

New Slicing Methods and Support Structure Reduction Methods in Robotic Additive Manufacturing

by

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**New Slicing Methods and Support Structure Reduction Methods in Robotic
Additive Manufacturing**

Koç University

Graduate School of Sciences and Engineering

This is to certify that I have examined this copy of a doctoral dissertation by

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To my Father Bülent, Mother Nilgün, Sisters Melis, and Esra. For a healthy, prosperous, and peaceful future without COVID-19.

ABSTRACT

Additive manufacturing (AM) has developed to be an essential part of the manufacturing sector since it significantly changes traditional production systems in machining tools, assembly processes, and supply chains. AM can deliver low quantity parts on-site, within hours, and without investment costs of dies and molds. The field of AM is rapidly developing to fill the voids found in traditional methods of manufacturing. With the introduction of robots into AM, new possibilities are getting unlocked. Compared to conventional 3-axis AM systems, robots have larger build volumes, more degrees of freedom for changing the AM end-effector orientation, and the possibility of changing the end-effector to a gripper to manipulate the manufacturing process.

This thesis proposes new methods to minimize support structures by introducing modular support structures and dynamic support structures. In modular support structures, the robotic arms gripper end-effector stacks pre-fabricated reusable support structures under the model. Two models were simulated, and the results are compared to the conventional methods to verify the improvement of the proposed strategy. With this method, the material used can be reduced by 75% on average, resulting in a reduction in fabrication time. In dynamic support structures, an array of actuated pins that move in the build orientation act as support structures. Modular support structures and dynamic support structures help obtain faster manufacturing times. They reduce support structures and thus lower the material costs and material waste.

With added degrees of freedom, parts can be manufactured in a non-planar manner to achieve new capabilities. This thesis introduces non-planar slicing algorithms of Helical, Spherical, and Cylindrical slicing. These are generalized algorithms requiring minimal user input and are applicable for any complex freeform CAD model. The proposed slicing methods are verified by fabricating parts using fused filament fabrication (FFF) end effector but are not limited to only FFF.

The introduction of Helical AM, Spherical AM, and Additive Turning methods help reduce the stair-stepping effect. Helical slicing reduces the defects in each layer where the extrusion starts and finishes. SEM images of the helical layers have been shown to verify the reduction in defects. The spherical slicing method slices the model with spherical shells, analogous to the shells of an onion. It generates a toolpath containing a three-dimensional position and the corresponding orientation. The proposed spherical slicing method is verified by fabricating the CAD model of Earth. Matlab and C++ have been used for coding the given methods. The algorithms perform well in an average modern laptop.

The Cylindrical Slicing method slices any complex model using cylindrical slicing layers. With the Cylindrical slicing method, a new Additive Turning Method can be introduced. Additive turning deposits parts on a rotating cylinder, instead of the conventional planar build bed. With Additive Turning, support structures were minimized and even eliminated for certain models. Since the way the material is deposited is changed, the manufactured parts' structural properties also change. Tensile testing results show that additive turning has achieved %30 higher tensile strength in comparison to conventional planar slicing methods. It is also demonstrated that stair-stepping effects have been minimized for certain models. Several models have been manufactured to verify the proposed method.

ÖZETÇE

Eklemeli imalat yöntemi, üretim yöntemlerinde, montaj süreçlerinde ve tedarik zincirlerinde, geleneksel üretim sistemlerini önemli ölçüde değiştirdiği için imalat sektörünün önemli bir parçası haline geldi. Eklemeli imalat, düşük adetli parçaları, birkaç saat içinde, sahada, kalıp gibi yatırım maliyetleri olmadan teslim edebilir. Eklemeli imalat, geleneksel üretim yöntemlerinde bulunan boşlukları iyileştirmek için hızla gelişmektedir. Robotların eklemeli imalata girmesiyle, yeni olasılıkların önü açılıyor. Geleneksel 3 eksenli eklemeli imalat sistemlerine kıyasla, robotlar daha büyük inşa hacimlerine, eklemeli imalat uç efektör yönünü değiştirmek için daha fazla serbestlik derecesine ve üretim sürecini manipüle etmek için uç efektörün bir kavrayıcı ile değiştirilmesi olasılığına sahiptir.

Bu tez, modüler destek yapıları ve dinamik destek yapılarını sunarak eklemeli imalatta destek yapılarını en aza indirmek için yeni yöntemler önermektedir. Modüler destek yapıları çalışmasında, robotik kol, modelin gereken bölgelerine önceden imal edilmiş yeniden kullanılabilir destek yapılarını istifler. Bu yöntem kullanılarak iki model simüle edildi. Bu yöntemle malzeme kullanımı ortalama %75 oranında azaltılabilmekte ve bu da üretim süresinde kısalmaya neden olmaktadır. Dinamik destek yapıları çalışmasında, inşa yönünde yukarı aşağı hareket edebilen bir dizi pimden oluşan dinamik destek yapıları, destek görevini üstlenir. Sunulan modüler destek yapıları ve dinamik destek yapıları çalışmaları, daha hızlı üretim süreleri elde edilmesine yardımcı olur. Ayrıca kullanılan destek yapılarını azaltırlar ve böylece malzeme maliyetlerini ve malzeme israfını azaltırlar.

Robot ile gelen ek serbestlik dereceleriyle parçalar düzlemsel olmayan bir şekilde de üretilebilir. Bu çalışma düzlemsel olmayan, helisel dilimleme, küresel dilimleme ve silindirik dilimleme algoritmalarını tanıtır. Bunlar algoritmalar herhangi bir karmaşık CAD modelini üretmek için kullanılabilen, minimum kullanıcı girdisi gerektiren genelleştirilmiş algoritmalar. Sunulan dilimleme yöntemleri, erimiş filament fabrikasyon yöntemi ile parçaların üretilmesiyle doğrulanmıştır, ancak kullanım alanı FFF ile sınırlı değildir.

Helisel eklemeli imalat, küresel eklemeli imalat ve eklemeli imalat yöntemleri, parçalardaki merdiven basamağı etkisinin azaltılmasında yardımcı olur. Helisel dilimleme her katmandaki başlangıç ve bitiş noktalarındaki kusurları azaltır. Tarayıcı elektron mikroskobu ile elde edilen görüntüler, kusurlardaki azalmayı doğrulamıştır. Küresel dilimleme yöntemi, bir soğanın katmanlarına benzer şekilde, modeli küresel yüzeyler ile dilimler. Dünya modelinin üretimi ile önerilen küresel dilimleme yöntemini doğrulanmıştır. Bahsi geçen algoritmalar Matlab C++ kullanılarak kodlanmıştır. Bu algoritmalar modern ortalama bir laptopta koştuğunda iyi performans sergilemektedir.

Silindirik dilimleme yöntemi, herhangi bir kompleks modeli silindirik katmanlar kullanarak dilimler. Silindirik dilimleme yöntemi, eklemeli torna yönteminin de önünü açar. Eklemeli torna malzemeyi düz plaka yerine dönen bir silindir üzerine sermektedir. Eklemeli tornalama ile destek yapıları en aza indirilir ve hatta belirli parçalar için ortadan kaldırılır. Parçanın serilme yönünün değişmesiyle parçanın mekanik özellikleri de değişmektedir. Eklemeli tornalama, geleneksel düzlemsel eklemeli imalat yöntemlerine kıyasla daha yüksek çekme dayanımlarına ulaşan parçalar üretebilir. Çekme testleri sonucunda eklemeli torna yönteminin geleneksel eklemeli imalat metotlarından %30 daha güçlü parçalar çıkarabildiği gözlemlenmiştir. Eklemeli tornada merdiven basamağı etkisinde de azalma görülmüştür. Farklı modeller ile önerilen yöntem doğrulanmıştır.

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Chapter 1

INTRODUCTION

This thesis presents the work accomplished by The Robotic Additive Manufacturing (RAM) Setups in Manufacturing and Automation Research Center (MARC), Koç University, Turkey. Two separate six degrees of freedom (6-DOF) industrial robotic serial manipulators have been retrofitted with additive manufacturing (AM) end effectors and custom external controllers. The use of robotic manipulators has extended the AM domain by bringing together the capabilities of the robots and AM [1]. The first chapter of this thesis presents a brief overview of the RAM and the current study's motivation.

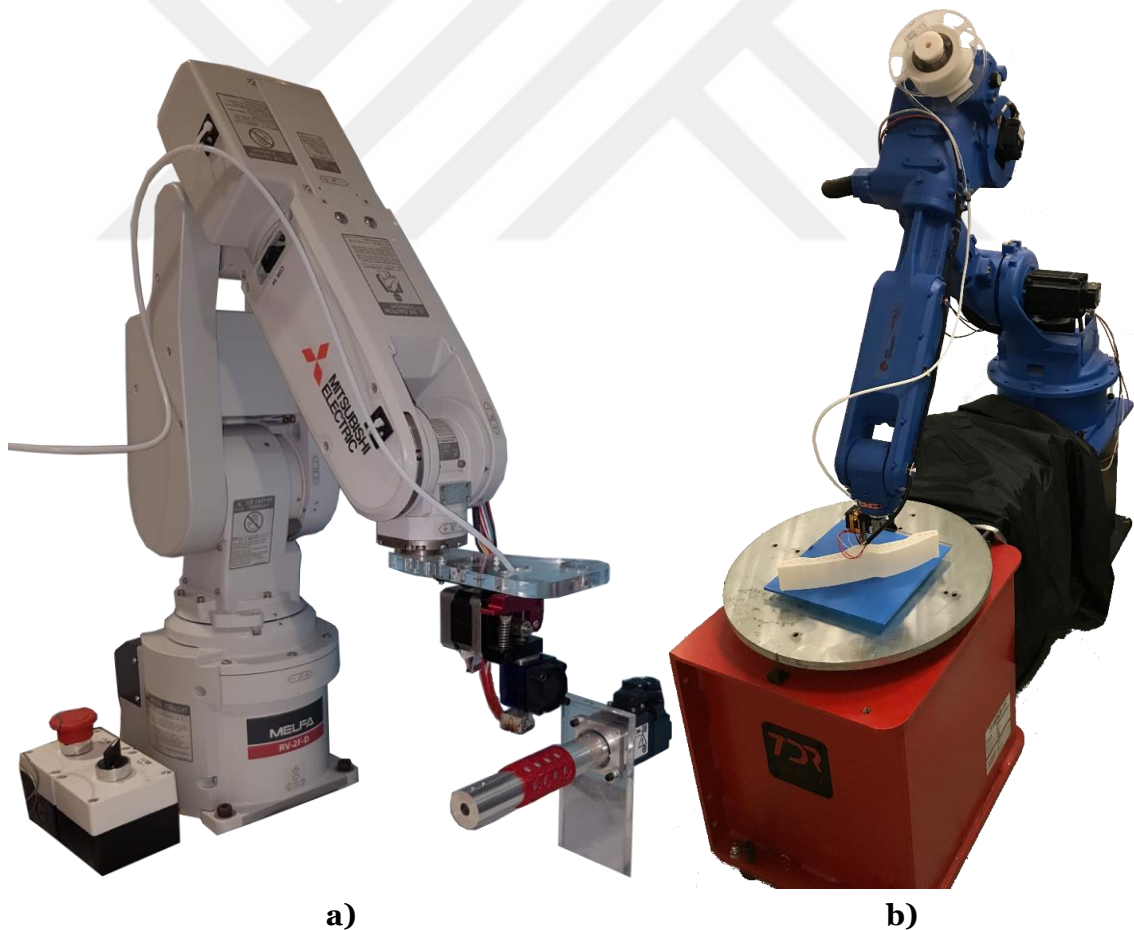


Figure 1. Robotic additive manufacturing setups: a) The Mitsubishi Melfa RV-2F Robotic Additive Manufacturing Setup. b) The Yaskawa Motoman HP20D Robotic Additive Manufacturing Setup

Manufacturing is the process where raw materials are transformed into desired final products using different fabrication methods [2]. Every year, new manufacturing methods are developed, and the current ones are advanced. Subtractive manufacturing has been the conventional way of fabricating products. In subtractive manufacturing, the parts are manufactured by removing material from a given stock and obtaining the final product. In recent years advances in AM have increased its adoption. It brings a revolution in how products are designed, manufactured, and delivered to end-users [3].

AM manufactures part by material addition. The AM methodology benefits include freedom in design, removal of tooling requirements, and low volumes, which are economically viable [4]. In AM, the material is selectively deposited layer by layer to form the desired final product. These layers are obtained by slicing the given computer-aided design (CAD) model of the product. Very thin layers slice the CAD model by the slicing software. These slices are then converted to a toolpath, which the machine can understand.

Slicing and the generated toolpath is different for different types of AM systems. AM methods are categorized as given in Table 1. This thesis employs fused deposition modeling (FDM), also known as fused filament fabrication (FFF), under the material extrusion category [5]. This FDM process is developed in 1992 by S. Scott Crump [6]. The classification of AM is given in Table 1. AM has been successfully employed in a wide range of sectors including, aerospace, automotive, biomedical, defense, and construction [7].

Table 1. Classification of additive manufacturing processes by ASTM International [5]

CATEGORIES	TECHNOLOGIES	PRINTED “INK”	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	• High Accuracy and Details • Fully dense parts • High specific strength & stiffness • Powder handling & recycling • Support and anchor structure • Fully dense parts • High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)		Electron Beam	
	Electron Beam Melting (EBM)			
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	• High building speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	• Multi-material printing • High surface finish • Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosities on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	• High surface finish • Low material, machine, process cost • Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	• Repair of damaged / worn parts • Functionally graded material printing • Require post-processing machine

Models are sliced by using dedicated slicing algorithms. These algorithms, in general, accept Stereolithography (STL) data of the CAD model. STL files describe an object's 3D geometry through a set of adjacent triangular facets [8]. The conventional way is slicing the model with equidistantly placed planes. The space between any two consecutive planes is referred to as a slice [9].

The FFF end effector shown in Figure 2 is attached to the Yaskawa Motoman HP20D robot arm using a custom-manufactured print head adapter. The filament, which is located on a spool on the robot arm, is pushed into the hot end by the feeding mechanism. This mechanism is powered by the feeder stepper motor, which is driven by the feeder stepper controller. The heating element heats the hot end, and the temperature is measured by a thermistor located next to the heating element. When the filament has melted at the desired temperature, it is extruded out of the extruder nozzle on to the manufacturing bed. The system is cooled down with the help of the fans and the neck. Mitsubishi Melfa RV-2F robot arm has been fitted with an identical setup.

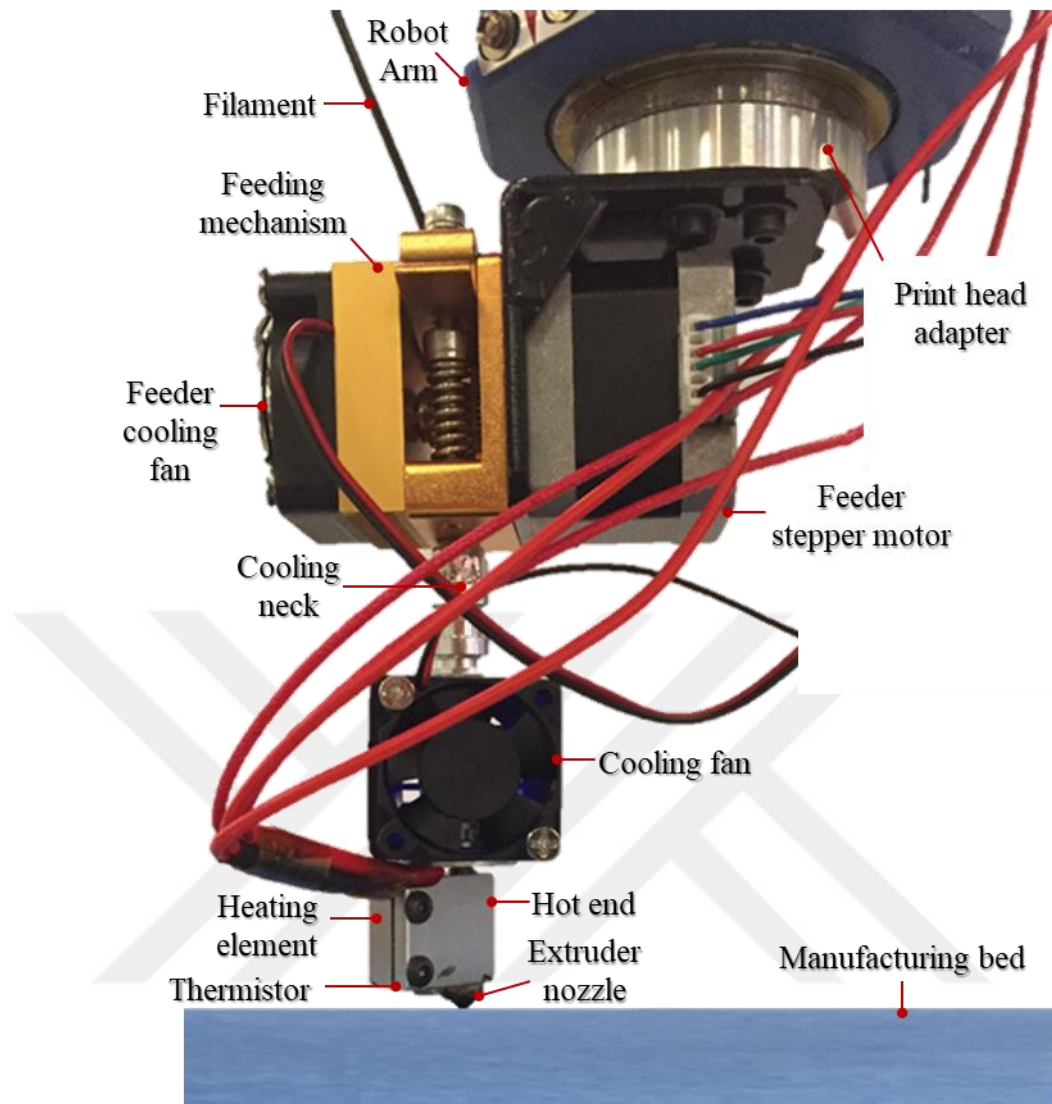


Figure 2. Fused Deposition Modeling Setup of The Robotic Additive Manufacturing Setup

The RAM process is controlled by the controller, given in Figure 3. The robot arm has six servos attached to its serial links. These are controlled by the servo packs located in the Motoman NX100 controller. The NX100 accepts commands from the Raspberry Pi Main controller. This controller is responsible for managing the Job files inside the NX100. It is also the controller that starts, stops, and pauses the printing process. The NX100 sends commands to the Arduino controller via the NX100 I/O port. The Arduino is responsible for the hot end's PID temperature control via the print head I/O. The Arduino also controls the feeder stepper motor based on the signals from the NX100 via the feed stepper controller.

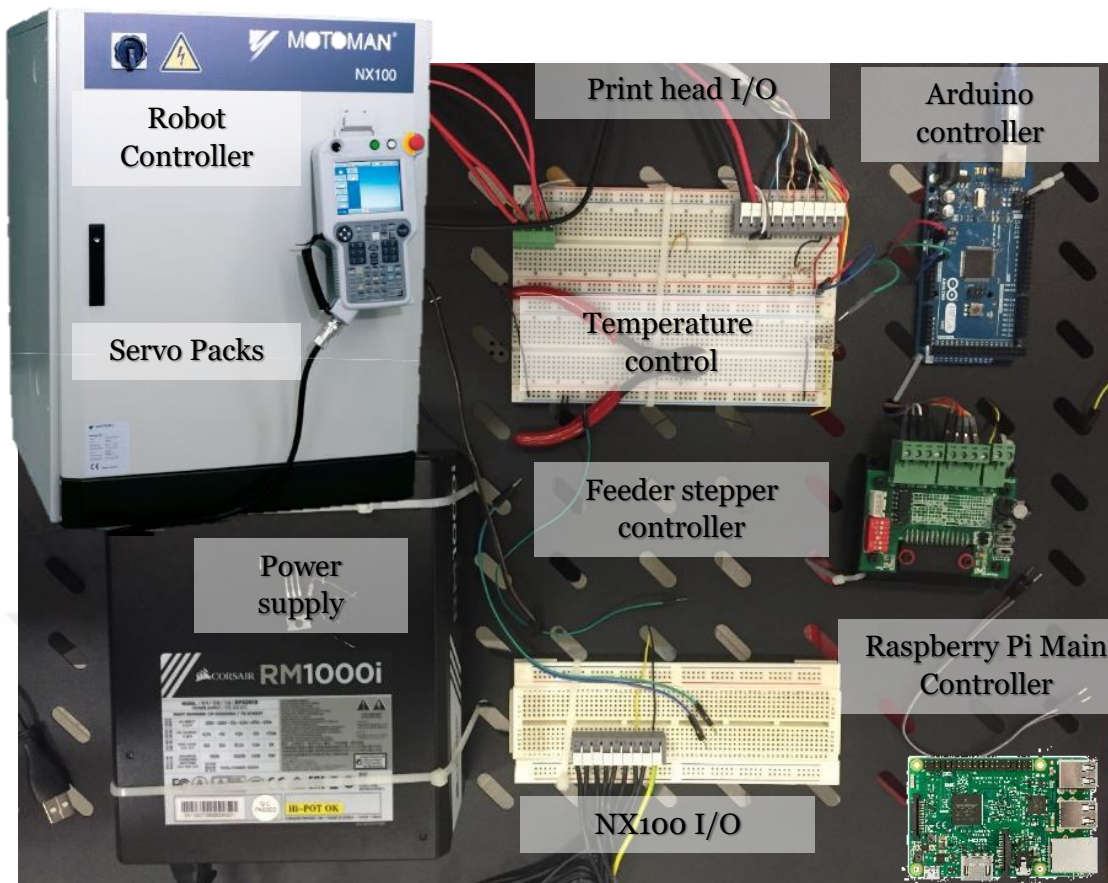


Figure 3. Controller of The Robotic Additive Manufacturing Setup

Serial robotic manipulators have larger build volumes compared to conventional 3-axis AM systems. The build reach of the Motoman robot used in this thesis is given in Figure 4. The added degrees of freedom of the robot enables the changing of the orientation of the FFF end-effector. Thus, the RAM setup can deposit in orientations other than the single perpendicular orientation found in conventional systems. This change of orientation can be observed in the work presented in chapter 5 and chapter 6. The possibility of changing the end-effector to a gripper for manipulation of the manufacturing process is possible. In chapter 3, a gripper system is proposed where a modular support structure system is employed.

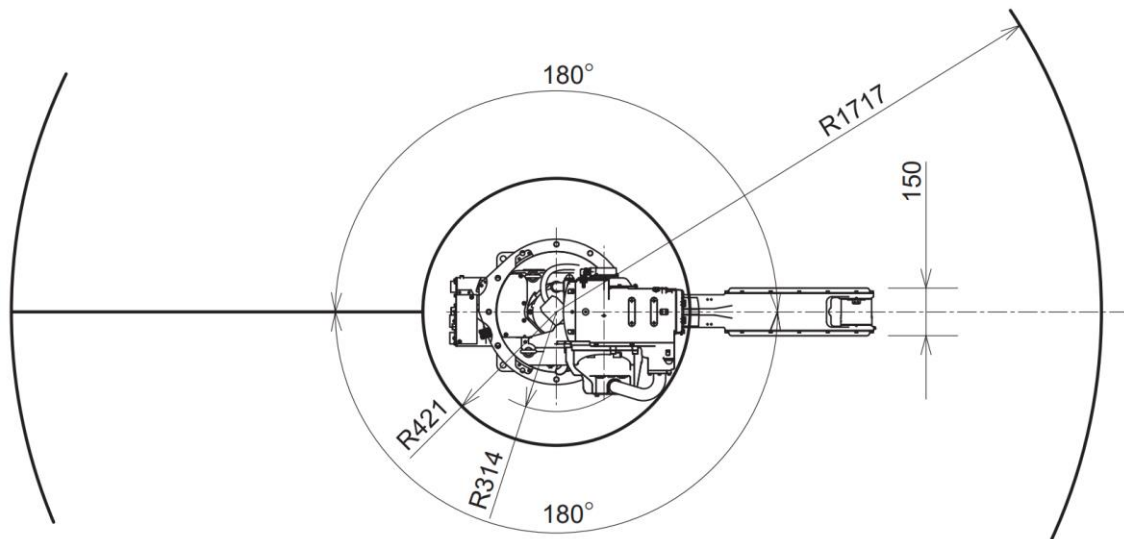


Figure 4. P-Point Maximum Envelope of the Yaskawa Motoman HP20D Robotic [10]

The stair-stepping effect is a widely observed phenomenon common to all layer-based AM processes. This phenomenon is due to discretization, e.g., a stack of layers causes "stair steps" on slanted or curved surfaces. So, the layer-wise nature of most AM processes causes edges of layers to be visible. In processes such as material extrusion, the individual filaments can be visible by the naked eye. [11]. Post-processing procedures such as sanding, acetone vapor bathing, or machining can remove this phenomenon [12]. Some of the work presented throughout this thesis attempts at minimized and even removed the stair-stepping effect.

