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A Study of the State of the Art of Process Planning for Additive Manufacturing



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A Study of the State of The Art of Process Planning for Additive Manufacturing

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Abstract.

In the manufacturing industry the term Process Planning (PP) is concerned with determining the sequence of individual manufacturing operations needed to produce a given part or product with a certain machine. In this technical report we propose a preliminary analysis of scientific literature on the topic of process planning for Additive Manufacturing (AM) technologies (i.e. 3D printing). We observe that the process planning for additive manufacturing processes consists of a small set of standard operations (repairing, orientation, supports, slicing and toolpath generation). We analyze each of them in order to emphasize the most critical aspects of the current pipeline as well as highlight the future challenges for this emerging manufacturing technology.

Keywords: *additive manufacturing, process planning, 3D printing*

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Abstract

In the manufacturing industry the term Process Planning (PP) is concerned with determining the sequence of individual manufacturing operations needed to produce a given part or product with a certain machine. In this technical report we propose a preliminary analysis of scientific literature on the topic of process planning for Additive Manufacturing (AM) technologies (i.e. 3D printing). We observe that the process planning for additive manufacturing processes consists of a small set of standard operations (repairing, orientation, supports, slicing and toolpath generation). We analyze each of them in order to emphasize the most critical aspects of the current pipeline as well as highlight the future challenges for this emerging manufacturing technology.

Discussion

The vast majority of the scientific publications ([SPK08, Jin12, ZB14b, VR14, Che13, GZR⁺15] etc.) agree that the PP for AM technologies consists of at least five fundamental building blocks: geometry repairing, shape orientation, support structures, slicing and machine tool-path generation. Geometry repairing ensures that the design geometry unambiguously encloses a solid object. The shape orientation determines the way the shape is sliced and the material deposited - this choice is strategic for many reasons, spanning from building time to surface quality. Support structures deal with overhanging portions of the shape that need to be sustained from below so as not to collapse or cause a loss of balance of the object at printing time. Slicing consists in decomposing the shape into a set of planar parallel layers to be printed one on top of the other whereas tool-path generation consists in generating the actual machine paths along which the printer will deposit material for each slice.

In the remainder of the section an overview of the state of the art PP tools and frameworks will be presented. A sub-section devoted to each fundamental building block will then complete the literature analysis presenting the most recent advances for mesh repairing, shape orientation, external supports generation, slicing and tool-path generation. Finally, we will draw some conclusions that emerged from the analysis of the scientific literature in the field.

In [GZR⁺15] Gao and colleagues organize the body of knowledge surrounding AM and present current barriers, findings, and future trends significant to the research community. Fundamental attributes of AM processes, evolution of the AM industry, and the affordances enabled by the emergence of AM in a variety of areas such as geometry processing, material design, and education is also discussed.

In [SPK08] Pande and Kumar propose a Computer Aided Process Planning (CAPP) for Fused Deposition Modelling (FDM). CAPP is meant to help the user finding an optimal model orientation according to different criteria (e.g. minimization of supporting structures, building time or quality), it supports both constant and adaptive slicing as well as different path planning techniques. Unfortunately, it is entirely focused on FDM and it inputs only 3D shapes being represented by their external surface, making many of the technical solutions proposed in the paper unsuitable for Selective Laser Sintering (SLM) which, instead, requires an explicit volumetric representation of the model to be manufactured.

Verma and Rai [VR14] developed a generic and near real-time framework for unified AM PP, providing a quick and unified approach to quantify the manufacturing build time, accuracy, and cost

in real time. Computational geometric solutions were developed to estimate tight upper bound of PP decisions that can be analysed in almost real time.

In Guoqing Jin PhD thesis [Jin12] a set of novel, integrated and systematic adaptive process planning algorithms and strategies have been developed to trade-off between geometric accuracy and build efficiency. The thesis focuses especially on adaptive tool-path generation and adaptive slicing algorithms for complex biomedical model fabrication and Functionally Graded Materials (FGM).

