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A Literature Review on the use of Robot Technology in Additive Manufacturing

Author:
Helene Boge

Supervisors:
Jan Tommy Gravdahl
Linn Danielsen Evjemo

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NTNU
Norwegian University of Science and Technology

Problem description

Main objectives for this thesis:

1. Become familiar with the field of Additive Manufacturing, both in industry and research
2. Identify some challenges in Additive Manufacturing and through literature review, find attempts on solving the identified problems
3. Identify advantages of using robotic manipulators in Additive Manufacturing
4. Investigate if solutions made possible by robotic AM currently exist

Abstract

Additive Manufacturing (AM), more commonly known as 3D printing, is gaining more popularity as the technology is improving. It currently have areas of application within orthopedics and medicine, automotive- and aerospace and in make-at-home communities due to its ability to fabricate customized parts in small batches. This thesis identifies challenges with current applications and finds that scale, support structures and the quality of the fabricated part are all factors that impose important limitations on the manufacturing technology and may prevent exciting applications for AM systems in the future. AM is often realized using a three axis, translation only-configuration and due to this, printed parts are often realized on the desktop-scale. The size of the printed part have to be smaller than the printer itself, so in order to print on the large scale, systems often have to be built specifically for each manufacturing job. Using only translational motion, it is also often necessary to add support structures beneath exposed regions which must be removed after the part is complete, having a negative impact on cost, build time and sustainability of the technology. Both exterior and interior quality of the part is important in order for the part to satisfy specifications before it is ready for the market, and many material- and technique specific properties can vary greatly depending on manufacturing parameters. It is found that many of these challenges can be overcome by applying a new type of system for AM. Adding rotational motion to the system by using a robot arm that can move around six axes opens for the development of a whole new group of methods for additive fabrication.

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Abbreviations

3D	Three dimensional
AM	Additive Manufacturing
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CLFDM	Curved Layer Fused Deposition Modeling
DCP	Digital Construction Platform
DDM	Direct Digital Manufacturing
DMLS	Direct Metal Laser Sintering
DOF	Degrees of Freedom
EBF	Electron Beam Freeform Fabrication
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
FM	Formative Manufacturing
FWP	Fast Wavefront Propagation
GCFA	Greedy scheme for Convex Front Advancing
LENS	Laser Engineered Net Shaping
MIT	Massachusetts Institute of Technology
US	United States
UV	Ultraviolet
RIA	Robot Institute of America
RM	Rapid Manufacturing
RP	Rapid Prototyping
SHS	Selective Heat Sintering
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
STEP	Standard for the Exchange of Product model data
STL	Stereolithography (file format)

Chapter 1

Introduction

This thesis is written as a part of the SFI Manufufacturing project, an interdisciplinary research project that aims to show that sustainable manufacturing is possible in high-cost countries such as Norway [1]. As a part of this project, Additive Manufacturing (AM), more commonly known as three dimensional (3D) printing, is investigated in application together with robot technology, or more precisely six degree of freedom (DOF) industrial manipulators. AM is a manufacturing method characterized by the stacking of cross sectional layers of material until it forms a complete object, and is in its traditional form greatly limited by several factors. Promising results from research show that many of these limitations can be overcome by utilizing a 6 DOF robotic system.

The objective of this thesis will be to identify some important challenges in AM and through studying published literature find promising solutions that uses robot technology to fully utilize AM and its potential for a high level of geometric design flexibility. The thesis should serve as a preparatory work for an upcoming master thesis on tool-path planning for robotic AM.

1.1 Motivation

Advances in AM are bringing about new design possibilities, products and production paradigms [2]. When the geometric design flexibility of AM can be fully utilized, it will make it possible to design parts according to its intended functionality, without having to consider how it is to be manufactured

[3]. In this section some motivation for research on this area is presented.

1.1.1 Industry perspective

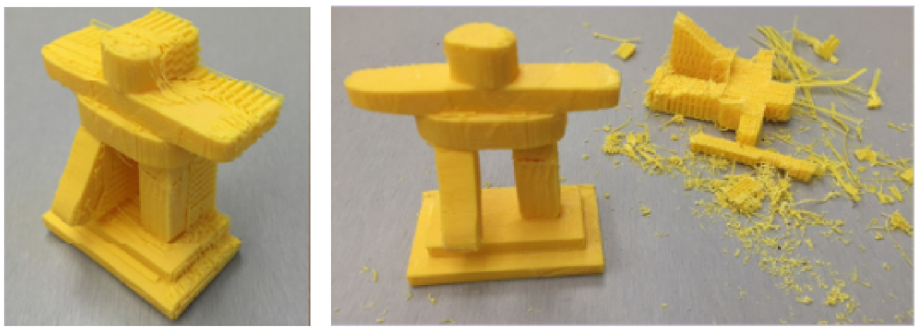
A typical cost model for the production cost for a single object is typically defined as the sum of: 1) pre-build cost, 2) build cost and 3) post-processing cost [4]. The pre-build cost is the cost of turning a design into a set of machine instructions and may be affected by the efficiency of the algorithms used by the software or by the amount of human interaction in the process [4]. A high level of automation and little time spent in this phase will often benefit the total pre-build cost. The material cost and the cost of using the AM machine chosen makes up the build cost. This cost may be reduced by using minimal amount of material and by reducing the manufacturing time [4]. The post-processing cost is the labour-, material- and time cost it takes to finish the part.

From an industry perspective, the objective will often be to minimize the sum of these costs. A product often needs to go through many iterations of these phases in order to fulfill all its specifications and be ready for the market. Prototyping using AM is speeding up this whole process, helping reducing both production cost and time to market [5]. Many papers refer to Wholers Report on the State of the Industry to show the impact of AM on production. Wholers annual report reviews and analyses AM and is said to be the industry-leading report on the subject [6].

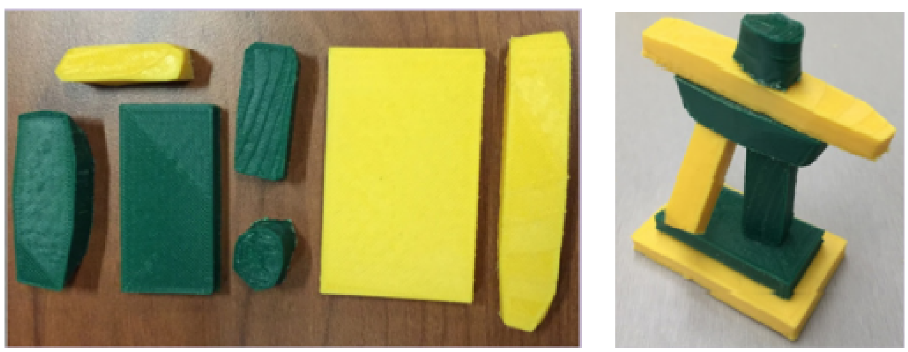
The cost of material is in many applications considerable and a lot of the material used is used for building additional support structures, which are removed and turned into waste after manufacturing. Developing methods for support slimming have the potential to reduce the cost of manufacturing. In Fig. 1.1 the result of a method developed to save material is shown and demonstrates the potential of support reduction algorithms.

Additive manufacturing technologies have provided an outlet for creativity in the "maker" community, due to their relatively low purchase and material costs [7]. Since AM requires no tools or molds, customization and flexibility comes with no additional costs [5].

Not every industry would benefit from converting its manufacturing into an additive one, so it is important to identify the applications where the benefits of AM can also be turned into additional value for producers and consumers [5].



(a)



(b)

Figure 1.1: Waste from support structures and proposed decomposition method. Images from [8].