AM is perceived as environmentally friendly and sustainable since it produces less material waste than conventional subtractive manufacturing. Additional support structures are often needed, which leads to material, time, and energy waste. Therefore, the reduction of support structures is of great importance for the future and further development of AM [13]. This thesis presents several attempts to reduce the support structures and, thus, lower costs, lower material waste, and reduce manufacturing times.

The inter-layer bonding between consecutive layers will result in weaker tensile strength in the build orientation than the other two axes. This weakness is due to the layer-wise nature of AM. Especially parts printed in an upright orientation will reduce the overall tensile strength [14]. The additive turning presented in this thesis attempts to solve this problem by introducing linear infills that span in the build orientation.

Figure 5 visualizes the information flow to fabricate a final part from the given CAD model on a RAM setup. The first step is to obtain the CAD model. In the next step,

the dedicated slicing algorithm, such as the ones introduced in this thesis, slices the given model [15]. Then the toolpath is generated using the slice data. This is saved as a G-code. If it is required, the inverse kinematics are solved for the generated G-code. Then the G-code is translated into the dedicated language of the robot. This language is Inform III for the Motoman and Melfa Basic V for the Mitsubishi. After this, the manufacturing process can start. Finally, the robot follows the provided instructions and manufactures the model.

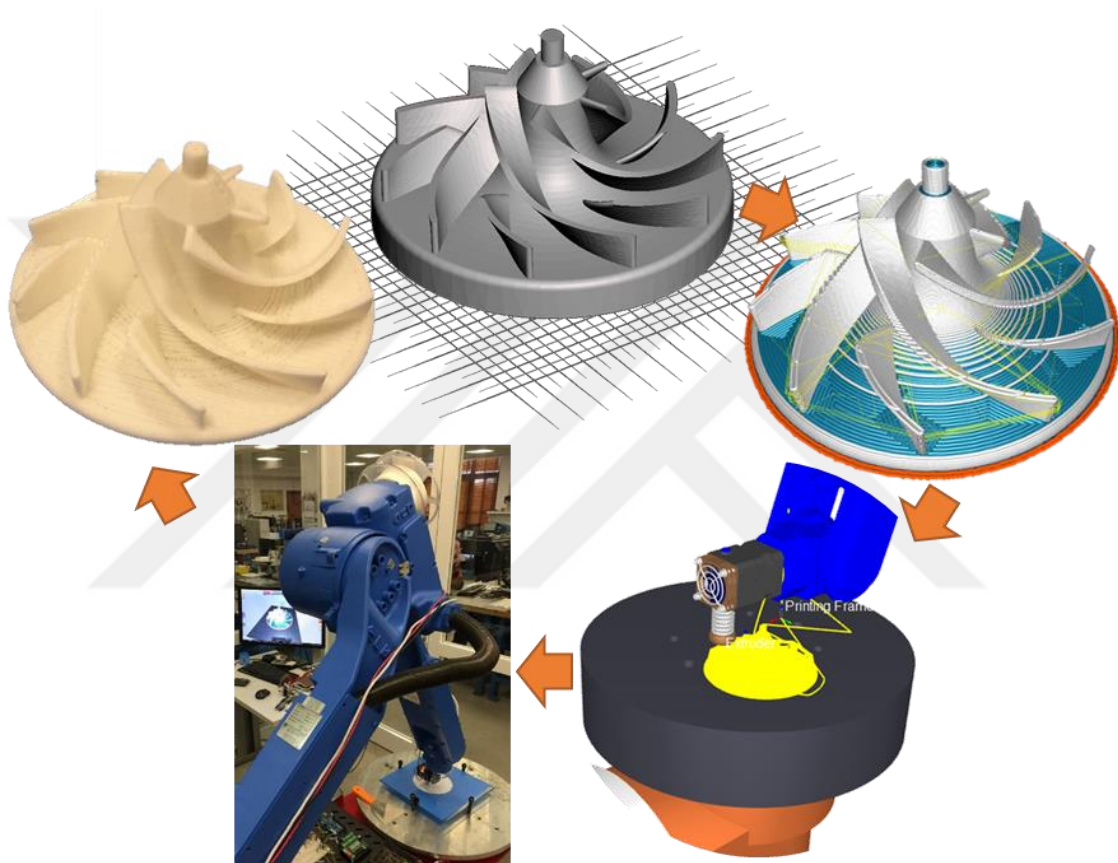


Figure 5. The information flow visualized to fabricate the Impeller part from the given CAD model on a RAM setup: 1) Obtain CAD Model 2) Slice the CAD Model & Generate G-code 3) Solve Inverse Kinematics & Translate G-code to Inform III Robot language JOB files 4) Manufacture with the JOB files 5) Obtain the Physical Impeller Model

The literature has recently started investigating the issues related to AM applications with robots and non-planar slicing methods. However, most commercially available AM systems are still 3-axis Cartesian coordinate robots or gantry systems [16]. The combined use of robot systems and AM technologies offers multi-axis additive manufacturing and the fabrication of unconventional, complex geometries in different manufacturing environments [1].

Wu et al. used the 6-DOF UR3 robotic arm to produce polymeric parts from polylactic acid (PLA) in a filament form, with minimal or no support structures. A computational tool was developed in C++ language to decompose the models into multiple supportless sub-models, printed in a collision-free order. Printing directions are determined by the software based on the defined decomposition strategy [17].

Similarly, Zhang et al. employed an ABB robot to control a filament extrusion-based manufacturing head. A computational platform, Robot Studio by ABB, was used to allow process fabrication simulation, optimization, and visualization. ABS parts were manufactured, but the system can be modified for other materials such as carbon fibers to produce composite parts [18].

Fry et al. have proposed a multi-axis additive robot manufacturing system (ARMS) based on two robot arms and a FFF extruder. The work proposes a Denso VS-068 6-axis robot arms precisely located on a 1.5 x 1.5m steel anti-vibration base plate, adding up to a 12-axis system. ARMS can manufacture steeply curved parts using conformal layers, leading to significantly greater strength than conventional AM. [19].

Zhao et al. have proposed a feature-based five-axis additive manufacturing methodology that automatically recognizes the input model's features. A KUKA KR6 robot is used for the implementation of the five-axis additive manufacturing tasks. The proposed path planning algorithm was tested through the experimental results of the three manufactured models. The results validate the feasibility of the feature-based five-axis path planning method that extends the AM technology to accumulate freeform layers, not limited to planar domains [20].

This thesis is presented in chapters where each chapter from chapter 2 to chapter 7 presents the introduced RAM setups' one unique application. Each of these chapters has been published in a respected conference or a journal. Chapter 2 provides tooling for composite structures that are manufactured with RAM. This method lowers costs and manufacturing times. Chapter 3 and chapter 4 studies the support structures problem. Chapter 3 reduces support structures by proposing a modular support structure system and chapter 4 reduces supports by utilizing a dynamic build bed system. Chapter 5 introduces the first non-planar AM of this thesis, the helical slicing method. Chapter 6 introduces one of a kind spherical slicing method, and chapter 7 introduces the cylindrical slicing method and the accompanying additive turning. Finally, with chapter 8, the thesis is concluded.

Chapter 2

Robotic Additive Manufacturing of Tooling for Composite Structures

With benefits like high specific stiffness, high specific strength, high fatigue strength, and high corrosion resistance, composites have become the go-to material in the transportation industry [21]. The aerospace industry was among the first industries to realize these composites' high-performance benefits, especially those of the carbon fiber for unmanned aerial vehicles, rockets, and satellites. Today composites make up fifty percent of the total aircraft weight in the new Boeing 787 Dreamliner, while this was only twelve percent for its predecessor [22]. With such advancements, the Dreamliner will be able to fly more economically while reducing its environmental impact.

Since composites are relatively more expensive than their counterparts, the automotive industry still has time to realize the full potential that composites have to offer. The main drive for composites in the automotive industry comes from weight reduction. The heavier the vehicle is, it will have higher fuel consumption and lower range. With fuel efficiency regulations getting stricter and the range demand for electric cars increasing every day, it is in the industry's best interest to reduce weight. For that, they are investigating affordable carbon fiber applications.

The raw carbon fiber takes the desired final shape with the lay-up on a mold (also known as tooling). The tooling used for laying the composites such as the carbon fiber reinforced plastics (CFRP) is generally made from various metals such as aluminum, steel, or invar. While metal tooling takes months to manufacture and prepare for lay-up, additive manufacturing (AM) tools are manufactured and are ready in hours. AM tools also cost a fraction of the metals and can be tested and iterated for optimized designs. Thus, design cycles are accelerated. For a small tool given in Table 2, over 90% of cost and time reduction is obtained, whereas a 75% reduction is obtained for large tooling in Table 3 [23].

Table 2. Time and cost comparison of a small tool (~1.8 meters long) [23]

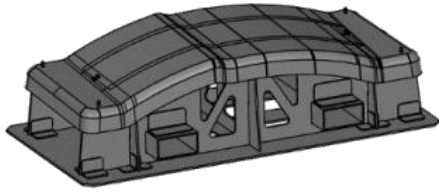
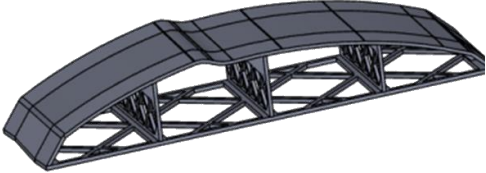
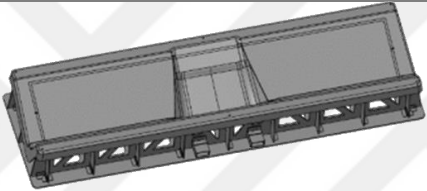
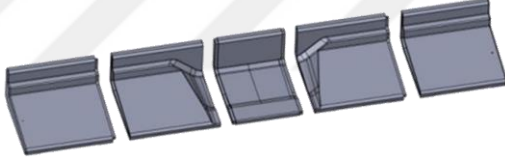
		Cost	Build Time	Weight
Existing Tooling		\$40-60K	10-14 weeks	More than 69 kilograms
AM tooling		\$25K	2 weeks	Less than 6.8 kilograms

Table 3. Time and cost comparison of a large tool (~4.5 meters long) [23]

		Cost	Build Time
Existing Tooling		\$80-120K	15-20 weeks
AM tooling		\$25K	2 weeks

Contrary to traditional subtractive manufacturing, in AM, the computer-aided design (CAD) data on the computer is manufactured by adding material in layers where each layer is a cross-section of the part derived from the original CAD data [24]. The most significant advantage of AM is direct part production without the need for tooling. Its use for rapid manufacturing of tooling to keep pace with faster composite part design cycles, cheaper costs, and the demand for faster overall manufacturing times is also one of the growing trends in the aerospace and automotive industries [25]. Other than tooling, AM can also support the production of composite parts along the whole process chain ranging from tooling to post-processing. Türk et al. have demonstrated the use of AM in additional fields reported as integrated positioning and fixation elements, lay-up and handling aids, structural curing aids, and post-processing aids [26].

Accordingly, it is possible to create complex, optimized tooling directly from CAD models instead of milling them from solid materials, as is frequently done today.

However, since AM is a relatively new field, and AM for tooling is even more recent, design concepts are still driven by producing components with traditional subtractive manufacturing processes [3]. These design concepts lead to additive manufactured tools that are conservatively designed, which means they are composed entirely of solid material. However, AM permits control over how the part will be manufactured, such as its interior fill strategy. By selecting the optimal infill for a given part, manufacturing time, as well as material consumption, can be minimized while obtaining the requirements for CFRP tooling [27].

With AM tooling, repairing the defects on the tool is made available. A 3D scan can capture part surfaces, either with a contact device like a coordinate measuring machine (CMM) or a non-contact laser scanning device. The scanned data is converted into a solid model. After that, the data can be given to an AM machine to quickly manufacture the missing part of the tooling for a replacement part [25]. The tool's defective part is cut away with an angle grinder and replaced with the newly manufactured replacement. It is then spot welded with a hot air welder and sanded down until it is flush with the rest of the tool. The sanded surfaces are then coated with epoxy and sanded again. With this process given in Figure 6, the tooling can be used for several more cycles.



Figure 6. AM Tool repairing process [23]

One of the challenges in traditional AM of tooling is the size limitation due to limited machine build space. It was previously solved by manufacturing the tools in segments, which increases the complexity and the person-hours required to finish the job. This challenge can be resolved with RAM, which has high reach distances and vast build spaces compared to conventional cartesian machines.

Another challenge is the temperature. The tools must withstand the heat cycles which are required for the curing of the epoxy. Also, the Coefficient of thermal expansion (CTE) should be low to achieve accurate final geometry. It is desired that the CTE of the

tool is equal to that of carbon fiber. This desire can be compensated with design decisions to a certain extent. For example, preferring male tooling instead of female tooling is a better option. Nevertheless, new materials with low CTE and withstand high temperatures will be incredibly beneficial for extending this field's applications.

Once the composite fabrics are laid-up on the AM tooling, it is enclosed in a vacuum bag tailored to the required shape, and the assembly is placed in an autoclave, a pressure vessel designed to contain gas at pressures generally up to 1.5MPa and heat up to temperatures to that required to cure the epoxy. The vacuum bag is first evacuated using a vacuum, thereby removing trapped air and organic vapors from the composite placed into the chamber, which is pressurized to provide additional consolidation during the curing process. The process produces structures of low porosity, less than 1%, and high mechanical integrity. Large autoclaves have been installed in the aircraft industry capable of encapsulating the complete wing or tail sections. For low-cost applications, such as the one in this research, non-autoclave processing methods are sufficient. Non-autoclave processing methods such as vacuum molding (VM), resin transfer molding (RTM), vacuum-assisted RTM (VARTM), and resin film infusion (RFI) can be used to obtain the final desired part geometry affordably [28].

2.1 Robotic Additive Manufacturing of the Tooling

An AM tool's advantage versus a traditionally manufactured tool is that an AM tool can have an intricate, highly functional design without sacrificing cost or time. The RAM setup's large build space allows large tool designs to be fabricated as a single piece, removing the need for assembly. AM also brings the opportunity for optimization. Analysis indicates that sparse build tools are preferable to solid build tools as the sparse tools only save tooling cost. However, it also causes less thermal expansion mismatch between the tool and part manufactured [29]. The tooling can also be shell-type rather than having infill. This tooling will further decrease the costs and speed up the manufacturing process. Figure 7 shows the CAD geometry of the Interior panel of an aircraft with a composite lay-up. This geometry is sliced in a vertical build orientation with slicing software. With a selection of 15% infill, the toolpath in Figure 8 is obtained.

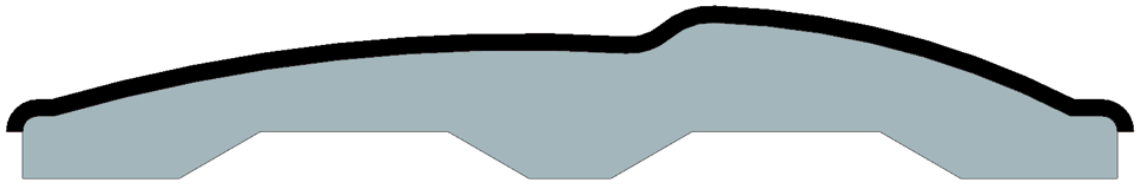


Figure 7. CAD geometry of the Interior panel of an aircraft with composite lay-up

The toolpath in Figure 8 shows the layer's outer perimeter in blue and the rectilinear infill pattern in green, and the extruder in grey at the bottom left corner. The layer is repeated until the desired extrusion height is achieved. This toolpath is given to the 6 degrees of freedom manipulator. After the reverse kinematics have been solved, the robot arm can start fabricating the layers one by one. In the RAM setup, fused filament fabrication, which is more commonly referred to as the fused filament fabrication (FFF) method, is implemented. The raw material is stored on spools in filament form and deposited at the desired locations with the help of a hot end for melting the material, and a feeding mechanism, which feeds the filament into the hot end. With the feeder's pressure, the melted material at the hot end will come out of the extruder and laid on top of the previous layers.

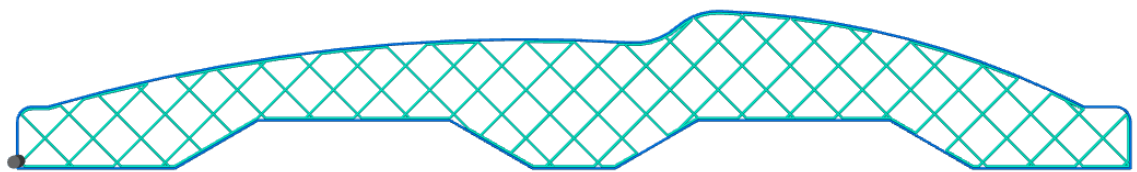


Figure 8. Toolpath for the AM tooling with 15% infill

Figure 10 shows the simulation and the actual setup of the RAM. The manipulator is given in blue, where the feeding mechanism in grey is attached. The filament comes in the white Teflon tubing. The hot end is shown in brown and has the yellow extruder at the tip where the material is deposited. The tooling can be seen to be manufactured in an upright vertical position.



Figure 9. Robotic additive manufacturing setup

Due to the layer-wise manufacturing nature of AM, the tool surface comes out rough. The selection of vertical manufacturing orientation minimizes this roughness. For further improvement, the tools' surface can be treated with an epoxy coating and sanded to reduce the roughness and improve part surface finish.

2.2 Results and Discussion

The tooling, manufactured using white polylactic acid (PLA) filament, is shown in Figure 10. The tool is a smaller model of aircraft interior panels with dimensions of 350x50x64 [mm] and was manufactured under an hour. This tooling is manually laid-up with carbon fiber and placed in a vacuum bag, and then it is left for curing at 50°C for 10 hours since PLA used in this study has a distortion temperature of 52°C [30]. Where higher curing temperatures are needed, the ULTEM 1010 can manufacture composite structures that can withstand temperatures exceeding 177°C and pressures of 690 kPa [31].



Figure 10. AM tooling for the Interior panel of an aircraft

Four layers of 245gr/m² 3k twill were laid-up using L285 epoxy with an H285 hardener [32]. A release agent was applied to the surface of the tool and the vacuum bag before the lay-up. Figure 11 shows the carbon fiber Laid-up on top of the manufactured tooling curing inside the vacuum bag under vacuum.



Figure 11. Laid-up part curing inside the vacuum bag

After the part is taken out of the vacuum bag, it is separated from the tooling with gentle prying. Extra material on the sides is cut with a hacksaw and sanded. One last layer of epoxy is applied and cured to get the final surface, as shown in Figure 12.

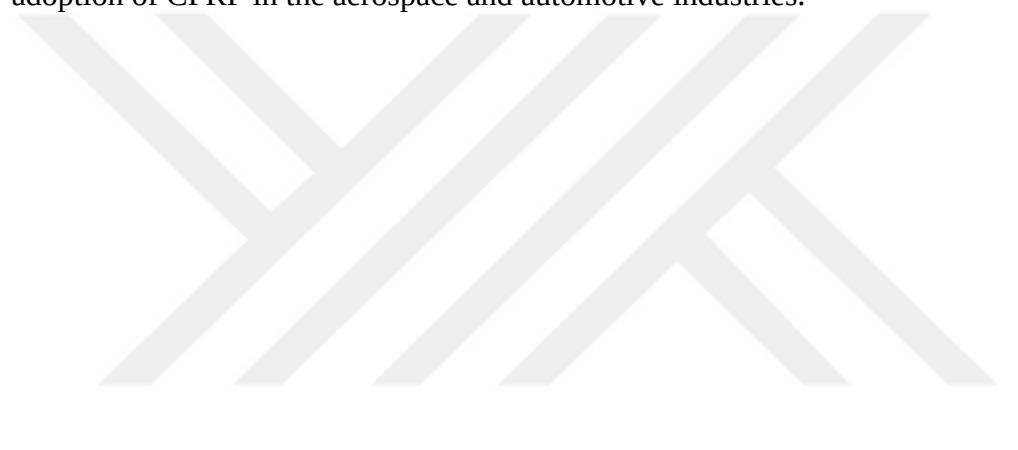


Figure 12. Manufactured carbon fiber part of the Interior panel of an aircraft

Currently, the tooling is made with RAM, but the lay-up process is still manual and laborious. This step can be automated with robotic automated fiber placement (AFP). The concept is to shorten the entire part design tool production robotic programming and part lay-up time. Future work would be to use high-performance materials such as the ULTEM 1010 for the RAM of the tooling and lay-up the fibers with an AFP setup and cure the final assembly in an autoclave to achieve the best possible results.

2.3 Conclusion

With the development of AM, toolmaking is no longer limited to conventional subtractive manufacturing methods. AM tooling of an aircraft's interior panel was fabricated and laid-up with carbon fiber layers impregnated with resin for demonstration. The assembly was vacuumed and left for curing. After the resin has cured, the CRFP part is taken out of the vacuum bag. Then it is separated from the tooling. A final layer of epoxy was applied to get a good surface finish, and the final desired part was obtained. With AM, iteration in design can be done relatively quickly, and the results can be optimized. Design cycles can be accelerated, and companies can reduce costs, especially for low volume productions. Up to %90 of cost and time savings can be achieved. These benefits will increase the adoption of CFRP in the aerospace and automotive industries.



Chapter 3

Additive Manufacturing with Modular Support Structures

AM is a process where the computer-aided design (CAD) model is manufactured additively, layer by layer [3]. The CAD models designed in various CAD software can be used after the triangulation into a Stereolithography (STL) file [8]. This triangulated mesh is sliced layer by layer to obtain the toolpath. This toolpath is given to the AM machine for the fabrication of the physical model. It might be required to build support structures that support the model's overhanging areas during the physical model fabrication. These support structures are fabricated simultaneously with the model. Hence they must be accounted for in the toolpath planning [33].

The manufacturing of the support structures increases the total manufacturing time of the input CAD model. In addition to fabrication time, the material cost of the support structures needed to create each part must also be considered [24]. These supports will be waste and reduce the buy-to-fly ratio of the AM process. Support structures need to be removed since they are not part of the final geometry to be created. This removal is a process that requires a significant amount of extra time and human effort. Thus, it is in the industry's best interest to reduce the amount of required support structures.

Different AM methods have been developed to minimize the use of support structures. Some of these methods try to determine the best manufacturing orientation with respect to the primary build axis [34]. Others use multiple build axes [35], [36]. Some target the easy removal of the support structures [37]. Some have split models into smaller parts, which can be fabricated separately to be assembled later [38]. Others use secondary material for the support structures. The use of secondary support structure materials, which are either weaker, soluble in a liquid solution, or melt at a lower temperature than the main material, was a significant improvement in simplifying the removal of supports. The extrusion-based equipment should have a secondary extruder to do this. The secondary material can be extruded at the same time as the current layer of build material [24].

This research proposes a new method for fused filament fabrication (FFF), which reduces the manufacturing of the conventional supporting structures by replacing them with pre-fabricated modular supporting blocks wherever possible. With the aid of a

robotic arm, the blocks are stacked under the CAD model's overhanging portions until the desired height is reached. The majority of the support will be covered with the modular blocks, and the remaining parts can be filled by fabricating conventional supports on top of the stacked support blocks. This strategy reduces the overall fabrication of conventional support structures. Thus, faster manufacturing times are obtained with higher buy-to-fly ratios. The next section starts by explaining the conventional support generation process for the overhanging areas.

3.1 Conventional support generation

Given the STL file of a model, the overhanging faces of the model which require support structures can be detected. These are found by checking each facet's angle, which is lower than the minimum self-supporting angle from the horizontal XY plane. Such overhanging faces are visualized in Figure 13.

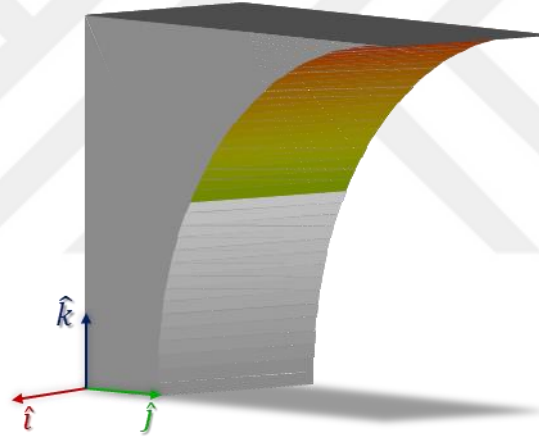


Figure 13. Overhanging faces that require support colored from green to red. Grey faces do not require support.

Using the vertices v_1, v_2 and v_3 from the model, the surface normal $\vec{N}$ for each facet is calculated by taking the vector cross product of two edges of that facet

$$\vec{N} = \frac{v_{12} \times v_{23}}{\|v_{12}\| \|v_{23}\|} \quad (1)$$

The Angle from the XY plane is calculated by using cosine law

$$\theta = \cos^{-1} \frac{\vec{N} \cdot -\hat{k}}{\|\vec{N}\| \|-\hat{k}\|} \quad (2)$$

The angle θ is calculated for each facet of the model. The minimum self-supporting angle θ ranges from 30 to 60 degrees, depending on which AM process is selected and its

parameters. Figure 14(a) shows the areas requiring support on the Stanford bunny. Facets where θ is lower than the minimum self-supporting angle are isolated from the rest of the model. Checking for the edges used only once in this list of facets gives the boundaries of the area that requires the supporting structures.