As many authors observed [ZB14b, Che13, GZR⁺15] the quality of the final product heavily depends on the parameters that govern each step in the PP pipeline. Zhang and Bernard [ZB14b] introduce a multi-attributes decision-making system (MADM) to select materials and determine a set of parameters to set up a process planning for AM. Furthermore, Chernows thesis [Che13] develops a PP module to select an optimal set of parameters for AM.

Since in recent years the research to fabricate multi-material products by RP is becoming very active, in [LJG⁺10] Li et al. propose an interesting update on the recent development of PP for multi-material RP. Notice that multi-material RP can be hardly implemented in powder bed printers because the printing chamber would need to be emptied and re-filled at each change of material, thus making the whole procedure extremely time consuming and error prone.

In [YLFW03, SD03, YFLW03] the authors discuss an interesting variation of the classical AM, where material can be deposited along two different directions (typically orthogonal to each other). In multi-orientation AM support structures are not needed and the surface is of higher quality. However, as for multi-material AM, this paradigm can be hardly implemented in powder-bed printers.

The authors of [ZB14a] and [ZBHK15] provide solutions to the orientation optimization problem of multi-part production, where a group of parts in the same build vat or chamber should be orientated simultaneously, with the goal of minimizing the total build time and cost at a global optimal level.

Luo et al. [LBRM12] propose a framework, called Chopper, to decompose a large 3D object into smaller parts so that each part fits into the printing volume. A number of desirable criteria for the partition is formulated and optimised, including assemblability, number of components, unobtrusiveness of the seams, and structural soundness.

In [HLZCO14] the object is decomposed into approximate pyramidal shapes, such that each component can be described by a flat base plus a height field over the base. Shapes of this type are optimal for layered 3D printing because they do not require any support structure to be built. Notice, however, that pyramidal decomposition may affect the robustness of the shape once it has been re-composed, a crucial factor in many industrial applications.

Attens paper [Att15] and [CZL⁺15] proposed methods to split a 3D model in parts that can be efficiently packed within a box, with the objective of reassembling them after delivery.

Method	Optimizes for				Applies to		
	Avoid supports	Fit print. volume	Packing/shipping	Surface roughness	Powder Bed	Material Deposition	Polymerized Light
[Att15]	○	○	●	○	●	●	●
[CZL ⁺ 15]	●	●	●	○	●	●	●
[HLZCO14]	●	○	○	○	●	●	●
[VGB ⁺ 14a]	○	○	●	○	●	●	●
[HBA13]	○	○	○	●	●	●	●
[LBRM12]	○	●	○	○	●	●	●

Table 1: A summary of available algorithms for decomposing a shape into printable pieces. Shape decomposition algorithm can strive to reduce the necessity of supporting structures, make the model fit the printing chamber of the available device, optimize the shape of the parts for packing/shipping and optimize the decomposition to reduce surface roughness. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ◐: not discussed in the manuscript.

Heigel et al.s work [HMR15] focuses on the AM process simulation: a thermo- mechanical model of directed energy deposition AM of Ti6Al4V is developed using measurements of the surface convection generated by gasses flowing during the deposition. This phenomenon is studied to improve the finite element analyses (FEA) and ultimately simulate the effects of the large thermal gradients that generate plastic deformation and residual stresses.

Lu et al.s [LSZ⁺14] and [ZXW⁺15] propose two methods to reduce the material cost and weight of the part, while providing a durable printed model that is resistant to impact and external forces. The former proposes to fill the volume with a set of honeycomb cavities whereas the latter proposes a branching structure that emanates from the medial axis of the shape towards its outer surface. Note that none of these approaches can be implemented in a powder bed printer in the case of the honeycomb structure it would be impossible to remove the remaining powder from the internal cavities, whereas for the medial axis tree the supporting structures needed to print it would be very hard to remove (the authors print them with a soluble material, something that cannot be done in the context of metal printing).

Method	Optimizes for			Applies to		
	Strength	Weight	Mat. waste	Powder Bed	Material Deposition	Polymerized Light
[ZXW ⁺ 15]	●	●	●	○	●	○
[LDJC15]	●	●	●	○	●	○
[LSZ ⁺ 14]	●	●	●	○	●	○
[WWY ⁺ 13]	●	●	●	●	●	○

Table 2: A summary of available algorithms for the generation of internal support structures. These structures can strive to optimize for model strenght, weight reduction and material waste. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ○: not discussed in the manuscript.

