Multi-Direction Layered Deposition – An Overview of Process Planning Methodologies

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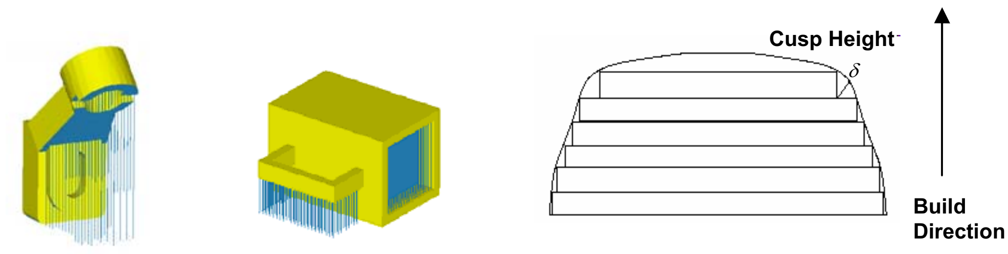
Abstract

Layered Manufacturing (LM) techniques build a part by adding thin layers of material. In many LM processes overhangs require the deposition of sacrificial supports resulting in an increase in the build time, wastage of material and costly post-processing. This has led to the development of LM systems which can deposit material along multiple directions and eliminate the need for supports. We survey the configurations of available multi-direction deposition systems. An overview of the process planning challenges is presented. Literature on process planning methodologies is reviewed.

1.0 Introduction

Layered Manufacturing (LM) processes have developed the ability to deposit a variety of materials with an increased emphasis on the fabrication of functional prototypes. There is a vast body of literature covering various aspects of Layered Manufacturing processes. The interested reader is directed towards [8] for a survey of LM processes and the Proceedings of the annual Solid Freeform Fabrication Proceedings hosted by the University of Texas, Austin.

In this paper we will concern ourselves with a specific set of LM processes which can deposit material along multiple directions. The development of these processes has been motivated by two salient characteristics of LM processes, namely the need for support structures to deposit overhanging features (refer Figure 1a) and the so called *staircase effect*. The staircase effect concerns the approximate construction of surfaces which are not aligned along the build (deposition) direction and is qualified by the cusp height (Ref. Figure 1b). The cumulative effect of these is a longer build time, material wastage, deterioration of surface quality and time consuming post processing.



(a) Supports required

(b) Approximate Surface – Staircase effect

Figure 1: The need for multi-direction layered deposition

Multi-Direction Layered Deposition Systems (MDLD) systems have the ability to deposit material along multiple directions. A part is decomposed into smaller sub-volumes which are built along multiple build directions. This enables support-less layered deposition and a better control over the cusp height. The focus of this paper is the survey of research into process planning for MDLD. Process planning refers to the generation of tool paths and selection of process parameters to build an object using a manufacturing process. The reader is referred to [7][8] for a survey of process planning tasks for LM. The use of multiple deposition directions necessitates additional process planning for MDLD. To better understand the tasks involved, we begin by briefly summarizing the capabilities of the available MDLD techniques and their process characteristics. The physics of the deposition processes is not discussed in detail; instead the focus is on deriving the process characteristics which have a bearing on the associated process planning. This survey also motivates the categorization of the process planning tasks.

2.0 Multi-Direction Layered Deposition Techniques

Multi-direction Layered Deposition processes have developed independently and employ a variety of deposition modes for part fabrication. The degree of freedom in choosing a deposition direction varies from one process to another.

Some of the MDLD processes use 2.5D LM machines retrofitted with specialized kinematics permitting limited MDLD capabilities. Examples are the Double Sided Layered Manufacturing [11] and the Multi-Orientation Deposition (MOD) processes [17]. Double-Sided Layered Deposition uses a traditional Fused Deposition Modeling (FDM) machine with an additional fixturing mechanism which permits the deposition of the part along two directions. The part to be built is divided into two halves with a parting plane. The bottom half is deposited first. It is then flipped over and the remainder is deposited on its backside. The MOD process uses two deposition nozzles aligned perpendicular to each other in conjunction with a deposition table with x-y and a rotational degree of freedom. This permits the support-less deposition of annular regions using offsets of a base layer.