After the areas that require support are found, the supports are generated. The first step is sampling the area. Initially, the minimum axis-aligned bounding box (AABB) of the part is found. The edges of the bounding box are used to generate two sets of planes with equidistant spacing. These planes face the direction of $\hat{i}$ and $\hat{j}$ unit vectors and are perpendicular to the manufacturing bed. The equidistant spacing is determined by the size of the desired supporting structures input by the user. The support points are found by first intersecting the boundaries with $\hat{i}$ planes. This intersection is a triangle-plane intersection. The intersection results in line segments lying on the $\hat{i}$ planes. Then, the intersection of these line segments with the $\hat{j}$ planes give support points. These are the points that can not be manufactured without depositing material underneath it. This space can either reach the manufacturing bed or lie on the surface or the model itself.

At each supporting point, a ray is cast in the $-\hat{k}$ direction using the Möller–Trumbore algorithm [39]. If the ray hits a triangle of the model, the support starts on the model. Otherwise, the support starts at the manufacturing bed. Rectangular support structures are generated using the selected support structure width and the length from either the model or the manufacturing bed to the support point. These support structures are plotted in green in Figure 14(b).

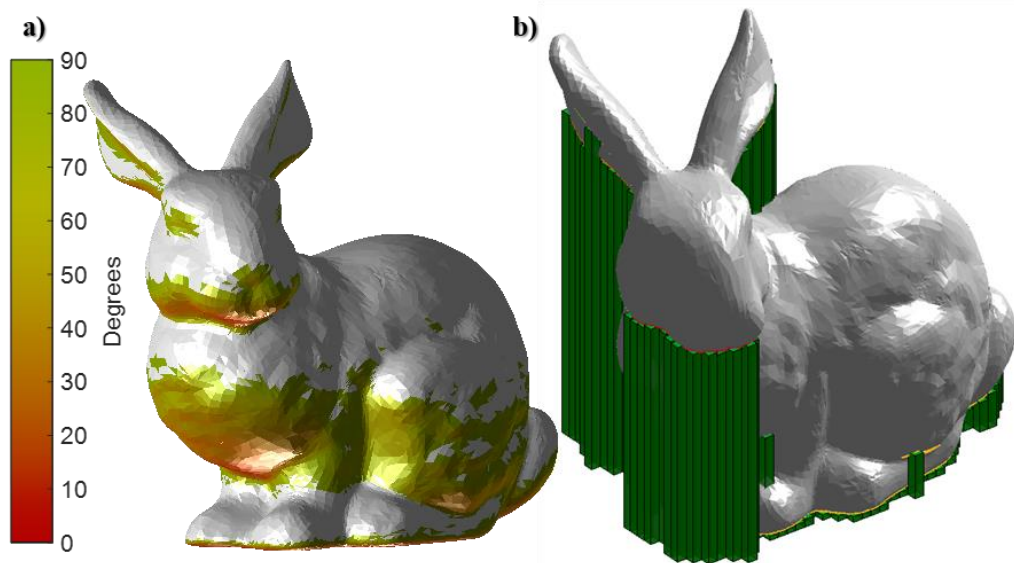


Figure 14. Analyzing the Stanford bunny for support structures: a) Angle of facets less than 90 degrees b) Conventional supporting structures generated for each support point

Supports that start from the manufacturing bed are appropriate candidates for replacement with modular support structures. By placing the pre-manufactured modular support blocks, the deposition of the conventional support structures is reduced. Thus manufacturing time is improved while reducing the total material costs. The next section gives the method to replace the conventional support structures with the newly developed modular support structures.

3.2 Modular support structure generation

For a reduction in cost and time, it is desirable to replace the conventional supports with modular support structures. To start, one needs to determine which supports can be replaced by the proposed modular support blocks. The process starts by dividing the supports into levels in the $\hat{k}$ orientation. The level at which the supports are split is determined by the height of the modular blocks. Support structures divided into different levels are given in Figure 15. Supports that lie on the model are not considered for replacement with the block placement since a uniform surface is required to place the blocks.

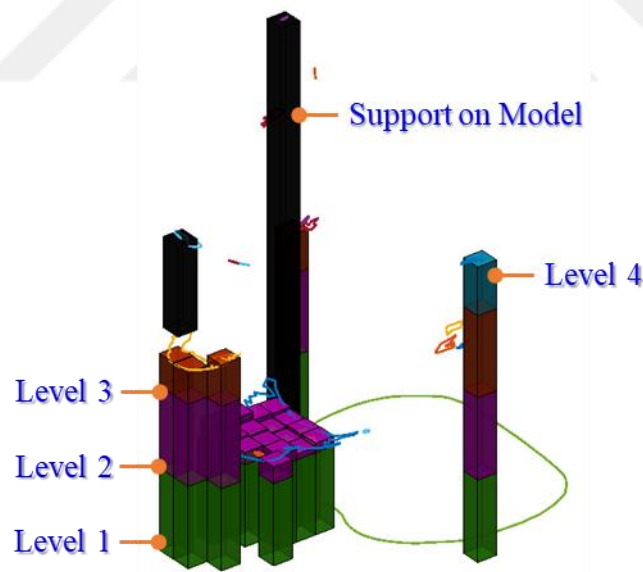


Figure 15. Conventional support structures split into multiple levels with the given modular block height of the Atatürk model. The boundaries show the areas that require support.

For each support structure level, a two-dimensional support structure map is generated. The map contains the normalized locations of the supporting structures within the AABB. Each pixel on the map is the size of one support structure. The map has the value of 1 (true) for each $\langle \hat{i}, \hat{j} \rangle$ coordinate pair containing support structure, and 0

(false) for the rest of the coordinates. A sliding window search is used on the map to find the optimum place for the modular blocks. This process is shown in Figure 16. The window has the size of a single block. The window first moves in the direction $\hat{i}$. When the edge is reached, $\hat{j}$ is incremented and $\hat{i}$ is swept again until every coordinate pair has been searched. At each increment, the number of support points covered by the block is saved. The first block is placed where the maximum number of support points are covered. Then the process repeats until all the points are covered.

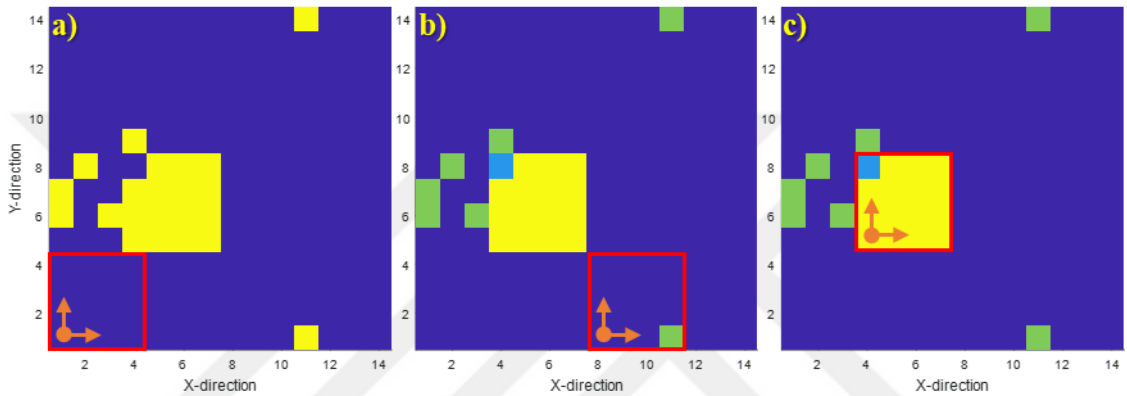


Figure 16. Sliding window search for placement of the modular block: a) Window is at the origin b) Window has moved in the x-direction c) Window has found the maximum location

At the same time, the support map is being swept, and two other maps are being checked. The first map is for the collision with the manufactured model, and the second map is for collision with previously placed modular blocks. The model map is given in Figure 17b, while the block maps are given in Figure 17c. With these checks, the modular blocks are only placed at feasible coordinates. A given location on the map may cover more support points, but it will not be selected if a collision exists. After each placement of one block, the covered support points are discarded. At the end of the cycle, if any support points are left that cannot be replaced with the modular support structures, it is saved for the manufacturing of conventional support structures. The remaining supporting points for the Atatürk model are shown in Figure 17d.

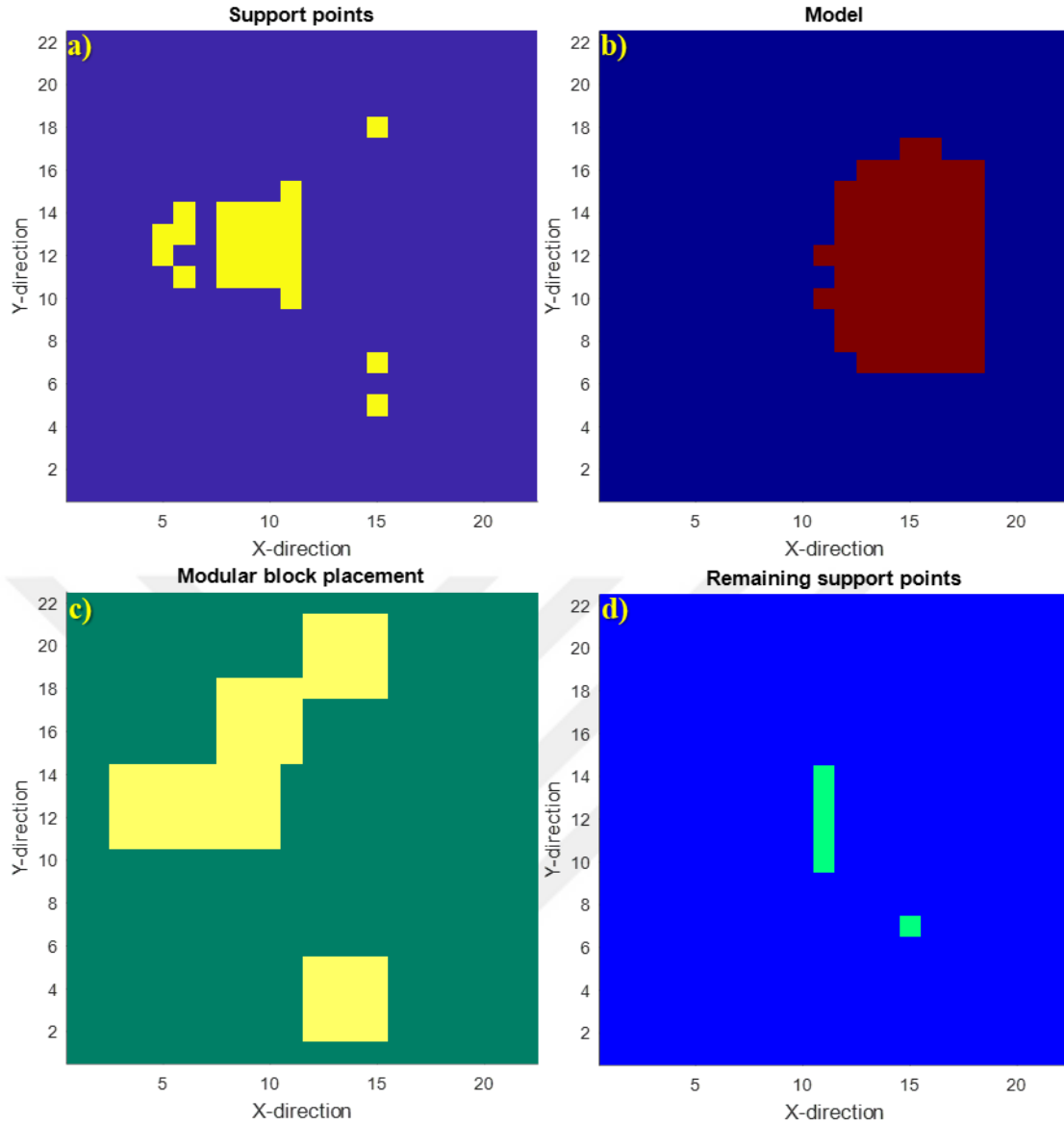


Figure 17. Block placement with consideration of collision with the CAD model: a) Conventional support structure map b) CAD model map c) Modular block placement map d) Remaining support points map.

For the successful implementation of the proposed modular support structure method, the design of the blocks is critical. The blocks should be placed with precision and should not be disturbed during the AM process. Thus, an interlocking system that limits the movement of the blocks is desired. This can be achieved by using magnetic aligners or mechanical interlocking structures such as that found in toy building blocks. The next section uses the modular support structure data and formulates the modular support placement strategy with a robotic manipulator.

3.3 Robotic placement of the modular support structures

The proposed method uses a robotic manipulator to place the modular blocks. The block placement for the given models is visualized in Figure 18. and the manufacturing setup is given in Figure 19. The blocks are initially stacked on the left-hand side on the stack platform given in. The robot can have a tool changer where two different tools are employed. The tools and the tool changer have not been shown in this work. The first tool is a suction cup tool that picks the blocks from the stack and places them at the desired locations. The second tool is an extruder that fabricates the layers of the model and the conventional supporting structures. The manufacturing bed is given in green, placed in front of the robotic manipulator.

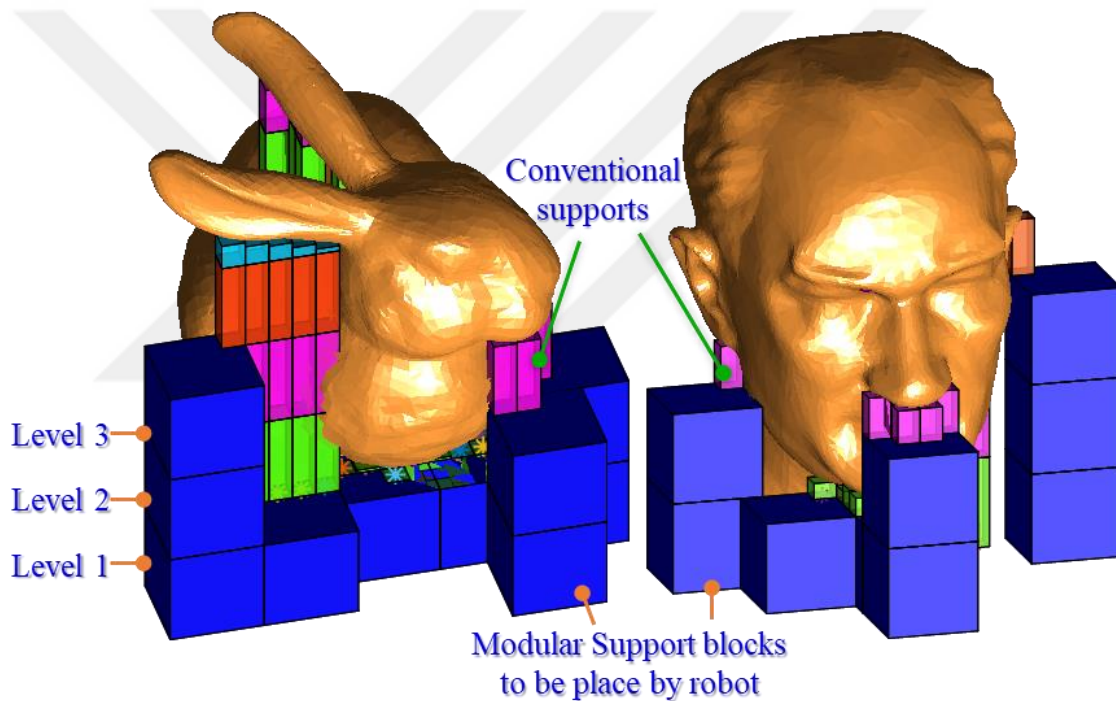


Figure 18. Modular support structures results: a) The Stanford bunny b) The Atatürk portrait

The process starts with the deposition of the first layers of the model with the deposition tool. When the height of the first modular support block is reached, the extrusion process stops. The robot changes the tool to the suction pick and place tool. This tool is used to pick and place the first set of blocks. After the blocks are placed, the tool is changed back to the extruder. The extrusion continues starting from this level, and the process is repeated until all the layers are manufactured. Depending on the overhang surfaces, new layers are deposited on some of the placed blocks, and others are used as the base for the new block placement. Given the initial position of the block on the stack and the desired

target position on the manufacturing bed, the joint interpolated trajectories for the 6DOF robotic manipulator are generated by using the robot toolbox [40]. These trajectories are plotted in red in Figure 19.

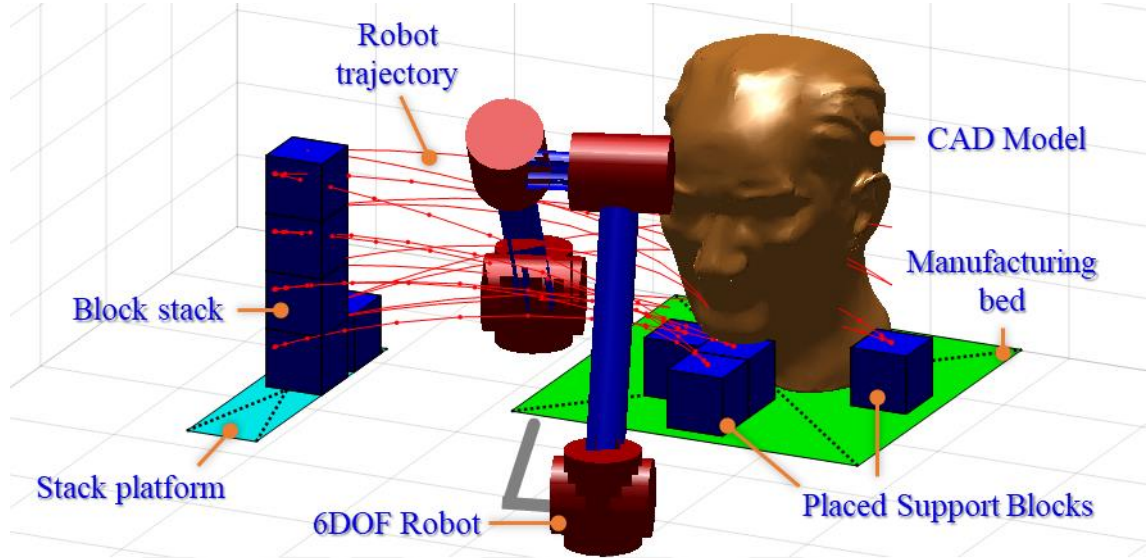


Figure 19. Robotic additive manufacturing setup with modular support block placement

With the introduction of the blocks, material waste is reduced, and the manufacturing time is improved. The next section gives the results for the proposed method.

3.4 Results and Discussions

The given algorithm was implemented on MATLAB© environment running on a computer with Intel© I7 CPU and 8 GB of RAM with modular support block dimensions of $40 \times 40 \times 40$ [mm] and support spacing of 10×10 [mm]. The percentage of volumetric improvement in the support structures is calculated and given in the table below.

Table 4. Comparison of the proposed method with the conventional method

Model	Facets	Dimensions	Conventional	Proposed	Improvement
Atatürk portrait	15270	181x154x226 [mm]	26.3[cm ³]	8.4[cm ³]	68%
Stanford bunny	33398	229x177x226 [mm]	46.5[cm ³]	8.0[cm ³]	83%

With two distinct example parts, it is shown that the proposed method works robustly and can reduce the supporting structures with significant improvement.

3.5 Conclusion

The CAD models that consist of large overhangs result in the fabrication of large support structures resulting in wasted material and high buy-to-fly ratios. In this work, a pre-fabricated reusable support structure system which minimizes the fabrication of conventional support structures is introduced. When an overhang is to be manufactured, modular support blocks are stacked under the overhang structure with a robot arm until the overhang of the CAD model is reached. After the support structure strategy is formulated, The Robot program is generated and integrated into the existing AM G-code. Two parts are simulated, and results are compared to the conventional methods to verify the improvement of the proposed strategy. With this method, the material can be reduced by 75% on average, which also results in a reduction in fabrication time.

Chapter 4

Dynamic Build Bed for Additive Manufacturing

Additive manufacturing (AM) is praised for having low material waste in comparison to traditional manufacturing methods such as subtractive manufacturing. This is not valid for all given computer-aided design (CAD) models. In deposition based AM methods, the material needs to be deposited on a prior surface. When the given CAD model has overhanging structures, the material cannot be directly deposited. In this case, the layer of the model needs to be supported by supporting structures. Support structures are manufactured just like the model itself only to support the overhanging geometries. These support structures are not part of the final part geometry. Thus, they need to be manually removed after manufacturing, and they end up as waste material. These support structures also increase the manufacturing time and require manual labor time.

In powder-based AM methods, the overhang structures do not cause problems since the powder material is equally deposited to cover the layer at a time. The powder material fills the space under the model and acts as a natural support structure for the whole geometry. Thus, any overhanging structures of the model are also supported by the deposited powder material. However, the powder degrades over time and once after it has been through a manufacturing cycle and becomes waste material. Therefore, it is beneficial to deposit the minimum amount of powder material on each layer. This study proposes the use of the dynamic build bed for reducing the manufacturing of supports in the first application and reducing the deposition of material in the second application.

The bed consists of an array of actuated pins which move in the build orientation. Each pin can be individually moved to the desired height for supporting the given model. The proposed dynamic bed system has been previously utilized in the human-computer interaction (HCI) field, but it has not been utilized in the field of AM. Sean Follmer and Daniel Leithinger introduced the inFORM system, which is a 2.5D shape display consisting of a 30x30 array of linearly actuated pins [41] given in Figure 20. Each pin can dynamically move in the Z orientation for interaction with the user or manipulation of the physical objects shown on display. A single pin can exert 1 Newton force and extend up to 100mm from the surface. The height map of the pins is calculated by OpenGL shaders and is sent to the 900 pins via a microcontroller.

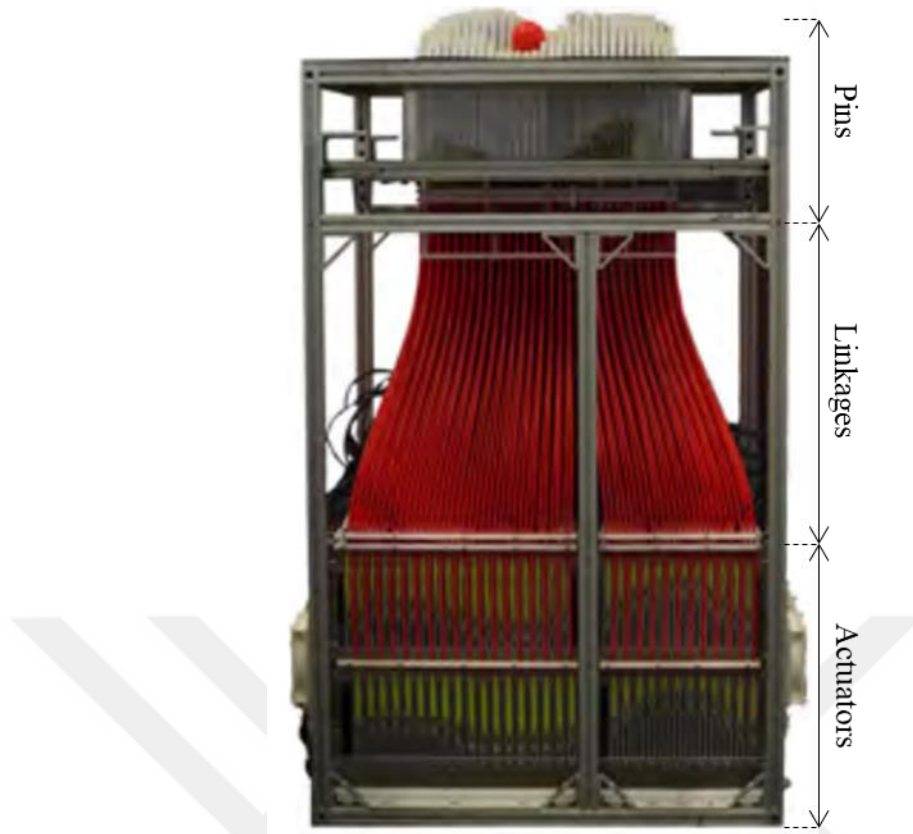


Figure 20: The inFORM system with 900 mechanical actuators connected to the pins with the linkages [41]

Leithernger et al. later used the inFORM shape display to render shapes and geometries physically [42]. They also proposed that users can use these shape displays to render real CAD models before they are additively manufactured. Rendering before AM will improve the prototyping cycles. In this work, it is proposed to use the given physical renders as support structures in the AM process.

Several works in the literature propose methods to reduce the use of support materials. Some of these are focused on multidirectional manufacturing, where the deposition tool has more than three degrees of motion and can deposit in non-conventional orientations [43]. Another method is the placement of foreign objects as support structures in convenient locations where the deposition head can continue deposition without collision [44]. Support structure optimizations are used, such as the sloping wall support structures [45], where the total volume of the supporting structures is reduced by reducing the cross-sectional area of the support with the minimum self-supporting angle. Another method is to support slimming to optimize the geometry by changing its shape to be more self-supported [46]. Optimization of the build orientation of the part [47], [48], is also a practical approach where the original model can be

fabricated on the conventional supports at an orientation requiring the minimum amount of support.