Geometry Repairing

Mesh repairing has received an increasing attention in recent years, not only for 3D printing, but in general for all the scenarios where a well- behaving mesh is required (e.g. Finite Element Analysis, advanced shape editing, quad-based remeshing, ...). Some repairing methods transform the input into an intermediate volumetric representation and construct a new mesh out of it [Ju04]. These methods are very robust but necessarily introduce a distortion. Robustness and precision are indeed major issues in this area, in particular when self-intersections must be removed [Att14]. In this case some approaches rely on exact arithmetic, while some others can losslessly convert the input into a finite precision plane-based representation, and then reconstruct a provably good fixed mesh out of it [WM13]. When used for 3D printing applications, however, the aforementioned approaches are useful only if the input actually encloses a solid, while they are not really suitable to fix open meshes (note that some designers use zero-thickness sheets of triangles to represent thin parts). Furthermore, even if a solid is described, it might have features which are not compatible with the printing technology (e.g., too thin walls). For a more comprehensive overview of mesh repairing methods, we point the reader to [ACK13].

Orientation

sByun and Lee [BL06b] studied the problem of determining the optimal build-up direction of a part for different RP systems. In their analysis they take into account a variety of elements, such as: surface roughness (e.g. stair stepping effect), build time (calculated by laser travel), part cost (calculated by build cost rate), labour cost rate, material cost, etc.

Thrimurthulu et al.s work [TPR04] is an attempt towards obtaining an optimum part deposition orientation for FDM process for enhancing part surface finish and reducing build time. Models for the evaluation of average part surface roughness and build time are developed; then a real coded genetic algorithm is used to obtain the optimum solution.

Ezair et al. [EME15] explore the effect that the orientation of a printed object has on the volume of the needed support structure: the paper shows that the volume of the support is a continuous but non-smooth function, with respect to the orientation angles. It also presents an algorithm that computes the model support volume for a given orientation.

Alexander et al. [AAD98] proposed to decouple the solution to the problems of determination of best build orientation and build cost minimisation from a specific LM technology, thus allowing the application of the solution to a variety of processes and providing more realistic cost comparisons of parts built on different machines.

In Table 3 we list the most important orientation algorithms available, emphasizing their features and their applicability to different 3D printing technologies.

Method	Optimizes for							Applies to		
	Model height	Fabric. cost	Supp. vol	Supp. contact area	Surf. acc.	Strength	Mult. parts	Powder bed	Mat. dep.	Polym. light
[ZBHK15]	●	○	●	○	●	○	●	●	●	●
[EME15]	○	○	●	○	○	○	○	●	●	●
[UKY ⁺ 15]	○	○	○	○	○	●	○	●	●	●
[VR14]	●	○	○	○	●	○	○	●	●	●
[HBA13]	○	○	○	○	●	○	○	●	●	●
[WYYS13]	○	○	○	○	●	○	○	●	○	○
[SPK08]	●	○	○	○	●	○	○	●	●	●
[CDMS06]	●	○	●	○	●	○	●	○	○	●
[BL06a]	○	●	●	○	○	○	○	●	●	●
[BL06b]	○	●	●	○	●	○	○	●	●	●
[TPR04]	●	○	○	○	●	○	○	●	●	●
[MR100]	○	○	○	○	●	○	○	○	●	○
[XLW99]	●	●	●	●	●	○	○	●	●	●
[PDG99]	●	●	●	○	●	○	○	●	●	●
[AAD98]	●	○	●	●	●	○	○	●	●	●
[HL98]	●	○	●	○	●	○	○	●	●	●
[LCCG97]	●	○	●	○	●	○	○	●	●	●
[CFN ⁺ 95]	●	○	○	○	●	○	○	●	●	●
[FF95]	○	○	●	●	●	○	○	●	●	●
[RC95]	○	○	●	○	●	●	○	●	●	●
[AD94]	○	○	●	○	○	○	○	●	●	●

Table 3: A summary of available algorithms for shape orientation. The orientation optimization can take into account different factors, such as: model height, fabrication cost, volume of the necessary support structures, contact area between the nominal shape and the supports, surface accuracy, model strength and printing of multiple parts all in once. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ◐: not discussed in the manuscript.