1.1.2 Environmental sustainability consideration

Additive manufacturing technologies have the potential to change the existing models for product development [9]. If AM can be used to update, repair and re-manufacture parts, a possibility for large reductions in energy consumption, environmental emissions and manufacturing costs appears, which may have a significant impact on sustainability considerations of production

[9]. A lower cost for the manufacturing of customized products may contribute to reduced production of unnecessary products.

In AM technologies that require additional support structures, research have great potential in improving the sustainability of the production method. Producing a part generally leaves an amount of waste, often from machining to finish the part surface or to remove support structures. Fig. 1.1 illustrates how new methods for AM can reduce, if not eliminate, waste. Fig. 1.1 a) shows an object manufactured by a conventional 3D printer before- (left) and after machining (right). Fig 1.1 b) shows the same object being printed but with a method with objective of decomposing the volume and optimizing the print direction. No waste was produced in this latter case.

In order to reduce emissions and waste, [10] present a methodology for electric-, fluid- and raw material consumption assessment for additive manufacturing with aim to help engineers to design parts optimized for AM from an environmental point of view.

1.2 Contributions in the thesis

The following contributions have been made in this thesis:

- An introduction to the AM production cycle including some important historical events are presented and a classification of common AM technologies are performed

- AM applications and limitations are discussed and an overview of recent attempts on solving said limitations of traditional AM is presented

- Some basic robot terminology is presented and a literature study is performed on the use of robot manipulators in AM

- A method for using robotic AM to realize models using curved layers without the need for support structures is presented and discussed.

- Suggestions have been made for future work in areas related to what is presented in the thesis

1.3 Outline

Chapter 1 serves as an introduction to the preliminary project. The problem is presented together with some motivation as to why it is important to work towards a solution. Chapter 2 takes on AM in its most common form. Section 2.1 gives some historical background on the technology. Section 2.2 introduces the production cycle and processing pipeline of most AM technologies and presents some popular areas of application, while section 2.3 classifies the technologies together with some advantages and drawback of the different methods. Section 2.4 presents the identified challenges that limits the applications of traditional AM, while Section 2.5 presents the result of a literature review with aim of identifying promising solutions to the limitations with traditional AM. Chapter 3 concerns the use of robot technology in AM. Section 3.1 introduces some important robotic terminology and concepts. Section 3.2 studies some of the main advantages of the application of robots in AM. Section 3.3 present the results from a literature review on research concerning problems solved by robotic AM and highlight two approaches that obtain the same result but in different ways. One of the methods is presented in greater detail in Section 3.5 while Section 3.6 discusses some future applications of AM.

Chapter 2

Additive manufacturing

Additive Manufacturing is defined as the process of joining materials to make parts from 3D model data, usually layer upon layer [11], and is, together with Subtractive Manufacturing (SM) and Formative Manufacturing (FM), one of the three major manufacturing technologies of today [2]. As the definition suggest, AM processes are characterized by methods for increasing work piece mass, unlike SM which start with a full block of raw material and machines or mills away excessive parts or FM where a mould or a cast is filled with material to set inside it [12]. In the literature, AM is often referred to as 3D printing. Other names used is layered manufacturing [13], additive layer manufacturing [14], solid free-form fabrication [15] [16] and rapid prototyping [17].

2.1 Some historical notes

AM is a relatively new manufacturing technology. In 1981, the Japanese researcher Hideo Kodama performed and documented experiments showing that solid models of complex shapes could be fabricated by stacking cross-sectional layers [18]. This was the first documented attempt on using an AM technology. Two years later, in 1983, a 3D printer based upon the same principles as Kodama's experiment was developed by Charles Hull in the U.S. His intention was to develop a system for the fast manufacturing of prototypes in plastic materials with objective of speeding up the whole manufacturing process, which traditionally could take several weeks or months [19]. In 1986 he patented the technique and named it Stereolithography (SLA) [20]. In the time period after these pioneer approaches, many different AM technologies emerged on several geographical locations.

It was the invention of AM that enabled the emergence of Rapid Prototyping (RP) which is defined as the manufacturing of short-term prototypes using an additive manufacturing technology [21]. As a process for rapidly creating a system or a part before final release or commercialization [3], it is still a popular design tool. The name describes the time saving associated with the negation of the traditional human modeller, or tool maker employed to create the object for evaluation as part of the design process [12]. The term Rapid Prototyping stopped being synonymous with the term 3D printing when users started to realize that the term did no longer describe more recent applications of the technology [3].

From Rapid prototyping to Rapid manufacturing

AM was first developed to aid and support engineers and designers in their conceptualization of a design, being the only technology enabling the fast production of almost any shape or geometry [22]. It quickly surpassed more traditional subtractive and formative methods that were simply to slow to compete. With improvements in AM technology, the speed, quality, accuracy and material properties have all developed to the extent that parts can be made for final use and not just to aid prototyping [3]. It have made it possible to produce objects with unprecedented control over appearance, deformation, aesthetics and functionality [7].

The direct manufacturing of a part using AM is now possible [3] and businesses, both small and large, are currently exploring and adopting the technology for the manufacturing of end use parts [2]. The terms Rapid Manufacturing (RM) and Direct Digital Manufacturing (DDM) are popular to describe this use for AM. A shift from prototyping to manufacturing of the final product necessitates broadening of the material choice, improvement of surface quality, dimensional stability, and achieving the necessary mechanical properties to meet the performance criteria [23]. A useful by-product of Rapid Manufacturing is the almost unlimited geometrical freedom and that moving parts can be constructed in a single build, negating the need for assembly [12].

2.2 Traditional Additive Manufacturing

Systems for AM ranges from relatively low cost commercial 3D printers [24] to highly advanced and expensive industry equipment. Independent of which technology used, a product must often go through many of the same steps on its journey from being a conceptualization to becoming a fully realized model. This section presents the processing pipeline of a product being fabricated by a traditional AM technology and some popular areas of application.

2.2.1 Processing pipeline

A product typically goes through four successive phases of manufacturing: 1) conception, 2) design, 3) realization and 4) service [4]. The sequence of operations required to move from step 2) to 3) is referred to as process planning. The steps are explained in general terms below and different technologies may require more or less attention for a number of the steps [3].

Step 0: Conception - Obtain a digital model

Before the sequence of operations in the process planning can begin, we need an input to the process. The input to a digital manufacturing process such as AM, must be a digital model of the object one want to manufacture. This model is often realized by a digital model made by a Computer-Aided Design (CAD) expert [4]. CAD is defined as the use of computer systems to assist in the creation, modification, analysis or optimization of a design [25], and we will refer to the digital input model as a CAD model. An other alternative for obtaining a digital model is to use reverse engineering to realize a physical model in CAD, e.g. laser scanning [3].

Step 1: Computer-Aided Manufacturing (CAM) representation

To be able to fabricate the CAD model we first need a geometry description of the data which will serve as the input to the manufacturing process. This conversion outputs what is often referred to as a Computer-Aided Manufacturing (CAM) model [4].