The proposed method in this work has been practiced by the flexible support structures [49]. In this work, a flexible platform consisting of actuated basic units used. The work includes a control module for support structure reduction and automatic unloading. Support structure reduction mainly includes three steps. The starting step is to discretize the model's manufacturing space to pieces. The next step is to identify the lowest point of each piece. The final step is to offset the base of the support structure. This work adds to the flexible support structure by introducing a universal algorithm valid for both deposition-based AM systems and powder-based AM systems.

This work starts by introducing the conventional support structures from the literature in section 4.1. Then in section 4.2, dynamic supports are introduced. Two distinct applications of the build bed are investigated in the following sections. The first application given in section 4.3 is the dynamic build bed in deposition based AM methods. In this application, the pins individually lift out of the build bed to support the overhang geometries at the given deposition height. The second application, given in section 4.4, is the use of a dynamic build bed in powder-based AM. In this application, the pin structures are used to fill the space of the powder where the geometry will not fill. The pins are individually lowered in the build orientation to make space for a new powder layer. The work ends by giving the conclusion.

4.1 Conventional Support Structures

AM is a process where the CAD model is fabricated in a layerwise fashion. The CAD model is usually given in the format of a Stereolithography (STL) file [8]. This file consists of a triangulated mesh of the model. The minimum self-supporting angle θ of each triangle is calculated to find the overhang geometries which require support structures, using the cosine law given in equation (3). In this equation $\vec{N}$ represents the normal of the facet and the $\hat{k}$ represents the build orientation. The self-supporting angle generally ranges from 30 degrees to 60 degrees which changes with different AM methods.

$$\theta = \cos^{-1} \frac{\vec{N} \cdot -\hat{k}}{\|\vec{N}\| \|\hat{k}\|} \quad (3)$$

The meshes that do not meet the minimum self-supporting angle criteria give the regions of the model which require support structures. These regions are then sampled in the two-dimensional plane parallel to the build bed. The sampled points give support points. The sampling density depends on the spacing of support structures. For each supporting point, a ray is cast towards the build bed [39]. If the ray hits a facet of the model, the support structure is located on the model. If the ray hits the build bed, the support structure is on the build bed, and it can be replaced by the pins of the dynamic build bed. The dynamic support structures are given in the next section.

4.2 Dynamic Support Structures

The dynamic support structures are consisting of a two-dimensional array of pins. Each pin moves independently in the direction of the build orientation. The geometry of the pins is identical. This is in a square prism with user-set width w and height h , as shown in Figure 20. In this figure, a total of 361 pins are shown where some of them are raised for illustration. The number of pins can be selected depending on the required manufacturing bed dimensions. The pin configuration consists of the width of the pins, the height of the pins, and the number of pins. The proposed method in this research calculates the dynamic support structures for any CAD model with any given pin configuration.

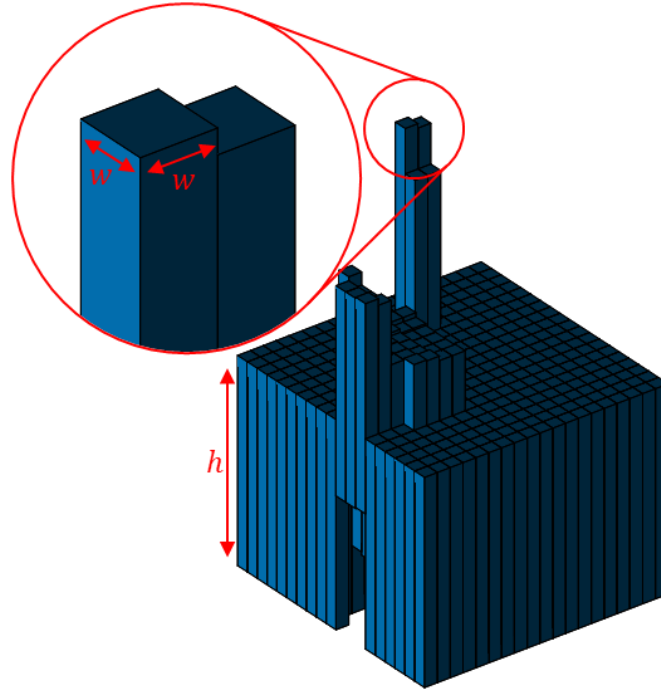


Figure 21: Dynamic build bed of 361 pins with a width w of 10 [mm] and the height h of 150 [mm]

After setting the pin configuration, the next step is to find the support points. When the width of the pins gets more coarse, the pins tend to collide with the manufactured model. A ray is cast from the corners of the pin to deal with this. Then collision is checked in a similar manner in which the support points were checked. The results are as shown in Figure 22. This figure shows the points where the ray hits in red. The points of the model that require support structures are shown in green. Any highlighted point which is reachable without colliding with the model is reached by a pin. Here the whole model is shown where the pins are at their last positions. During the manufacturing, the pins will raise in increments of the given layer height. At the beginning of each layer, the pins will raise as much as the layer height for support. When the pins their final heights, they will be fixed at that position until the printing process is reset. The pins can move in a wave-like motion to release the model from the build bed. This enables easy removal of the model.

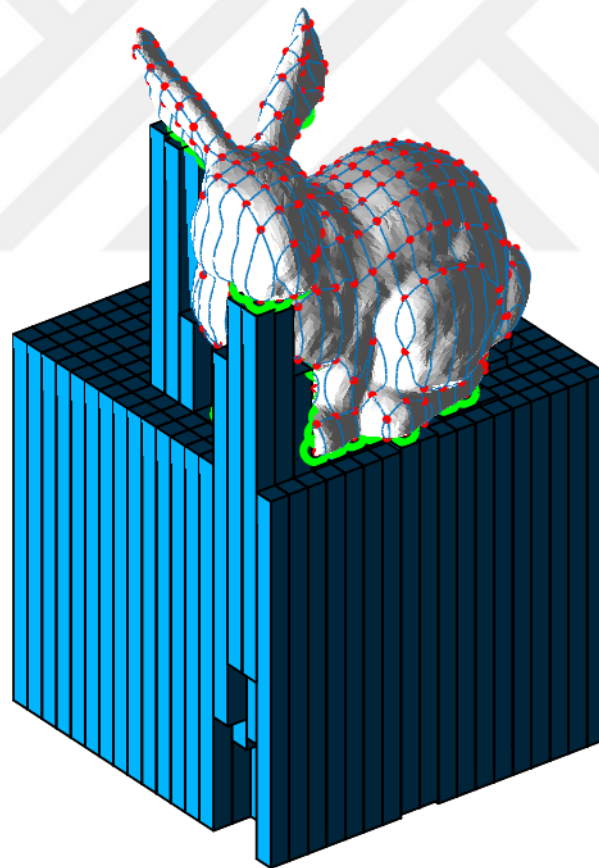


Figure 22: Support points of the Stanford bunny model

As previously introduced, the dynamic build bed can be used in two different AM application. The figures up to this point have shown the application for deposition-based

AM methods, where the pins are raised out from the build bed. The following section investigates the use of the dynamic build bed in deposition-based AM.

4.3 Dynamic Build Bed in Deposition Based Additive Manufacturing

The first application of the proposed dynamic build bed is the utilization of the pins as support structures employed in deposition-based AM methods. Each pin can individually raise out of the build bed for support of the overhanging geometry at the given height. At this point, the pin can move either up or down, depending on the AM method. Simulations are conducted for both AM applications with two different models to verify the proposed dynamic build bed method. Figure 23 and Figure 24 give the results for the deposition-based AM method.

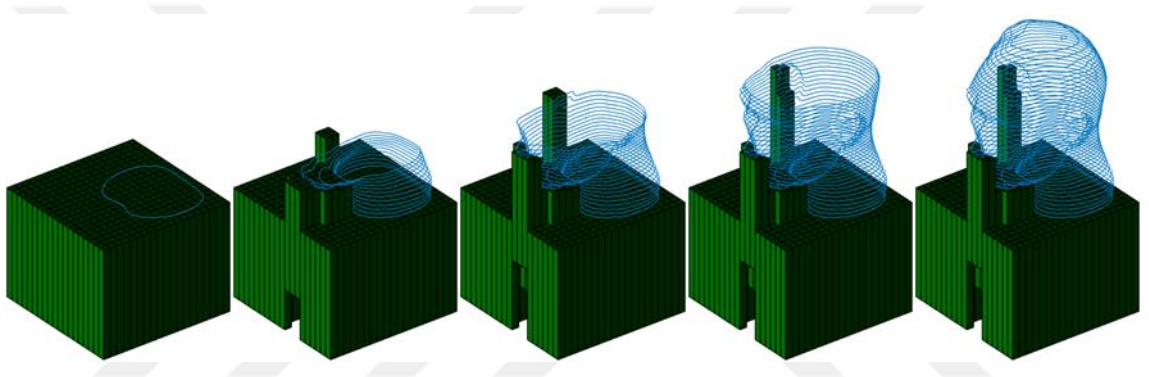


Figure 23: Dynamic build bed in deposition-based AM with Ataturk Model

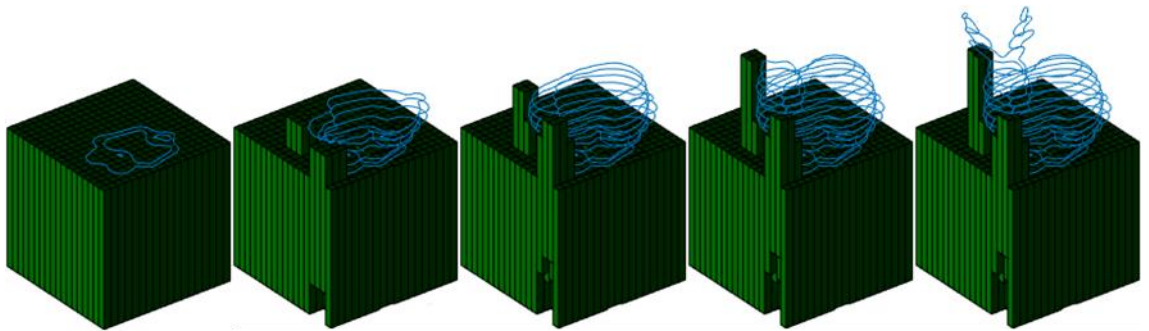


Figure 24: Dynamic build bed in deposition-based AM with the bunny model

The corner that has the lowest collision height is taken as the maximum height that the pin can rise. The maximum values are stored on a 2-dimensional matrix after the maximum height is calculated for each pin. When the manufacturing starts, each pin rises as much as the layer height while the extruder moves to the next layer. At each height, the maximum height of the pin is checked. If the height of the pin is at its maximum value,

the pin is fixed at that position. This dictates that the pin is ready to support the model and will not move anymore.

4.4 Dynamic Build Bed in Powder Based Additive Manufacturing

The second application is for powder-based AM methods. There is no need for support structures as the powder itself acts as a natural support structure in powder-based methods. The powder used to fill up each layer will go through a heat cycle and deteriorate over time. This will be more significant in the case when most of the build box is empty. Since the powder is an expensive resource, it is in our best interest to lay the minimum amount of powder. In this section, the pins are used to fill the space which the powder will occupy. Each pin is individually lowered in the build orientation to make space for the model. Thus, excessive deposition of powder is prevented. Figure 25 and Figure 26 illustrate the results for powder-based AM

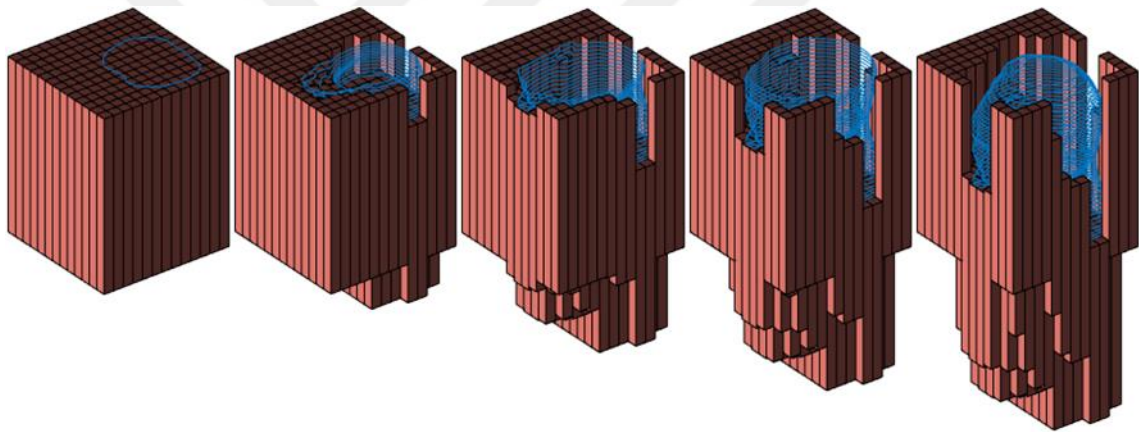


Figure 25: Dynamic build bed in powder-based AM Ataturk Model

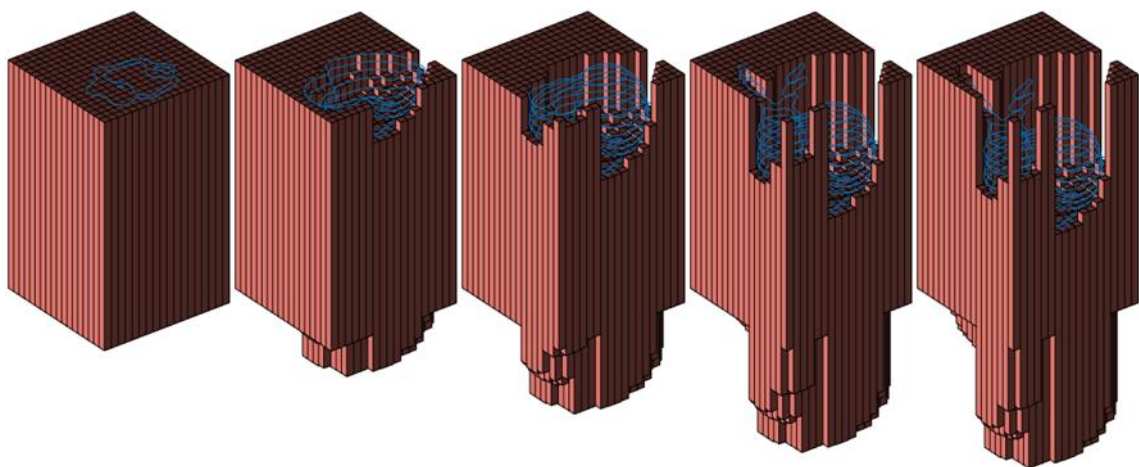


Figure 26: Dynamic build bed in powder-based AM with Bunny Model

4.5 Conclusion

The dynamic build bed for the reduction in the use of support structures and powder material is introduced. An array of actuated pins that can move in the build orientation are assisting the AM process. Each pin is individually actuated to reach the desired position under the given CAD model. Two separate implementations are given in this research. The first is for deposition-based AM, where the dynamic build bed is used as support structures. Each pin rises to support the overhanging parts of the geometry at the required height. The second implementation is in for powder-based AM, where the pins fill the space that the powder initially fills. Each pin is lowered in the direction of the build orientation to make space for the new layer. This results in less usage of powder. Two models are simulated to verify the improvement of the proposed implementations, and the results are compared to the conventional methods. By minimizing the fabrication of support structures, the material waste can be reduced, which also results in a reduction in fabrication time.

Chapter 5

Helical Slicing Method for Material Extrusion Based Robotic Additive Manufacturing

The major market driver for Additive Manufacturing (AM) has been the interest of fields that require low to medium fidelity prototyping in the early stages of part design. AM has become an essential part of manufacturing since it significantly changes traditional production models in terms of machining tools, assembly processes, and supply chains [3]. AM delivers low quantity parts on-site, within hours, and with no initial investment costs of as dies and molds. AM is rapidly being developed and adopted by the industry to fill the voids that traditional manufacturing methods cannot fulfill. The helical slicing method can be used in material extrusion-based robotic AM of different materials, especially where the start-stop of the extruder is costly or not possible.

Slicing of the model is a vital step before a given Computer-aided design (CAD) model can be manufactured additively. Each slice is used to generate the tool path that is used to move the machine in 3-dimensional space. Planar slicing methods are the currently adopted methods in AM, and therefore, most of the available research investigates planar slicing methods. In some instances, the final product can be improved by using non-planar slicing strategies [50], [51]. One of the non-planar strategies, which is investigated in this research, is the helical slicing method. Instead of having many planar slices and discontinued extrusion tool paths, a single continuous extrusion tool path is formed with a single extrusion start and endpoints. This method significantly reduces the defects in each layer where the extrusion starts and finishes. Therefore, the seam is removed from the manufactured part. Furthermore, this method also reduces non-extrusion movements. This work presents the mathematical model and the results of a novel helical slicing method for additive manufacturing.

In the literature, numerous research [52]–[55] investigates topics such as adaptive slicing and optimal slicing orientations directions. A review of slicing procedures has been given by Pandey et al. [9], which is based on planar slicing. Other research in fields such as single point incremental forming, spiral tool paths has been proposed. These are similar to the tool paths generated in this work [56]–[59]. Nonetheless, in these works, the scallop height is kept constant between each pass. This is not preferred for a layered

deposition since the layer thicknesses are not important. Proposed helical slicing for additive manufacturing makes sure that the pitch in-between every layer is kept constant.

Multi-orientation slicing strategies such as the ones given in [60]–[65] have focused on slicing the models in more than one slicing direction and helped to eliminate support structures and lead to improved fabrication times. Curved layer laminated object manufacturing and Curved Layer Fused Deposition Modeling (CLFDM) is similar to non-planar slicing given in [66]–[69]. Software packages such as Slic3r and Cura have implemented the spiralize feature. This feature obtains similar results to the proposed method by just incrementing the Z height of the extruder at each step of the layer. However, this method does not consider where the point truly lies in 3-dimensional space, i.e., the difference in the X and Y coordinates.

The work of Hopkins and Holzwarth has focused on building parts with concealing seam defects that have a slicing methodology that defines the interior and exterior regions in the given layer [70]. Using these regions, it places at least one of the extrusion start or stops points of the toolpath so that the point lays inside the interior region of the given layer. Unfortunately, this does not apply to a helical toolpath.

The proposed method applies to the additive manufacturing of genus-zero models that do not contain any infills. The selected part needs to be a single-walled shell-type part where the slicing of each layer results in a single perimeter. Any models resulting in multiple perimeters cannot be fabricated by the proposed method. The proposed method does not produce infills since the infill cannot be introduced helically. However, shell type models can be filled using different foams or epoxies, depending on the application field. Also, having shell parts means models can be manufactured much faster.

This work will initially introduce the planar slicing method as studied in the literature. Secondly, the new proposed helical slicing procedure and its mathematical model will be presented. Thirdly, the manufacturing setups will be introduced. Finally, the results of helical slicing will be compared to the currently available spiralize feature, and the improvements over the planar slicing will be demonstrated with experimental validations.

5.1 Helical Slicing Procedure

The initial step of the proposed helical slicing approach is to obtain the Stereolithography (STL) file consisting of the mesh of triangles. This triangular mesh is the tessellation of the model into many small triangular facets within given tolerance ranges. STL files only describe the first order piecewise approximation of the surface of a 3-dimensional object without any representation of any CAD attributes. Although much information is lost in the conversion from a CAD file to an STL file, the resulting mesh data is more convenient to utilize in a computer environment. Thus, STL data is enough for additive manufacturing applications. Figure 27 presents the graphical summary of the helical slicing method.

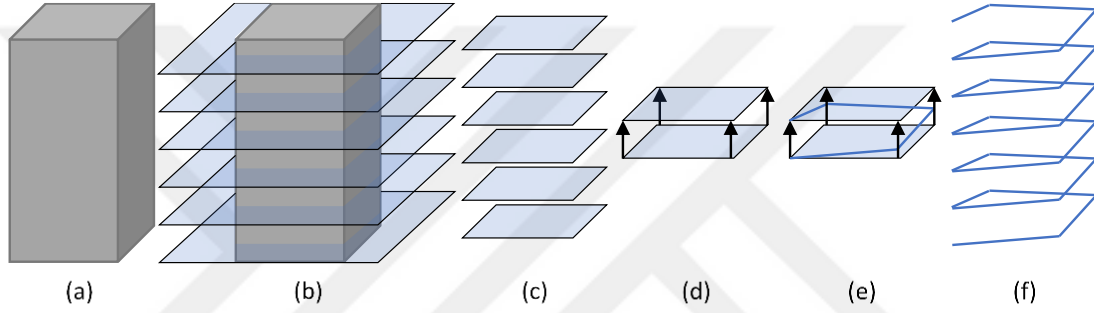


Figure 27. The helical slicing strategy: (a) Input the model, (b) The slicing planes, (c) Obtain the planar slices, (d) Generate the direction vectors, (e) Generate the helical points, (f) Generate the helical tool path

Before a helical tool path can be obtained, equidistantly spaced planar slices are required as reference points for the helical slices. Planar slices are generated by intersecting each triangle of the tessellated geometry with the generated planes. The planes lay parallel with the manufacturing bed and increment in the build direction. The length in between the manufacturing bed to the current Z height is referred to as layer height. The distance between each of the layers is determined by the layer thickness.

5.2 Obtaining Planar Slices from the intersection of tessellated geometry and slicing planes

Planar contours are generated using the intersection of the given triangular mesh and the generated equispaced slicing plane. Intersection occurs when the layer height is in between two vertices of a given triangle. The intersection of a triangle from the mesh with the vertices V_n, V_{n+1} and V_{n+2} in $\mathbb{R}^3$ with the slicing plane L_i as visualized in Figure 28,

will result in the two intersection points $P_{i,k}$ and $P_{i,k+1}$ where n is denoting the number of the vertices, i is the number of the layer and k is the number of the points in each layer.

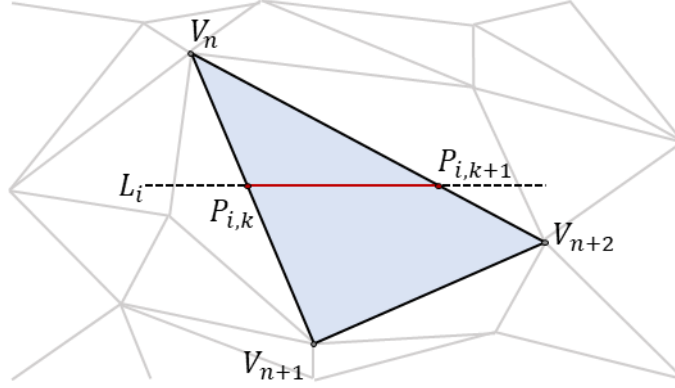


Figure 28. Intersection points from a given triangle in the tessellated geometry

The intersection problem is simplified to a point line intersection. The general parametric equation of a line is

$$\vec{r} = \vec{r}_0 + t\vec{v} \quad (1)$$

Where parameter t is calculated for a given plane L_i using the z values as t_k with

$$t_k = \begin{cases} \frac{z_{P_{i,k}} - z_{min}}{z_{max} - z_{min}}, & z_{min} \leq z_{P_{i,k}} \leq z_{max} \\ \frac{z_{P_{i,k}} - z_{mid}}{z_{max} - z_{mid}}, & z_{mid} \leq z_{P_{i,k}} \leq z_{max} \\ \frac{z_{P_{i,k}} - z_{min}}{z_{mid} - z_{min}}, & z_{min} \leq z_{P_{i,k}} \leq z_{mid} \end{cases} \quad (2)$$

$$z_{max} = \max_{j=1,2,3} z_{V_j}, z_{min} = \min_{j=1,2,3} z_{V_j}, z_{mid} = \text{mid}_{j=1,2,3} z_{V_j}$$

Plugging the t_k from Equation (2) in the general equation given in Equation (1) will result in the first intersection point $\vec{P}_{i,k}$ as shown in Equation (3)

$$\vec{P}_{i,k} = \vec{r}_k + t_k \vec{v}_k \quad (3)$$

Where the $\vec{r}_k$ and $\vec{v}_k$ is defined as

$$\vec{r}_k = \min_{j=1,2,3} z_{V_j} \quad (4)$$

$$\vec{v}_k = \max_{j=1,2,3} z_{V_j} - \min_{j=1,2,3} z_{V_j} \quad (5)$$

The second intersection point can be found using the third vertex point, in this case $\vec{r}_{k+1}$ and $\vec{v}_{k+1}$ becomes

$$\vec{r}_{k+1} = \text{mid}_{j=1,2,3} z_{Vj} \quad (6)$$

$$\vec{v}_{k+1} = \max_{j=1,2,3} z_{Vj} - \text{mid}_{j=1,2,3} z_{Vj} \quad (7)$$

In some cases, the z coordinate of the midpoint may be equal to z of either the maximum or the minimum vertex point. The second intersection is found if the unused point is used as the midpoint.