External Supports

Dumas et al. [DHL14] developed an automated support generation technique using little material while ensuring fine surface quality and stability during the printing process, by exploiting the ability of Fused Filament Fabrication (FFF) printers to print bridges across gaps overcoming drawbacks of current support generation systems. This system proved to be more reliable and robust of the tree-like supports generated by Autodesk MeshMixer [SS10].

In [VGB14b] an optimization framework for the reduction of support structures in the context of fused Deposition Modelling (FDM) is also presented. This method is capable of reducing the amount of material by a factor of 40.5% and the printing time by a factor of 29.4% w.r.t. previous approaches.

In [SU14] Schmidt and Ubetani propose a method to reduce wasted time and material in fused-filament 3D printing by generating space-efficient branching support structures. In the example the support uses 75% less plastic than the manufacturer-provided supports, which also reduces print time by one hour.

In Table 4 we list the most important algorithms for the generation of support structures, emphasizing their features and their applicability to different 3D printing technologies.

Method	Optimizes for			Applies to		
	Material waste	Build time	Contact area	Powder Bed	Material Deposition	Polymerized Light
[Ca14]	●	●	●	●	○	○
[VGB14b]	●	●	○	●	●	●
[DHL14]	●	●	●	●	●	●
[SU14]	●	○	●	●	●	●
[SHEE13]	●	●	○	●	●	●

Table 4: A summary of available algorithms for the generation of external support structures. These structures serve to hold the part in place and can be optimized for: reduction of material waste, building time or minimization of the contact area with the object to be printed. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ◐: not discussed in the manuscript.

Slicing

Volpato et al. [VOS05] developed a rapid prototyping (RP) software to slice STL file, generate information for layer addition and send data to machine. The main objectives are to obtain autonomy on the processing parameters and to develop a system which could be used in different RP technologies. The software was validated with FDM process.

Zhiwen Zhao and Luc Laperriere [ZL00] discuss the method of direct slicing, a technique capable of slicing a CAD model without passing through an explicit discretization of the geometry (e.g. converting it to a triangle mesh, typically coming in the form of an STL file). Direct slicing adapts the layer thickness to the shape so as to reduce the number of slices and aliasing artefacts (i.e. staircase effect) and it is a good alternative to crude geometric tessellated STL representations.

In Table 5 we list the most important slicing algorithms available, emphasizing their features and their applicability to different 3D printing technologies.

Path Planning

Jin, Li and Gao [JLG13] propose an adaptive approach to improve the PP of RP, basing on Non-Uniform Rational B-Spline (NURBS) curves to represent the boundary contours of the sliced layers, a tool-path generation algorithm to preserve geometrical accuracy, an adaptive speed of the RP nozzle/print head to address the geometrical characteristics of each layer and to identify the best slope degree of the zigzag tool-paths towards achieving the minimum build time.

Castelino et al. [CDW03] developed an algorithm for minimizing the non-productive time or airtime for a tool by optimally connecting its tool paths. The problem is solved using a heuristic method.

King Wah et al. [WMJC02] studied the same problem and solved it by firstly introducing a Genetic Algorithm (GA)-based approach; then a new strategy is presented using a combination of the Asymmetric Traveling Salesman Problem and Integer Programming (TSP-IP) to solve it.

Volpato et al. [VFLS13] describe two methods for identifying the direction of each contour in a set, i.e., for sorting them into internal and external contours. Three alternative tests to check whether

Method	Features			Applies to		
	Direct	Tessellated	Adaptive	Powder bed	Mat. dep.	Polym. light
[JLG13]	●	○	●	●	●	●
[HBA13]	○	●	○	●	●	●
[SLS+05]	●	○	●	●	●	●
[PRD03]	●	●	●	●	●	●
[PVRD03]	●	●	●	●	●	●
[ZL00]	●	○	●	●	●	●
[MKD99]	●	○	●	●	●	●
[TFBA98]	○	●	●	●	●	●
[KD96]	●	○	●	●	●	●
[SHHB96]	○	●	●	●	●	●
[JH95]	●	○	●	●	●	●
[DM94]	○	●	●	●	●	●

Table 5: A summary of available algorithms for slicing. Slicing can be applied either to a tessellated model (typically a STL file) or a continuous CAD model. The slicing can be performed either in a regular or adaptive way. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ◐: not discussed in the manuscript.

a point is inside or outside a polygon were evaluated. The tests are based on the ray-tracing principle and the classical point-in-polygon test. The proposed algorithms were devised and implemented in an AM process planning system.