The conversion from CAD to CAM can be done using a variety of methods. One common method uses the principle of tessellation. Tessellation is

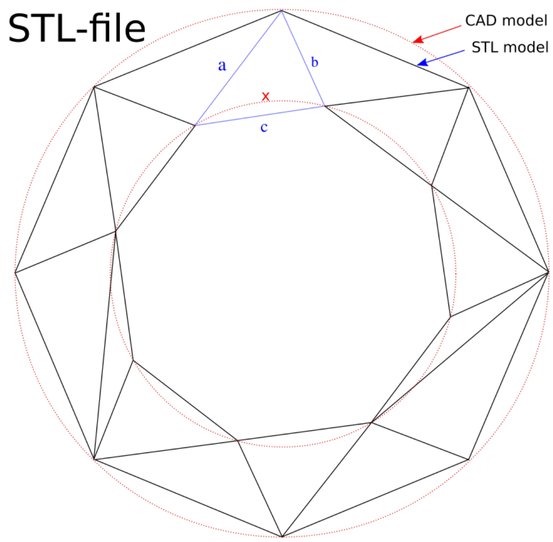
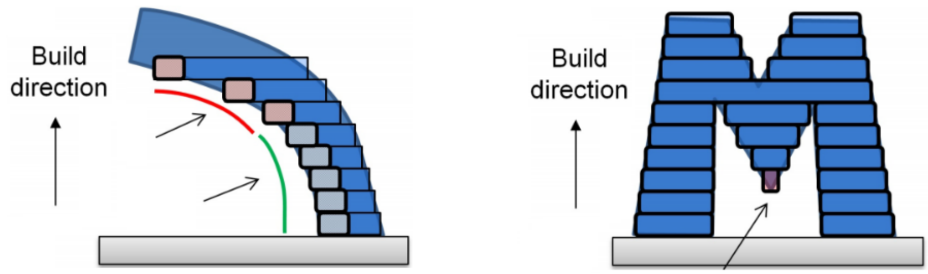


Figure 2.1: Tessellation of CAD model. Figure from [28]

a way to approximate a 3D body [26] by using a mesh of triangles [27], see Fig. 2.1. The tessellated model takes the file format STL and is accepted by most 3D printers [3]. It is important to note that tessellation outputs an approximation of the CAD model. The accuracy of the approximation of the model can be adjusted by the size of the tessellation triangles, smaller triangles will give a more accurate representation. An alternative method that gives a mathematically accurate description of the geometry data is the STEP file format [27].

Step 2: Determine build direction

After the model have been converted from CAD to CAM, the build direction can be calculated. AM is defined as fabrication performed layer by layer, so the build direction is crucial and directly influences important factors such as build time, necessity of support structures, surface quality and the functionality of the part [4].



(a) (b)

Figure 2.2: Regions that traditionally cannot be manufactured without additional support structures. Images from [4]

Step 3: Generate support structures

Many AM processes require support structures in order to fabricate the part successfully. Two examples of situations that require support is shown in Fig. 2.2.

Fig 2.2 a) shows a situation of large overhang. Due to the planar layering, the material will simply fall to the working platform unless it is deposited onto a previously cured layer. The threshold for when the material will stuck or not stuck to the previous layer is material- and method specific and is sometimes called a self-supporting angle [29]. Fig 2.2 b) shows one of the layers containing an island, a solid region that is not supported from below. The material forming this island will not be supported by already solidified or deposited layers and cannot in general be manufactured without support given this build direction.

Step 4: Apply slicing algorithm

This is the step where the 3D CAM model is to be divided into a set of layers, sometimes called slices [4]. In traditional AM we assume that the build direction z is aligned with the height of the model and the contours are usually constricted to be planar, but in reality the slicing algorithms are not limited to this methodology, as we will see later in the thesis.

Assuming for now that we are slicing the model into planar layers, most AM software apply algorithms that outputs a uniform division of the object, meaning that all layers have the same thickness or height. A commonly known problem this method sometimes introduces when the object is curved is the staircase effect, see Fig. 2.3. Thinner slices lead to a better finish, but also a more time consuming manufacturing.

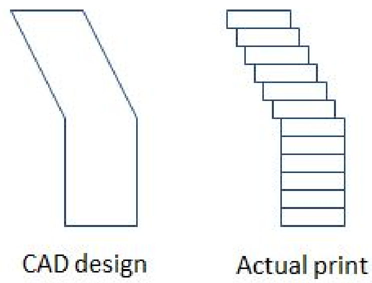


Figure 2.3: The staircase effect. Image from [30]

Step 5: Translate tool-path into machine instructions

The final step of the process planning is to determine the machine instructions that the fabrication tool must execute to build the part [4]. Each layer needs to be covered with material. The tool-path of the nozzle determines how the material is to be distributed on each layer.

Post processing

Post processing may include removal of support structures, machining or assembly of individual parts in order to obtain the finished product.

2.2.2 Applications

AM offers the potential for developing complex, customized products that is expensive to produce with other techniques [9], and was developed to aid engineers and designers in making new products, primarily through prototyping [3]. Through recent advances within the technology, it is also developing into being well suited for applications where end use parts of low quantity and high customizability is an advantage.

Unlike traditional manufacturing processes, AM technologies impose virtually no additional cost for near-arbitrary shape complexity and high frequency material variation [7]. If the market environment is characterized by uncertainty, high product variety or fluctuating customer tastes, the firms that are equipped with flexible manufacturing technologies such as AM may obtain an important competitive advantage [5]. The research team in [5] identify four patterns that characterize markets for AM: 1) small production output, 2) high product complexity, 3) high demand for product customization tailored to individual customers needs, 4) spatially remote demand for products. Automotive, medical, aerospace and military industries are all industries that require high precision an reliability, and they are all industries that benefit from AM technologies [31].

The research team in [9] present a timeline of significant developments for the use of AM techniques within different groups of society. Companies such as materialise[1] delivers 3D printing services on areas such as aerospace, aeronautics, automotive and healthcare. Some common applications is presented below.

Orthopaedics and medicine

The ability for AM to automatically manufacture complicated and personalised physical objects, objects that can be custom-fit to an existing person or object [2], make the technology highly applicable in medical [32] and orthopaedic setting. It is used for making anatomic models, surgical instruments and tools, splints, implants and prosthesis [32][33]. Data sets created from a medical imaging technology can be used as a basis for creating a CAD model as input to the AM process, making it relatively easy to make personalized products [32]. Companies like Brinter[2] and Organovo[3] are developing methods for 3D printing of functional biological tissue in cooparation with the medical industry.

[1] www.materialise.com
[2] www.brinter.com
[3] www.organovo.com

Aerospace industry

The aerospace industry suffers from an extremely high buy-to-fly ratio [34]. The ability to fabricate customized products from expensive raw materials makes AM highly applicable in the aerospace industry.

Construction

Automation of construction processes can simplify logistics, reduce construction time and decrease labour costs [35]. Companies like COBOD[4] use layered manufacturing to fabricate small buildings on demand. COBOD presents on their web pages the office space "The BOD" which they present as Europe's first 3D printed building., see Fig. 2.4. The BOD is short for "Building on Demand".

Figure 2.4: The BOD. Image from [36]

2.3 AM technologies

Many technologies based on the AM principle of stacking cross section layers of material have been developed since the technology's outspring in the 1980's. 3D printing is the most common and commercially used term for the technology, and often refers to extrusion based methods that make prototypes from heated polymers. This technology is only a small part of the extent of AM and in this section several other methods will be presented.

[4]www.cobod.com

2.3.1 Classification

Many ways of classifying the different AM technologies have been proposed. The author in [37] divided the AM processes into liquid-based, powder-based and solid-based systems. A different approach is based on a function framework where the methods is classified based on functional similarities [38].

The research team in [4] point out that all AM technologies mainly differ by whether they locally deposit material or whether they solidify material within a non-solid substance, and divide the technologies into material deposition- and layer solidification methods.

Material deposition

Additive manufacturing methods based on material deposition work by locally deposit material onto a plane or onto already cured material to create a new layer. The deposition methods can either deposit material along continuous or along discrete paths. Livesu et al. [4] divide the deposition methods into three categories: Material extrusion, Material jetting and Directed energy deposition.