Repeating the intersection strategy for every single triangle in the given tessellated geometry that intersects with the current slicing plane results in a randomly sorted list of intersection point pairs $\langle \vec{P}_{i,k}, \vec{P}_{i,k+1} \rangle$. The sliced contours are formed from these intersection point pairs acquired from the line segments using Gauss's area formula [71]. All slices are sorted either in a clockwise or counterclockwise manner. The area of layer i is given in Equation (8) where m is the number of lines, and x_j and y_j are the components of the intersection points. When the area's sign is positive, the Gauss formula states that the contour is sorted in a clockwise orientation. When the sign is negative, it is sorted counterclockwise orientation. An example CAD file, as given in Figure 29, is used to show the results throughout this research.

$$A_i = \frac{1}{2} \sum_{j=1}^{m-1} x_j y_{j+1} - x_{j+1} y_j \quad (8)$$

Since Z is incremented in between two layers, before continuing to the next layer, the material deposition should be interrupted. The movement to the next layer should be conducted, and material deposition should be restarted. This will result in discontinuities in the process and cause defects on the surface and the fabricated part's structure. Furthermore, this process is two and a half dimensional. It is not genuinely three-dimensional, as famously referred to as 3D printing by the consumers.

5.3 Generation of The Helical Tool Path Using the Planar Slices

The helical tool path is generated separately for every two layers L_i and L_{i+1} , later to be connected. If the helical slice has its starting point at L_i the ending point will be given at L_{i+1} . The general overview of the helical layer is visualized in Figure 29 and investigated in detail in Figure 30.

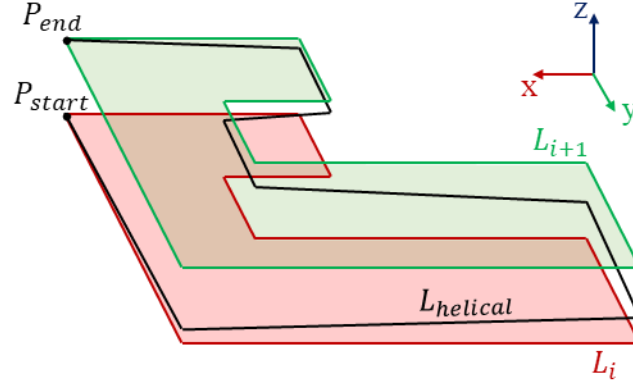


Figure 29. The general overview of the helical slice that is located in between two planar slices. The current layer L_i is shown in red and the following layer L_{i+1} is shown in green. The helical layer resulting from the two layers is shown in black with its starting point P_{start} and the ending point P_{end} .

For each point of the i^{th} layer, the closest point $R_{i,k}$ of the next layer is found using linear projection of the current point $P_{i,k}$ on to the following layer. Equation (11) is used to obtain the projection. With the closest point, the direction vector $\overrightarrow{P_{i,k}R_{i,k}}$ is used to generate the helical tool path is formed.

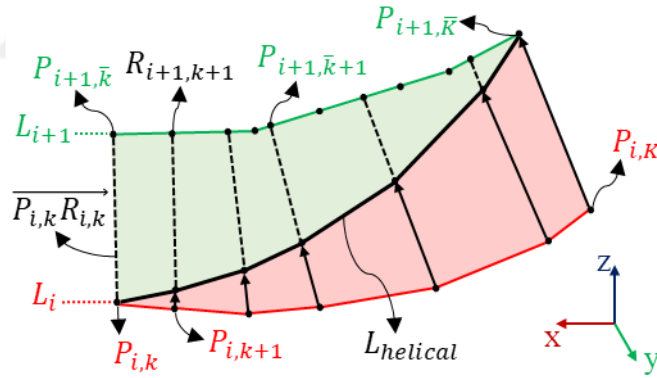


Figure 30. The helical layer is shown where the current layer is L_i and given in red and the next layer is L_{i+1} and given in green. The helical layer formed using the two layers is shown in black. At each point of the current layer, a direction vector points towards the helical layer, given in black.

The point of the helical slice will be on this vector and displace towards the next layer at each increment of k in $P_{i,k}$. The displacement of the point is calculated by the ratio of the layer length up to the current point $\|L_{i,k}\|$ to the total layer length $\|L_i\|$. The length up to the current point $P_{i,k}$ is given in Equation (9), and total length is given in Equation (10). The direction vector $\overrightarrow{P_{i,k}R_{i,k}}$ multiplied by the calculated ratio $\frac{\|L_{i,k}\|}{\|L_i\|}$ is added to the current

point for getting the point on the helical tool path as is given in Equation (12). This is the geometrical equivalent of moving the selected point on the current layer in the direction of the closest point on the next layer.

$$\begin{aligned} & \|L_{i,k}\| \\ &= \sum_{j=1}^{k-1} \sqrt{(x_{P_{i,j+1}} - x_{P_{i,j}})^2 + (y_{P_{i,j+1}} - y_{P_{i,j}})^2 + (z_{P_{i,j+1}} - z_{P_{i,j}})^2} \end{aligned} \quad (9)$$

$$\begin{aligned} & \|L_i\| \\ &= \sum_{j=1}^{K-1} \sqrt{(x_{P_{i,j+1}} - x_{P_{i,j}})^2 + (y_{P_{i,j+1}} - y_{P_{i,j}})^2 + (z_{P_{i,j+1}} - z_{P_{i,j}})^2} \end{aligned} \quad (10)$$

$$R_{i+1,k} = P_{i,k} + \frac{\overrightarrow{P_{i+1,\bar{k}} P_{i,k}} \cdot \overrightarrow{P_{i+1,\bar{k}} P_{i+1,\bar{k}+1}}}{\overrightarrow{P_{i+1,\bar{k}} P_{i+1,\bar{k}+1}} \cdot \overrightarrow{P_{i+1,\bar{k}} P_{i+1,\bar{k}+1}}} \overrightarrow{P_{i+1,\bar{k}} P_{i+1,\bar{k}+1}} \quad (11)$$

$$P_{helical} = P_{i,k} + \frac{\|L_i\|}{\|L_{i,k}\|} \overrightarrow{P_{i,k} R_{i,k}} \quad (12)$$

After calculating the helical toolpath, the normal at each point of the helical toolpath is found. The normal vector can be used for fixing the orientation extruder so that the extruder is always perpendicular to the fabricated layer. The opposite of the normal vector, the vector from the current helical layer to the previous helical layer, is used to calculate the extrusion rate. Normal vectors for two points are visualized in Figure 31

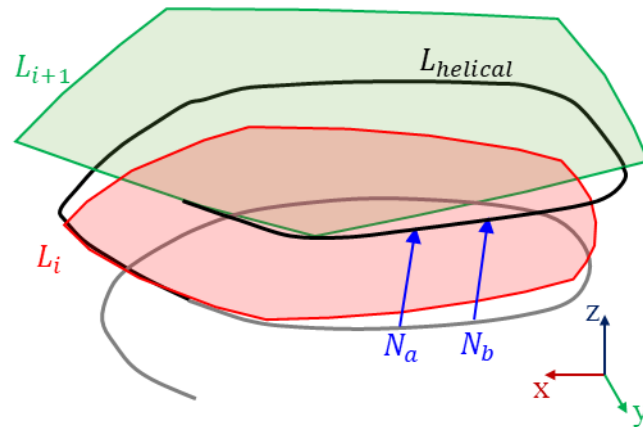


Figure 31. Normal vectors of N_a and N_b of two points A and B are shown in blue. The previous helical layer is shown in gray, and the next helical layer is shown in black. The current planar layer is shown in red, and the next planar layer is shown in green

5.4 Robotic Additive Manufacturing Setup for Helical Slicing

The given models are fabricated on a RAM setup. This setup consists of an extruder connected to the Motoman HP20 industrial robotic arm as the end effector. The six servos of the manipulator are controlled with the NX100 controller. The controller takes JOB files written in the language of Inform, which is similar to the G-code that is used in most AM machines. This controller is originally designed to handle relatively small JOB files for tasks such as pick and place and welding. Thus, it has a limited amount of memory for storing a limited amount of JOB files. An AM program can contain thousands of lines telling the controller where to place itself in what orientation and where to deposit material. To overcome this problem, a Raspberry Pi Computer is used to update the JOB files on the controller continuously. So this takes the place of the main controller. The robotic arm has an open build bed, which can be extended to manufacture large AM parts. The setup is given in Figure 32.



Figure 32. Robotic additive manufacturing setup using Motoman HP20 industrial robot

The results of the proposed helical slicing strategy are presented in the next section.

5.5 Results and Discussions

The formulation of helical slicing has been introduced for a single layer. Now we need to get the whole toolpath. When the part is sliced throughout, separate helical sections are formed between every two consecutive layers. These sections are connected end to end, forming a single helical tool path. In material extrusion-based AM, the adhesion of the first layer to the manufacturing bed is crucial. Thus, the first layer is kept planar, and the helical slices start from the second layer. Since it is desired to preserve the initial CAD model, it is also kept planar for the top layer. Figure 33 visualizes the tool path of the helical slicing of the given model. The color gradient is representing the z level. Figure 34 shows an example part manufactured using both methods with a layer thickness of 0.5 millimeters. The model in Figure 34a is manufactured with a planar tool path. The seam defects are clearly visible at the points where the extrusion of the material starts and stops.

When the start-stop points of each layer are aligned with other layers, a stitching line can form. This line can be removed by placing these points at random locations on the layer. However, this strategy will only distribute the seams. It will not eliminate the seams. The cad model in Figure 34b is manufactured using the proposed helical method. It can be seen that the seam is removed. Figure 35 visualizes further detail with a scanning electron microscope (SEM) images. In Figure 35a, the planar tool path is shown. It is observed that at the extrusion start-stop points, the material is not deposited uniformly, whereas in Figure 35b helical tool path has deposited the material uniformly without having any defects. Extrusion rates at each point of the helical toolpath are calculated from the previous layer point's distance. The layer thickness depends on the sliced model. With the current models, a maximum of %10 difference was observed, and this was compensated by increasing the extrusion rates.

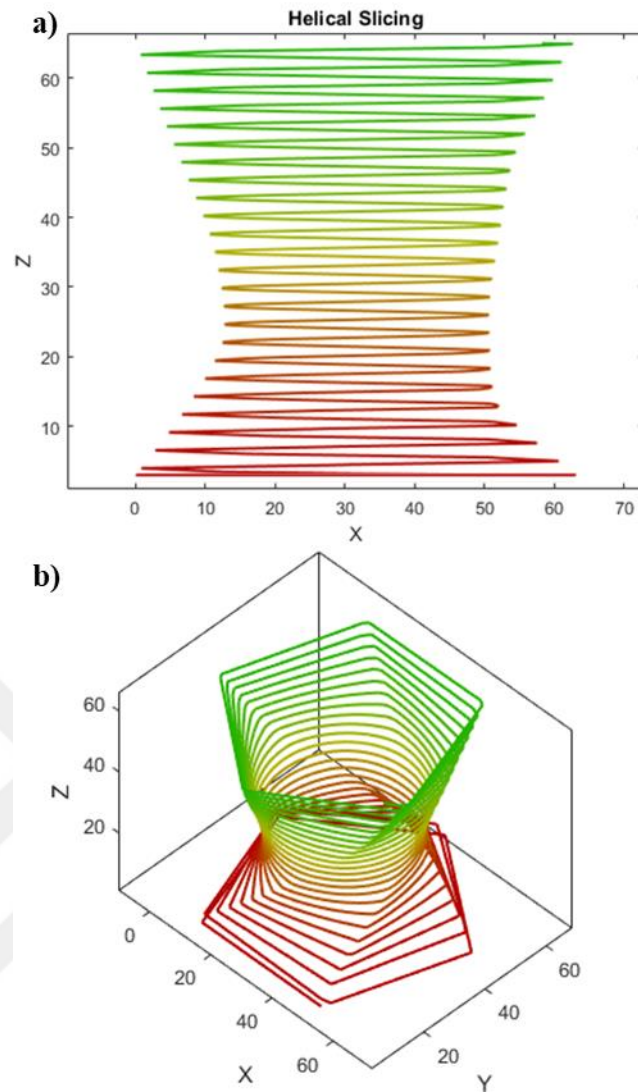


Figure 33. Helical slicing tool path: a) X-Z view b) Isometric view

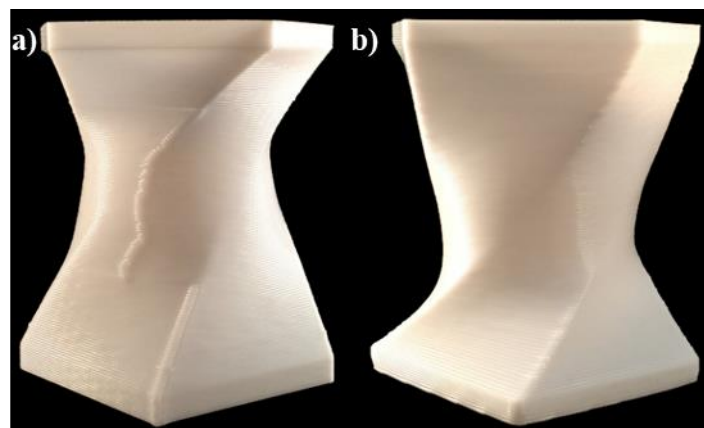


Figure 34. Example part manufactured on robotic AM setup: (a) Planar slicing (b) Helical slicing. Dimensions are 60 mm width, 65 mm depth, and 70 mm height.

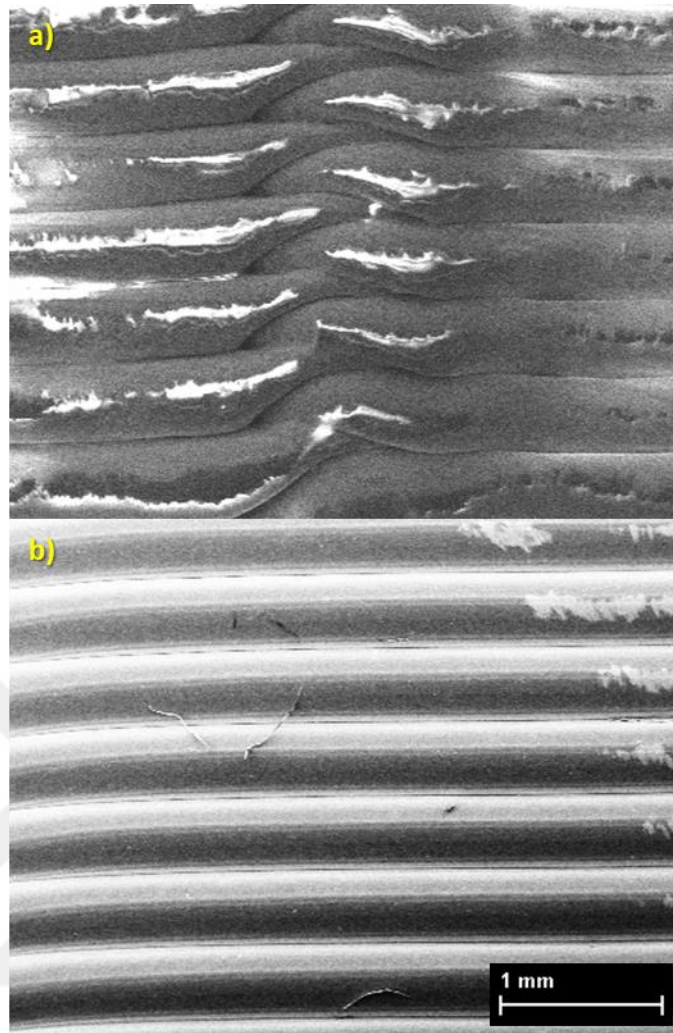


Figure 35. SEM images of the two methods: a) At extrusion start-stop points of planar slicing method b) Throughout the layers of helical slicing method

The results of the helical slicing algorithm for different geometries are given below. It is shown that the algorithm works robustly on several different models that are not bounded by the limitations stated before. Figure 36 is showing a toolpath of windmill blades from different angles together with the manufactured model. Figure 37 is again showing the toolpath and the manufactured model of a plastic beverage bottle.

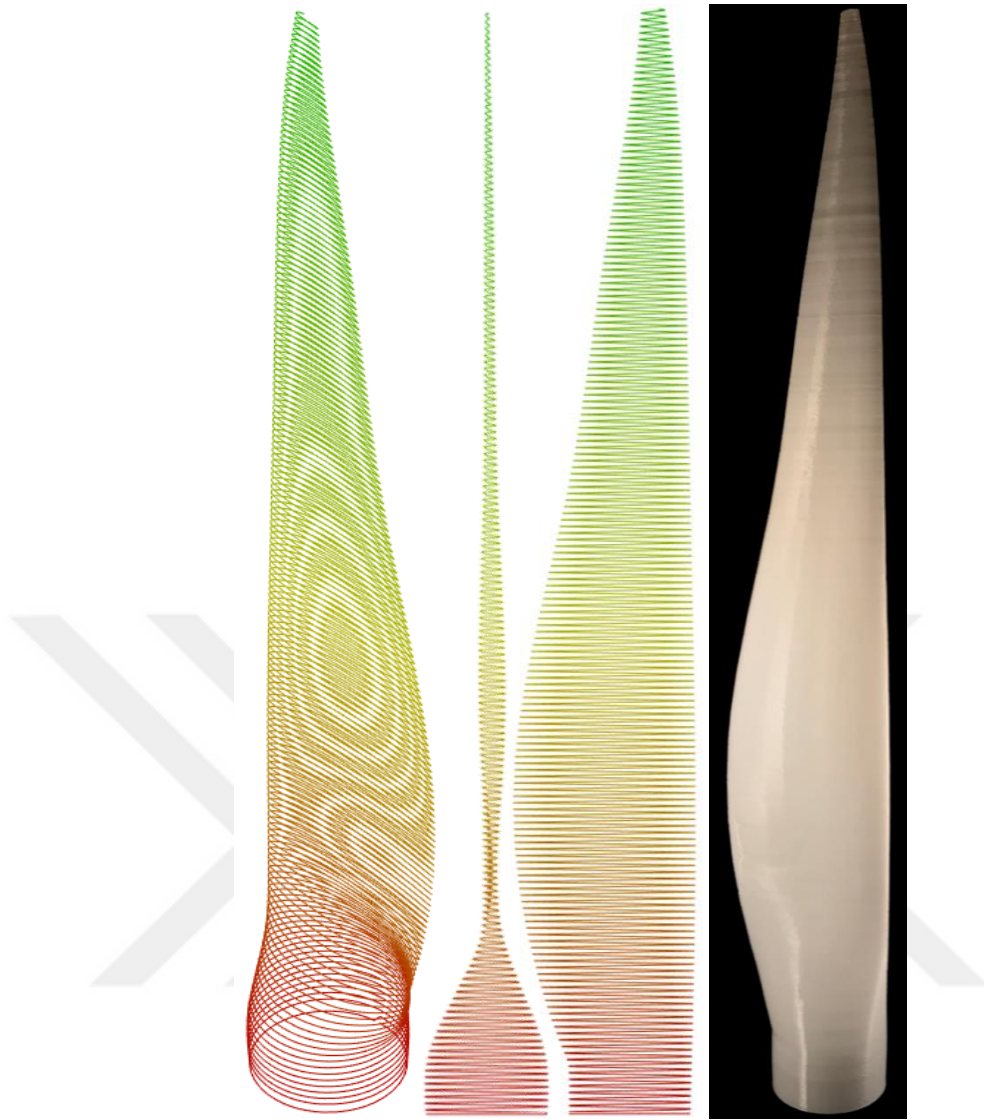


Figure 36. Helical slicing method for a windmill blade: Toolpaths and the fabricated model are shown. Dimensions are given as 100 mm width, 70 mm depth, and 700 mm height.



Figure 37. Helical slicing method for a plastic bottle: Fabricated model and the corresponding toolpaths. Dimensions are given as 35 mm width, 35 mm depth, and 90 mm height.

A similar slicing method can be found in the commercial slicing packages such as Slic3r and Cura as the spiralize feature. This feature obtains a single continuous toolpath by only incrementing the Z height of the extruder according to the extruder's movement. However, since it only increments Z, it does not consider the direction vectors X and Y components. This strategy can lead to errors in the toolpath relative to the part. When large parts are manufactured with the robotic setup, the errors will increase since the layer thickness increases. Figure 38 is comparing the toolpath, which results from the spiralize feature and the helical slicing method. The difference between the two toolpaths at a given step is given as the error vector $\vec{e}$. This vector results from the error $\vec{e}_x$ in the X direction and error $\vec{e}_y$ in the Y direction. For a model with a layer thickness of 0.5 millimeters, when there is an overhang with an angle of 45 degrees from the build orientation, the error will be equal to the layer thickness of 0.5 millimeters. When the overhang is 60 degrees, the error increases to 0.86 millimeters and so on. Since the helical method considers the next layer L_{i+1} for calculating the helical layer, as demonstrated in previous sections, the X and Y components are considered. For the case of the spiralize feature, the direction vector is towards the imaginary L' layer exactly on top of L_i and thus only has the Z vector component.

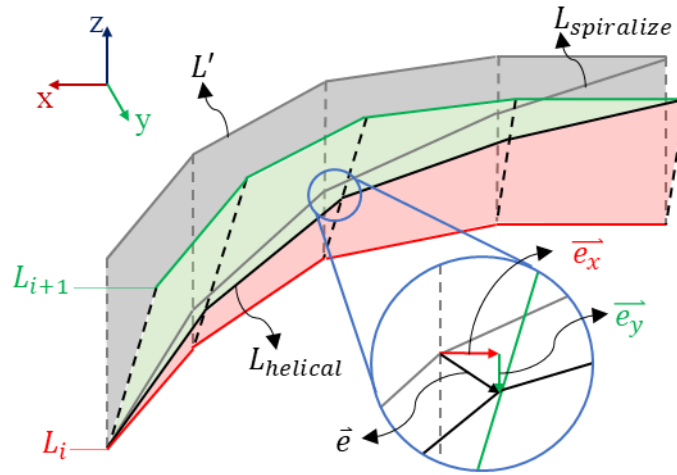


Figure 38. The proposed helical slicing method versus spiralize feature: Error $\vec{e}$ visualized with its X component $\vec{e}_x$ shown in red and Y component $\vec{e}_y$ shown in green. the current layer L_i is shown in red, the next layer L_{i+1} is shown in green and the layer L' is shown in gray. The spiralize layer is visualized in gray, and the helical layer is pictured in black.

5.6 Conclusion

The helical slicing strategy was introduced. Initially, the given CAD model is sliced into planar contours, as in the case of conventional methods. These planar contours are then used to generate the helical toolpath. This method is a truly 3-dimensional AM method, whereas the planar slicing methods are two and a half dimensional. Instead of having many slices and discontinues toolpaths, a single helical toolpath is formulated with a single extrusion start and end points. This strategy significantly reduces the defects in each layer where the extrusion starts and finishes.

Due to the continuous extrusion strategy, the switching control of the extrusion mechanism is simplified. Additionally, rapid movements of the extruder are eliminated. The advantage of the helical toolpath over the planar toolpath is visualized using SEM images of manufactured models, which are manufactured on a robotic AM setup. It is possible to extend the proposed method and manufacture more complex geometries, which also includes infills by combining the proposed method with the current planar slicing strategies and having a hybrid slicing method. Furthermore, the proposed method can be improved by introducing adaptive layer heights and multi-planar slicing directions.

Chapter 6

Spherical Slicing Method and its Application on Robotic Additive Manufacturing

Additive Manufacturing (AM) delivers low quantity parts on-site, within hours, and with no initial investment costs of dies and molds. AM is rapidly being developed and adopted by the industry to fill the voids that traditional manufacturing methods cannot satisfy. AM serves the market from low to medium volume prototyping in the early part design stage [3] to final products manufactured from metal that is used on airplanes [72]. AM methods have started to mature in many of its subfields, such as planar slicing methods, but it has yet to make progress in nonplanar manufacturing methods. Methods that fall outside planar manufacturing methods are yet to be investigated.

In AM, the manufacturing of the desired part starts with the Computer-Aided Design (CAD) of the part model. The CAD model is taken as the main input of the slicing software. Generally, the CAD data is stored in the form of a triangular mesh [8]. Recently Materialise, and Toyota has teamed up to fabricate a lightweight seat of a car with a bionic design using their new slicing technology that even skips the STL file and generates just layer data, which is enough for AM [73]. After obtaining the STL, each triangle in the mesh is intersected with equidistantly spaced planes. These planes lay parallel to the manufacturing bed and increment in the build orientation. The distance between the layers is determined by the thickness of the layer. The slices are used to formulate the toolpath, which is used to move the tool of the machine in 3-dimensional space. The planar slicing method is the widely adopted method in AM, and most of the available research is investigating planar slicing methods. Since the layers of planar slices are two dimensional, the planar slices are not able to conform to the 3-dimensional freeform surfaces of models [74]. Curved surfaces such as those on a surface of a sphere are prone to the stair-stepping effect [9], [67]. In such cases, the final manufactured model can be improved by using the nonplanar slicing strategies [75]. One of the nonplanar strategies, which is investigated in this research, is the method of spherical slicing.