In Table 6 we list the most important algorithms for the generation of machine tool paths, emphasizing their features and their applicability to different 3D printing technologies.

Method	Optimizes for			Applies to		
	Multi material	Speed	Precision	Powder Bed	Material Deposition	Polymerized Light
[JHF+14]	○	●	●	○	●	○
[JLGP13]	○	●	●	●	●	○
[JLG13]	○	●	●	●	●	○
[CZ10]	●	●	○	○	●	○
[CC06]	●	●	○	●	●	○
[CDW03]	○	●	○	○	●	○
[WMJC02]	○	●	○	●	●	●
[QLD+01]	●	○	○	◐	●	◐
[KP98]	○	○	○	◐	●	◐
[HLA94]	○	○	○	◐	◐	◐
[EMET93]	○	○	○	○	○	○
[Hel91]	○	○	○	◐	◐	◐

Table 6: A summary of available algorithms for the generation of machine toolpaths for 3D printing. Machine toolpaths can be computed to optimize for multiple materials (e.g. more than one extruder moving at the same time), speed and precision. We also report, for each method, to what printing technologies it applies to (powder bed, fused material deposition or stereolithography). Legend: ●: yes - ○: no - ◐: not discussed in the manuscript.

Conclusions

From the study of the scientific literature the following points have emerged:

- Fundamental problems like mesh repair, shape orientation, slicing, tool path planning and external supports are common to all the printing technologies. The way these fundamental building blocks relate to each other is not completely understood and is to be considered as an open problem. Most authors agree that they cannot be treated separately - a better understanding of the mutual relations between the parameters that govern these steps would make 3D printing more predictable, less error prone and would ultimately produce higher quality objects;
- The solutions to each fundamental problem is often both technology and material dependent. For example, good strategies for printing on plastic may not be as good (or even not apply at all) to powder bed printing, and vice versa;
- Technologies like Selective Laser Melting (SLM) require an explicit volumetric description of the 3D objects to be printed. As many of the contributions in the literature deal with objects represented by their external surfaces, methods to convert a surface model into a volumetric one should be produced, and specific solutions may be found for each step of the PP pipeline;
- The problem of balancing between weight and structural strength is somehow controversial. Printing a dense model would make it very strong but would require too much material and would dramatically increase its weight. Depositing only a thin layer of material on the outer surface would make the model lighter but also structurally fragile. Methods that try to trade-off between weight and strength propose inner structures that, to be printed, would require external supports which are difficult to remove after printing. Moreover, they do not consider that the final shape may be completely closed, and its interior inaccessible after printing. Last but not least, for powder base technologies a way to remove the residual powder after the print needs to be taken into account at the early stages of the pipeline;

Summarizing, here is a list of the main factors to take into account for a PP pipeline:

- Mesh repairing: does the design geometry unambiguously enclose a solid object? Is such a solid printable with the technology at hand?
- Volume decomposition: does the shape fit the printer volume? Is the shape subject to structural constraints (strength, resiliency to external forces, etc.)? Shall the part be decomposed for packing/shipping? Shall it be decomposed to avoid external supports?
- Shape/part orientation: what are we optimizing for (cost, speed (minimize height along slicing direction), surface roughness (avoid the staircase effect), minimize external supports, model strength (w.r.t. to e.g. external forces), mixed factors)?
- Shape editing: do we need external supports? Does the shape corrupt during printing (e.g. thermal analysis)? Do we need to edit the surface to make the object more robust? Do we need to fill the interior to make it stronger (e.g. cavities)? Are there closed chambers impossible to empty after printing?
- Slicing: Regular/Adaptive?
- Toolpath: how do we print each slice?

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