Extrusion-based systems is based upon the principle that material contained in a reservoir is forced out through a nozzle when pressure is applied [3]. A majority of the AM processes developed for polymers and polymer composites are extrusion-based processes [39]. If a solid material can be presented in a liquid state, usually by heat or chemical reaction, it is likely to be suited for this process. A print layer is made from pressure through the nozzle and movement of the nozzle. If both nozzle speed and pressure are constant, and the material is in a semi-solid state, the system will make a cylindrical path of material with constant diameter. Once a layer is finished, i.e. when it is completely filled with paths of material, the nozzle either moves up by distance equal layer height or the build platform moves down the same amount. Fused Deposition Modeling (FDM) patented by company Stratasys[5] [40], or Fused Filament Fabrication (FFF) which the method is sometimes called [41], is the most common material extrusion technique [3]. It makes parts from heated polymer.

[5] www.stratasys.com

Material jetting creates objects similar to how 2D prints are created with an ink jet printer [42]. Material drops is deposited from a horizontal moving nozzle and onto a surface. The material layers are then cured using ultraviolet (UV) light.

Directed energy deposition is defined as a process in which focused thermal energy is used to fuse materials by melting as they are being deposited. Metallic wire or powder is fed directly into the focal point of an energy beam. As the metal is being melted by the energy beam, it is deposited onto previous layers. One method using this process is the Laser Engineered Net Shaping (LENS), developed in 1995 [9] [15]. This method melts powder onto a solid substrate to build the layers. Similarly, we have Electron Beam Freeform Fabrication (EBF), which is a method using a metal wire as food to the process in stead of powder [16].

Layer solidification

Some methods realize models by the solidification of a non-solid material, such as powder or liquid, typically within a tank [4].

The method of Stereolithography (SLA) mentioned in Section 2.1 is a layer solidification method and is based on the vat photo-polymerization technique [4]. A photopolymer is a polymer that changes its properties when exposed to light [43]. Most often in vat photo-polymerization processes, UV light is used to cure photopolymer in a vat, or a tank [44]. The light either cures material on the top of the tank or through a transparent bottom [45]. The cured material sits on a platform which is being lowered down into the tank or risen up from the tank a fixes amount after each layer is completed.

Powder bed fusion is a different solidification process that uses powdered material as food to the process, and uses either a laser or an electron beam to melt material powder and create the individual layers. Examples of methods using this process is the Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Direct Metal Laser Sintering (DMLS), Selective Heat Sintering (SHS) and Selective Laser Melting (SLM) [46].

Similar to the deposition method Material Jetting, Binder Jetting deposits material onto a platform. The difference is that the material deposited is a binder, and is selectively deposited onto a powder bed ready for solidification. The binder works as a glue and binds the covered areas together forming a layer [47]. Common materials used for this method are metals, sand and ceramics.

2.3.2 Advantages and drawbacks

Material deposition have the advantages of the ability to combine multiple materials, while a drawback of layer solidification is that it is more challenging to build a part with mixed materials [4].

The printing time in deposition methods are mostly dependent on the part volume, while the printing time in solidification methods is more impacted on the height (number of layers) of the volume because the printing of each layer is faster than the process of preparing for next layer [4].

A major advantage of the layer solidification methods is the reduced need for support structures on complex geometries [4]. In deposition, material can only be deposited on a previous deposited layer, meaning that there is a strong need for support structures, which is a drawback of this method [4].

2.4 Challenges in AM

Through studying literature, challenges concerning some, or all, of the AM technologies have been identified. The true flexibility of AM cannot in general be fully utilized until solutions for these challenges have been found. Many solutions have emerged as the manufacturing discipline have grown in size.

In this section, the challenges will be introduced.

2.4.1 Size

Most AM facilities have a closed fabrication platform which limits the size of the object to be printed [48]. Many AM systems are also gantry systems, meaning that the printing tool is mounted onto an overhead system and is only allowed a motion in Cartesian x- y and z- direction. Gantry systems are typically heavy and constrained to their internal workspace [49]. In Fig. 2.5 we see an image of a commercial FDM 3D printer. This image demonstrates that the chamber volume, which is the workspace of the system, impose constraints on how large the object to be manufactured can be. We encounter the same problem in solidification methods, see Fig. 2.6. What we see is a schematic drawing of how the solidification method SLA works. The volume of the tank holding the liquid and the weight of the liquid itself are constraining factors in this case.

A common "workaround" for this problem is to either scale up the size of the systems so that the chamber- or tank volume gets larger or to decompose the object before printing and have a separate assembly phase after manufacturing. However, these are not very flexible solutions for the additive fabrication of large scale structures.

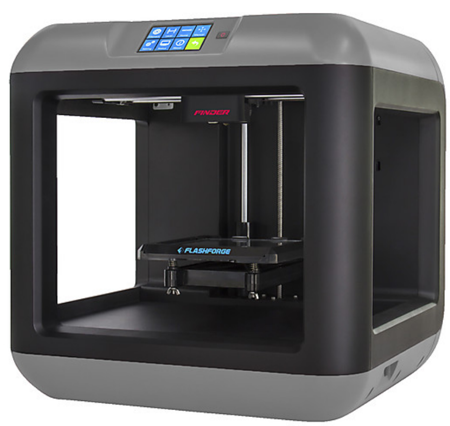


Figure 2.5: Commercial 3D printer. Image from [24]

2.4.2 Support structures

AM systems based on deposition strategies are traditionally only able to print in a 2.5D manner, meaning that all layers are constrained to be printed on top of already cured material. An attempt to deposit material in mid-air would

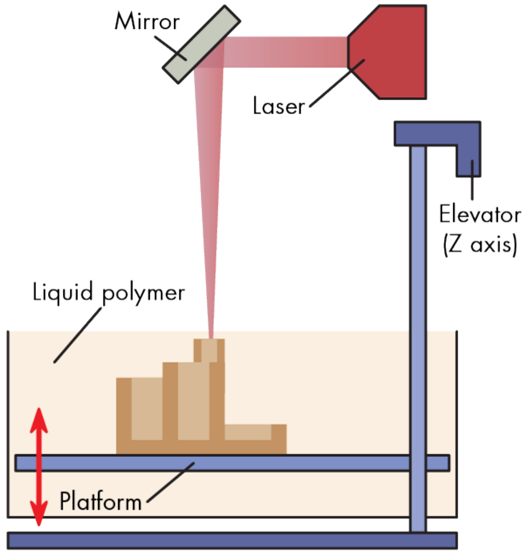


Figure 2.6: Schematic drawing of SLA method. Image from [50]

due to gravity simply result in the deposited material falling to the ground. A common "workaround" for this problem is to calculate and add support structures in the digital model wherever needed, e.g. below overhangs and islands such as in Fig. 2.2, and print the support structures together with the part.

There are many ways support structures can be realized. They can be in the same material as the part or in a different one, e. g. in a dissolvable material. When the support material is dissolvable, it can be removed easily by a post-process. If the support material isn't dissolvable or it is made from the same material as the print, we are faced with some problems. If the volume of printed support structures is large compared to the actual build, which it sometimes is, the study in [29] shows that up to 63.3% of the manufacturing time in FDM could be spent on fabricating the support structures. In addition to time spent, we would also have substantial amounts of waste material from the process, which is bad for both cost and the environment.

2.4.3 Quality of part

The availability of printing resolution (e.q. nozzle size) imposes a limitation on the printing accuracy, layer thickness and surface smoothness [48]. Orientation of the part within the machine can also affect part accuracy [3]. Many methods with objectives of finding the optimal build direction have been developed. The research team in [51] presents in their paper a review study on the role of build orientation in layered manufacturing. They found that the most important factor when choosing build orientation is the quality of the surface finish followed by dimensional accuracy, build time and support structures.