Planar slicing of spherical objects results in loss of form of the part and reduced tensile strength. The development of new multiaxis AM machines enables new slicing methods to be implemented. When the part is sliced spherically, not only the stair-

stepping effect will be eliminated, but the manufactured model will also have higher tensile strength and increased structural integrity. It is reported that with nonplanar AM methods, such as the one given in this research, with the right analysis and knowledge of how the part is used, parts, which are five times stronger can be manufactured [76].

Up to date, few nonplanar cases have been investigated. Zhao et al. proposed two nonplanar slicing strategies: a curved surface slicing strategy, which is decomposition-based, and a cylinder surface slicing method, which is transformation-based. These reduce the need for support structures and decrease the required number of layers and thus manufacturing time. They have validated the proposed methods by fabricating the parts with a robotic fused filament fabrication (FFF) system [50]. Tsao et al. proposed a new method that has two features: Varying directional deposition along the tangent of the surface, eliminating stair-shape surface with uniform horizontal layer deposition, and varying dimensional material deposition depending on the local geometry, allowing increased build rate [51]. Singamneni et al. Proposed a curved layer material deposition for thin shell parts, which ensures fiber continuity. They have developed a mathematical model for curved slicing and manufactured a few models as case studies. They have observed improved mechanical characteristics with their nonplanar parts [77]. Lim et al. has proposed a Curved Layered Fused Deposition Modelling (CLFDM), which has been tested with a large-scale construction AM system. It calculated a curved layered tool path and was evaluated with laying concrete material. The process revealed three principal benefits: Better surface quality, shorter manufacturing time, and higher surface strengths [68]. Allen et al. have demonstrated the use of Curved Layer Fused Filament Fabrication (CLFFF) tool paths, enabling the extruder to follow the topology of the given CAD model. Using a delta type manipulator and the generated CLFFF tool paths, the surface finish of the parts has been improved, and the time costs have been notably reduced [66]. Kerschbaumer et al. present a toolpath generation method for 3-dimensional laser cladding using adaptive and curved slicing. Parametric curved slicing planes are used to intersect with the STL file and obtain the nonplanar tool paths. Then point inversion is used for mapping the boundary into u, v domain, and generating infill. Afterward, the infill is mapped back, and the final toolpath is laid on a previously manufactured model. [78]. Ding et al. have developed an eight-axis robotic direct metal deposition system that is laser-based. They proposed a hybrid slicing method which maps the overhanging parts of a revolving part to a planar base. As a result, the traditional tool paths can be used to

generate new the tool paths for the mapped structures. The method is successfully applied to build a propeller [35]. Most of the given work is focused on mapping, transforming techniques and does not investigate the core of the nonplanar slicing. The nonplanar slicing used for the curved surface slicing can be divided into two main sections. These are elementary surfaces, such as cylinders, spheres, ellipsoids, etc., and freeform surface. This research suggests an analytical solution to the spherical slicing problem.

In this work, initially, the base is sliced using the conventional planar slicing strategy. The features of the model that are on top of the base are sliced using the newly developed spherical slicing method. After the slicing, the tool path is generated for both slicing strategies. The planar slices' toolpath consists of X, Y, and Z coordinates required to navigate the 3-dimensional space. In nonplanar freeform operations, such as the spherical toolpath, a 3-dimensional orientation definition is also required. This is achieved by introducing the I, J, and K angles. In the end, the spherical layers are laid conformally on the base with the generated 6-axis toolpath. The strategy is visualized in

Figure 39, where blue features are the planar layers, and the green is the spherical features.

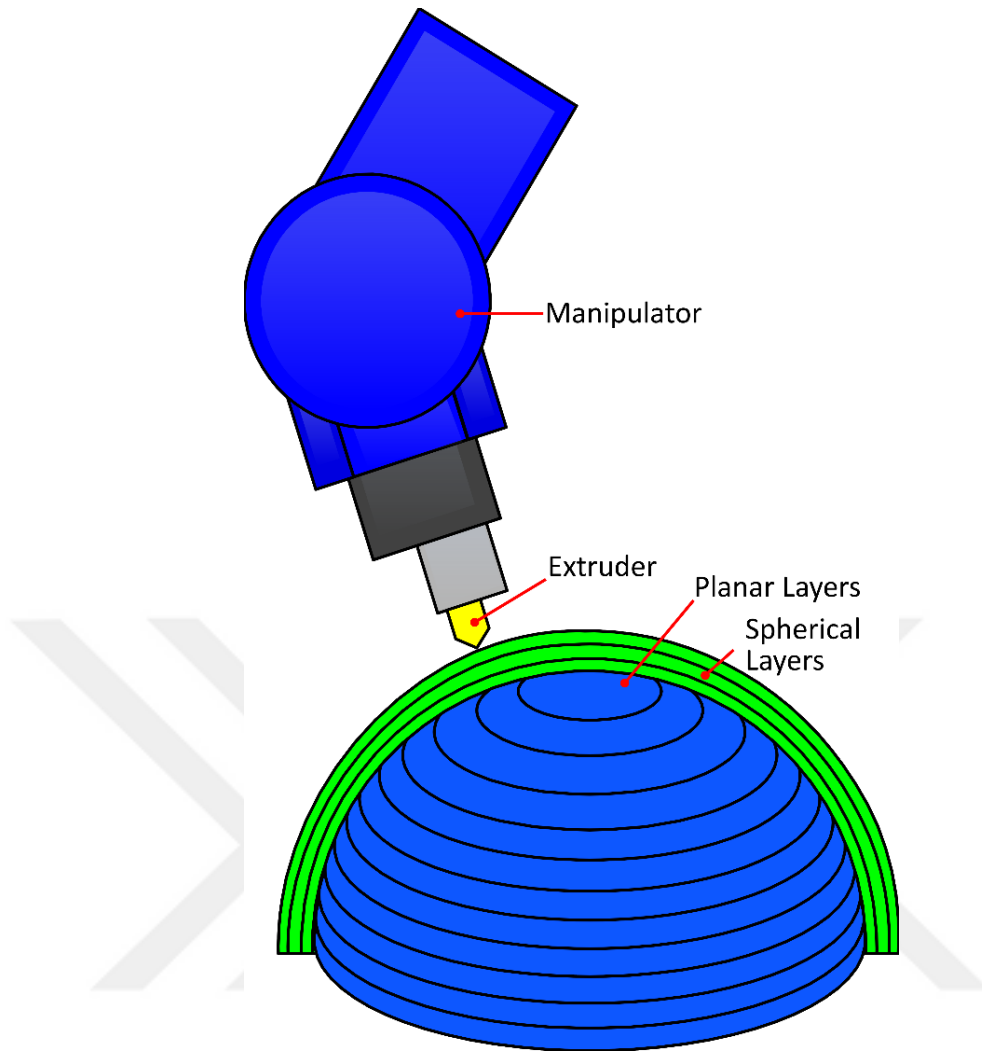


Figure 39. Overview of the spherical slicing method. The planarly sliced base is given in blue, and spherically sliced features on top of the planar base are given in green. The manipulator is positioned on top of the part, where the extruder is given in yellow.

Section 6.1 of this work formulates the spherical slicing strategy. Section 6.2 describes the algorithm used for the infills of the layers found in the former section. Section 6.3 introduces the toolpath generation that is required to transfer the layers and the infills to machine instructions. Section 6.4 gives the RAM setup on which the generated toolpath is tested. Section 6.5 introduces the manufactured part: The model of Earth. It is manufactured from two filaments. The green filament to show the lands, and the blue filament to show the oceans. Finally, Section 6.6 concludes the chapter with the conclusion of the work.

6.1 Spherical Slicing Method

The proposed spherical slicing strategy accepts Stereolithography (STL) files, consisting of a triangular mesh. The mesh is the tessellation of the Computer-Aided Design (CAD) model into triangles, which are the first order piecewise approximation of the part geometry. This simplifies the data irreversibly, removes all CAD attributes but preserves the model geometry, and is practical to work within AM applications.

Each triangle from the STL file is intersected with a sphere surface to obtain a spherical layer. Then the radius of the sphere is increased to get the next layers. The intersection problem is repeated until the whole model is sliced from the center to the surface. The sphere-triangle intersection problem is visualized in Figure 40a and formulated as follows. The single edge of the triangle is given in the formulation. The same procedure is carried for the remaining two edges. To get all intersections

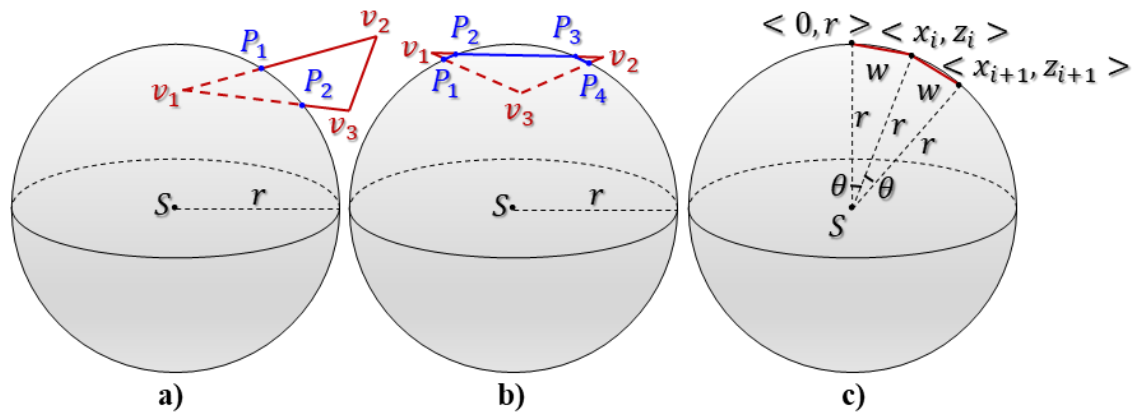


Figure 40. The problem of Sphere-triangle intersection visualized. The spherical shells are given with center point S and radius r . a) Double intersection case where P_1 and P_2 are the intersection points. v_1, v_2 and v_3 , are vertices forming a triangle from the STL shown in red. b) Quadruple intersection case resulting in points P_1, P_2, P_3 and P_4 , given in blue. These points are connected end to end to form the three line segments of the intersection. (c) Calculation of the radius r and the height z for the discs i and $i+1$. The top point is given by point $0, r$. Extrusion width is given by w .

The parametric equation of a line which spans from one edge of the triangle to the other edge, v_1 to v_2 , is given in vector form as

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} v_{1x} \\ v_{1y} \\ v_{1z} \end{bmatrix} + t \begin{bmatrix} v_{12x} \\ v_{12y} \\ v_{12z} \end{bmatrix} \quad (4)$$

where the vector v_{12} from is given as

$$\begin{bmatrix} v_{12x} \\ v_{12y} \\ v_{12z} \end{bmatrix} = \begin{bmatrix} v_{2x} \\ v_{2y} \\ v_{2z} \end{bmatrix} - \begin{bmatrix} v_{1x} \\ v_{1y} \\ v_{1z} \end{bmatrix} \quad (5)$$

The parametric equation of the sphere with the center point S and radius r is given in as

$$r^2 = (P_x - S_x)^2 + (P_y - S_y)^2 + (P_z - S_z)^2 \quad (6)$$

Using the values P_x , P_y and P_z in the equation of a sphere, Eq. (6), the quadratic equation of the sphere-triangle intersection is obtained as

$$t^2 (v_{12x}^2 + v_{12y}^2 + v_{12z}^2) + t (2(Av_{12x} + Bv_{12y} + Cv_{12z})) + A^2 + B^2 + C^2 - r^2 = 0 \quad (7)$$

where the coefficients A , B , and C are given as:

$$A = v_{1x} - S_x \quad (8)$$

$$B = v_{1y} - S_y \quad (9)$$

$$C = v_{1z} - S_z \quad (10)$$

Solving the quadratic equation given in Eq. (7) for the parameter t will result in two roots.

The roots are given as

$$t_{1,2} = \frac{-b \pm D}{2a} \quad (11)$$

Where D is the discriminant of the quadratic equation. The discriminant is given as

$$D = \sqrt{b^2 - 4ac} \quad (12)$$

where the coefficients a , b , and c are

$$a = (v_{12x}^2 + v_{12y}^2 + v_{12z}^2) \quad (13)$$

$$b = 2(Av_{12x} + Bv_{12y} + Cv_{12z}) \quad (14)$$

$$c = A^2 + B^2 + C^2 - r^2 \quad (15)$$

Plugging in the roots obtained from Eq. (11) in the parametric equation of the line will result in either one or two intersection points given as

$$P_1 = v_1 + t_1 v_{12} \quad (16)$$

$$P_2 = v_1 + t_2 v_{12} \quad (17)$$

Depending on the case, there can be a single intersection, double intersection, or no intersection. The intersection is carried out for the remaining two edges, and all the intersection points are found for a given triangle. Repeating for all the triangles in the STL file for each spherical layer, all the intersection points for the given layer are found. The intersection for a triangle can result in double or quadruple intersection points. The intersection points are connected to form the intersection line segments. The connection of double intersection points results in a single intersection line segment, while the connection of quadruple intersection points results in triple intersection line segments. The case of quadruple intersection points is visualized in Figure 40b. with points P_1 , P_2 , P_3 and P_4 . In this case, three intersection line segments are formed.

These intersection lines are connected end to end to form the spherical intersection boundary. The distances to the next line segments' endpoints are calculated to find the next line segment. When the overlapping point is found, it is saved as the next line segment. In the end, a closed boundary is formed. While sorting the lines, multiple boundary loops may form depending on the geometry. These boundaries are stored as island boundaries of a single spherical intersection layer. The next spherical layer is found by incrementing the layer number i in the layer radius equation

$$r_i = r_{base} + il_t \quad (18)$$

where r_{base} is the radius of the base and l_t is given as the thickness of a single layer.

The approaches mentioned are repeated for each layer, and multiple spherical layers are generated. After the island boundaries have been generated, the infill is required to manufacture a solid layer. The formulation of the infill is given in the next section.

6.2 Horizontally-oriented zigzag infill generation for spherical island boundaries

Several infill types, such as rectilinear, concentric, can be found in the literature [79]. In this research, a zigzag infill strategy for a spherical case is developed and used. In this strategy, the toolpath is generated as back and forth motion within the island boundary. The island boundaries are filled using these horizontal zigzag infills. The infill can be sparse or dense, depending on the design requirements. Infill density is selected as %100 to have a solid layer. This corresponds to deposit material equally at each point inside the island boundary. In planar slicing, zigzag infill is composed of equidistantly spaced lines connected at the endpoints. For the spherical application, it is composed of arc segments. To generate the arc segments, initially, discs are generated covering the sphere from top to bottom. The radii r_i of discs are given by Eq. (19), and the heights are calculated by Eq. (21) and intersected with the island boundaries.

$$r_i = r \cos(\theta_i) \quad (19)$$

$$z_i = r \sin(\theta_i) \quad (20)$$

The angle θ from the Z axis is calculated from the cosine formula as

$$\theta = \arccos\left(\frac{2r^2 - w^2}{2r^2}\right) \quad (21)$$

The values are visualized for discs i and $i + 1$ in Figure 40c.

When dealing with planar slices, it is easy to determine if it is inside an island boundary or not and where to generate the infill. With the spherical layers, sending a simple ray is not enough to determine where the point is located. To determine if the current point is located inside an island boundary, an initial reference point, such as the sphere's topmost point, is needed. A ray is cast towards the surface's normal direction at this reference point using Möller–Trumbore [39] ray casting algorithm. The ray casting problem is formulated below.

A ray $R(t)$ with origin O and normalized direction, D is defined as:

$$R(t) = O + tD \quad (22)$$

A point $T(u, v)$ on a triangle is given by with barycentric coordinates of u and v as

$$T(u, v) = (1 - u - v)V_0 + uV_1 + vV_2 \quad (23)$$

Plugging in Eq. (22) into Eq. (23) results in

$$O + tD = (1 - u - v)V_0 + uV_1 + vV_2 \quad (24)$$

Rearranging the terms gives:

$$\begin{bmatrix} -D & V_1 - V_0 & V_2 - V_0 \end{bmatrix} \begin{bmatrix} t \\ u \\ v \end{bmatrix} = O - V_0 \quad (25)$$

Where u and v must satisfy $u \geq 0$, $v \geq 0$, and $u + v \leq 1$. If these conditions are satisfied for any triangle from the STL model, there exists an intersection. If there exists an odd number of intersections, the point is inside an island boundary. If there is an even number of intersections, the point lies outside.

A vertical disc is intersected with the island boundaries to determine where the infills will be placed. The angle of each intersection from the vertical disc is calculated as:

$$\alpha = \text{atan2}(VD_x, -VD_z) \quad (26)$$

Where VD consists of vertical disc intersection points. The inside-outside condition of each infill disc's starting point is tracked using these angles. If the initial point is inside the model and the vertical disc crosses a boundary at odd times, the point ends up outside the island. If it crosses even times, the point is inside the island. A similar approach is followed when the initial point is outside the model. The infill segments can be correctly placed inside the island boundaries using this method. Infill segments shorter than a critical infill length determined by the user are removed.

After infill segments for the interior of each island boundary are generated, the segments are grouped. The endpoints of the infill segments are connected in a zigzag manner to achieve this. This is done by checking if the next disc has an infill segment within a certain distance to the end of the current segment and does not cross any island boundaries. The arc segments are also offset from the island boundaries as much as the extrusion thickness to not overlap with the island boundaries. The next section gives the toolpath generation, which generates the final list of instructions for the RAM setup.

6.3 Toolpath Generation of Spherical Slices

Up to this section, the island boundaries and the corresponding infill groups for each spherical layer have been generated. These are all the points where the extruder must lay material. Non-extrusion movements must be introduced to move between two island boundaries. Linear movement is not sufficient to navigate on a spherical surface without colliding with the surface. To move from point A to point B on the surface of the sphere, an arc motion is required. This is accomplished with the spherical linear interpolation (SLERP) [80]. With the SLERP equation given in Eq. (27), a collision-free toolpath along the great circle arc is generated on the unit sphere's surface in which SLERP was performed.

$$SLERP(A, B, t) = \frac{\sin(1-t)\Omega}{\sin\Omega}A + \frac{\sin t\Omega}{\sin\Omega}B \quad (27)$$

By selecting an appropriate step length to approximate the arc motion, t can be selected as an array of values in the range of 0 to 1. Ω denotes the angle of the arc from point A to point B on the sphere. When the current island is finished, the extruder retracts in the direction of the normal. The arc motion is conducted at each retracted point, hovering over the next island's starting point. Finally, the extruder is lowered to the point to start extruding the current layer. With the introduction of rapid movements, a complete toolpath for manufacturing the given model is formulated.

In general, most of the machine controllers are accepting G-codes. The controller of the Motoman robot arm accepts the Inform language, which is saved as job files. A Job file consists of two distinct sections: The first section gives the coordinates of the points. The second section consists of movement instructions referring to the previously introduced coordinates and the relating velocity data. The next section introduces RAM.

6.4 Robotic Additive Manufacturing of Spherical Slices

The positioning of the extruder in X, Y, and Z coordinates are required to fabricate planar layers in a cartesian AM configuration. When handling freeform nonplanar toolpaths, in addition to the position data of the extruder, the orientation data is also needed. Yaskawa Motoman HP20D 6-axis robotic serial manipulator is used to reach the desired orientations, as shown in Figure 41. The orientation data is given by the I, J, and K angles. The position and the orientation combination is referred to as the pose of the extruder. A serial manipulator is able to reach a given pose with multiple configurations. To find the

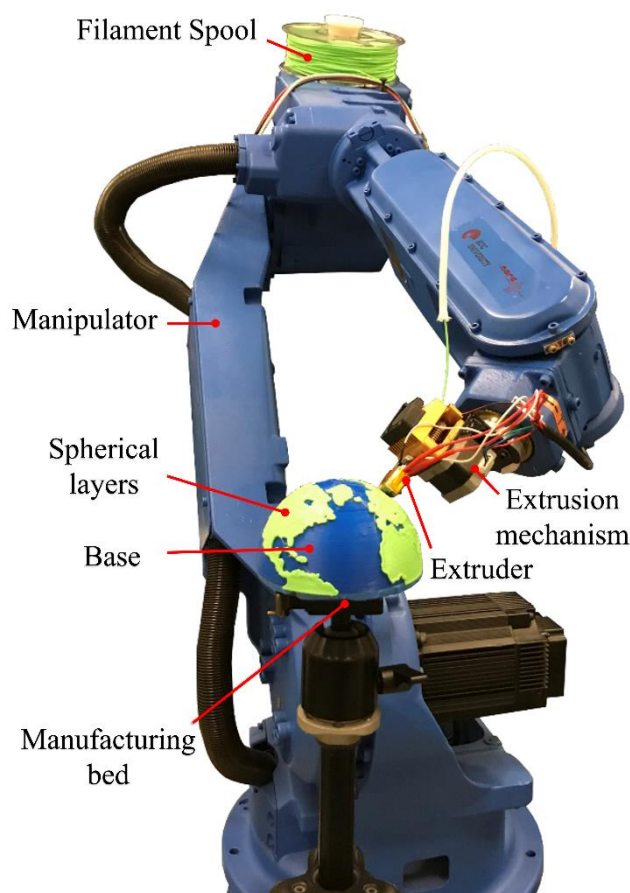


Figure 41. 6-axis Motoman Yaskawa robotic manipulator is laying the spherical layers on top of the planar base. The base is placed on the circular manufacturing bed. The extruder feeds the filament from the filament spool onto the part with the help of the extrusion mechanism.

Together with the pose and the configuration data of the manipulator at each point of the toolpath, the speed and the extrusion commands are also given. The speed commands tell the robot at which rate it should move from the current point to the next point of the toolpath. It is the linear speed, and it is given in $[mm/s]$. The extrusion commands consist of starting and stopping the extrusion and setting the new extrusion rates. When all the

required data is generated, the CAD model can be manufactured additively. The next section introduces the additively manufactured parts and the discussion.

6.5 Results and Discussions

The stair-stepping effect is improved by using the spherical slicing method. This is shown with an example part in Figure 42. In this figure, the same features on a sphere are manufactured by using spherical and planar slicing methods.

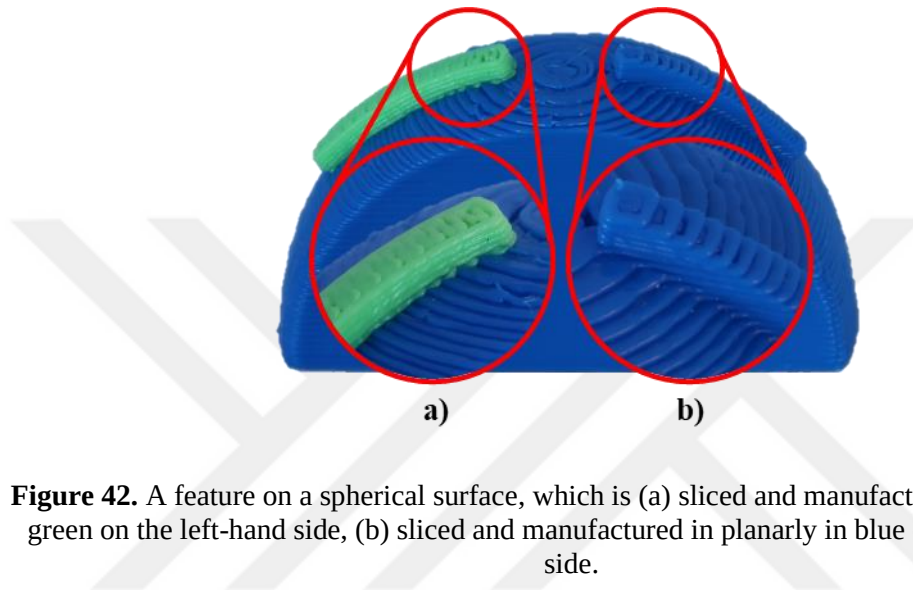


Figure 42. A feature on a spherical surface, which is (a) sliced and manufactured spherically in green on the left-hand side, (b) sliced and manufactured in planarly in blue on the right-hand side.

The spherical slicing code is run on MATLAB© environment run on a computer with Intel© I7 CPU, 8 GB RAM. It took 3.5 seconds to spherically slice a single layer of the model of Earth with 27K triangles. The slicing algorithm produces 29K lines of toolpath. The performance is sufficient for proof of concept and can easily be improved with parallel processing in a more efficient environment for commercial applications. The model of Earth has a 115 mm diameter, and it is sliced using a 0.4 mm layer thickness with a 0.8 mm width of extrusion. Thirty island boundaries are generated and filled with the introduced zigzag infill algorithm. Island boundaries with lengths shorter than 5 mm are removed due to being very small for fabrication. The spherical slicing results for the model of Earth is given in Figure 43a.



Figure 43. The model of Earth (a) Toolpath for the spherical layer is given in three different angles. The spherical layers are shown with green, the rapid movements are given in red, and the planar base is given in blue. (b) The fabricated model where the planar base is manufactured in two halves with blue filament on top of a bed matching the exact diameter of the base. The spherical layer is on the planar base using the green filament.

