek the attention of researchers to make these systems automate and allow units to work collaboratively without human intervention. As Figure 2.8 shows, Thermwood is a printing system focused on both additive and subtractive technologies to fabricate large scale products (Patent, 2018).

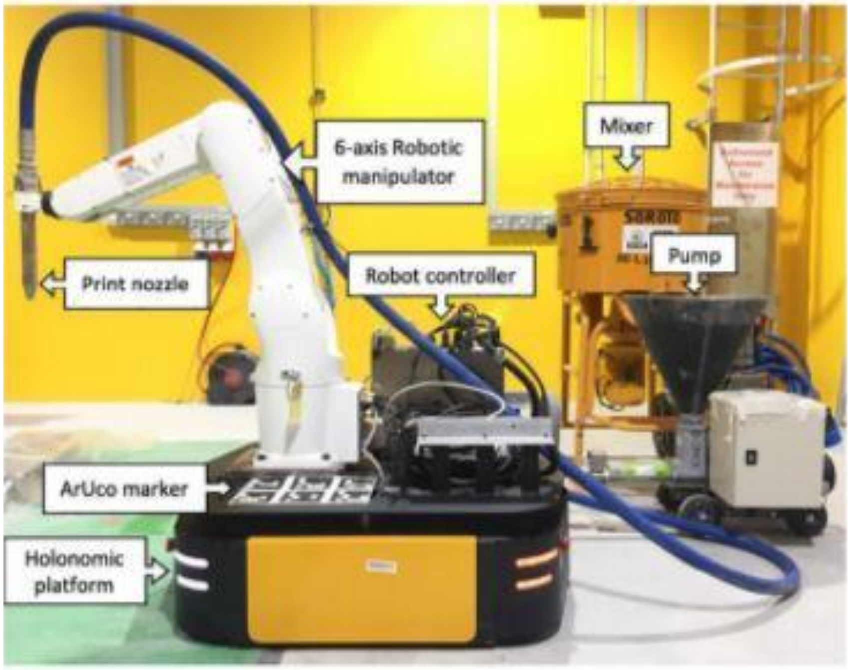
Figure 2.8

Combination of Additive and Subtractive Tooling by Thermwood

Moreover, “Large-scale 3D Printing by a Team of Mobile Robots” (Zhang et al., 2018) has demonstrated a multi-robot printing system that is capable of on-site printing large structures in a safe, efficient and scalable manner. The system configuration contains several modules: planning of robot placement to optimize workspace, mobile robot navigation and localization to reach target printing location, and planning of manipulator trajectory to deposit material accurately on desired path. While a mobile robotic arm system helps extend the printing range, a single print nozzle still hoards the entire print space, limiting the efficiency of the printer. Each mobile robot printer in our setup consists of a holonomic mobile platform, a 6-axis robotic arm, a stereo camera and a pump as shown in Figure 2.9.

Figure 2.9

System Setup for One Robot Printer



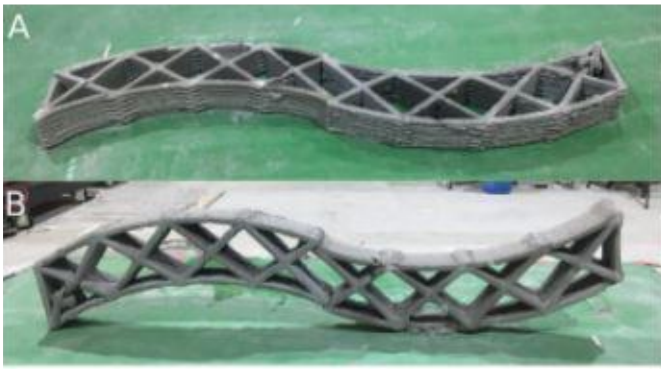
The robotic arm is mounted on the holonomic mobile platform and is equipped with a print nozzle. In the simulation as shown in Figure 2.10, two robot printers were required to build a large-scale structure whose size is beyond the printing volume of one single robot printer. Regarding the junctions in Figure 2.17, there were some drawback issues in printing parts positioning and orientation between two mobile robots but noted that the bonding strength was high enough to easily support the specimen's own weight when it was placed on its side.

Figure 2.10

Simulation of Multi-Robot Printing Process

Figure 2.11

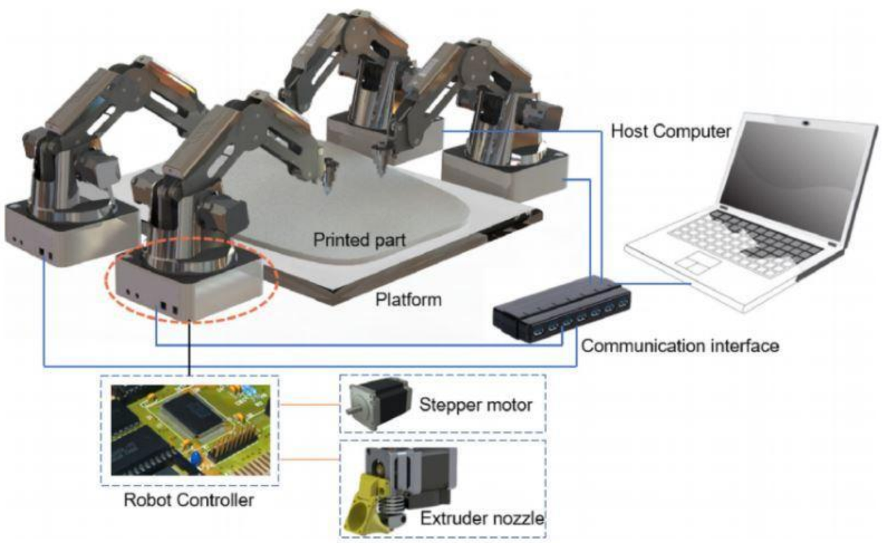
Printed Specimen after 10 Days of Curing



Moreover, "Research on Large-scale Additive Manufacturing Based on Multi-robot Collaboration Technology" (Shen, Pan and Qian, 2019) is a development of a multi-robot collaboration system used for large-scale AM. In this research, a multi-robot collaborative system with an upper computer is designed as shown in Figure 2.12, to improve the efficiency of the collaborative printing system, an optimized segmentation algorithm is adopted to assign printing tasks to each printer according to the time consistency and a solution that divides regions as interference areas and safe areas for each robot and then executes the print jobs sequentially to avoid collision between them, however this research cannot fulfill the complex parts.

Figure 2.12

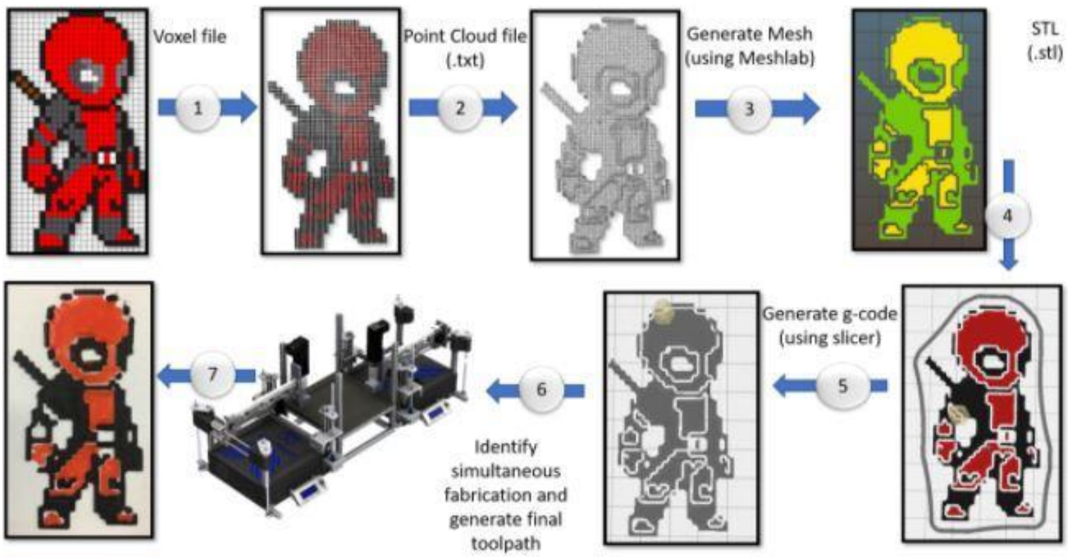
A Schematic of the Multi-Robot 3D Printing System



Furthermore, to achieve the concept of collaborative additive manufacturing, (Senal, 2019) develops a collaborative system, see Figure 2.13 which consists of identification of layer attributes, tool-path generation and communication among computer and additive manufacturing units. However, there is still a gap for additional development to enhance the functionality of developed concept, software and prototype to fabricate a final product.

Figure 2.13

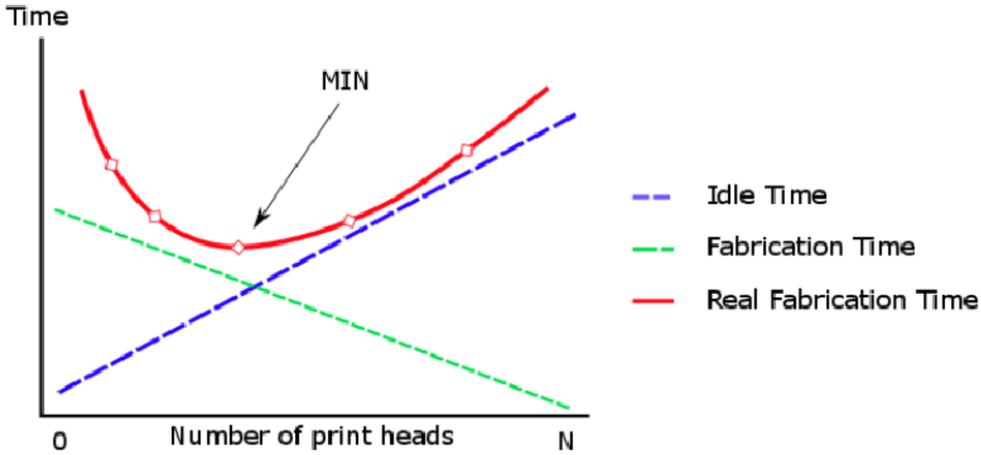
Process Flow of Collaborative Additive Manufacturing for Multi-Material Deposition



According to research “Multiple Collaborative Printing Heads in FDM: The Issues in Process Planning” (Leite et al., 2020), the result of the graphic in fabrication time regarding the number of print heads assigned is expected to have a shape like the one presented in Figure 2.14. One factor is that the more heads are used, more collision possibilities exist, which means, if two heads share a printing area, the process planning will have to idle one head to allow the other to deposit material which, at the limit, might increase printing time.

Figure 2.14

Relationship between Number of Print Heads, Idle Time, Theoretical Fabrication Time and Real Fabrication Time



CHAPTER 3
CONCEPT GENERATION

3.1 Idea Generation

Collaboration has become a key factor in additive manufacturing in solving the universal problem of fabrication time, limited printable sizes, etc. The use of collaboration in additive manufacturing creates challenges in both design and software features such as collision avoidance, tool-path generation while depositing the material. Some researchers conducted this area with the use of multiple deposition heads by creating the chunks or boundaries which means that they need to identify the multiple chunks or boundaries and schedule the printing job in every fabrication process in order to avoid the collisions between them. Therefore, the main idea of this study becomes to eliminate the chunks and boundaries while multiple AM units are printing simultaneously in the common platform and the details of the process will be described in next session 3.2. Figure 3.1 and Figure 3.2 illustrate the design of the modular AM units that enable to achieve the main concept with the use of many types of configurations. Although this design can be used for multiple AM units, only two AM units will be used in the implementation process because of the limited time and budget.

Figure 3.1

Modular Design of Multiple AM Units

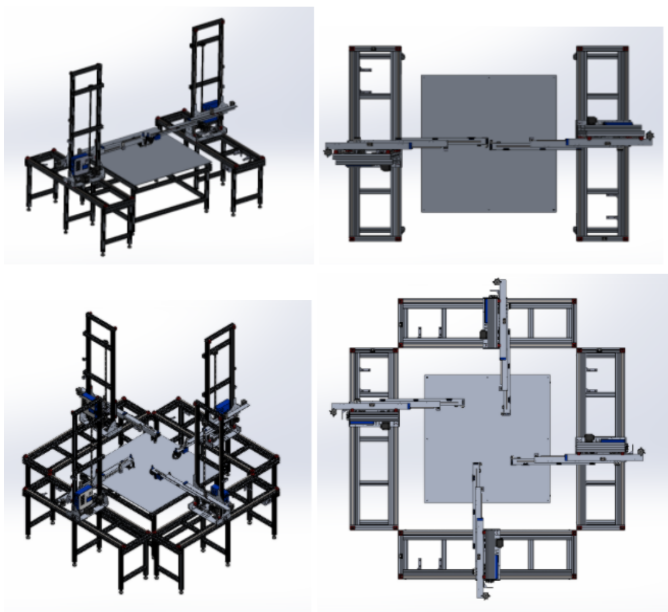
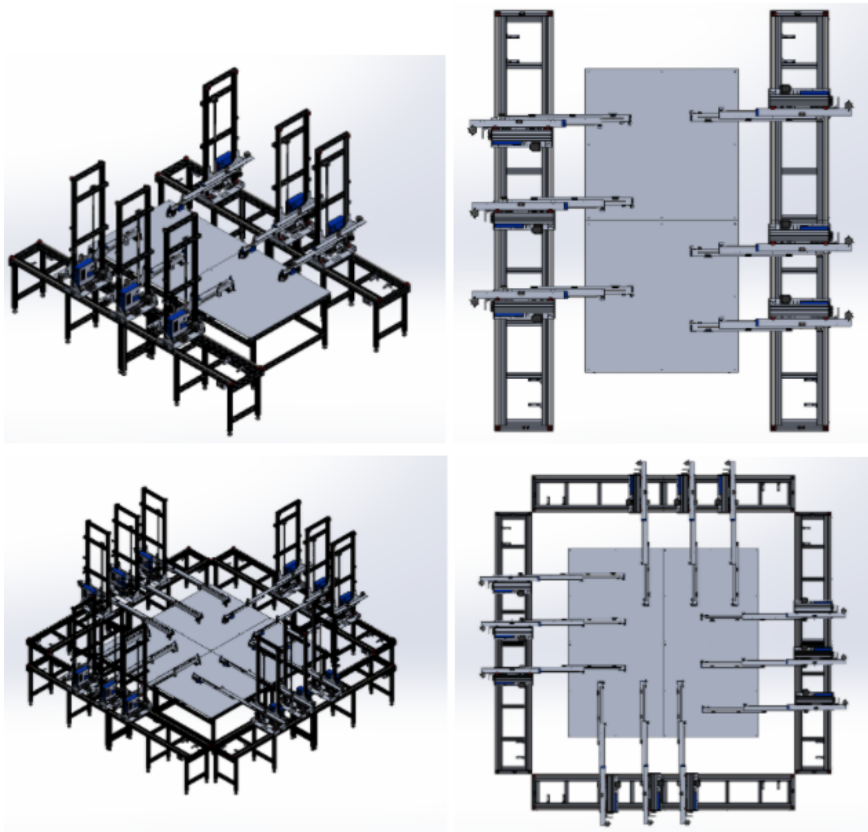