When slicing a curved object, we are in reality approximating the surface with a stack of layers along the printing direction [4]. This introduces what is typically called the staircase or stair-step effect, see Fig. 2.3. It is the discrete nature of the layers that often introduce this phenomena and it can be reduced by selecting appropriate process parameters such as the layer-height. Unfortunately, thinner layers result in longer build-times [52].

Removal of support may also lead to poor surface quality [3]. After fabrication external support structures are chemically or mechanically removed [4]. The surface of the object is easily damaged during this process [29].

2.5 An overview of research

This section will present some attempts on solving the challenges identified in Section 2.4. Even though the research teams often aim to solve one isolated problem, sometimes the solution give improved results in other areas as well.

2.5.1 Size

Additive techniques are normally used to make small components, on the ”desktop” scale [53]. The advantages of traditional AM are still present at large scale [54], but large scale AM is a relatively new field of research. The research team in [54] propose a large-scale 3D foam printing system which uses a 6 DOF cable-suspended parallel mechanism for positioning which can construct any 3D geometry. A gantry-type system is here used for positioning of the deposition tool, so even though it can successfully print large models, it is not very a very flexible system.

The main application of large-scale AM, and where the most of the research is focused, is in the automation of construction processes [54]. In construction, every structure is often unique in dimension so traditionally either standard size materials are cut down to fit specifications or moulds are created to form each component [53]. Companies are now exploring the market's interest for 3D printed buildings.

2.5.2 Support structures

Large overhangs can easily collapse under gravity [29]. In traditional AM, designers often manually change the shape of a design in order to make the individual parts of the object be self-supportive. This is done to limit the amount of additional support structures needed for manufacturing. The research team in [29] try to find a method to automate this process and present an orientation-driven shape optimizer to slim down the supporting structures used in single-material based AM. The method tries to deform an input model so that it have a shape that needs less support without losing important details of the original model. The method assumes that some deformation of the model is possible, which may exclude some important areas of applications and makes the method have a setback in terms of relevance.

Demir et al. [8] propose a divide-and-conquer approach, which have been an important approach in fabrication for decades, for 3D printing which utilizes the properties of near-convexity. First, a model is decomposed into a low number of near-convex components. The components should all consist of only horizontal faces or faces with a larger angle than a printer-defined threshold. Letting the components be near-convex as opposed to convex reduces the complexity of the problem from being NP-hard and results in fewer components. The second phase is called the configuration phase, which aim to reduce printing time by laying the components out for printing so that all element can be printed in one go. After manufacturing, the model is assembled from the individual components. The report demonstrates that the approach reduces the consumption of printing resources and improves printing quality. One of the experimental results can be found in Fig. 1.1.

2.5.3 Quality of part

Many techniques have been developed for the production of high-quality 3D printed end use parts, but more studies are still required to improve their systems and quality [31].

Adhesive strength between layers (or across filaments) of parts made by FDM is less than the strength of continuous filaments (longitudinal strength) [13]. In extrusion based techniques, the paths of the layered material can be considered as the building units of the process. The properties and performance of the finished product is strongly affected by the tool-paths [23] which becomes an important factor in determining the quality of the part, both aesthetically and mechanically [14].

A general agreement among many researches is that the mechanical properties of printed elements are closely related to which manufacturing technology was used and that it can vary significantly depending on production parameters such as printing temperature, velocity, and infill density [55]. The research team in [55] considers some mechanical properties of polymers commonly used for prototyping and obtains experimental results for evaluating the materials. Stava et al. [56] propose a method for detection and correction of major structural problems in 3D models before they are printed while simultaneously minimize altering of the appearance. The method is similar to the one for support slimming in [29] in the way that it also optimizes the shape of the model.

Livesu et al. [4] defined the term fidelity as the degree of exactness with which a part has been reproduced starting from its design. Events like the staircase effect explained in Section 2.4 contribute to a reduced level of fidelity. In a number of cases, proper choice of orientation of the part in the FDM chamber may eliminate some of the above mentioned drawbacks [13].

Several papers have explored printing in curved layers as a mean to improve the fidelity and the structural properties of a printed part. The research teams in [13], [57] and [14] develop different methods for AM using curved layers.

Back in 2008, Chakraborty et al. [13] presented a new technique developed for rapid prototyping named Curved Layer Fused Deposition Modeling (CLFDM) which they argue to be more suited than FDM in the manufacturing of thin, curved parts. By depositing material in curved-non hoizontal layers using FDM, they investigate the manufacture of curved, thin parts. With small curvatures, this method may be realized using a 3DOF machine, but if the curvatures are large it would need 5DOF, such that the extruder axis can always coincide with the normal of the curved surface at the point to be manufactured. In [57] a project with objective of building a machine capable of constructing a part by deposition of material as curved layers is presented. By modifying a Fab@Home desktop RP machine and developing of algorithms, dynamic z-values was utilized. The research team in [14] propose an automated method for the generation of curved layer tool-paths.

Chapter 3

Utilizing robot manipulators in AM

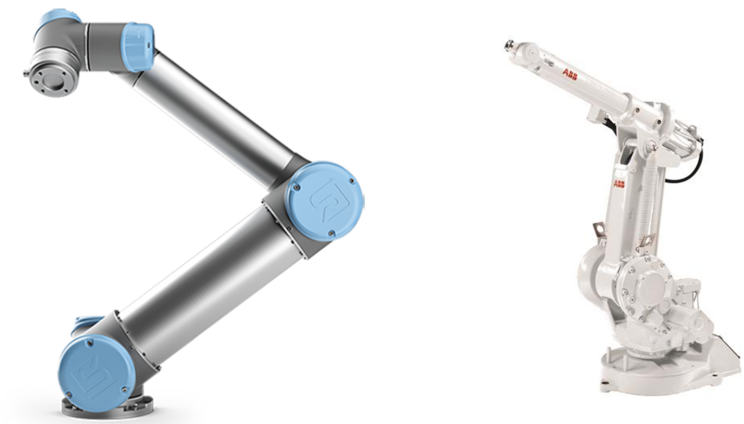
In order to really benefit from the geometrical flexibility of AM, the use of several multi-axis systems have been studied. In literature it is mostly the deposition of material in more than three directions that have been studied. Many of the solidification methods is not only limited by the movement of the printing tool, but also greatly by the vat containing a liquid or the platform holding some powdered material. In addition, some of the problems we see in deposition methods, e.g. concerning support, are not problems when it comes to solidification methods.

The scope of this chapter will be on deposition methods and on how objects can be additively manufactured using a six axis industrial manipulator, a robot arm used in many industrial applications.

3.1 Robotics

3.1.1 What is a robot?

Robot Institute of America (RIA) defines a robot as a "reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks". In this thesis the term robot will refer to a mechanical arm operating under computer control, sometimes called a computer con-



(a) UR5 [59] (b) ABB IRB 1410 [60]

Figure 3.1: Typical 6 DOF industrial manipulators

trolled industrial manipulator [58]. Fig. 3.1 shows industrial manipulators from two different companies, both having the ability to move around six axes.

3.1.2 Some terminology

The book "Robot modeling and control" by M. W. Spong and colleagues [58] defines some robot terminology. Some important concepts is presented in short below.

Links and joints

An industrial robotic manipulator is made up of joints, either revolute or prismatic with links between them. To be of any use, it also need an end effector, a hand, to carry what ever tool it may need to use in order to perform its tasks.

End effector

An end effector is the device attached to the end of a robotic arm and is designed to interact with the environment [61]. It holds the tool that actually performs the specified task of the robot [58]. The end effector can take any shape or form. In many applications it has form as a gripper, in AM it may be a deposition nozzle or a laser.