6.6 Conclusion

The spherical slicing method for AM that is used to lay layers additively on a spherical surface is introduced. The CAD model that given in the format of an STL file is sliced by spherical shells, such as the shells of an onion. The intersection points resulting from the spherical slices are then used to generate the island boundaries. The zigzag infill method is developed to fill the interior of the spherical island boundaries. Then, rapid movements are introduced to move between the islands without collision. Using these data, the toolpath to guiding the robotic manipulator in 3-dimensional space, together with the corresponding orientation to lay the spherical toolpath on top of the previously fabricated base, is generated. The feasible toolpath is found by solving for the inverse kinematics of the robot at each point in space and providing the robot with the proper configurations. Using the FFF tool, the planarly sliced base is finished off by laying the stair-stepping prone spherical layers. The proposed method is verified by manufacturing the model of Earth using the six-axis robotic serial manipulator. As a result, it is shown that the stair-stepping effect is minimized, and the original form of the spherical model is preserved.

Chapter 7

Cylindrical Slicing Method and Additive Turning for Robotic Additive Manufacturing

The invention of the lathe has been a real turning point for the history of humankind. It has led to the manufacturing of high precision machinery and, thus, the industrial revolution. Machine tools lie at the heart of the industrial revolution, and in the spotlight of the machine tools is the lathe machine and the turning process. Without the significant developments in the lathe between 1750 and 1830, the steam engine would not be possible, and the revolution would not have taken place [81]. Since the first recorded lathe, the lathe has improved gradually and reached a point where it is entirely computer numerical controlled (CNC). From the lathes of the ancient Egyptian times to the CNC Turning centers of the modern-day, the fundamentals of the turning process on the lathe have not changed much. In the turning process, the workpiece is manufactured by material removal. Material is removed from the rotating workpiece by a stationary cutting tool where the tool is guided on the workpiece that is mounted on a rotating axis. The process is controlled by the CNC using the toolpath generated from Computer-Aided Manufacturing (CAM) software. This toolpath is manually generated using the CAM tools by the CAM operator.

On the contrary to subtractive manufacturing, Additive Manufacturing (AM) manufactures parts by layer-wise addition of material [82]. Being a much more complicated process, AM marks the fourth industrial revolution. With AM, highly complex freeform parts can be manufactured with ease using different kinds of materials. AM is under rapid development, and it is helping to fill the voids which traditional manufacturing methods cannot fulfill [3]. Most methods of the day use a 3-axis cartesian system to guide the material deposition and build the workpiece layer by layer in a planar manner. The tool paths for a given model is generated using slicing software. Unlike CAM software, slicing software is more straight forward. There are few operations to choose from with several parameters such as the layer height, infill density, and deposition speed. This research investigates the area where AM is introduced to the turning process.

Additive turning adds a new manufacturing method to turning where the part is manufactured additively in contrast to the subtractive norm. It can accomplish this for any intricate freeform 3-dimensional Computer-Aided Design (CAD) model by introducing a generalized cylindrical slicing method. The cylindrical slicing method is used to get the tool paths that are required for the given CAD model to be additively manufactured on an additive turning setup. The planar slicing method is the currently adopted method in AM, and most of the available research investigates planar slicing methods. With the adaption of new multi-axis AM machines, few works have started focusing on nonplanar slicing methods.

Isa et al. have developed a new five-axis AM system to facilitate the implementation of novel 3D curve paths for five-axis AM of freeform models using the buildup of transition layers. In their work, they have designed, built, and programmed the five-axis capable hardware. Additionally, they have developed a new five-axis toolpath planning method that uses the surface profiles of the given freeform CAD model. They have eliminated stair-stepping effects by depositing on successive transition surfaces whose layer thickness varies to change the form of the surfaces [83].

Alkadi et al. have developed a conformal AM process that builds complex 3D structures on freeform surfaces using a direct printing process. The developed algorithm takes the 3D model of both the part to be printed and the base part to be printed on and returns the generated G-code. The slicing surfaces are not planar and are generated by offsetting the surface of the base part by a selected layer height. 3D Infill toolpath is generated by projecting a 2D toolpath to the surface of the base model. The developed algorithm was validated by the material extrusion-based printing of several models [84].

He. et al. have manufactured a Wire arc additive manufacture (WAAM) propeller by using a cylindrical surface slicing method. It has applied a slicing method based on the principles of conformal slicing to WAAM, with slicing sections coaxial to the hub of the propeller. It has obtained dimensional error of the product is within ± 1.6 mm. The mechanical properties of WAAM propeller components are higher than the casting ones with the same composition [85].

Wang et al. also proposed a cylindrical slicing and path planning of propeller in WAAM. Previous work manufactured parts on the plane and along the vertical direction. The purpose of this work is to propose a method for revolved parts, e.g., blades of a propeller. The generated slicing contours on the cylinder are transformed to lie on a plane

so that the planar path planning algorithms can be adopted [86]. Zhao et al. have proposed a nonplanar slicing and path generation method for RAM. Typically in AM, the planar slicing strategy is used. However, when building overhanging structures and curved parts, the needed support structures generates a large number of planar layers, which lead to spending more time in manufacturing. To reduce the need for support structures and decrease the number of layers, the author suggests nonplanar slicing approaches. First is a decomposition-based curved surface slicing strategy and a transformation-based cylinder surface slicing method. The proposed methods are validated by printing two sample parts with a robotic FFF system [50].

The literature has started picking up on nonplanar slicing methods. However, currently, there has not been any generalized cylindrical method that can be used for additive turning. This work proposes a generalized cylindrical slicing method that can handle any complex freeform parts. Section 7.1 of this work formulates the cylindrical slicing method. Section 7.2 then describes the circular infills used for getting solid layers for the layers found in the former section. Section 7.3 introduces the linear infills, which play an essential role in increasing the tensile strength of the part. Section 7.4 provides the toolpath generation, which is required to be able to transfer the layers and the infills to machine understandable instructions. Section 7.5 describes the RAM Setup for Additive Turning, in which the toolpath is used. Section 7.6 gives manufactured parts and the discussion. Finally, Section 7.7 marks the end of the chapter with the conclusion.

7.1 Cylindrical Slicing Method for Additive Turning

The proposed cylindrical slicing method takes any complex freeform Stereolithography (STL) files as an input CAD model. STL files consist of a triangular mesh. This mesh is the tessellation of the CAD model into triangles, which are the first order piecewise approximation of the model. It simplifies the model but preserves the original geometry and is more practical to work within AM applications [8].

The model has to be sliced with cylindrical layers to manufacture parts with additive turning, as opposed to planar layers of conventional AM. Each triangle from the STL file is intersected with a cylindrical surface to obtain cylindrical layers. Layers consist of radius (r_i) where (i) denotes the layer number. The first layer will start at the cylindrical build bed, and the radius will increase at each layer until the whole model is covered. The layer radius is calculated using Eq. (28).

$$r_i = R + hi \quad (28)$$

Where (R) is the radius of the cylindrical manufacturing bed and (h) is given as the layer height. Layer number i starts from 1, and the first layer radius is equal to the build bed radius plus the layer height.

Using a single triangle from the STL model, Figure 44a represents the cylinder-triangle intersection problem where the cylinder is represented with the center point (C) and the radius (R). (v_1), (v_2) and (v_3) are vertices forming a triangle from the STL file and (P_1) and (P_2) are the intersection point. The following formulation is given for a single edge of a single triangle from the STL file. The same formulation is carried for the remaining two edges of the triangle.

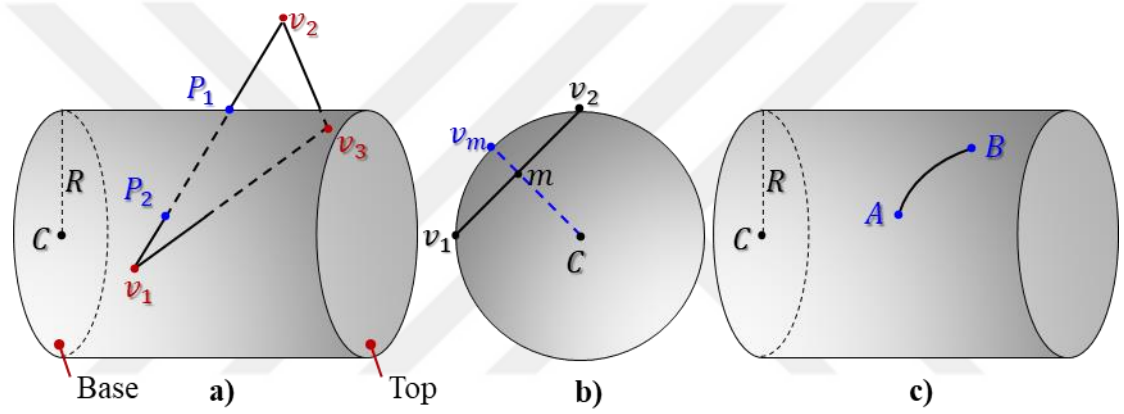


Figure 44. Cylindrical Slicing Method Visualized where C denotes the center of the cylinder, R the radius. a) Cylinder-triangle intersection problem is visualized where v_1, v_2, v_3 are the vertices of one triangle, and P_1, P_2 are the intersection points of edge v_{12} with the cylinder. b) Finding the midpoint v_m of the arc formed by the points v_1 and v_2 c) Helical movement from point A to point B .

The parametric equation of a line which spans from one vertex (v_1) of the triangle to the other vertex (v_2), is written in vector form as:

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} v_{1x} \\ v_{1y} \\ v_{1z} \end{bmatrix} + t \begin{bmatrix} v_{12x} \\ v_{12y} \\ v_{12z} \end{bmatrix} \quad (29)$$

The vector from the vertex (v_1) to the vertex (v_2) is given as the vector (v_{12}) as:

$$\begin{bmatrix} v_{12x} \\ v_{12y} \\ v_{12z} \end{bmatrix} = \begin{bmatrix} v_{2x} \\ v_{2y} \\ v_{2z} \end{bmatrix} - \begin{bmatrix} v_{1x} \\ v_{1y} \\ v_{1z} \end{bmatrix} \quad (30)$$

The equation of a cylinder with its base circle on the XY-plane, which is centered at the point (C) and has radius (R) is given in Eq. (31) as:

$$(x - C_x)^2 + (y - C_y)^2 = R^2 \quad (31)$$

Rearranging Eq. (29) and Eq. (31) and selecting the center (C) as (0,0,0), the quadratic equation of the cylinder-triangle intersection is given as:

$$t^2 (v_{12x}^2 + v_{12y}^2) + 2t (v_{1x}v_{12x} + v_{1y}v_{12y}) + v_{1x}^2 + v_{1y}^2 - r^2 = 0 \quad (32)$$

Solving the quadratic equation given in Eq. (32) for the parameter (t) will result in two roots. The roots are given as:

$$t_{1,2} = \frac{-b \pm D}{2a} \quad (33)$$

Where (D) is the discriminant of the quadratic equation. The discriminant is given as:

$$D = \sqrt{b^2 - 4ac} \quad (34)$$

where the coefficients (a), (b) and (c) are:

$$a = (v_{12x}^2 + v_{12y}^2) \quad (35)$$

$$b = 2(v_{1x}v_{12x} + v_{1y}v_{12y}) \quad (36)$$

$$c = v_{1x}^2 + v_{1y}^2 - r^2 \quad (37)$$

Plugging in the roots obtained from Eq. (33) in the parametric equation of the line results in either one or two intersection points, which are given as:

$$P_1 = v_1 + t_1 v_{12} \quad (38)$$

$$P_2 = v_1 + t_2 v_{12} \quad (39)$$

The intersection points are saved if there is an intersection between the current edge (v_{12}) of the triangle and the current cylinder with radius (r_i). A single edge can result in either one or two intersection points. The remaining intersections with edges (v_{23}) and (v_{31}) are carried out to complete the cylinder-triangle intersection problem. This results in either double or quadruple intersection points. These intersection points are connected to get the intersection line segments. Double-intersection points result in a single intersection line segment, and quadruple intersection points result in three intersection

line segments. Repeating the intersections for all the triangles in the model for every cylindrical layer, the intersection points for the layer with a given radius (r_i) is found.

Unlike planar slicing, line segments resulting from cylindrical slicing cannot be used directly. In planar slicing, every line segment lies on a flat plane and forms the final shape of the flat 2D layer. In cylindrical slicing, the layer is not flat, and any obtuse triangles can contain two long edges, and the cylindrical intersection can result in a straight long line segment that does not fit the base circle of the cylinder. These line segments have to be interpolated to fit the cylindrical surface. The following equations are used to split the line segment from (v_1) to (v_2) recursively until it fits the existing cylindrical surface. The points are visualized in Figure 44b.

$$m = \frac{v_1 + v_2}{2} \quad (40)$$

Where (m) in denotes the center point from (v_1) to (v_2).

$$v_{cm} = m - C \quad (41)$$

Where (v_{cm}) denotes the direction vector from the center of the circle to the midpoint.

$$v_m = \frac{v_{cm}}{|v_{cm}|} r_i \quad (42)$$

and (v_m) gives the midpoint lying on the circle where (r_i) is the radius of the current circle.

After all intersection lines are found, they are sorted by stitching each segment end to end, which forms a closed loop of a cylindrical island boundary. While sorting the cylindrical layer lines, multiple island boundaries may exist depending on the given STL geometry. All the boundaries in the current layer are stored as island boundaries of a single cylindrical intersection layer. The next cylindrical layer is found by incrementing the layer number (i) in the radius equation Eq. (28) and following the same steps. The triangles and the cylindrical slicing results are shown in Figure 46 a and b.

These steps are repeated for each cylindrical layer, and multiple cylindrical layers are generated to build the whole model one layer at a time. After getting the island boundaries, the appropriate infills are generated to fill the inside of these island boundaries. Two types of infills are introduced. The first is the circular infill, which fills the island boundaries while the cylinder is rotated. This infill is used to form the solid layers. The second infill is the linear infill, spanning from the base circle of the cylinder

to the top of the cylinder. Linear infills provide the extra tensile strength in the build direction, which the traditional planar AM methods lack. Infill generations are introduced in detail in the following two sections.

7.2 Circular Infills for Cylindrical Slicing

Circular infills in cylindrical slicing are the infills where the material is deposited circularly by keeping the extruder fixed and rotating the cylindrical build bed. Depending on the given CAD geometry, the deposition at each step is either a full circle deposition covering the whole rotation or an arc segment deposition starting and ending at island boundaries. The first step in calculating the circular infill is generating the circular slicing planes (CP). These planes are equidistantly placed planes parallel to the base plane of the cylinder. They start from the base of the cylinder and end at the top of the cylinder ($CP_1, CP_2, \dots, CP_n$) as visualized in Figure 45a. The distance between two planes is given as the circular infill width (w_c). The second step is to obtain cylindrical infills by intersecting the island boundaries, generated in section 7.1, with the circular slicing planes. This is accomplished by plane-line intersection studied in previous works, such as the helical slicing method [75].

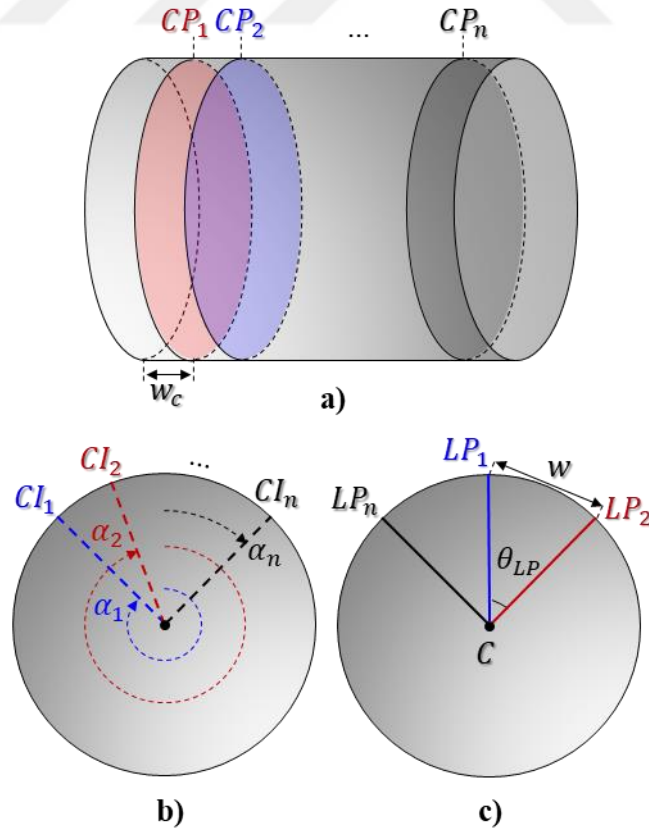


Figure 45. Infill strategies for cylindrical slicing visualized: a) Circular infill slicing planes CP_1, CP_2 to CP_n are shown with equidistant spacing of w_c . b) Circular infill points CI_1, CI_2 to CI_n and the angles $\alpha_1, \alpha_2, \alpha_n$ of these points are visualized. c) Linear infill slicing planes LP_1, LP_2 to LP_n are shown with equidistant spacing of w and angle of θ_{LP} .

The intersection for each cylindrical layer with circular infill slicing planes can result in either multiple intersection points or no intersection points. In the case of multiple intersection points, for each layer, the intersection points will be first sorted from lowest to highest by their horizontal angles (θ_{IP}). The horizontal angles of the intersection points are given in Eq. (43)

$$\theta_{IP} = \text{atan} \frac{IP_y}{IP_x} \quad (43)$$

Where IP_x denotes the X and IP_y the Y-coordinate of the intersection point.

Each two sorted intersection point is used to form an arc segment. These arc segments fill the areas inside the island boundaries. If the generated segments lie outside the model, the first intersection point is not in the correct order. The first intersection point will be shifted to the end of the sorted list of intersection points to match to insides of the island boundaries. Using Möller–Trumbore ray casting algorithm, a ray is cast towards the normal direction of the surface at the point of the arc to understand if the segment is inside or outside the model. The ray casting problem is studied in the previous spherical slicing method [87].

If there are no intersection points found from the intersection of the current layer island boundaries with the current infill slicing plane, there can be two conclusions: 1) full circular infill 2) no infill. To figure this out, a selected point on this circular infill is checked for being inside the model. If it is, there is a full circular infill. If the point is outside since there are no intersection points, every possible point will be outside, and there will be no infill. This is again checked with casting a ray, as explained for the arc infills.

The circular infill (CI) is generated using the following equations for both arc and full circular infills. It is visualized in Figure 45b.

$$CI_{x_j} = C_x + r_i \cos(\alpha_j) \quad (44)$$

$$CI_{y_j} = C_y + r_i \sin(\alpha_j) \quad (45)$$

Where α_j is the linearly spaced angles between the starting and the ending points. For the full intersection case, the angle is from 0 to 360 degrees. For arc infills, the same equations are used to generate arc segments starting and ending at the angles calculated using Eq. (43). The z coordinate of the circular infills (CI_{z_j}) is equal to the z of the (j^{th}) circular infill slicing plane. The results are shown in Figure 46e.

7.3 Linear Infills for Cylindrical Slicing

Linear infills in cylindrical slicing are the infills which are deposited parallel to the axis of the cylindrical build bed. At one pass, the infill is deposited linearly from the base circle of the cylinder to the top of the cylinder. The model is intersected with multiple slicing planes to obtain the linear line segments where the material will be deposited. These linear infill slicing planes (LP) are located on the axis of the cylinder at an angle with the XZ plane. They start at 0 degrees and cover the whole circle ($LP_1, LP_2, \dots, LP_n$) as visualized in Figure 45c. The angle of each linear infill intersection plane (θ_{LP}) at each layer (i) with radius (r_i) is calculated based on the specified extrusion width (w) using the equation given in Eq. (46).

$$\theta_{LP_i} = \arccos\left(\frac{2r_i^2 - w_v}{2r_i^2}\right) \quad (46)$$

Intersecting the line segments with the linear infill slicing planes gives the start and endpoints of the linear infills. The plane line intersection problem is studied in previous works [75], [87]. The points are connected end to end, after sorting them based on Z coordinates, to form the linear infill line segments. Single or multiple linear infill line segments may be found on a single slicing plane. The results are shown in Figure 46f.

7.4 Toolpath Generation for Additive Turning

In prior sections, the island boundaries and the related infills for each cylindrical layer has been generated. These are all the line segments which the extruder will follow and deposit material. The next step is to introduce non-extrusion movements. Non-extrusion movements are used to move between island boundaries and infills without extruding material. These non-extrusion movements are called rapid movements, and they follow a helical movement pattern to avoid colliding with the previously deposited areas. Assume that an island boundary has finished at point (A) and the next step is to extrude infill which starts at point (B). To move from point (A) to point (B) on a cylindrical surface,

a helical motion is required. The helical motion (H) is composed set of 3-dimensional points and calculated using the following equations. The helical motion is visualized in Figure 44c. The rapid movements are shown in Figure 46c to f.

$$H_{x_j} = C_x + r_i \cos(\theta_j) \quad (47)$$

$$H_{y_j} = C_y + r_i \sin(\theta_j) \quad (48)$$

$$H_{z_j} = A_z + sj \quad (49)$$

Where the step angle (θ_j) is the array of equidistantly placed angles starting from the entrance angle at point (A) and ending at the exit angle at the point (B). The step (s) is calculated based on the number of points it takes for (H_z) to reach from (A_z) to (B_z).

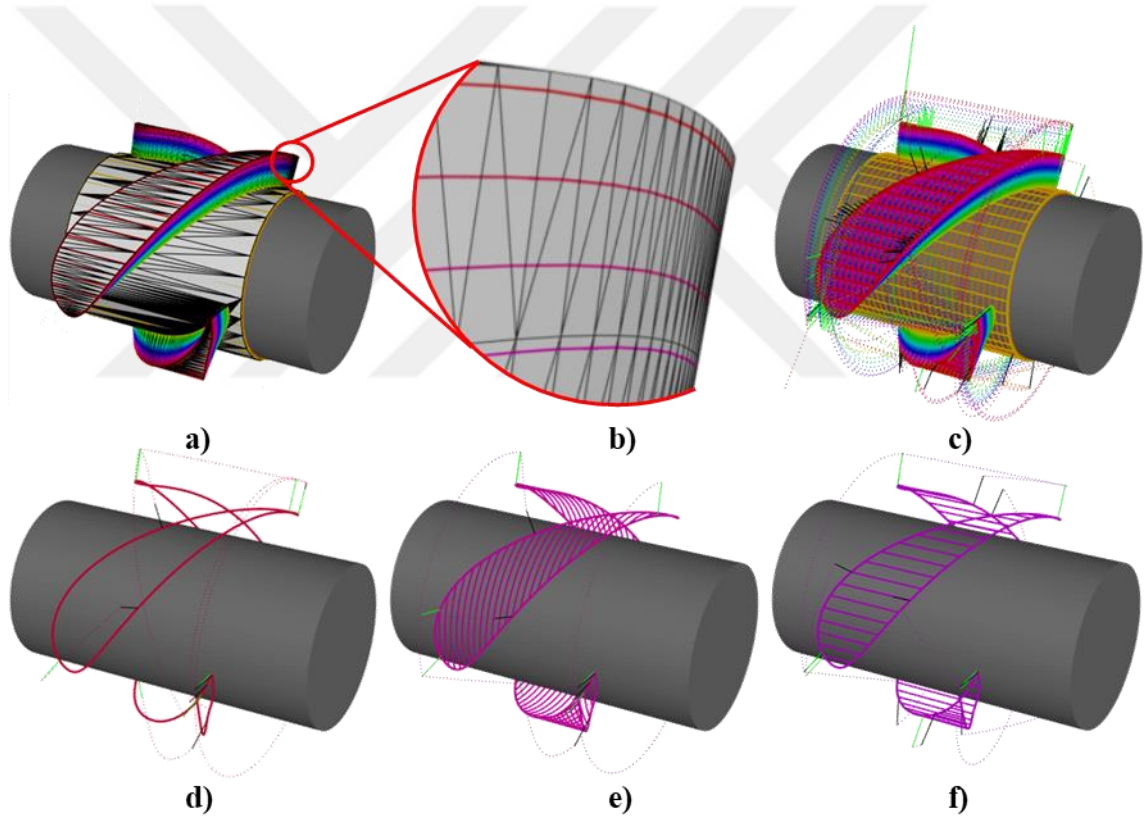


Figure 46. Cylindrical slicing visualizations: a) Cylindrical slices where each layer is given in a different color and the STL geometry where the triangles are shown with black lines. b) Close up of the triangles and the boundaries on the cylindrical layers. c) The toolpath of the given part, including the island boundaries, circular infills, linear infills, rapid movements, approaches, and retractions. Rapid movements are given in dashed lines. d) Island boundaries for a single layer where the layer is given in red, the approach movements in black, and the retractions in green. e) Circular infills for a single layer. f) Linear infills for a single layer.