Figure 3.2

Modular Design of Multiple AM Units (continue)

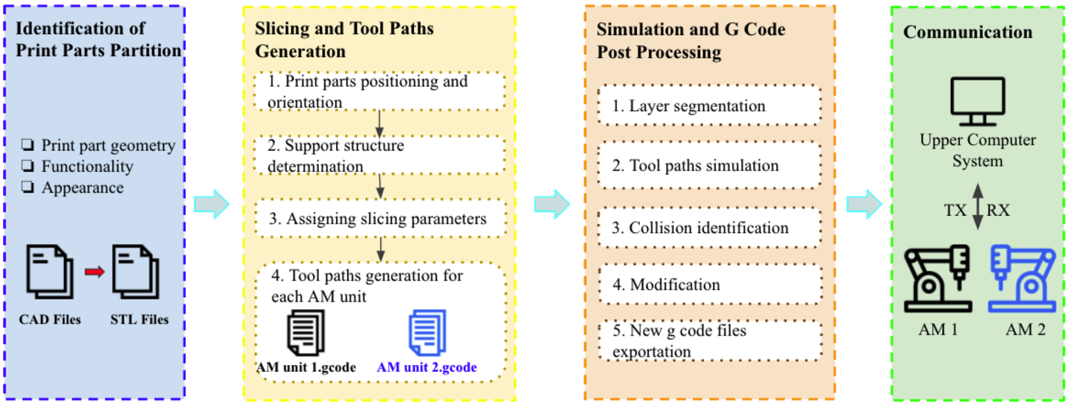


3.2 Collaborative Large-Scale Additive Manufacturing (Co-LSAM)

Collaborative large-scale additive manufacturing (Co-LSAM) can be defined as large-scale multiple AM units working together in a common platform. The main idea of this study is to implement a total control of the fabrication process in real time and ensure no failures during the fabrication process. The normal FDM process includes five steps: creating the part model from CAD software to STL format file, determining the print part orientation, adding support structures, slicing into layers and generating the tool path. Once planning to fabricate multiple parts at the same time in one location, some considerations come into play in the Co-LSAM system. In order to accomplish this goal taking into account the challenges, there are four main steps and an overview of the process planning is presented in Figure 3.3 and all these steps are explained in detail next.

Figure 3.3

Process Planning Overview

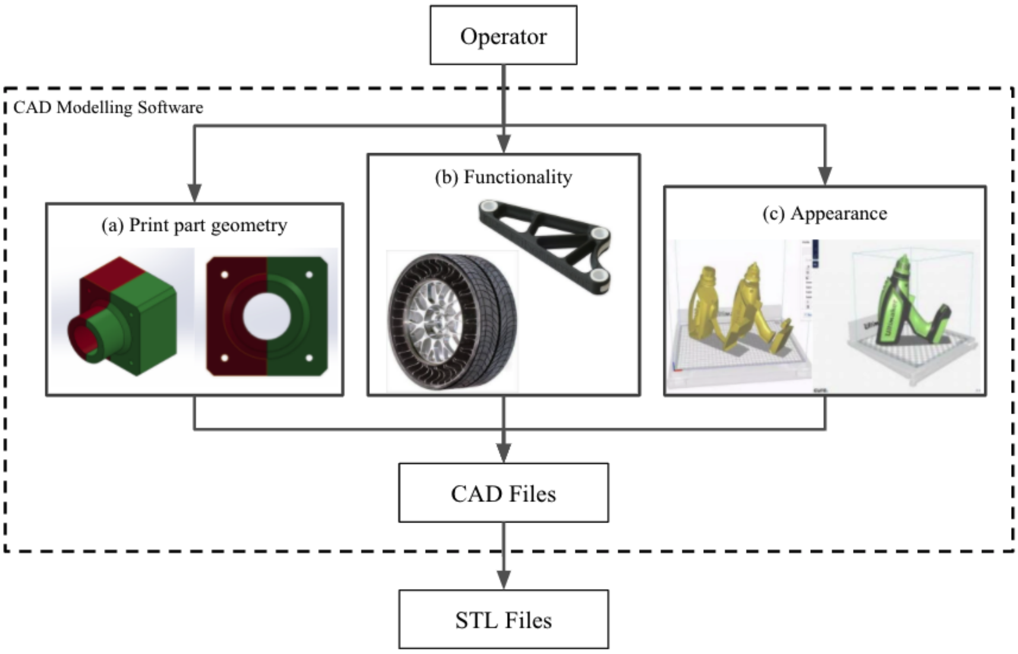


3.2.1 Identification of Print Parts Partition

The generic AM process starts with 3D CAD design and information. There are many ways to create 3D models or CAD files by using Autodesk, AutoCAD, Sketch Up, Fusion360, Solidworks, Siemens NX, etc. Products developed through AM are created beginning with a software model containing the exterior geometry. Another viable option is to reverse engineer an item or part using a laser or scanning device as described in session 2.1.1. When dealing with CO-LSAM, the operator needs to carry out the print part partition by separating the CAD model into required multiple CAD files according to three stages: print part geometry, functionality and appearance as shown in Figure 3.4. The partition of the print part according to geometry is for most symmetrical parts, according to the functionality is for some specific components in which some segments or portions of the print part need different material properties for example flexible material, strong and durable material, etc. and according to appearance is for multiple color print parts.

Figure 3.4

Print Parts Partition According to Operator



The next step requires converting CAD files to STL format files, which is the current standard and can be produced by the majority of the CAD systems. The process of converting CAD models to STL files is automatic within most CAD systems. The STL files are required because they contain the dimensions of the closed exterior surfaces.

3.2.2 Slicing and Tool Paths Generation

For slicing and tool paths generation, Ultimaker Cura Slicing Software is used to determine the required print parts by inputting multiple STL files. Before the slicing process, the specifications of the corresponding AM units i.e. the dimension of X, Y and Z axes, the dimension and speed of the extruder heads, the preprocess commends of before and after printing processes (G-code scripts) are needed to be installed in the slicing software. In this stage, there are four steps for slicing and tool paths generation as shown in Figure 3.5. The part positioning and orientation between multiple STL models in the working space is important in order to get optimal quality of the products as shown in Figure 3.6.

Figure 3.5

Slicing and Tool Paths Generation by Using Ultimaker Cura Slicing Software

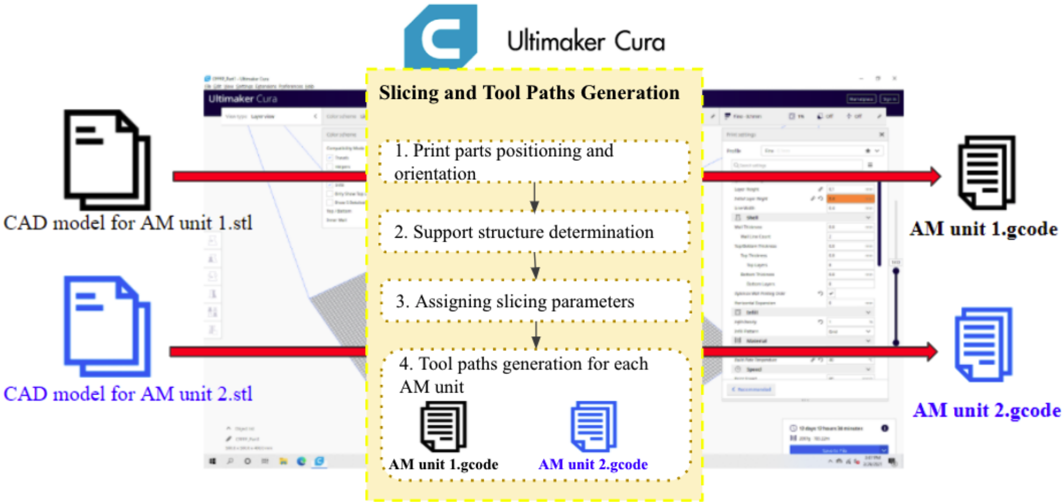
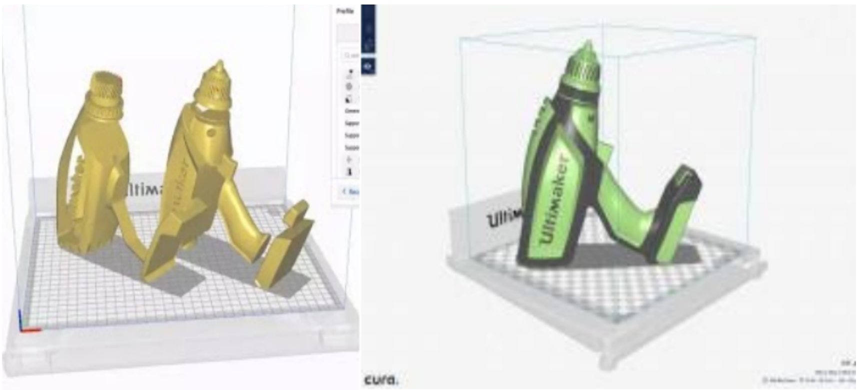


Figure 3.6

Part Positioning and Orientation between Multiple STL Models



A bad positioning and orientation can lead to failure in fabrication and thus can result in poor quality products. The part positioning and orientation is intended to center the part among the fabrication areas of each AM unit. Figure 3.7 and Figure 3.8 illustrate the position error and correct position of multiple print parts. The parts need to be adjusted carefully to get into the center of the layout in Ultimaker Cura software.

Figure 3.7

Position Error of Two Print Parts

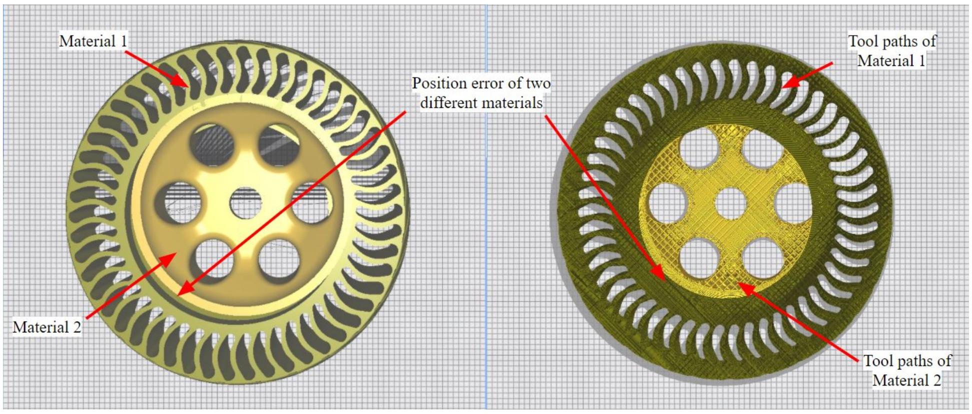
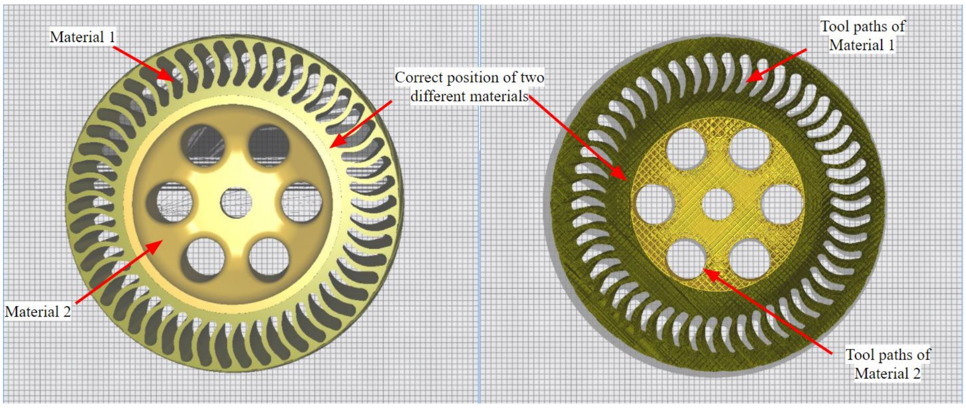


Figure 3.8

Correct Position of Two Print Parts



Moreover, support structures determination for the print parts is also important in the FDM process in order to get a final print part. Tool-paths generation is performed after assigning some parameters such as layer height, line width, print speed, infill density and pattern. Figure 3.9 is a software layer of Ultimaker Cura. It can generate the tool paths for each STL model which means that each STL file is sliced and generates the tool paths as G-code files for each AM unit. The G-code file contains commands in G-code format which is a language used to describe how a machine should do its job. It stores instructions in plain text and the instructions are provided to a machine controller that tells the motors where to move, how fast to move, which path to follow, and at what temperature it should be set. Figure 3.10 is an example of a G-code commands file for the AM unit.