Position and orientation

We are often interested in describing the position of the end effector together with its orientation in order to specify the positioning of the tool. The links and joints of a robot manipulator forms a kinematic chain and the position is described in terms of the joint variables of the joints that make up the arm. The joints between the arm and the end effector is referred to as the wrist [58]. The joint variables of the wrist describes the orientation of the end effector.

The configuration space

The configuration space of a robot is the set of all possible configurations of the robot, where one configuration is a complete specification of the location of every point on the manipulator, typically described by joint variable values, often either degrees or linear displacement.

Degrees of freedom (DOF)

An object is said to have n degrees of freedom if its configuration can be specified with minimum n parameters. For a robot manipulator, we may count the number of joints to deduce the number of DOFs.

The workspace

The workspace of a manipulator is the total volume made up of all single point the end effector can reach. To be able to reach any rigid object in the work space, the robot needs to possess at least 6 DOFs.

3.2 Advantages of robot manipulators in AM

Compared to conventional gantry systems, industrial robots have the advantage of workspace flexibility and adaptability [49]. By mounting a printing tool, e.g. a deposition nozzle, a laser or a printing platform, onto the wrist of a robot arm, we get a new and improved AM system.

Regardless of which AM technology is used, traditional configurations often consist of a 3DOF positioning system enabling for translational printing in the x, y and z directions, aligned with the axes of a Cartesian coordinate system. By introducing some additional axes, the system obtains some important advantages over the traditional configurations. In [62], some of these advantages have been studied. With a nozzle attached to the wrist of a robot arm with more than 3DOFs, the nozzle head motion also have multi-DOF. This means that deposition can happen along multiple directions. The research team also points out the ability for the system to print on a base surface at any inclination, even up-side down, as opposed to only horizontal surfaces. The company Mataerial[1] is experimenting with robot manipulators and the deposition of fast curing materials.

The application of robot manipulators in additive manufacturing enhances the flexibility and intelligibility of the technology [63]. A strength with multi-DOF systems is that a variety of tools can be attached to the wrist of the robot arm, enabling for many different AM technologies to be performed by the system, not only material extrusion [49]. This also opens for the application of robot manipulators in subtractive and formative fabrication, a combination of two or all technologies together.

The workspace of a robotic manipulator can accommodate parts larger than the arm itself and can also access interior regions that are not possible for a gantry-based machine [35].

The use of robot manipulators in AM also enables for the cooperation of more than one machine building on the same part. Zhang et al. [64] propose a 3D printing system based on a team of mobile robots printing a single-piece concrete structure concurrently. An other example of this can be found in Fig. 3.2, where we see a bridge which is printed in metal designed by Joris Laarman Lab[2] in cooperation with MX3D[3]. It is printed by a team of robot manipulators. The art and construction project is installed over a canal in

[1]www.mataerial.com
[2]www.jorislaarman.com
[3]www.mx3d.com

the city of Amsterdam.

Figure 3.2: The MX3D bridge designed by Joris Laarman Lab

3.3 Literature review on AM by robot manipulator

With the help of additional degrees of freedom, more possibilities for 3D printing are being explored [65]. Robot arms allows for a part to be built along more than one direction [62], making the technology more flexible than it is traditionally. In the following, some recent research on the use of robot manipulators in AM is presented.

3.3.1 Large-scale structures

We know that unlike traditional AM systems, the workspace of a robot manipulator can accommodate parts larger than itself [35]. A lot of the literature on the printing of large scale structures are concerned with applications in the field of architecture and construction. The use of AM techniques to create buildings would change the cost of manufacturing buildings to be based on total raw material cost, rather than on geometric complexity [35]. Due to the extensive cost and labour of building concrete walls, design tend to be simple and repetitive in order to keep expenses at a low level [66].

Full size walls

The researchers in [35] propose a system for constructing customized architectural-scale structures on-site. The prototype of the system presented in the article, named Digital Construction Platform (DCP), is composed of a 4 DOF hydraulic arm and a 6 DOF smaller electric arm which is attached to the endpoint of the other, mounted on a mobile platform. Also developed for applications within construction, the research team in [67] present a FDM-like technique for layered manufacturing of ultra-high performance concrete. The system consist of a deposition nozzle mounted on a 6 DOF robotic arm and demonstrates the ability for producing large-scale structures without temporary support.

Formwork and reinforcement structures

The research team in [68] argues that cementitious materials are not ideal for fast, precise and geometrically unconstrained extrusion. On the basis of this, they work on The Mesh Mould research project, which aim to develop a robotically fabricated construction system that allows for a cost and material efficient fabrication of geometrically complex concrete constructions. The project aim to develop a new approach for large scale digital fabrication which include using a robot manipulator in the production of formwork and reinforcement structures of concrete walls. An early prototype can be seen in Fig. 3.3 and serves as a demonstration of the concept.

3.3.2 General free-form models

The research team in [69] suggest that to overcome the limitations of layer-based manufacturing, research needs to take along the directions of 1) adding more DOF into motion and 2) optimizing shape or direction of fabrication. The following research presented have taken along both directions and have obtained some very promising results on the additive manufacturing of general free-form models, i. e. models of arbitrary shapes.

Many papers on AM use decomposition methods to reduce the need for support structures. Here, two methods based on volume decomposition and planar slicing is presented followed by a method that decomposes the model into curved layers based on a dimension reduction strategy.

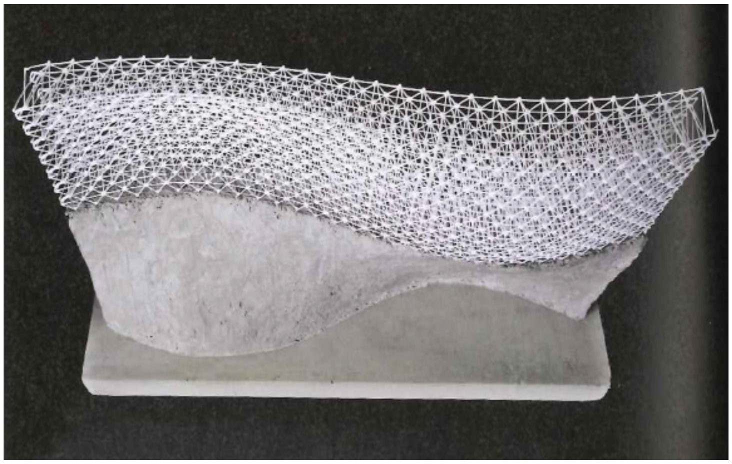


Figure 3.3: Robotically printed mesh prototype half way filled with concrete. Image from [66].

Taking advantage of the ability of robotic AM to print in different directions, the research teams in [34], [69], [65] and [70] proposes different strategies to print general CAD models in multiple directions by first decomposing the model into parts that can be printed individually, completely without or with reduced use of support structures. By changing the orientation of the part during manufacturing, these methods can be used to produce parts with areas that traditionally would require support structures. Unlike the decomposition methods from Section 2.5.2 these methods do not require a separate assembly phase.

The methods in [69], [65] and [70] are realized using the same physical system. A printing platform is attached to the wrist of a UR3[4] 6DOF robotic arm and a deposition nozzle is fixed on a frame above the robot arm with platform. The methods is demonstrated using the deposition of heated polymer. The method in [34] is developed for deposition methods using metal wire.