After the extrusion of the current island is finished, the extruder will retract in the direction of the normal vector. From the retracted point, the helical motion is conducted

to reach over the next island's starting point. After that, the extruder approaches to start extruding the next island. With the introduction of non-extrusion movements, retractions, and the approach movements, a complete toolpath for the additive turning of the given model is obtained in the Cartesian coordinate system. The approach movements are shown with black and the retractions with green in Figure 46c to f. The complete toolpath can now be post-processed to conform to the programming language of the additive turning hardware controller.



7.5 Robotic Additive Manufacturing Setup for Additive Turning

In this study, a fused filament fabrication (FFF) head was mounted as an end effector to the Mitsubishi Melfa RV-2F robotic manipulator, which was modified to incorporate a synchronous rotary axis using a Mitsubishi servo motor. Two cartesian axes aligned on top of a turning axis is required to realize the proposed slicing method and obtain additive turning parts. Any existing 3-DOF Cartesian AM setup can be modified for additive turning by the addition of the synchronous turning axis, which is used as a rotary build bed. For the setup in this work, the rotary axis was aligned parallel to the Z-axis of the cartesian space. A mandrel of $\phi 24$ mm x 150 mm was attached to the servo motor to act as the rotating cylindrical build bed. The FFF setup employs a $\phi 0.3$ mm nozzle extruding polylactic acid (PLA) thermoplastic. The build bed was coated with an adhesive masking tape to enhance the adhesion of the extruded thermoplastic. The RAM setup is given in Figure 47.

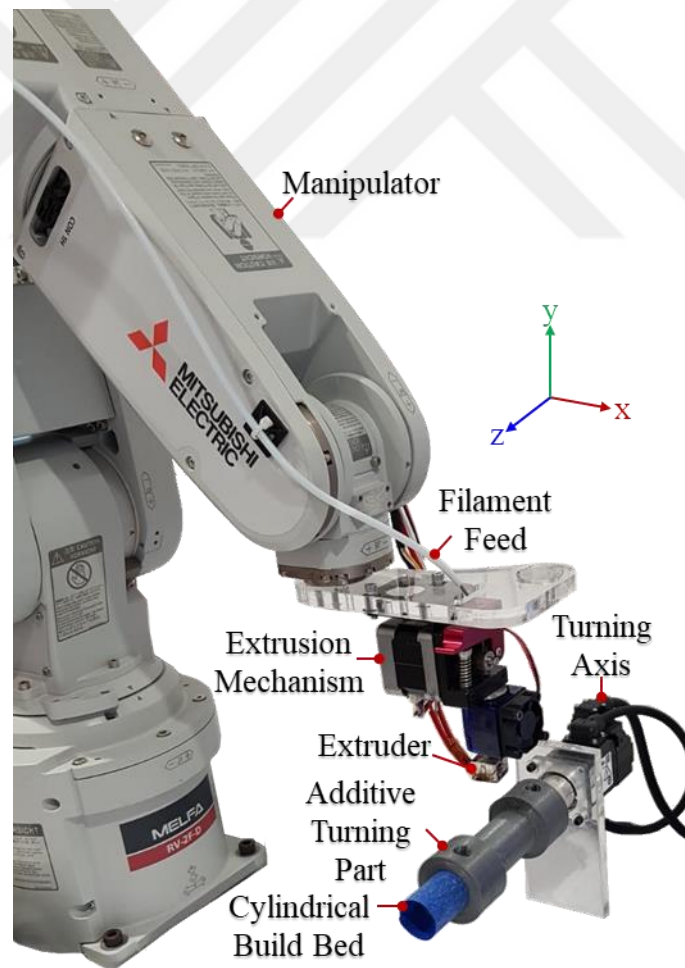


Figure 47. The 6-axis robotic manipulator is laying the cylindrical layers to the additive turning part located on the cylindrical build bed. The build bed and the part are rotated using the external turning axis. The extrusion mechanism is feeding the filament to the extruder via the filament feed.

The toolpath was transformed into a cylindrical coordinate system (R, θ, z) with the axis of rotation about the Z-axis and was post-processed to conform to the Melfa Basic V programming language to communicate with the controller of the robotic manipulator. The Melfa code outputs several job files. A typical job file consists of movement coordinates, the orientation of the manipulator, extrusion commands, and the velocity of the axes. The extrusion rate and direction are controlled through the robot, based on an external stepper controller.

7.6 Results and Discussions

Several geometries were manufactured using both the proposed cylindrical slicing method for additive turning and the conventional planner AM to demonstrate the versatility of additive turning and its advantage in terms of shape retention. The geometries were sliced with a layer thickness of 0.2 mm and the extrusion width of 0.4 mm for both the slicing techniques. A cylindrical thin-walled geometry having hexagonal holes was manufactured using the additive turning and conventional planner AM. Voids on thin walls are especially challenging to produce with conventional planar AM as the voids require support structures. Three NACA 0024 airfoil geometries wrapped around a cylindrical hub was manufactured to demonstrate the ability of the additive turning to handle freeform geometries without the need for support structures. The thin-walled geometry and the blade geometries manufactured with additive turning are illustrated in Figure 48.

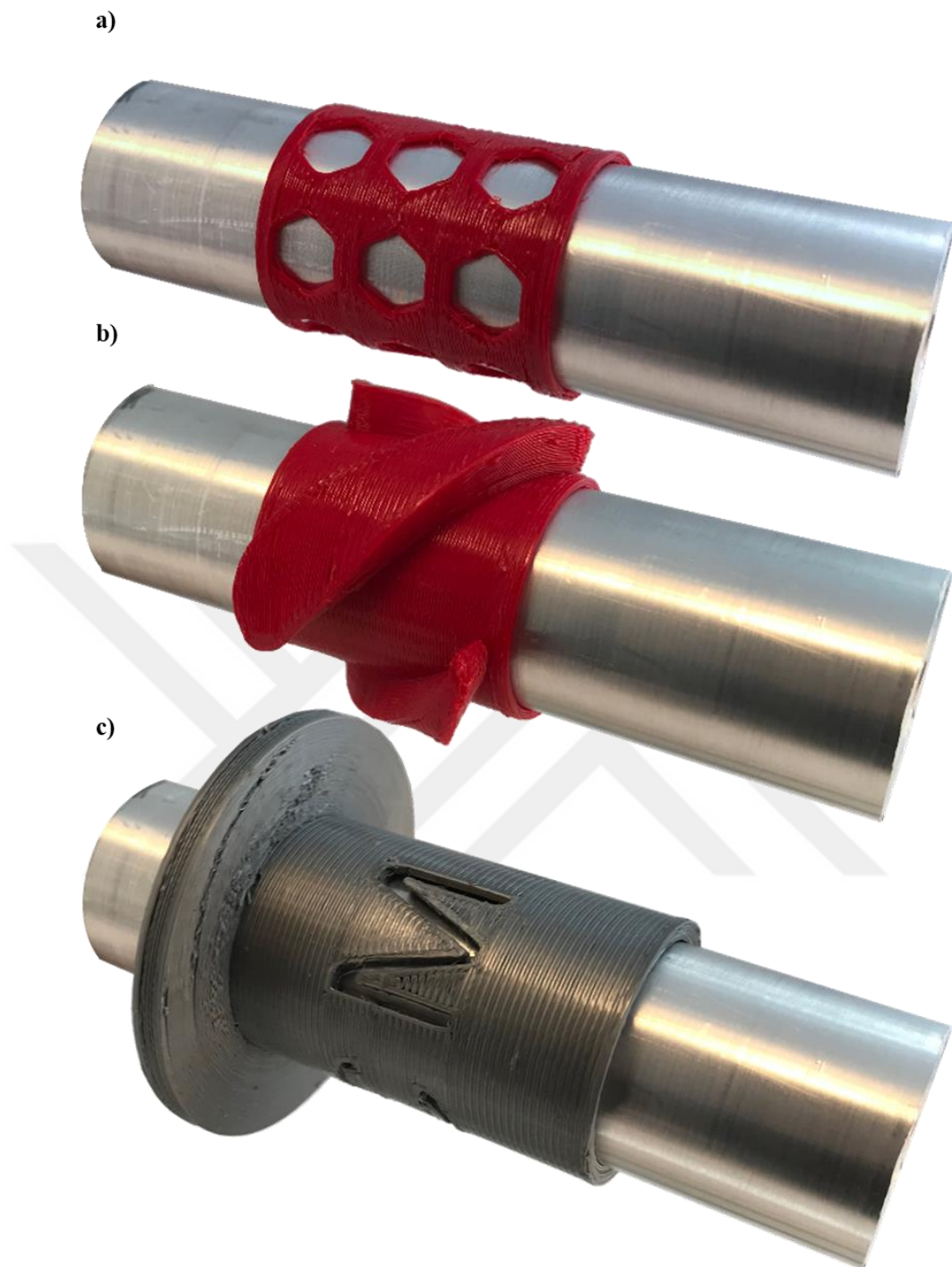


Figure 48. Parts manufactured with additive turning: a) Thin wall geometry with hexagonal holes b) NACA 0024 airfoils wrapped around a cylindrical hub c) Bicycle handle geometry

A bicycle handle was manufactured using additive turning to demonstrate the ability of additive turning to handle large overhangs without the need for support structures. The bicycle handle contains the letters of MARC wrapped around the cylinder, where each letter is located at a 90-degree increment. Each step of the additive turning process is shown in the manufactured part in Figure 49. It has different layers changing from top

left to bottom right. The figure overlays the CAD model, the generated STL model, the cylindrically sliced toolpath, and the manufactured part on the cylindrical build bed. It can be seen that the proposed slicing method can handle any freeform complex geometry. With additive turning, the handle guard on the left and letters were manufactured with ease. The Handle guard, the M, and C would have needed support structures or would fail when manufactured with planar AM.

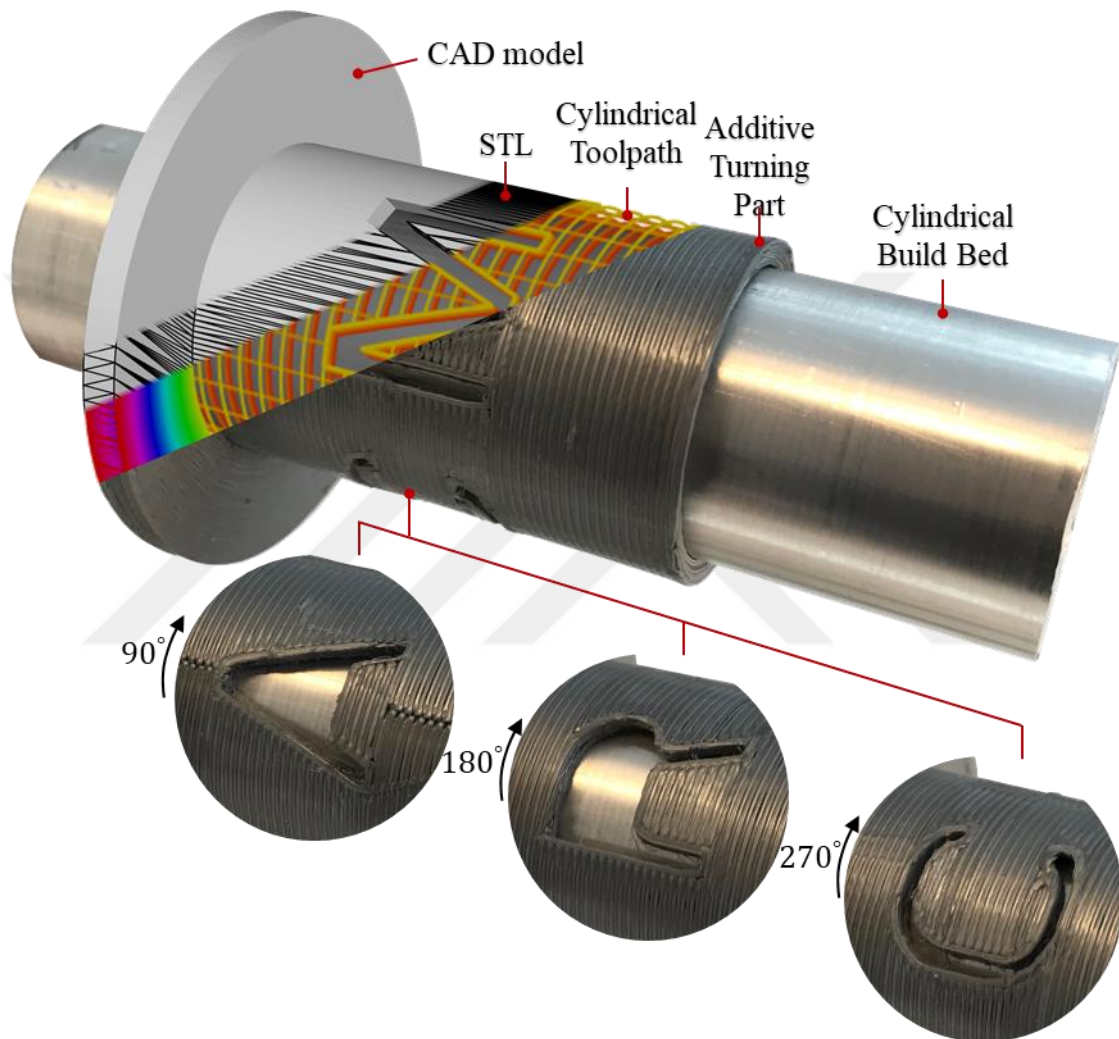


Figure 49. Bicycle Handle with the letters of MARC. The process steps are shown from the top left to bottom right: 1) CAD model. 2) Model is in STL format. 3) Cylindrical layers and cylindrical toolpaths. 4) The part manufactured with additive turning.

When compared with planar AM, the stair-casing effect is also significantly reduced in the additively turned airfoils. A comparison of airfoil geometry manufactured by additive turning and conventional planar AM is illustrated in Figure 50. Here the blue part on the left is sliced in planes and manufactured using planar AM. The zoomed view on the blade shows that the blades have the stair-stepping effect on the upper portion and unsupported layers on the lower portion. The red part on the right is sliced with cylindrical slicing and manufactured with additive turning. The blades do not have previously observed defects.

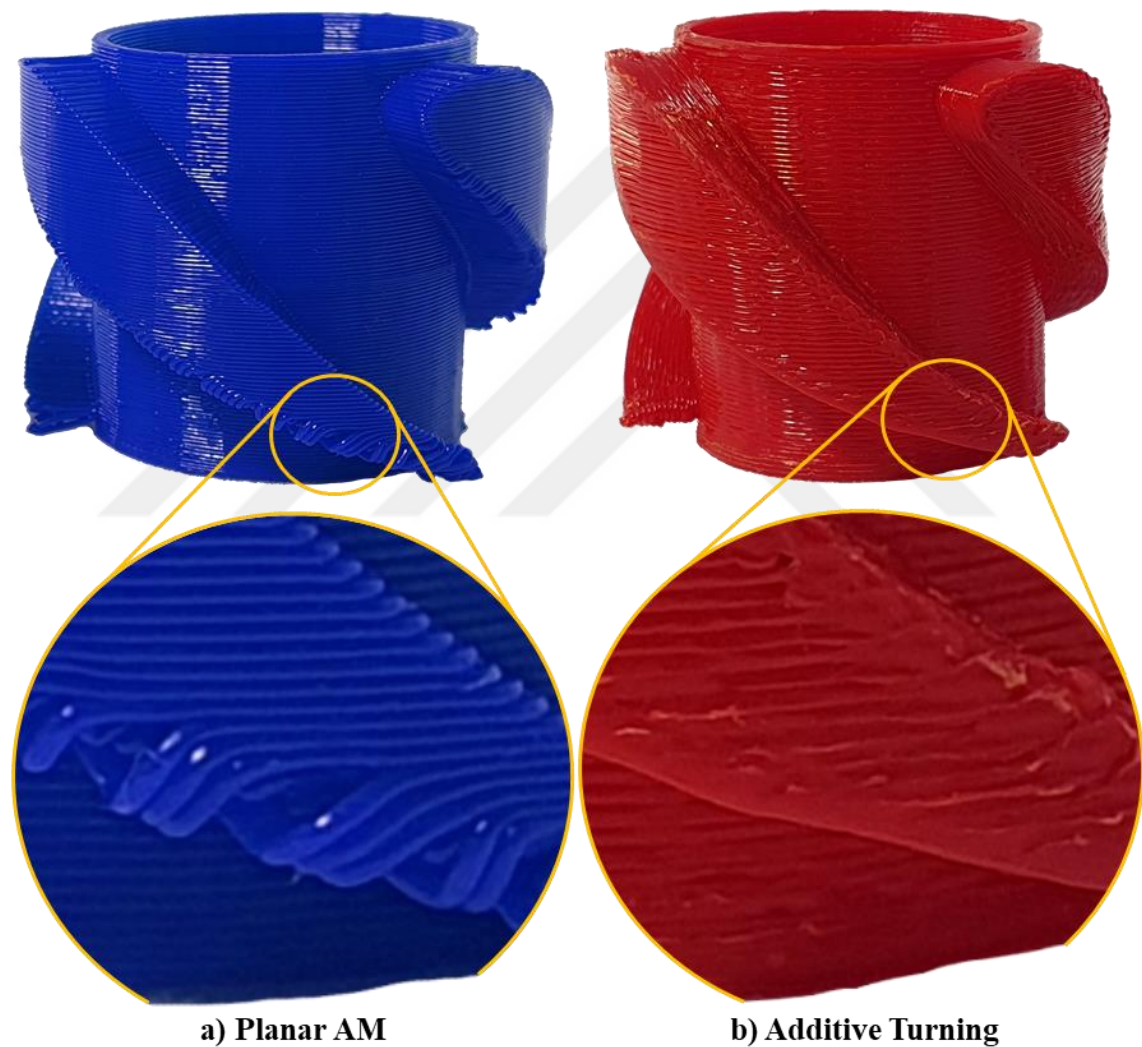


Figure 50. NACA 0024 airfoil geometries wrapped around a cylindrical hub: a) Blue part manufactured using conventional Planar Additive Manufacturing. b) Red part manufactured using the proposed Additive Turning Method.

Tensile test geometries were manufactured to demonstrate the potential of the linear infills of the cylindrical slicing in improving the tensile strength of the parts manufactured by additive turning. The tensile test specimens were manufactured with a 25% infill density, 0.2 mm layer thickness and, 0.4 mm extrusion width using the proposed additive turning method and conventional planar AM. The tensile tests were carried out at a strain rate of 10 mm.s^{-1} with a load cell of 50 kN. The tensile test specimen manufactured using conventional planar AM failed at the load of 552 N, whereas the one manufactured using additive turning failed at the load of 785 N. This 30% increase in the strength is owed to the linear infills as they reinforce the additively turned part in the axial loading direction. On the contrary, the lower load-bearing capacity of the specimen manufactured using conventional planar AM is consequent to the delamination of layers under axial loading. The tensile test figures are given in Figure 51.

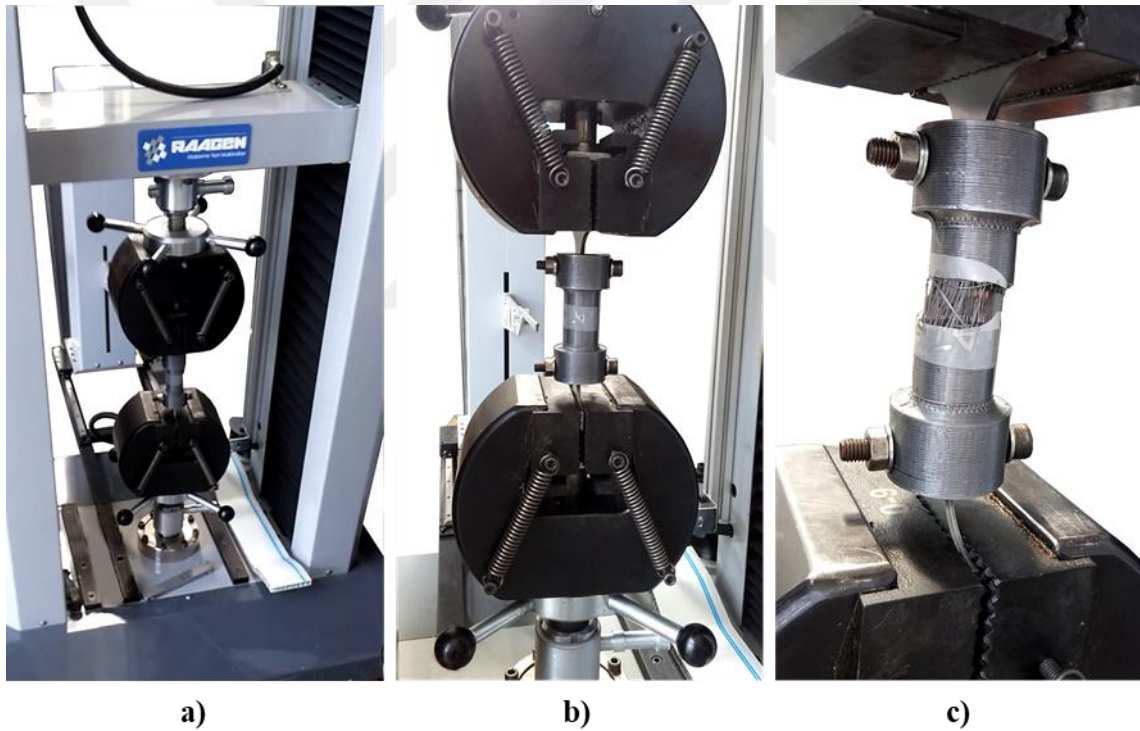


Figure 51. Tensile test of the additive turning part: a) The tensile test setup b) Additive turning part clamped to the tensile test setup using special clamps. c) Additive turning part after failure.

7.7 Conclusion

The scope of the turning process has been broadened with the introduction of AM. A generalized cylindrical slicing method for AM, which can generate nonplanar 3-dimensional cylindrical layers on a cylindrical surface and thus additively turn complex freeform CAD models, is introduced. The CAD model given in STL format is sliced using

cylindrical layers with increasing radii at each layer. The points resulting from the intersection of the cylindrical layers and the triangles of the STL file are used to generate island boundaries. Appropriate infills are calculated using these boundaries. Two different infills strategies, namely, circular and linear, are introduced. Finally, non-extrusion movements are introduced to move between the islands. The toolpath is generated using this data. The proposed method is verified by manufacturing several models using a 6-axis robotic serial manipulator. It is shown that the complex freeform surfaces can be sliced by the proposed method and manufactured on the proposed additive turning setup with a reduction in stair-stepping effects. Additionally, it is shown that models that would typically require support structures are manufactured without support structures. Finally, tensile testing is conducted both on additively turned and conventional AM parts, and it is shown that the tensile strength of the additively turned parts can be improved by 30% percent on the build orientation axis.

Chapter 8

CONCLUSION

The domain where robotics meets additive manufacturing has been studied. Two custom setups were developed where 6 degrees of freedom industrial robotic serial manipulators have been retrofitted with additive manufacturing (AM) end effectors. These are the Yaskawa Motoman HP20D and the Mitsubishi Melfa RV-2F. Larger manufacturing volumes were achieved in comparison to conventional 3-axis AM systems.

In addition to manufacturing parts additively, the robot can change its end effector to a gripper to manipulate the manufacturing process. Support structures have been minimized by introducing modular and dynamic support structures. In modular support structures, the robotic arm stacks pre-fabricated reusable support structures under the model, with its gripper end effector, until the model's overhang is reached. The performed simulations showed a 75% reduction in the support structures. In dynamic support structures, an array of actuated pins which move in the build orientation are used as support structures. This is simulated for both deposition-based and powder-based AM systems. With modular and dynamic support structures, faster manufacturing times were obtained with reduced support structures. This also resulted in lower material and operational costs and also lower material waste.

The advantages of the added degrees of freedom of the robotic manipulators have been explored in this study. Nonplanar slicing algorithms such as Helical, Spherical and Cylindrical slicing have been introduced, handling any complex freeform CAD models. The results of each algorithm have been verified by manufacturing parts with a fused filament fabrication end effector. The turning process has been extended to include AM enabled by the toolpaths generated from cylindrical slicing. With that, additive turning has been introduced. The stair-stepping effect has been reduced with the introduction of helical AM, spherical AM, and additive turning.

With helical slicing, a single helical tool path is formed with a single extrusion start and endpoints. This significantly reduces the defects in each layer where the extrusion starts and finishes. A reduction in defects was shown with SEM images. Due to continuous extrusion, the switching control of extrusion is simplified. Additionally, non-extrusion movements of the extruder are eliminated. In the spherical slicing method, the

model is sliced with spherical shells, analogous to an onion. The feasible toolpath is found by solving the inverse kinematics. The proposed method is verified by manufacturing the Earth model.

The scope of the turning process has been broadened with the introduction of AM. A generalized cylindrical slicing method for AM, which can generate nonplanar 3-dimensional cylindrical layers on a cylindrical surface and thus additively turn complex freeform CAD models, is introduced. The model is sliced using cylindrical layers with increasing radii at each layer. Support structures were minimized and even eliminated for certain parts also in additive turning. Higher Tensile strengths have been achieved with additive turning. Tensile tests resulted in 30% higher tensile strength in the build orientation for the additively turned parts compared to the conventional planar parts.

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