Figure 3.9

Software Layout of Ultimaker Cura Slicing Software

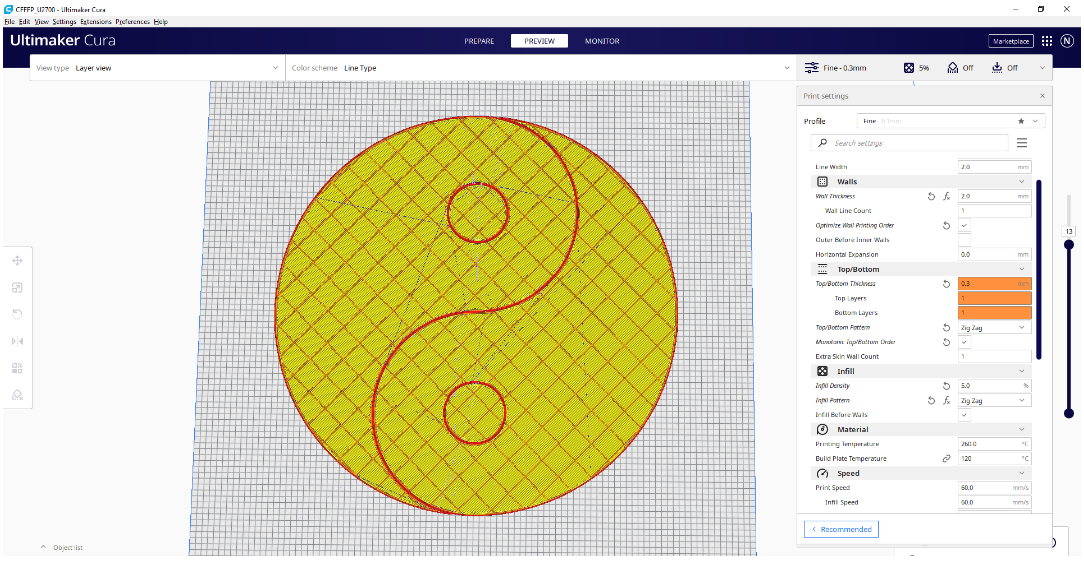
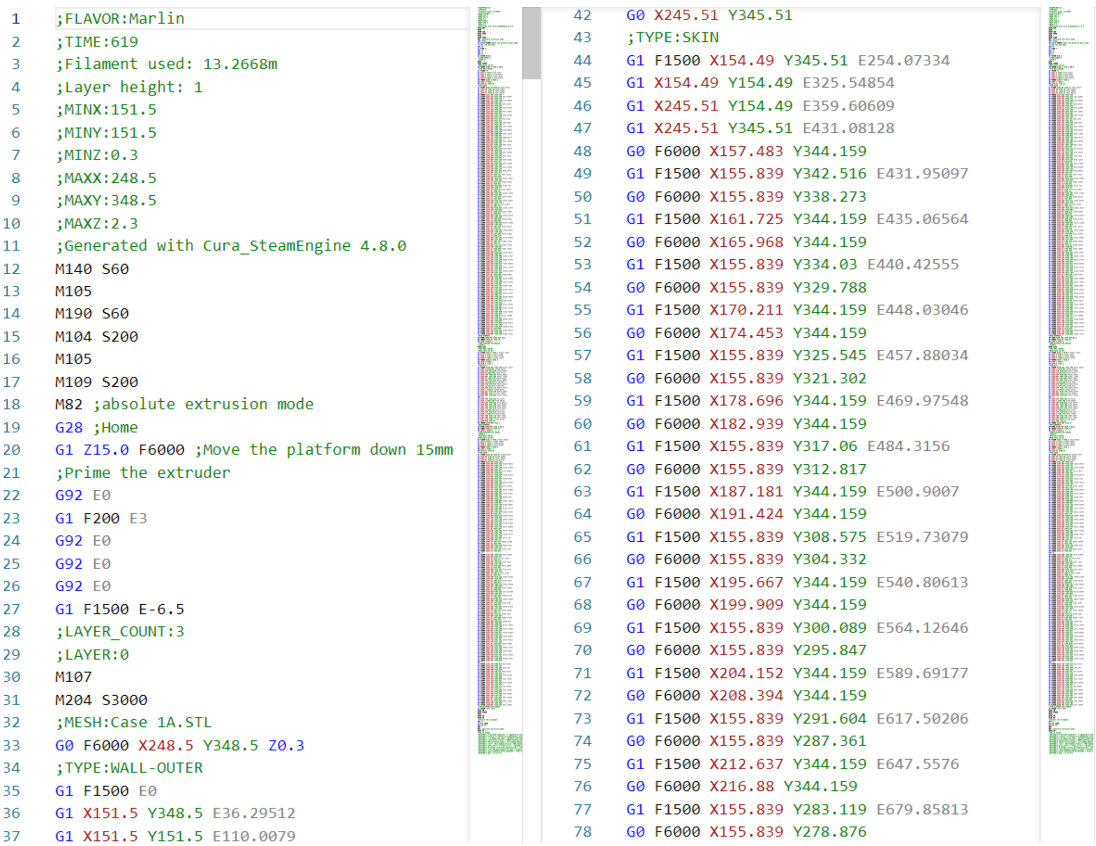


Figure 3.10

Example of G-code Commands File



```
;FLAVOR:Marlin
;TIME:619
;Filament used: 13.2668m
;Layer height: 1
;MINX:151.5
;MINY:151.5
;MINZ:0.3
;MAXX:248.5
;MAXY:348.5
;MAXZ:2.3
;Generated with Cura_SteamEngine 4.8.0
M140 S60
M105
M190 S60
M104 S200
M105
M109 S200
M82 ;absolute extrusion mode
G28 ;Home
G1 Z15.0 F6000 ;Move the platform down 15mm
;Prime the extruder
G92 E0
G1 F200 E3
G92 E0
G92 E0
G92 E0
G1 F1500 E-6.5
;LAYER_COUNT:3
;LAYER:0
M107
M204 S3000
;MESH:Case 1A.STL
G0 F6000 X248.5 Y348.5 Z0.3
;TYPE:WALL-OUTER
G1 F1500 E0
G1 X151.5 Y348.5 E36.29512
G1 X151.5 Y151.5 E110.0079
```

```
G0 X245.51 Y345.51
;TYPE:SKIN
G1 F1500 X154.49 Y345.51 E254.07334
G1 X154.49 Y154.49 E325.54854
G1 X245.51 Y154.49 E359.60609
G1 X245.51 Y345.51 E431.08128
G0 F6000 X157.483 Y344.159
G1 F1500 X155.839 Y342.516 E431.95097
G0 F6000 X155.839 Y338.273
G1 F1500 X161.725 Y344.159 E435.06564
G0 F6000 X165.968 Y344.159
G1 F1500 X155.839 Y334.03 E440.42555
G0 F6000 X155.839 Y329.788
G1 F1500 X170.211 Y344.159 E448.03046
G0 F6000 X174.453 Y344.159
G1 F1500 X155.839 Y325.545 E457.88034
G0 F6000 X155.839 Y321.302
G1 F1500 X178.696 Y344.159 E469.97548
G0 F6000 X182.939 Y344.159
G1 F1500 X155.839 Y317.06 E484.3156
G0 F6000 X155.839 Y312.817
G1 F1500 X187.181 Y344.159 E500.9007
G0 F6000 X191.424 Y344.159
G1 F1500 X155.839 Y308.575 E519.73079
G0 F6000 X155.839 Y304.332
G1 F1500 X195.667 Y344.159 E540.80613
G0 F6000 X199.909 Y344.159
G1 F1500 X155.839 Y300.089 E564.12646
G0 F6000 X155.839 Y295.847
G1 F1500 X204.152 Y344.159 E589.69177
G0 F6000 X208.394 Y344.159
G1 F1500 X155.839 Y291.604 E617.50206
G0 F6000 X155.839 Y287.361
G1 F1500 X212.637 Y344.159 E647.5576
G0 F6000 X216.88 Y344.159
G1 F1500 X155.839 Y283.119 E679.85813
G0 F6000 X155.839 Y278.876
```

3.2.3 Simulation and G-code Post Processing

This third step is a core value in the Co-LSAM system. Since multiple AM units are working together in a common build area and they work in accordance with the G-code commands generated by the Ultimaker Cura software as shown in Figure 3.10, the print heads can overlap the adjacent print heads. So, collisions may occur if a pair of print heads get in close vicinity. Moreover, in order to fabricate efficiently, simultaneous fabrication becomes a key factor in Co-LSAM. In order to execute simultaneously, collaborative tool paths simulation and post processing is needed. The system has five main steps: layer segmentation, tool paths simulation, collision identification, modification and new G-code files exportation.

3.2.3.1 **Layer Segmentation.** In layer segmentation, to assign G-code commands from each layer to arrays, each layer has to be separated and assigned to arrays as feed rate F, x and y coordinates for each AM unit as shown in Figure 3.11 because each G-code file has multiple layers depending on the slicing parameters of the software. The tool paths simulation is performed layer by layer and it will be presented in detail in the next session.

Figure 3.11

Assignment of G-code Commands from each Layer to Arrays

G code File for AM unit 1

	F	X	Y
Layer 0	3600	484.958	375.253
	1800	480	375.497
	1800	475.042	375.253
	1800	470.152	374.528
	1800	465.342	373.323
	1800	460.675	371.654
	1800	456.192	369.533
	1800	451.952	366.991
	1800	447.962	364.033
	...	...	...
Layer 1	1800	489.073	370.609
	1800	484.573	371.276
	3600	462.08	365.913
	1800	439.085	342.918
	1800	438.378	342.211
	3600	436.362	334.539
	1800	470.459	368.635
	3600	477.031	369.551
	1800	435.446	327.966
	...	...	...

G code File for AM unit 2

	F	X	Y
Layer 0	3600	484.958	725.253
	1800	480	725.497
	1800	475.042	725.253
	1800	470.152	724.528
	1800	465.342	723.323
	1800	460.675	721.654
	1800	456.192	719.533
	1800	451.952	716.991
	1800	447.962	714.033
	...	...	...
Layer 1	1800	489.073	720.609
	1800	484.573	721.276
	3600	460.701	715.26
	1800	439.738	694.296
	1800	439.031	693.589
	3600	436.605	685.506
	1800	469.491	718.392
	3600	476.268	719.512
	1800	435.485	678.73
	...	...	...

3.2.3.2 **Tool-path Simulation.** In each layer of each AM unit, the tool paths simulation is performed as the pre-processing according to G-code data of each unit. The distance s_i between two points is calculated by using eq. (1). For the speed of the AM unit v_i, feed rate F_i is divided by machine velocity factor v_f as shown in eq. (2). The time taken t_i to move the print head from point to point is calculated by using eq. (3) and the total time taken T is calculated by using eq. (4). By doing so, two types of graphs: X coordinate graph and Y coordinate graph according to the time taken for each unit will be obtained as shown in Figure 3.12 and Figure 3.13.

$$s_i = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^{\,2}} \qquad \text{eq. (1)}$$

$$v_i = \frac{F_i}{v_f} \qquad \text{eq. (2)}$$

$$t_i = \frac{s_i}{v_i} \qquad \text{eq. (3)}$$

$$T = \sum_1^n t_i \qquad \text{eq. (4)}$$

Figure 3.12

X Coordinate Graph according to Time Taken for Each Unit

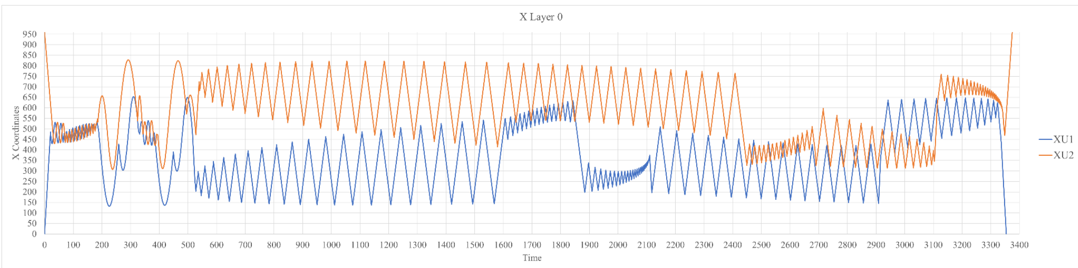
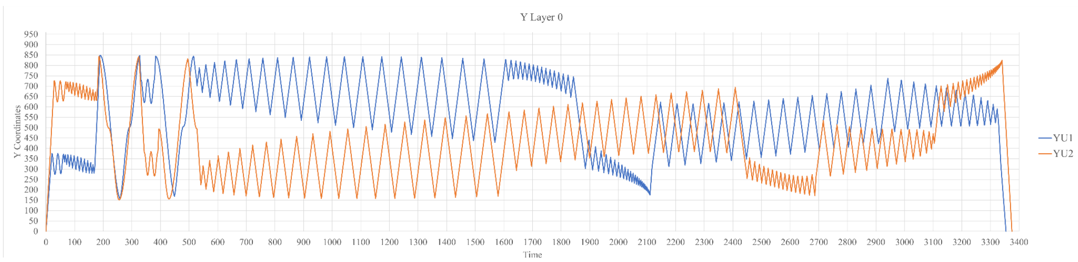


Figure 3.13

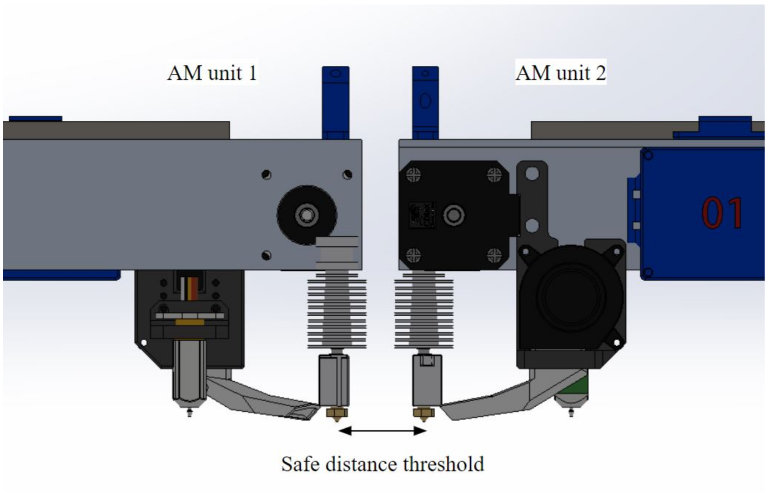
Y Coordinate Graph according to Time Taken for Each Unit



***3.2.3.3* Collision identification.** Collisions occur when two or more print heads come into contact with each other. In other words, to avoid the collisions, print heads should be sufficiently far from each other during the whole fabrication process. One simplification conducted in this work is identifying the shortest distance threshold which is the shortest distance between each print head as seen in Figure 3.14. The minimum safe distance threshold can be described as that in X axis and Y axis. Both of them can vary depending on the design of AM units but the minimum safe distance threshold will be assigned as 100 millimeters in this system.