[4]www.universal-robots.com

Volume decomposition strategy

The basic idea of the work in [69] and [65] is to decompose a volume into individual segments and to find a "good" orientation for each part so that layer based accumulation of material can be performed without adding support structures. Cutting planes are used to decompose the volume and printing directions d_i that needs to be perpendicular to each plane $\mathcal{P}_i$ is found. Each segment is sliced in uniform layers and deposition of material can happen as in traditional methods. During fabrication, the platform is stationary, i.e. standing completely still. Moving all degrees of freedom together during the process of fabrication need relative expensive devices and control systems [65], therefore the methods are developed so that the platform only have to move between the deposition phases. When a segment is finished, the platform changes its configuration, and a new segment can be fabricated on top of the last segment.

The methods in [69] and [65] mainly differ in how the volume is decomposed. The method in [69] is based on extracting a 1D skeleton from the digital input model and decomposes it by determining regions close to the branches of the tree structure. A skeleton extraction method based on the work in [71] is used for this. To be decomposed by this method, the part needs to have a skeletal structure. For models that do not have this structural property, the method in [65] have been developed. This method searches for a decomposition of the volume such that all faces on a sub-region are safe according to a definition using a pre-determined self-supporting angle from [29]. For a given model $\mathcal{M}$, the sequence of manufacturing is determined by searching for a sequence of clipping planes that progressively decompose $\mathcal{M}$ into N components.

One of the results from the report in [65] can be seen in Fig. 3.4. Part a) of the figure shows a kitten printed using a conventional FDM 3D printer, while part b) shows the same model printed using the decomposition method. The model have been successfully manufactured without any use of additional support structures. The surface finishing and structural properties however may be poorer with the decomposition method.

(a) (b)

Figure 3.4: Kitten model printed in polymer. Images from [65]

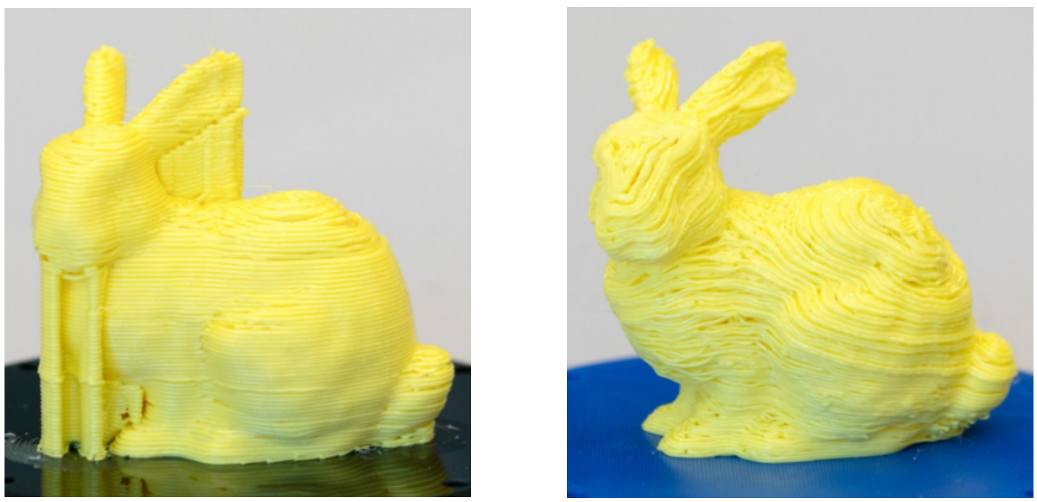
Dimension reduction strategy

The method of [70] is presented as a two step method, where step 1 is to perform a volume-to-surface decomposition and step 2 is to perform a surface-to-toolpath decomposition. The first step of the method reduces the dimensionality of the problem from three to two dimensions, and the second step reduces the dimensionality further, from two dimensions to one dimension.

First, a sequence of curved layers is extracted from the three dimensional volume. The layers is in the next step covered by tool-paths.

The input to the algorithm for generating the individual layers is a voxel representation of the CAD model and it is assumed that material accumulation is performed by adding voxels one by one. A voxel is the three-dimensional analogue of a pixel, a volume element representing some numerical quantity [72]. In this context, this numerical quantity is a point in three-dimensional space. The voxel representation is a discretized version of the original model.

The result of the method proposed by the research team in [70] can be seen in Fig. 3.5. It is displayed together with the same model printed using a commercial FDM 3D printer. The object is again attached to a moving platform and is produced by movement around a fixed deposition nozzle. The method uses curved tool-paths to produce each individual layer enabling a general volume with large overhangs to be printed in one session without added support structures.



(a) (b)

Figure 3.5: Bunny model printed in polymer. Images from [70]

3.4 A closer look at the dimension reduction strategy

The method in [70] enables for the support-free 3D printing of solid models and seem to generate some of the best results currently in this area of research. In this section some of the considerations the algorithms have to take is presented followed by some limitations and the results generated.

3.4.1 Important considerations

Determining self-supportive regions

A self-supported region is an overhanging region that can be printed without adding support structures [29]. In [70] they take a voxel approach and formulate a support-free constraint as:

> **Constraint 1** (*Support-free*) A voxel can only be accumulated if one of its ASNs have already been solidified.

To understand this constraint, we need to know what an ASN is. An ASN is an AM-stable neighbour to the current voxel, defined as:

> **Definition** Two voxels, $v_{i,j,k}$ and $v_{r,s,t}$, are defined as *AM-stable-neighbours* (ASN) if $||(i,j,k)-(r,s,t)||_1 \in \{1,2\}$

An illustration of the concept in two dimensions can be found in Fig. 3.6. A voxel is AM stable to another voxel if the 1-norm, sometimes referred to as the Manhattan distance, the distance between two points measured along right angles [73] is equal to numerical value 1 or 2.

The p-norm is defined as:

$$||\mathbf{x}||_p = \left(\sum_{i=1}^{n} |x_i|^p\right)^{\frac{1}{p}} \tag{3.1}$$

Let (i,j,k) be the coordinate of the center of the current voxel and (r,s,t) be the coordinate of the center of the voxel to be evaluated. Then we have the 1-norm as:

$$\begin{aligned} ||(i,j,k)-(r,s,t)||_1 &= ||(i-r,j-s,k-t)||_1 \\ &= |i-r|+|j-s|+|k-t| \end{aligned}$$

Which can easily be evaluated numerically.

The rotational capabilities of a 6DOF system is reflected by the support-free constraint when noting that is allows for accumulation of voxels on all sides of the current voxel.

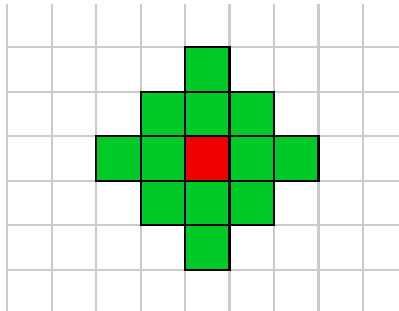


Figure 3.6: Current voxel in red together with its AM-stable neighbours in green.

Ensuring accessibility for tool

The support-free constraint do not take into account accessibility of the voxel, or the printability of the part of the volume. It is required that the printing tool can actually reach the point in space it is going to fill with material, so the accessibility constraint ensure that the nozzle can reach every current voxel.

The constraint of accessibility is formulated as:

> **Constraint** (*Accessibility*) When adding a new voxel to a set of already fabricated voxels $\mathcal{V}$, the motion of the printer head should not collide with $\mathcal{V}$.

This constraint depends on system- and method specific properties like the size and shape of the printer head, the sequence of material accumulation and the local geometry of the working surface [70]. A volume may consist of several hundreds of thousands of voxels, so performing collision-detection explicitly on all voxels can be extremely time consuming. Therefore, the research team uses a conservative approach. Convex shapes are more printing-friendly [8], so a surface that will always be accessible no matter how thin or thick the printer head is, is the convex hull of the body, denoted $\mathcal{C}(\mathcal{H})$. An illustration of the convex hull in two dimensions i shown in Fig. 3.7. The convex hull is the minimum convex surface including every point in a space. Being a conservative approximation of the accessible working surface, the convex hull is determined as sensible to use for collision-avoidance.