Figure 3.14

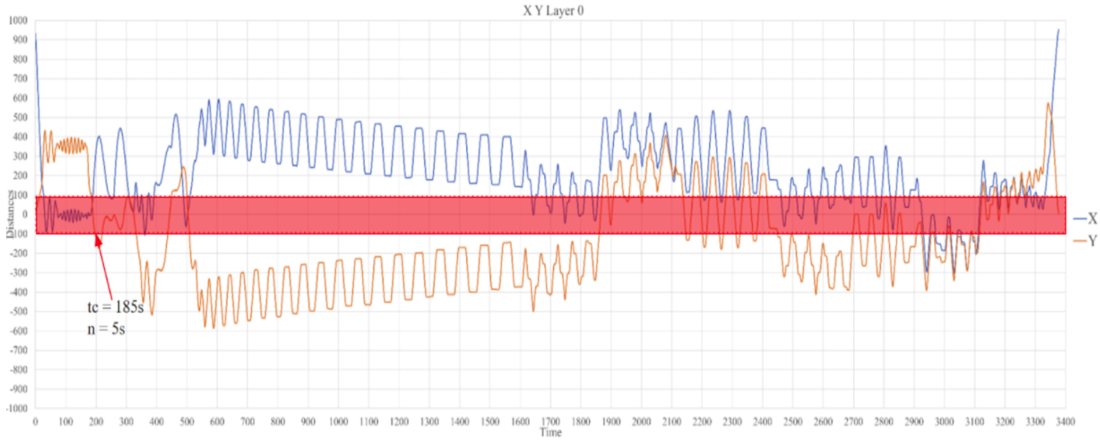
Safe Distance Threshold



Two types of collisions can occur in collaborative fabrication processes. One is a collision in the X axis and another one is in the Y axis. There will not be a collision in the Z axis because the two AM units move the print heads only in X and Y axes. In order to find the collision, firstly, X and Y coordinates of the corresponding unit need to be changed from according to time taken to according to uniform seconds for each unit because the coordinates of both units can only be compared when the values of the coordinates are in accordance with the uniform second. By doing this, the distances between two printing heads will be obtained in the X and Y directions as shown in Figure 3.15.

Figure 3.15

Distances between Two Printing Heads in X and Y Directions



After this, the collision can be identified from the graph. The distances between the two printing heads can also be negative when they pass through each other. Collision will occur when the both values in X and Y of the two printing heads' distances are in the range of safe distance threshold. For example, when the safe distance threshold is 100 millimeters, the red box from Figure 3.15 shows the collision status in the printing process of layer 0 and the first collision time t_c is 185s and the collision time period n is 5s.

3.2.3.4 **Modification.** With the ability to identify the collision between AM units, now the system needs to modify the G-code in order to avoid collision. Firstly, there are three types of collisions in collaborative printing processes and the modification process is different according to the types of collision.

The first type collision occurs when the two print heads collide for the first time. For the first type of collision, the one which has shorter printing time according to the distances graph will be modified by adding a time delay $(n + 1)$s without changing X and Y coordinates at the time before the collision happens $(t_c - n_c)$s where n_c is a period of time to avoid collision correctly.

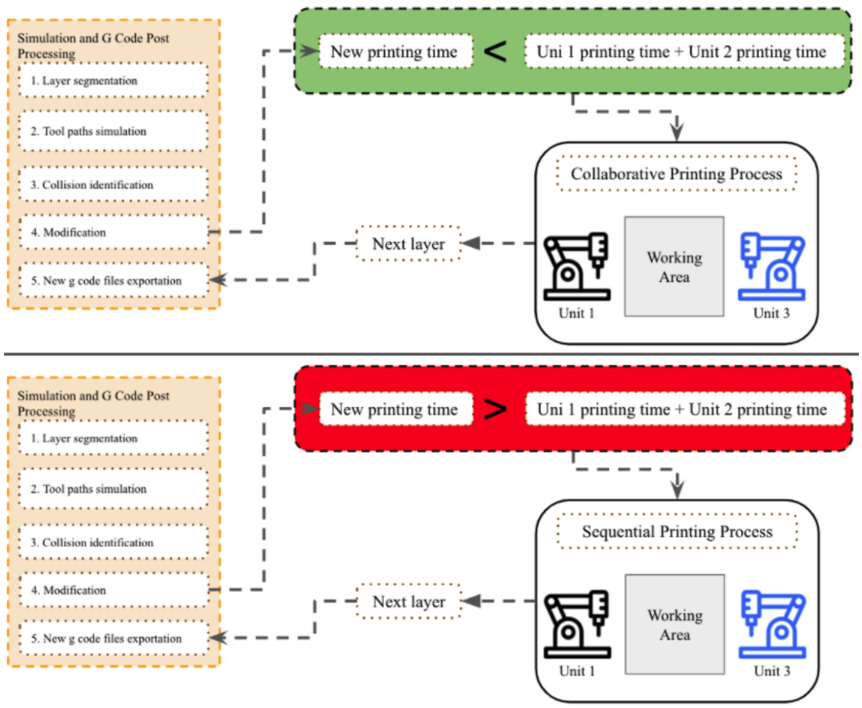
The second type of collision occurs when the new collision time period and the previous collision time period overlap. This is because the print head of the current working unit does not have enough distance to print simultaneously. Therefore, the previous modified unit needs to be modified by replacing with two new G-code commands. The first command is to go to the minimum (for AM unit 1) or maximum (for AM unit 2) position of the X axis. The second command is to return to the previous coordinates.

The third type of collision occurs when the current working unit's print head runs into the modified unit's print head which is retracting. Therefore, the current working unit needs to be modified by adding a time delay $(n + 1)$s at the time before the collision happens $(t_c - n_c)$s. The details of the modification process are shown in Figure 3.19.

***3.2.3.5* New G-code File Exportation.** Once the modification process is finished, the new printing time obtained from the modification process is needed to be compared with the sum of individual printing time in order to know whether this modification process is effective or not. If the new printing time is longer than the sum of individual printing time, the collaborative printing process will change to a sequential printing process as shown in Figure 3.16. After finishing this process, the new data bases of G-code for each layer are created as new G-code format files of corresponding AM units. Flow diagram of tool paths simulation and G-code post processing is presented in Figure 3.19.

Figure 3.16

Decision Making on Printing Processes



3.2.4 Communication

The last step of the Co-LSAM process is communication which covers the communication between upper computer and AM units. In this study, two raspberry pi are connected to each AM unit and controlled by OctoPrint server as presented in Figure 3.17 which is a snappy web interface for 3D printers that allows controlling and monitoring and it will be described in detail in session 4.3.4. Communication between raspberry pi and AM units are based on serial communication and AM units having a limited buffer size. Raspberry pi holds the G-code commands until it receives an 'ok' feedback from the AM units for the previous G-code commands as shown in Figure 3.18. The AM units send 'ok' only when the G-code command is buffered into the receiving buffer. If the buffer is full, the AM units will hold the 'ok' feedback until the G-code command is buffered into the buffer. This method will ensure no data loss while sending commands. Before it starts the printing process, an upper computer system will send commands to corresponding AM units to get ready for printing. For example, setting the nozzle temperature, print bed temperature and reference positioning. Figure 3.19 shows the flow of the printing process in communication of AM units.

Figure 3.19 is the complete flow chart of the Co-LSAM which consists of the identification of print parts, slicing and tool path generation, tool paths simulation and G-code post processing and communication of AM units.

Figure 3.17

OctoPrint Server Connection

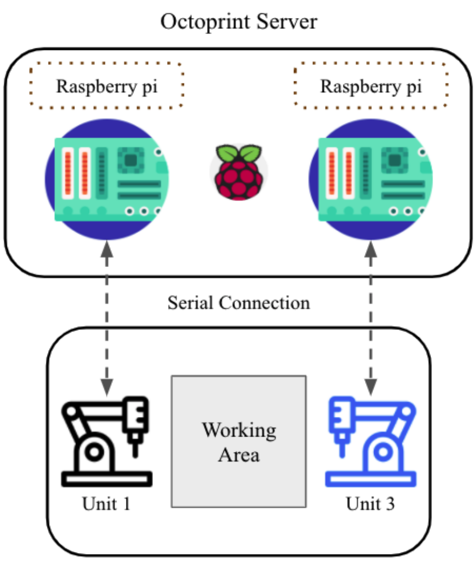


Figure 3.18

Serial Communication of AM Units

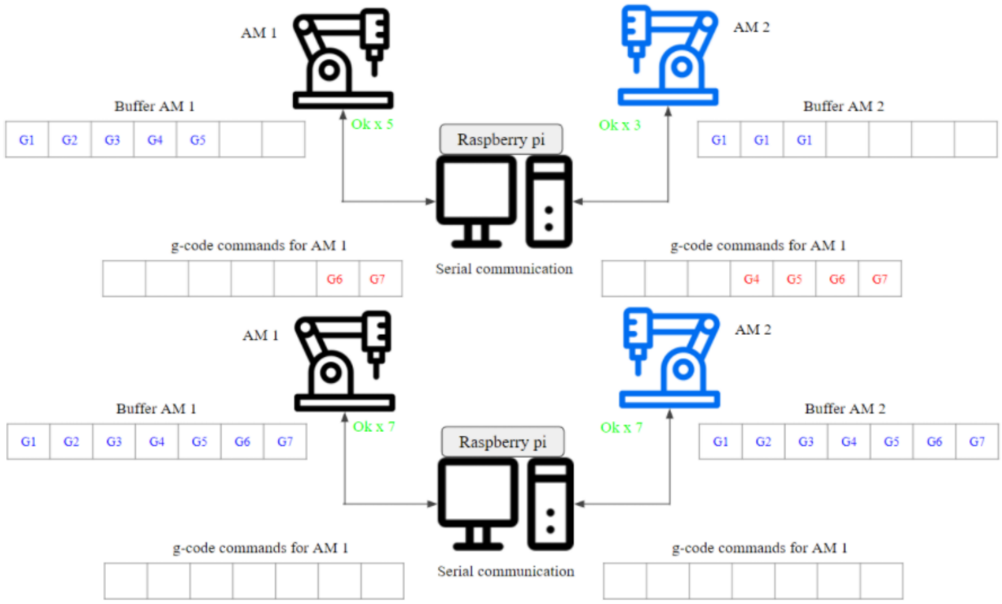


Figure 3.19

Flow Diagram of CO-LSAM

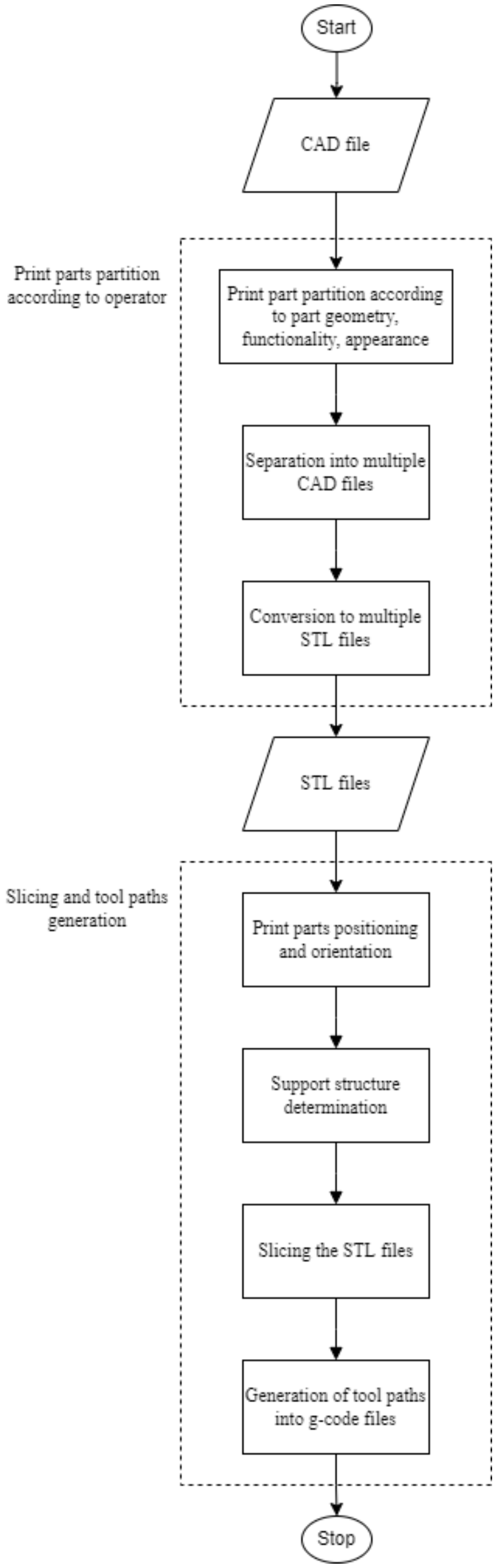


Figure 3.20

Flow Diagram of CO-LSAM (continue)

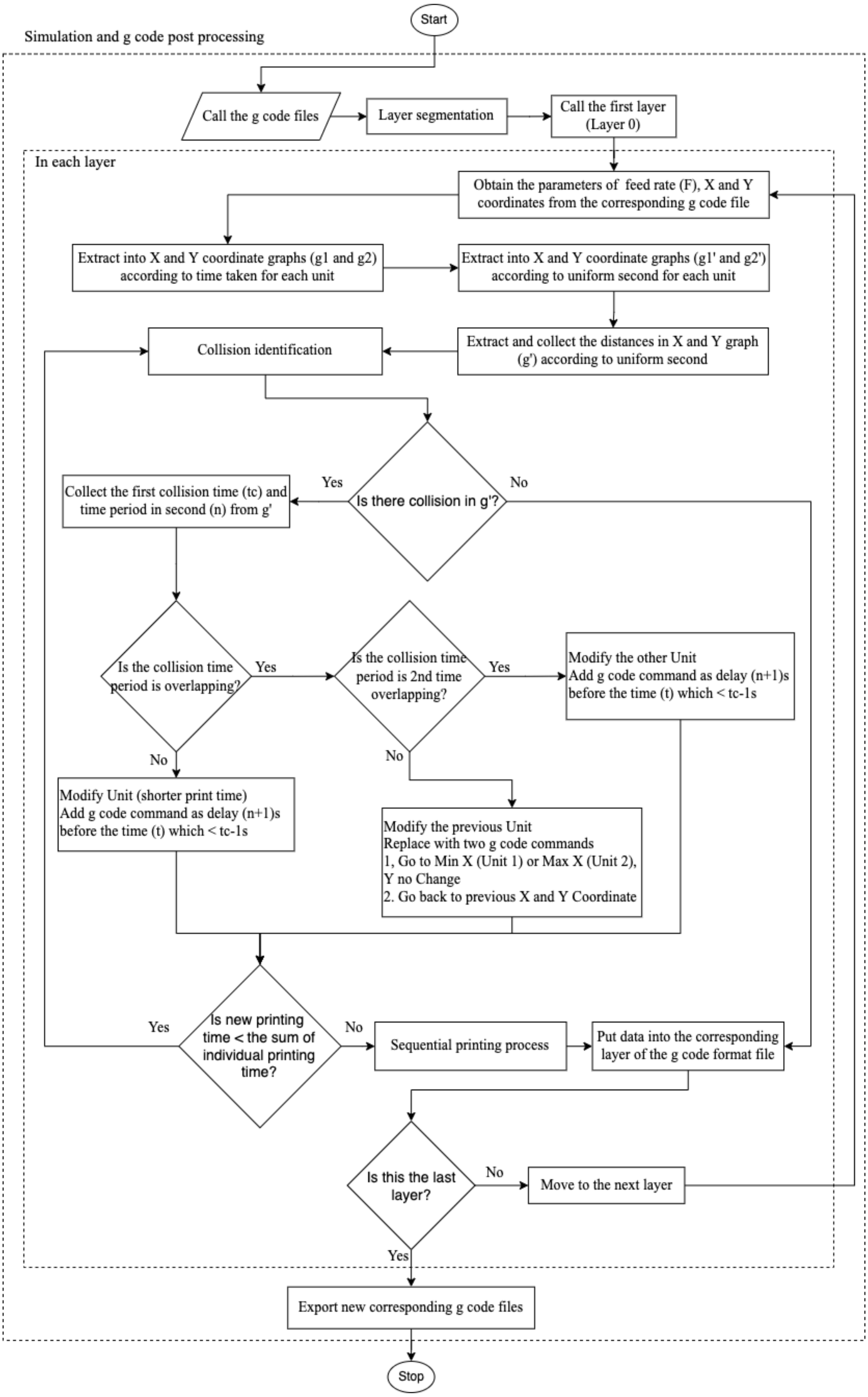
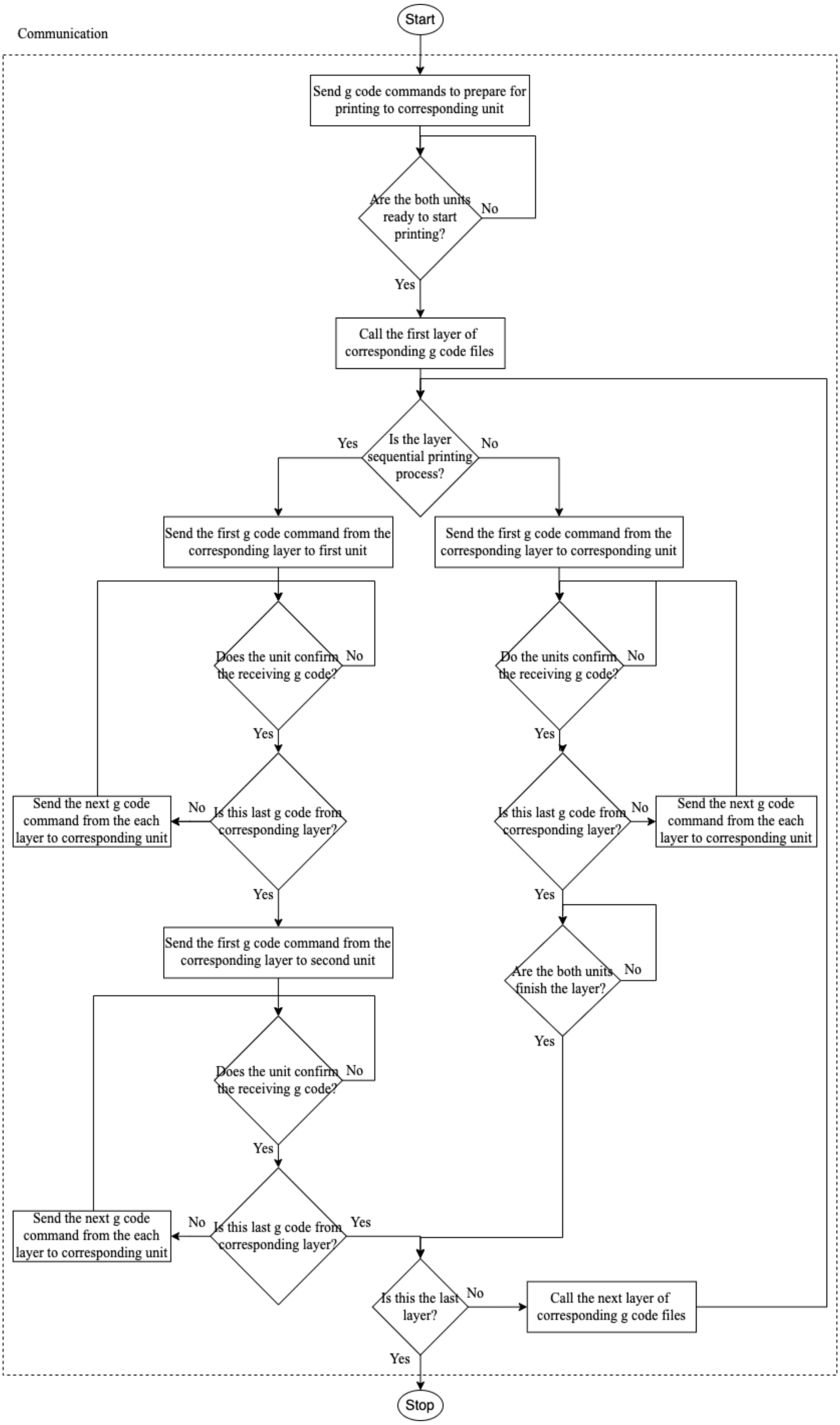


Figure 3.21

Flow Diagram of CO-LSAM (continue)



CHAPTER 4
SYSTEM DEVELOPMENT

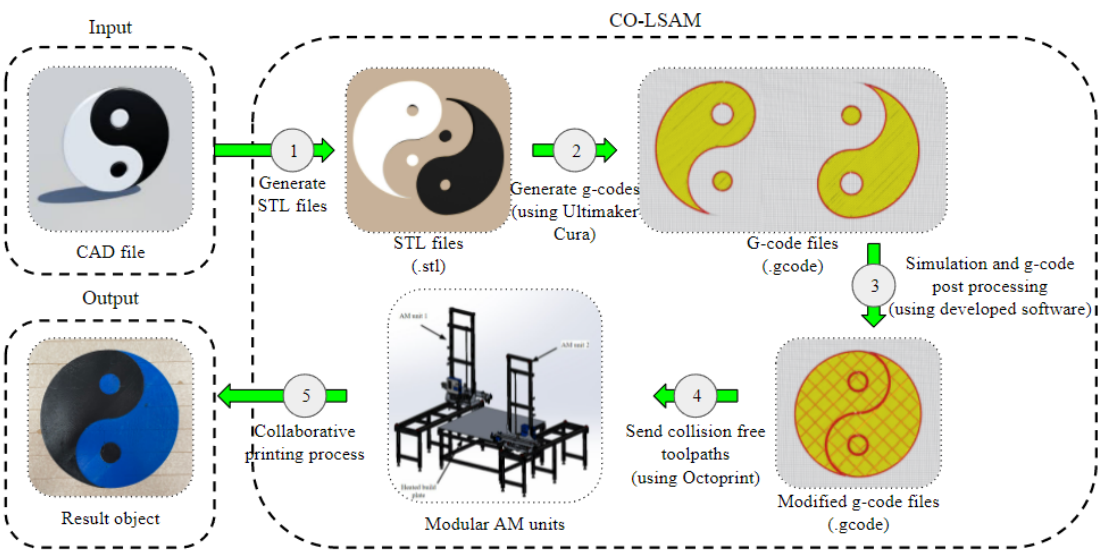
This chapter explains how the developed concept transforms into an algorithm and put into practice using two modular AM units. The development process of the Co-LSAM system is explained in detail as software development and prototype development in this chapter.

4.1 Algorithm Development

Collaborative Additive Manufacturing (Co-LSAM) system mainly focuses on the simulation and G-code post processing which include collision identification and G-code modification for collision avoidance. In order to implement this, the developed concept is transformed into an algorithm to fabricate the large-scale products starting from CAD file. Figure 4.1 shows the flow diagram of the developed algorithm.

Figure 4.1

Developed Algorithm for Co-LSAM



4.2 Software Development

In order to validate the developed concept, a software was developed as "G-code Simulation and Modification for Collaborative Additive Manufacturing" by using Visual Studio 2019. It consists of 6 parts. As shown in Figure 4.2, the first part (a) has two buttons to upload the G-code files of each AM unit which are generated by the

Ultimaker Cura slicing software, already presented in session 3.2.2. This part will also display the number of layers and estimated total print time of each G-code file. The second part (b) is used to check and create the coordinate graphs for each print head layer by layer which will be displayed in part (c) as Delta X-Y graph, coordinate graphs of Head 1 and Head 2. In order to identify collisions between head 1 and head 2 of each AM unit, part (d) is designed by updating the proximity limit in millimeters, that is the minimum distance threshold between head 1 and head 2, pre buffer and post buffer in seconds. Part (e) is designed to start the simulation and modification processes and it will display the numbers of simultaneous print layers, sequenced print layers and the estimated total print time. The last part (f) is used to export the modified G-code files for each AM unit which have no collision between the print heads. Figure 4.3 is a sample for developed software implementation. Figure 4.4 presents a software layout after the simulation process.