Before a voxel is added to a layer, the algorithm checks if it is outside the convex hull of the platform and previous fabricated layers, named as the convex front. If it is, it can be accessed by the tool and manufacturing of this voxel is possible. Material accumulation is always performed on the convex-front. All accumulated voxels in a layer is added to what is called the Growing field $\mathcal{G}(\cdot)$

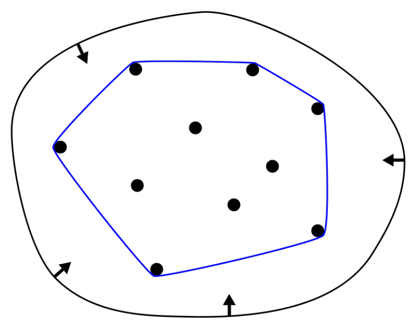


Figure 3.7: Illustration of the convex hull (blue line) in two dimensions. Image from [74]

Tool-path planning

In [70], a three-step algorithm is used to compute a continuous deposition path. In the first step, an exact geodesic boundary distance-field is built over the curved surface $\mathcal{S}$. This is done by *Fast-Wavefront-Propagation* (FWP) from [75]. Next, iso-contours is constructed over the surface mesh. Iso-contours are closed curves having the same iso-values. The final step is to generate a 3D Fermat spiral tool-path following the principles from [76].

After a continuous deposition path have been successfully generated, an algorithm that determines the tool orientation at every point must be applied.

3.4.2 Limitations

The current system have a some limitations. In Fig. 3.8 we see that the frame on which the nozzle is fixed, impose constraints on the workspace of the manipulator. In this system, the arm have to consider where the frame is and avoid collisions with it. Secondly, the size of the object have to fit

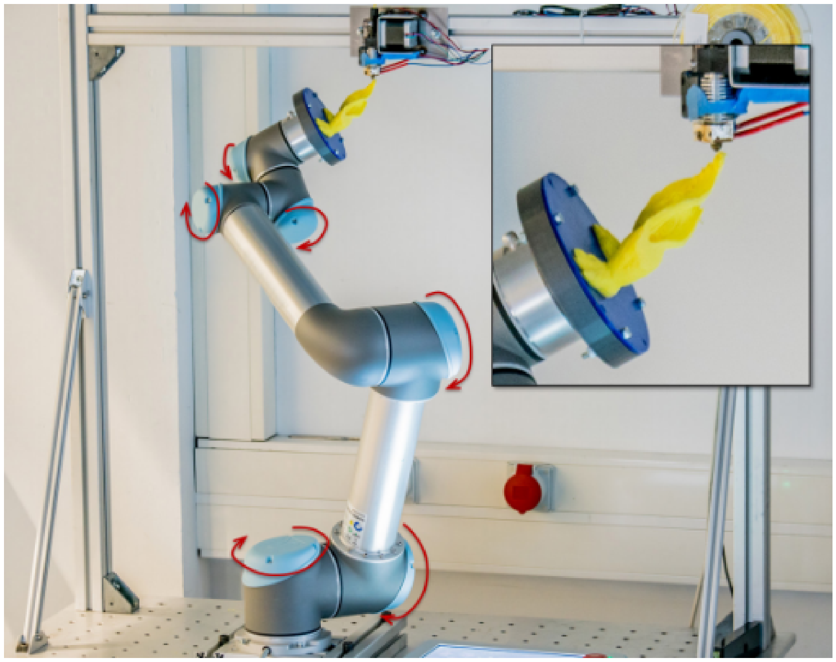


Figure 3.8: AM system using 6DOF robot arm with attached printing platform. Image from [77]

on the printing platform, which is relatively small. So this setup is currently limited to the fabrication of small and light-weight objects.

3.4.3 Results

The research team developed three methods for voxel accumulation which all generated different results on the test models: Greedy scheme for Convex-front advancing (GCFA), shadow prevented(SP) GCFA and peeling-governed(PG) SP-GCFA. The best results in terms of tradeoff between computation speed and quality of part was obtained by the latter approach.

The printed objects exhibit some errors. The main reasons referred to by the authors for these errors is based on hardware position error, non-uniform layer thickness and gaps between tool paths.

3.5 Future prospects

The researchers in [9] discusses some trends and challenges in AM and say that we are emerging towards a third industrial revolution and that many companies are now rethinking how traditional manufacturing will be transformed. The uses for robotic arm systems in digital fabrication are growing and will continue to grow due to their flexibility and size advantages over gantry-style positioning systems [49].

3.5.1 Mass customization

The traditional way of manufacturing is to produce a large quantity of identical products and sell with price depending on the size of the batch, the larger the batch, the cheaper the product will be for consumers. If a product is specifically designed to suit the needs of a unique individual then it can be said to be customized [3]. Customization used to be expensive. The direct digital workflow and free-form geometry of AM can be combined to fabricate objects with any degree of customization and enables for the production of mass-customized products that can be produced with infinite variations [2].

Due to its ability to directly involve customers in the design step, AM technologies can contribute in the customization of products [9]. Since AM build parts directly from digital models, customization is possible at lower cost. Web based design-tools such as TinkerCAD[5], freeCAD[6] and Shapeways[7] gives customers the opportunity to be directly involved in the design of products, enabling for highly customized manufacturing.

3.5.2 Robotic digital fabrication

Research teams are working to promote new ways of working and interacting with robotic fabrication systems.

Researchers at Massachusetts Institute of Technology (MIT), US, are developing a new approach to fabrication which they coin as Compound Fabrication [49]. They propose and demonstrate a multi-functional robotic arm

[5]www.tinkercad.com
[6]www.freecadweb.org
[7]www.shapeways.com

platform capable of both additive, subtractive and formative fabrication, taking advantage of the manipulators ability to change end-effector tool. The main benefit from such an integrated manufacturing technique comes from the ability to process a single work piece using multiple effectors without having to re-fixture, re-calibrate or be operated by humans during any part of the processes.

3.5.3 Robotic construction

The authors in [49] envision mobile systems with robotic arms capable of "swarm construction", meaning that many smaller robotic platforms work together on large, complex construction missions.

The DCP platform presented in section 3.3.1 and similar systems have the potential to revolutionize construction and a key step forward is the integration of the platform into existing construction workflows and the ability for it to be completely self-sufficient [35].

Chapter 4

Summary

Manufacturing technologies based on the layering of material are limited by several factors, including its inability to in general fabricate large scale structures, its dependency of additional support structures which have negative impact in terms of wasting material, and by structural properties which are strongly dependent on the choice of AM technology. This thesis have presented some approaches that show promising results within robotic AM. Advances in research concerning the use of robot manipulators in AM opens for a more flexible and intelligent production environment which do no longer suffer under the limitations of traditional approaches. Some pioneering companies have already adopted these systems, and as the technology gains more attention, more solutions may follow and contribute to a new production paradigm where customization serves as the common production strategy.

Chapter 5

Further work

Suggestions for further work related to the methods and results of [65] and [70] follows.

- By replicating some or all of the results from the papers, it may be possible to detect limitations or restrictions in the methods not yet identified by the authors
- Perform a comparison of the results of [65] and [70] in terms of structural properties of the parts and aim to detect differences in weaknesses and strengths in the fabricated models
- Investigate if the methods can become more flexible (e.g. be applied to large scale structures) by changing the configuration from fixed to moving deposition nozzle

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