Figure 4.2

Software Layout

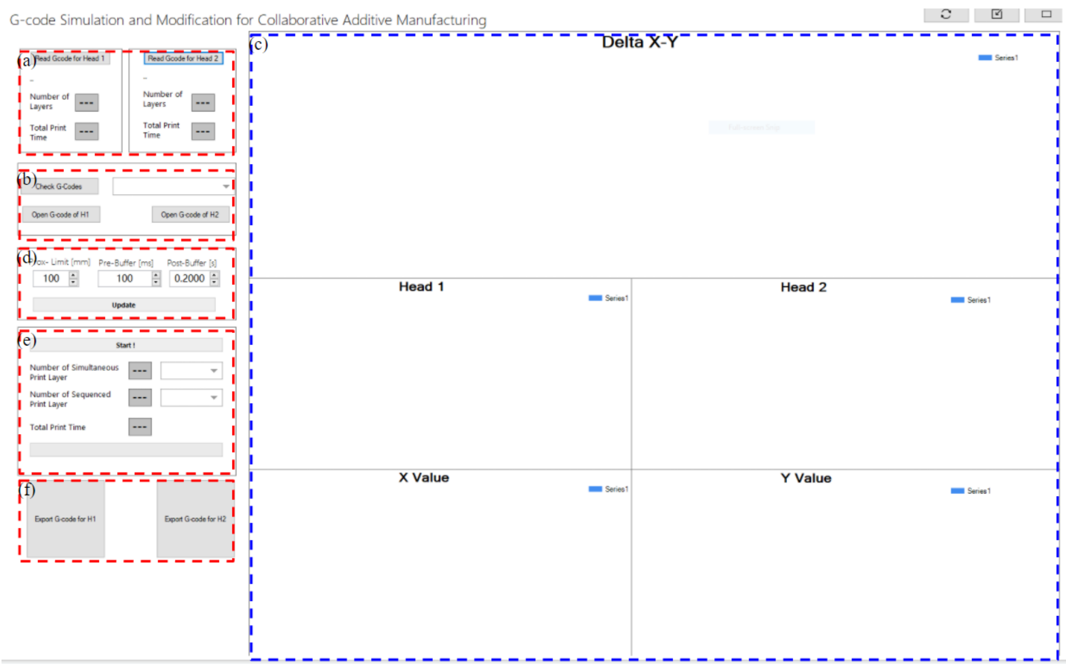


Figure 4.3

Software Implementation Test Sample

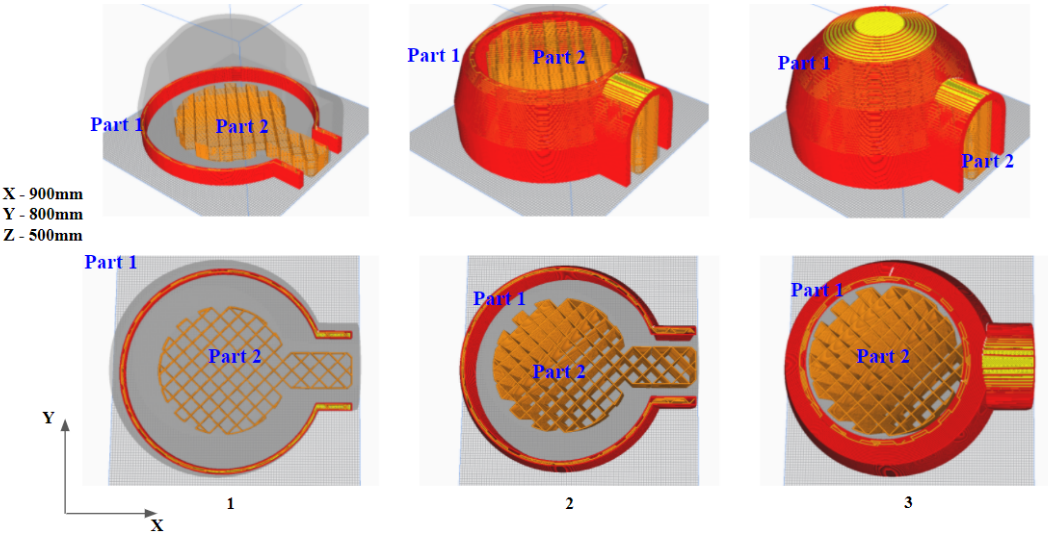
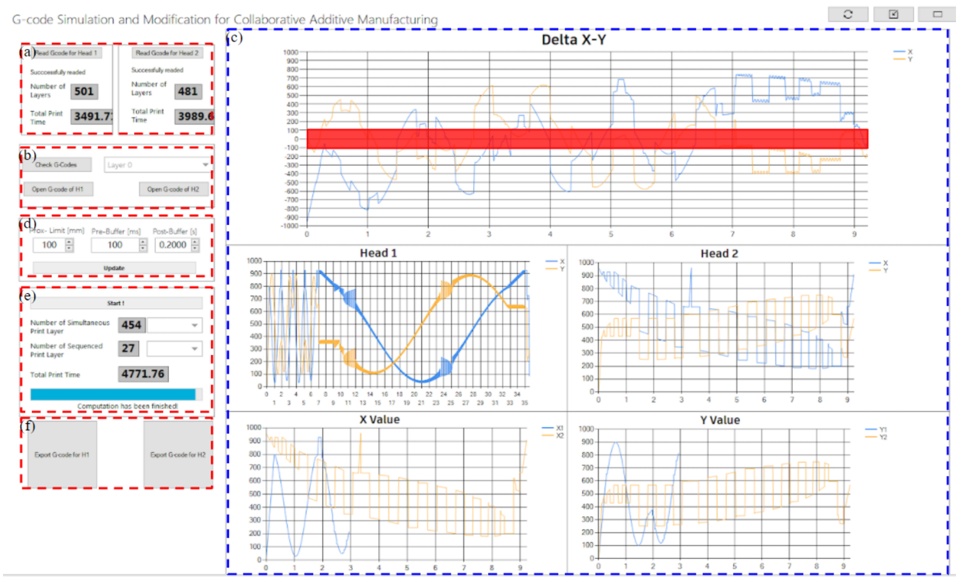


Figure 4.4

Software Layout after Simulation Process



4.3 Prototype Development

The idea of Co-LSAM concept is to enable multiple AM units to work collaboratively on a common platform by using many types of configurations as presented in session 3.1. Fused Filament Fabrication (FFF) process is used for fabrication in prototype development and there are few considerations for machine design; the machines need to have modular design, the machines enable to print large volumes, the machines capable of working on a common platform which means that the printing heads of each AM unit are able to move independently in all X, Y and Z axes in a common printing area. Moreover, in order to work together in a common working space, the coordination between AM units has become important. Therefore, all AM units must have the same coordinate and accurate positions such as home position and reference position of each print head.

4.3.1 Development of Modular AM Unit

Modular AM unit design is to enable the multiple AM units to work collaboratively on a common platform. Figure 4.5 is the CAD model overview of the machine design with two modular type AM unit's configuration and 1-meter square area of the build plate. The build plate has a heating system in order to fabricate various kinds of materials because some need a heated plate to stick well during the fabrication process. The CAD model is designed with Solidworks and the multi-view of the CAD model is shown in Figure 4.6. The real setup of two AM units with a common platform is shown in Figure 4.9. Furthermore, the size of the machine depends on the size of the print object i.e, the machine size cannot be smaller than the print object. In order to reduce the machine size, telescopic arm design comes to play an essential role and the detail will be shown in next session 4.3.2.

Figure 4.5

CAD Model of Two AM Units and A Common Printing Platform

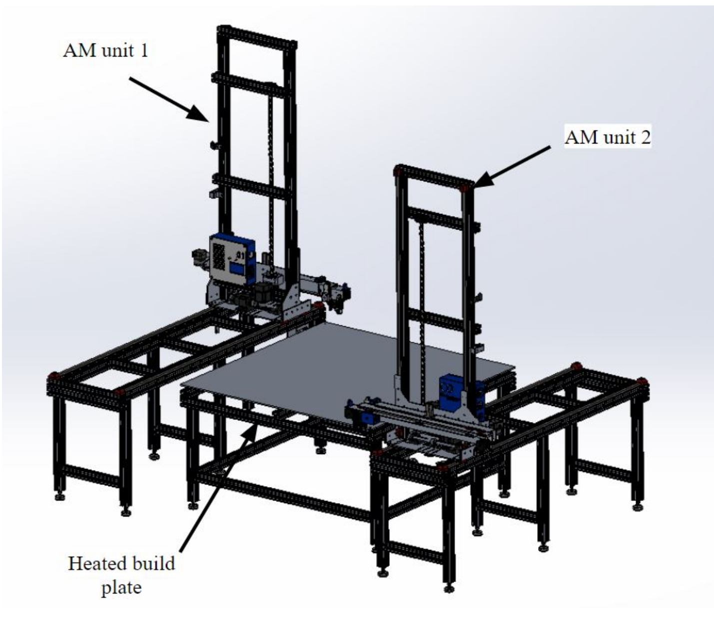
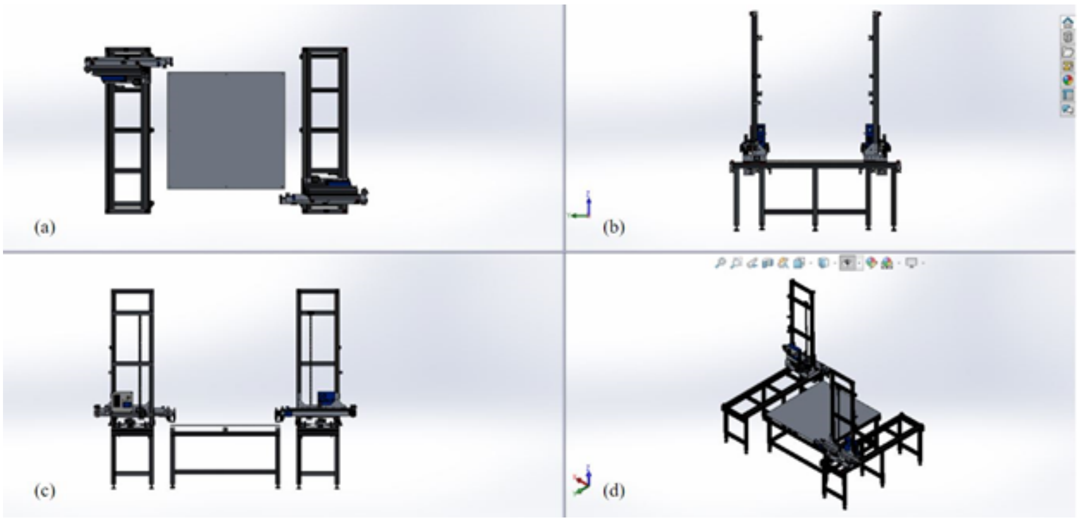


Figure 4.6

Multi View of Co-LSAM Solidworks CAD Model



Note. (a) top view, (b) side view, (c) front view, (d) isometric view

For movement mechanism, belt drive mechanism for X and Y axes and ball screw drive mechanism for Z axis are used. Arduino Mega 2560 and RepRap shield are used as a main controller in which Marlin firmware is uploaded to control all motions and processes necessary for the fabrication process. Marlin firmware will be explained in session 4.3.3 as AM unit firmware. Each AM unit includes the following as main components and two sizes of motors (NEMA 17 and NEMA 23) are used for their different payload.

- One Nema 17 stepper motor for X axis
- One Nema 23 stepper motor for Y axis
- One Nema 23 stepper motor for Z axis
- Two Nema 17 stepper motors for extruders
- Two double gear extruders
- One Arduino mega 2560 for controller
- One RepRap Ramp 1.4b shield
- One RepRapDiscount full graphic smart controller for display
- One power supply (24V, 30A, 750W)
- One heater for hot end (24V)
- Four silicone heaters for build plate (400 mm x 400 mm, 220VAC, 750W)

● Two NTC thermistor 100k Temperature sensors (one for hot end, one for build plate)
● One e3D V6 volcano hot end nozzle
● Three limit switches for end stops
● One blTouch sensor for auto bed leveling

4.3.2 Development of Telescopic Arm

The aim of the telescopic arm mechanism is to get maximum length of the X-axis in the fabrication process without increasing the machine size. Figure 4.7 is the detail of the telescopic arm design with two 2GT belts mounted with one NEMA 17 stepper motor in order to perform a linear motion. According to the CAD model, the mechanism can give a maximum stroke of 1 meter as shown in Figure 4.8. There are two more NEMA 17 stepper motors mounted on each side to feed the material (1.75 mm filament). One side of the motor is used to deliver the filament from the filament spool which is attached on the base frame to another motor mounted on the other side and it is used to feed the filament to the hot end nozzle.

Figure 4.7

Telescopic Arm for X-Axis

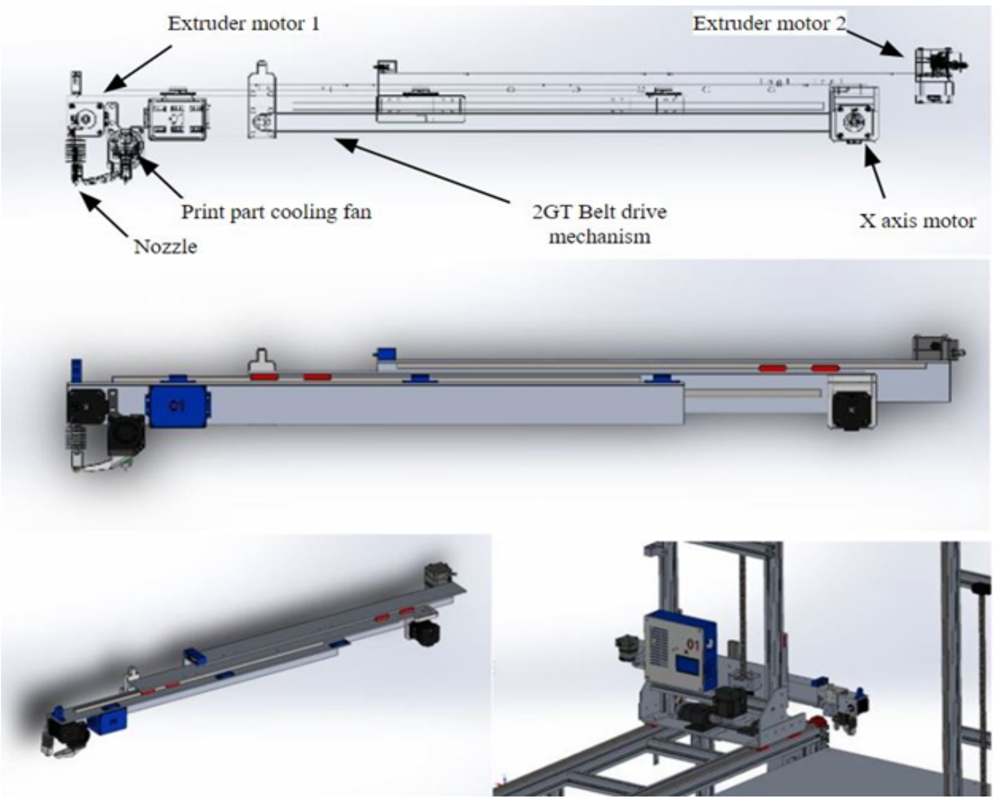
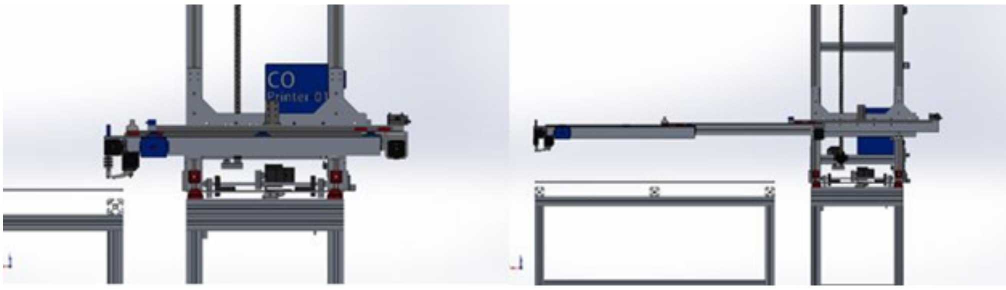


Figure 4.8

Illustration of Maximum Stoke in X-Axis



The real setup of two AM units with a common platform is shown in Figure 4.9. The size of the modular type AM unit is obviously reduced especially in X-axis to 600 mm with the help of a telescopic arm whose size would be at least 1200 mm without a telescopic arm and the dimensions of the machine are described in the following Table 4.1. Moreover, the specifications of each AM unit are as follows.

- Nozzle size - 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, 1.2 mm
- Nozzle max temperature - 250 °C
- Print bed max temperature - 60 °C
- Filament diameter - 1.75 mm
- Resolution - 0.1-1.0 mm
- Maximum printing speed - 80 mm/s

Figure 4.9

Real Setup for Two AM Units with a Common Platform

Table 4. 1

Dimension of Modular Type AM Unit

Axes	Maximum printable size (mm)	Overall machine size (mm)	Minimum safe distance thresholds (mm)
X axis	960	600	100
Y axis	1000	1400	100
Z axis	900	1800	100

In order to work together in a common working space, the coordination between AM units need to be considered and each AM unit must have the same coordinate and accurate positions for each print head. Moreover, the minimum safe distance thresholds which are the shortest distances between each print head are identified as shown in Table 4.1. In order to collaborate, each AM unit has home position and reference position and the distance between the two nozzles can be adjusted by both mechanically and programming.

4.3.3 AM Unit Firmware

Each AM unit has a main controller unit: Arduino Mega 2560 and Marlin firmware is uploaded to it. The Marlin firmware runs on the AM's main board, managing all the real-time activities of the machine. It coordinates the heaters, steppers, sensors, lights, LCD display, buttons, and everything else involved in the fabrication process. Marlin implements an additive manufacturing process called Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF). In this process, the extruder motor pushes plastic filament through a hot nozzle that melts and extrudes the material while the nozzle is moved under computer control. After several minutes of laying down thin layers of plastic, the result is a physical object. The control language for Marlin is a derivative of G-code. The following Figure 4.10 describes the RepRap G-code commands which work in Marlin Firmware. G-code commands tell a machine to do simple things like "set heater 1 to 250 °C," or "move to XY at speed F." To print a model with Marlin, it must be converted to G-code using a Ultimaker Cura slicing software. As Marlin receives movement commands, it adds them to a movement queue to be executed in the order received with the help of OctoPrint server which will be described in next session 4.3.4.

Figure 4.10

RepRap G-code Cheat Sheet

RepRap GCode Cheat Sheet

Comm.	Parameters	Description	Example
G0	Axis [X/Y/Z] Position	Rapid Movement	G0 X50
G1	Axis [X/Y/Z/E] Position Feed [F]	Controlled Movement	G1 F150 X10
G4	Time in ms [P]	Dwell / Wait	G4 P500
G20	none	Set units to inch	G20
G21	none	Set units to mm	G21
G28	<Axis [X/Y/Z]>	Home	G28 X Y
G90	none	Absolute Positioning	G90
G91	none	Relative Positioning	G91
G92	Axis [X/Y/Z/E] Value	Set Position to value	G92 X5 Y10

Comm.	Parameters	Description	Example
M0	none	Stops everything after buffer is empty	M0
M17	none	Enable all stepper motors	M17
M18	none	Disable all stepper motors (move freely)	M18
M20	none	List files at the root folder of the SD Card	M20
M21	none	Initialise (mount) SD Card	M21
M22	none	Release (unmount) SD Card	M22
M23	Filename	Select File for Printing	M23 print.gco
M24	none	Start / Resume SD Card Print (see M23)	M24
M25	none	Pause SD Card Print (see M24)	M25
M26	Bytes[S]	Set SD Position in bytes	M26 S12345
M27	none	Report SD Print status	M27
M28	Filename	Write programm to SD Card	M28 print.gco
M29	Filename	Stop writing programm to SD Card	M29 print.gco
M40	none	Eject part (if possible)	M40
M41	none	Loop Programm(Stop with reset button!)	M41
M42	none	Stop if out of material (if supported)	M42
M43	none	Like M42 but leave heated bed on (if supported)	M43
M80	none	Turn on ATX Power (if neccessary)	M80
M81	none	Turn off ATX Power (if neccessary)	M81
M84	none	Stop idle hold (DO NOT use while printing!)	M84
M92	Steps_per_unit[X]	Programm set S steps per unit (resets)	M92 X123
M101	none	Set extruder 1 to forward (outdated)	M101
M102	none	Set extruder 1 to reverse (outdated)	M102
M103	none	Turn all extruders off (outdated)	M103
M104	Temperature[S]	Set extruder temperature (not waiting)	M104 S100
M105	none	Get extruder Temperature	M105
M106	<PWM Value[S 0-255]>	Set Fan Speed to S and start	M106 S123
M107	none	Turn Fan off	M107
M108	none	Set extruder speed (outdated)	M108
M109	Temperature[S]	Set extruder Temperature (waits till reached)	M109 S123
M110	Line Number[N]	Set current line number (next line number = line no. +1)	N123 M110
M111	Debug Level [S]	Set Debug Level	M111 S6
M112	none	Emergency Stop (Stop immediately)	M112
M113	<PWM [S]>	Set Extruder PWM to S (or onboard potent. If not given)	M113 S0.7
M114	none	Get Current Position	M114
M115	none	Get Firmeware Version and Capabilities	M115
M116	none	Wait for ALL temperatures	M116
M117	none	Get Zero Position in steps	M117
M119	none	Get Endstop Status	M119
M126	Time[P]	Open extruder valve (if available) and wait for P ms	M126 P500
M127	Time[P]	Close extruder valve (if available) and wait for P ms	M127 P500
M128	PWM[S]	Set internal extruder pressure S255 eq max	M128 S123
M129	Time[P]	Turn off extruder pressure and wait for P ms	M129 P500
M140	Degrees[S]	Set heated bed temperature to S (not waiting)	M140 S55
M141	Degrees[S]	Set chamber temperature to S (not waiting)	M141 S30
M142	Pressure[S]	Set holding pressure to S bar	M142 S1
M143	Degrees[S]	Set maximum hot-end temperture	M143 S275

4.3.4 OctoPrint Server Setup

OctoPrint server, python code runs on the raspberry pi 4B which provides a web interface for controlling the AM units. As shown in Figure 4.12, it allows the user to start a printing process by sending G-code to AM units connected via USB as serial communication. It can monitor the status of the printing process, as well as the AM unit itself, including the temperature of the print head (hot end) and print bed (platform). Moreover, it can also show the output of a connected webcam in order to monitor the state of the print, and can visualize the G-code in sync with the printing process as shown in Figure 4.13.

Figure 4.11

OctoPrint Server Setup with Marlin Firmware

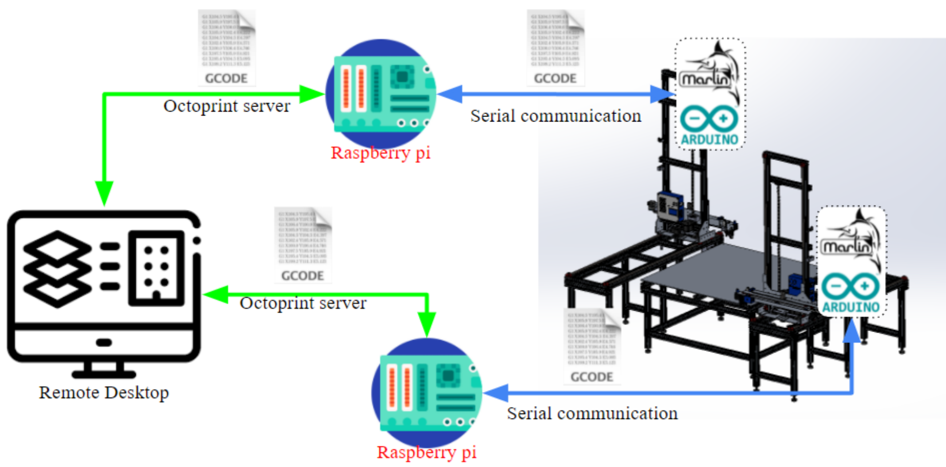


Figure 4.12

OctoPrint Server Interface Layout (Temperature Tab and Control Tab)

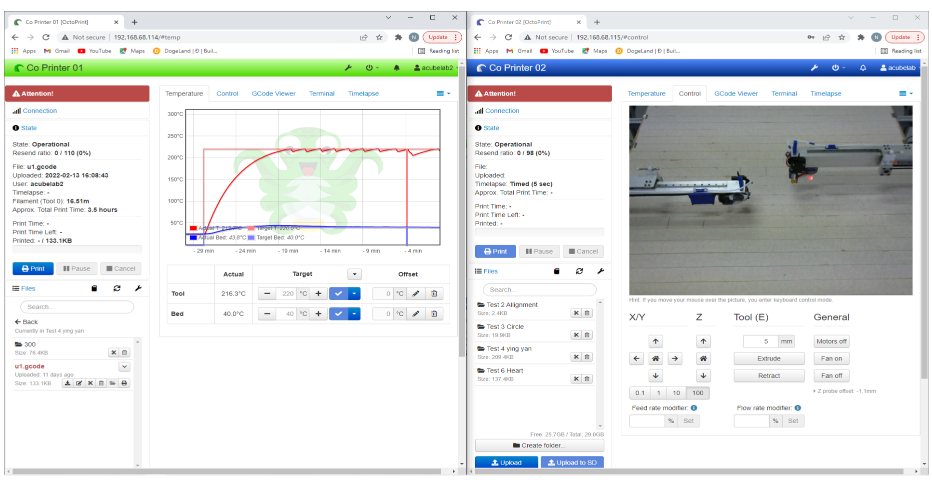
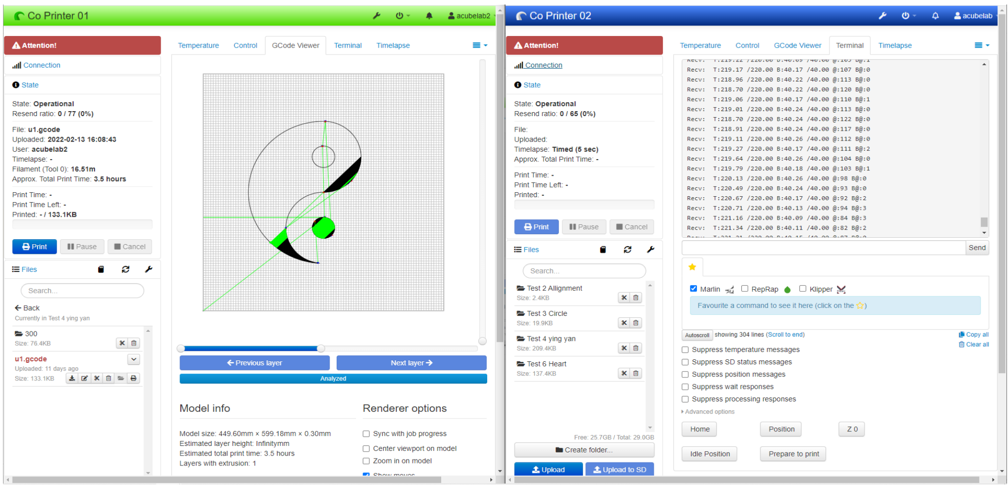


Figure 4.13

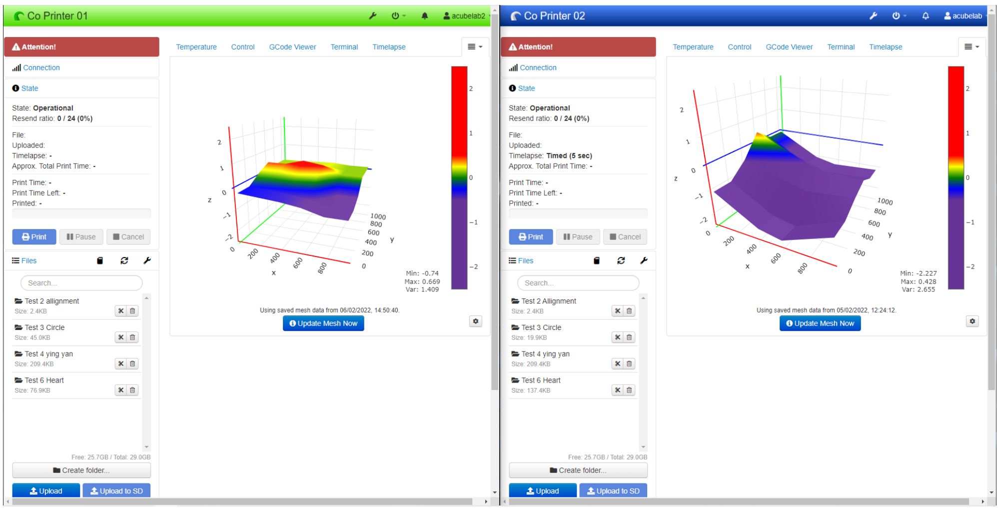
OctoPrint Server Interface Layout (G-code Viewer Tab and Terminal Tab)



Before the printing process, the OctoPrint server sends commands to corresponding AM units to get ready for printing. For example, setting a nozzle temperature, print bed temperature and print heads positioning. Moreover, since this study focuses on large scale, calibration is needed for print bed leveling. Each AM unit has a blTouch sensor to collect the value of height between the print head and print bed all over the print area. Figure 3.14 is a bed level visualization of each AM unit.

Figure 4.14

OctoPrint Server Interface Layout (Bed Level Visualization)



CHAPTER 5
IMPLEMENTATION AND RESULTS

5.1 System Operation

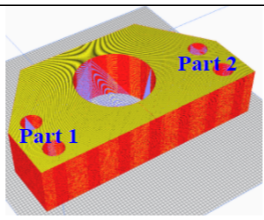
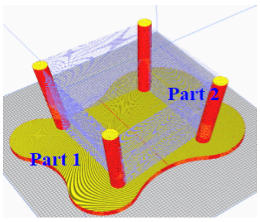
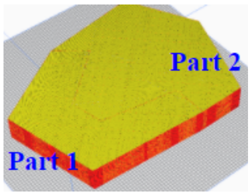
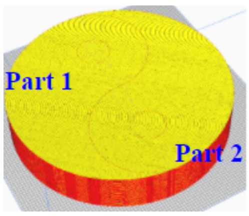
Co-LSAM concept had already been established in session 3.2 and implementation process was carried out according to the developed algorithm as mentioned in session 4.1 with the assistance of Ultimaker Cura slicing software, developed software (G-code Simulation and Modification), OctoPrint server and hardware prototype. The whole process starts from connecting the AM units to corresponding raspberry pi and setting up the OctoPrint server. Afterwards, the desired CAD model is converted into multiple STL format files for slicing and G-code generation. G-code files obtained from slicing software contain many kinds of collisions. The developed software (G-code Simulation and Modification) is used to identify the collisions between the print heads, and modify layer by layer to avoid collision. The obtained collision free G-code files are uploaded to corresponding AM unit through the OctoPrint server and it will provide a real time fabrication process using AM units.

5.2 Implementation

In order to validate the concept of Co-LSAM, the implementation process was conducted with seven samples in which each sample has two different sizes (medium and large) as described in Table 5.1 with figures, dimensions and numbers of layers of each AM unit. Each sample has two print parts (part 1 and part 2) for the corresponding AM unit.

Table 5. 1

Samples for Implementation Process

No	Printed part name	Figure	Dimension	Number of layers Unit 1	Number of layers Unit 2
1	Mechanical part		600mm x 330mm x 50mm	167	167
			800mm x 440mm x 200mm	677	677
2	Table		400mm x 300mm x 160mm	536	536
			800mm x 600mm x 320mm	1072	1072
3	Irregular shape		600mm x 450mm x 50mm	167	167
			800mm x 600mm x 100mm	333	333
4	Yin & Yang		400mm x 400mm x 50mm	167	167
			800mm x 800mm x 150mm	500	500

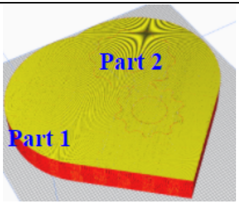
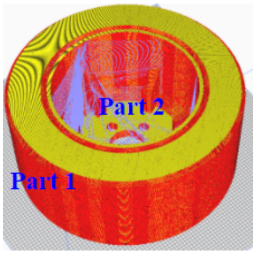
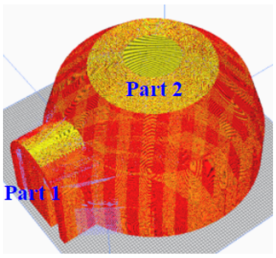
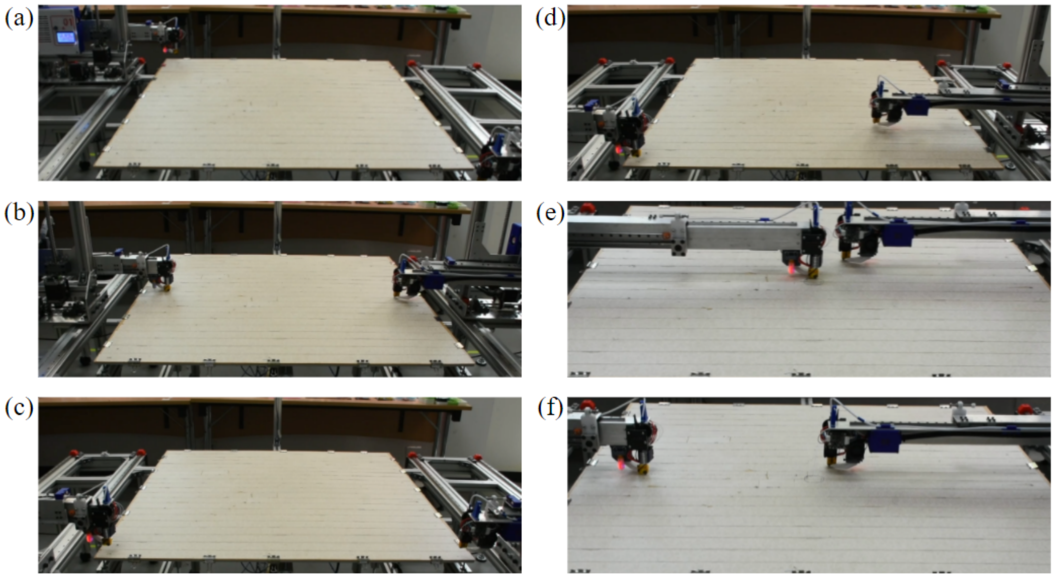
No	Printed part name	Figure	Dimension	Number of layers Unit 1	 Unit 2
5	Heart shape		500mm x 500mm x 30mm	100	100
			800mm x 800mm x 100mm	333	333
6	Wheel		500mm x 500mm x 233mm	778	778
			700mm x 700mm x 326mm	1089	1089
7	Snow house		600mm x 530mm x 330mm	1067	1111
			900mm x 800mm x 500mm	1600	1667

Figure 5.1 and 5.2 represent the fabrication stages of print part (Yin & Yang) in which stage (a) shows the beginning of the fabrication process (unit 1 is left side, unit 2 is right side), stage (b) describes the movement of going home position of each AM unit, stage (c) shows the AM units which are waiting to heat up the nozzles and print bed at their reference positions. The fabrication process will only begin when both nozzles and print bed of each AM unit reach the required temperatures (225 degree Celsius for nozzles and 50 degrees Celsius for print bed). As shown in stage (d), unit 2 starts printing while unit 1 is waiting at the current position because they are going to print an interference area.

Figure 5.1

Fabrication Stages in Co-LSAM



According to the modification process as described in session 3.2.3.4, when the time that both heads don't have enough space to fabricate together or one arm of AM unit blocks in tool-path of other arm, the AM unit which has shorter printing time must retract to its minimum or maximum X coordinate to avoid collision. In stage (e), (f) and (g), unit 1 has shorter printing time and its arm blocks the unit 2. So, the arm of the unit 1 retracts to its minimum X coordinates and returns back to its previous position. Stage (h) and (i) show the printing process for the outer layer of each part and stage (j) and (k) show the printing process for infill of each part. Stage (l) shows the end of the printing process in which unit 2 finishes the printing process, returns to its reference position and waits for unit 1 to move on to the next layer. Figure 5.3 (a) is the print result of Yin & Yang and Figure 5.3 (b) is the print result of heart shape.

Figure 5.2

Fabrication Stages in Co-LSAM (continue)

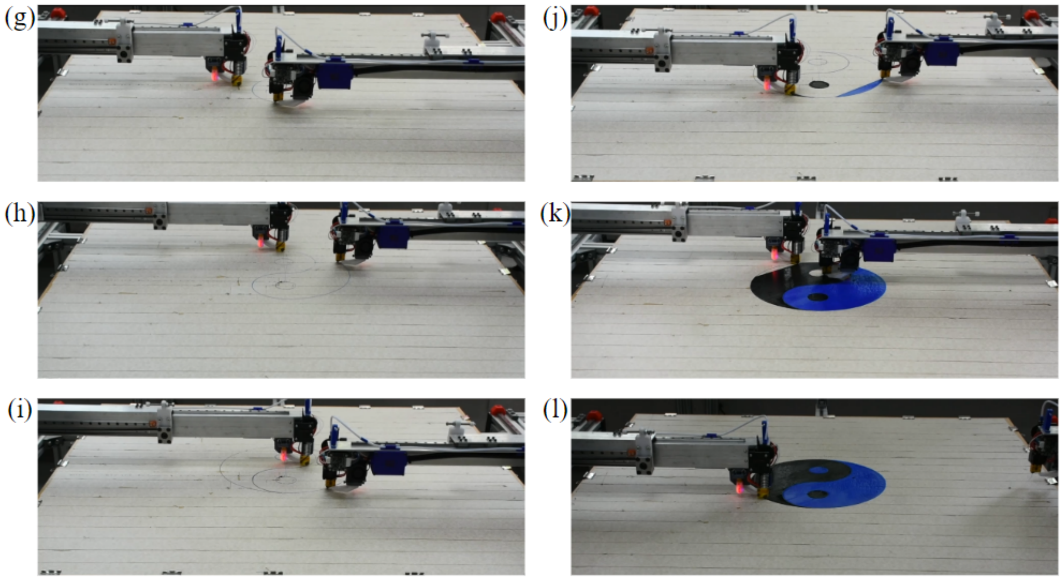
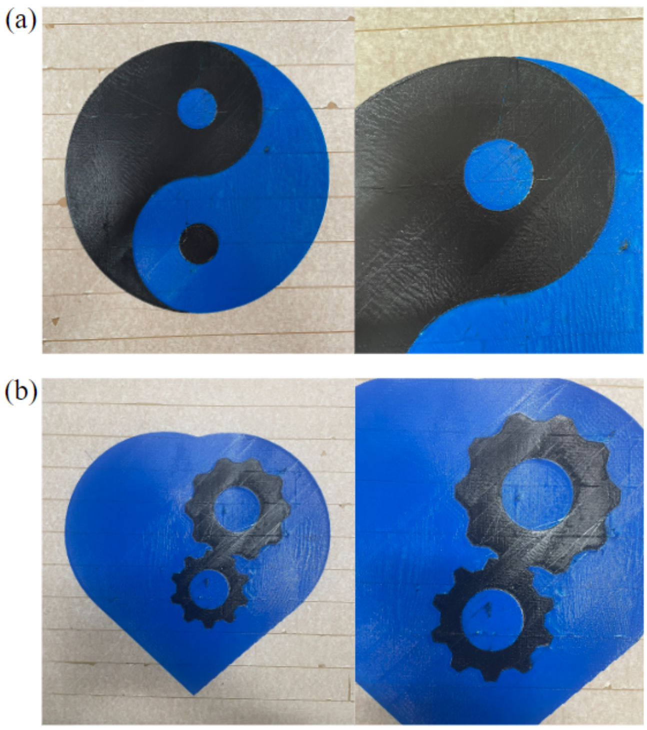


Figure 5.3

Print Results



Note. (a) Yin & Yang, (b) Heart shape

5.3 Result

In this chapter, the results obtained from the implementation process of seven samples are described in two sessions. The first session describes the results of total fabrication time in hours according to the conventional and collaborative upon seven samples in which the conventional fabrication time of each sample is generated from Ultimaker Cura slicing software whereas collaborative fabrication time of each sample is obtained from developed software and the numbers of layers that can be printed simultaneously and sequentially are shown in Table 5.2. Moreover, Figure 5.4 illustrates the comparison of conventional and collaborative fabrication time. Application of Co-LSAM concept reduces the fabrication time to a great extent. The second session describes the fabrication time reduced by Co-LSAM as fabrication efficiency, shown in Figure 5.5. According to the chart, as the complexity of the print samples grows, the fabrication efficiency reduces, yet still meets expectations.

Table 5. 2

Result of Total Fabrication Time in Hours and Number of Layers in Simultaneous or Sequential

No	Printed part name	Total fabrication time in hours		Number of layers	
		Conventional	Collaborative	Simultaneous	Sequential
1	Mechanical part	15.65	8.39	167	0
		67.28	34.58	677	0
2	Table	8.57	5.44	536	0
		36.55	20.75	1072	0
3	Irregular shape	20.08	14.09	167	0
		48.65	31.71	333	0
4	Yin & Yang	14.88	8.79	167	0
		93.52	48.72	500	0
5	Heart shape	15.93	12.20	100	0
		69.22	50.28	333	0

No	Printed part name	Total fabrication time in hours		Number of layers	
		Conventional	Collaborative	Simultaneous	Sequential
6	Wheel	63.77	48.08	710	68
		131.37	94.23	1021	68
7	Snow house	62.02	45.88	1027	84
		155.15	112.00	1562	105

Figure 5.4

Comparison of Conventional and Collaborative Fabrication Time

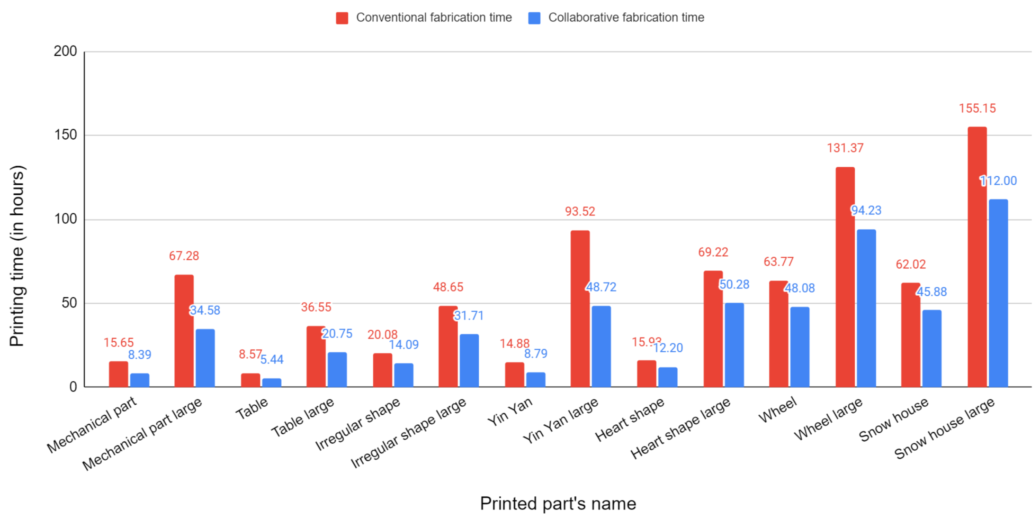
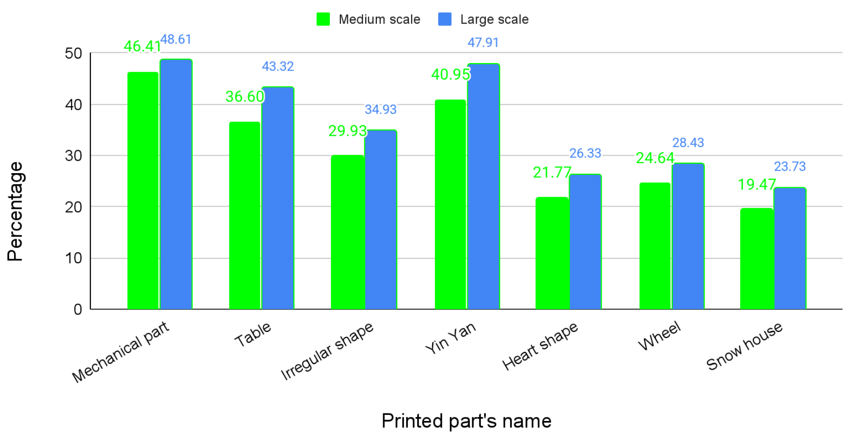


Figure 5.5

Result of Fabrication Efficiency



CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The main objective of this study is to develop collaboration among multiple AM units by working together in a common working area to reduce the fabrication time. To achieve this, the concept of Co-LSAM is successfully developed which consists of print parts partition, tool-path generation, G-code simulation and communication between AM units. To implement the concept of Co-LSAM, an algorithm is developed along with the simulation software which enables the identification of collision and modifications for collision avoidance. Moreover, this paper is set out to provide a design idea for a collaborative AM system. The significance of this design lies in its potential to be implemented with a collaborative fabrication process, which aims to solve the current issues of 3D printing such as size constraints, fabrication time. To achieve this target concept, the design of modular type AM units that can print nearly one meter cube of volume and telescopic arm mechanism are successfully developed without increasing the overall machine size. Moreover, the results of the prototype conclude that the concept of collaborative additive manufacturing can be implemented to reduce the fabrication process.

6.2 Recommendations

The Co-LSAM concept is successfully developed and a simulation software along with the prototype with multiple AM units is successfully tested in the implementation process. However, there still needs improvements to be done mainly in two aspects. The first aspect is related to the G-code simulation process. The software developed for G-code simulation and post processing needs to be improved to get quicker processing in collision identification and decision making for collision avoidance. The second aspect is to upgrade the prototype for stability and smooth motion by using bigger linear rails such as MGN16 and above.

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