Processes specifically designed to have MDLD capabilities include Direct Metal Deposition (DMD) [10], Five Axis Rapid Metal Forming [19], Laser Chemical Vapor Deposition [15][16] (LCVD) and 3D Welding [4]. Both DMD and the Rapid Metal Forming process utilize a laser cladding process with CO_2 and Nd:YAG lasers respectively. A high power laser generates a small melt pool on the substrate while metal powder is injected through a concentric nozzle. MDLD is realized by the use of a deposition table with translational and rotational degrees of freedom. The Rapid Metal Forming process uses a 5-axis CNC milling machine in addition to the deposition process. This improves the surface quality while the part is being fabricated.

LCVD is an adaptation of the traditional Chemical Vapor Deposition (CVD) process. In this process the substrate is placed in a chamber with a supply of CVD reagent gases. The substrate is heated close to its melting point; thereafter a laser is used to locally heat a spot on the surface. This initiates a thermal decomposition of the reactant gases resulting in the deposition of material at the same spot. MDLD is realized by moving the substrate relative to the laser beam. Since the mode of deposition is via a local chemical reaction, a variety of substrate shapes are possible.

The 3D welding process was one of the earliest attempts at creating an MDLD system using a welding torch mounted on a highly articulated robot arm. The weld electrode provides the deposition material.

3.0 Process Constraints affecting Process Planning

The objective of MDLD is support-less part fabrication. The overhang angle [2] between two contiguous layers is the most important process constraint in MDLD process planning. It determines the extents of a part volume that can be deposited without the need for sacrificial supports. The overhang angle is defined as the maximum of the minimum distance between a point on the *i-1* layer and the corresponding point on the *i*th layer. The angle, θ between the surface normal and the build direction, and the overhang, Δo (with Δl being the slice thickness) are related as: $\Delta o = \Delta l * \cot\theta$ [2]. The process specific maximum value of the angle θ is called the overhang angle. It is an inverse function of the slice thickness and also depends on the surface tension of the deposited material. Figure 2 shows the relationship between the layer thickness, the surface normal, the build direction and the overhang angle.

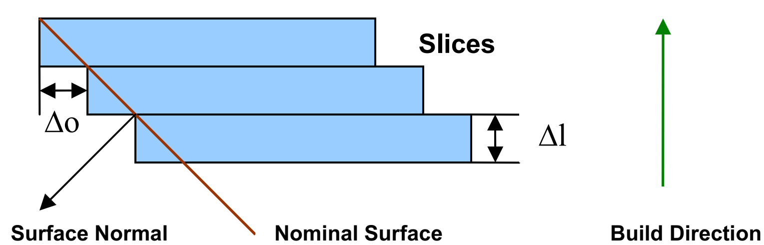


Figure 2: Relationship between the overhang angle, the slice thickness, the surface normal and the build direction.

Other constraints which restrict support-less part deposition are the machine kinematics and the bounding volume of the deposition mechanism. The effect of both these constraints is manifested by the need for support structures. This is discussed in greater detail in the next section.

4.0 Process Planning Challenges and Solutions

In MDLD, support-less fabrication of parts is facilitated by changing build directions so that the overhang angle between the layers is not exceeded. The discussion in the previous section explained the conditions under which an overhanging layer requires supports.

Figure 3 provides an overview of the process planning tasks in MDLD. The first task in MDLD is setting the orientation of the part relative to the deposition table. This is followed by two computational tasks which comprise the core of MDLD process planning. The first of these is determining the extents of the part volume which can be deposited along a certain build direction. The second task is the estimation of a new build direction in the event a part cannot be deposited completely along one direction. The change in build direction is realized by re-orienting the part using a multi-axis deposition table or by moving the nozzle mounted on a multi-axis robot arm. In either case the direction of deposition is perpendicular to the deposited layers. Together, these tasks are used to decompose the part into smaller volumes which are deposited along the associated build directions. These tasks are usually carried out recursively. In the ideal case part decomposition enables support-less fabrication. However, real world MDLD systems are constrained by limited freedom of motion and the likelihood of collisions during the deposition process. Depending on the part geometry, sacrificial supports may be required. The volume of sacrificial supports can be minimized by appropriately choosing an initial orientation of the part relative to the deposition table.

After part decomposition, build direction determination and support structure generation are completed the part is sliced. This is succeeded by the generation of deposition path patterns (path planning).

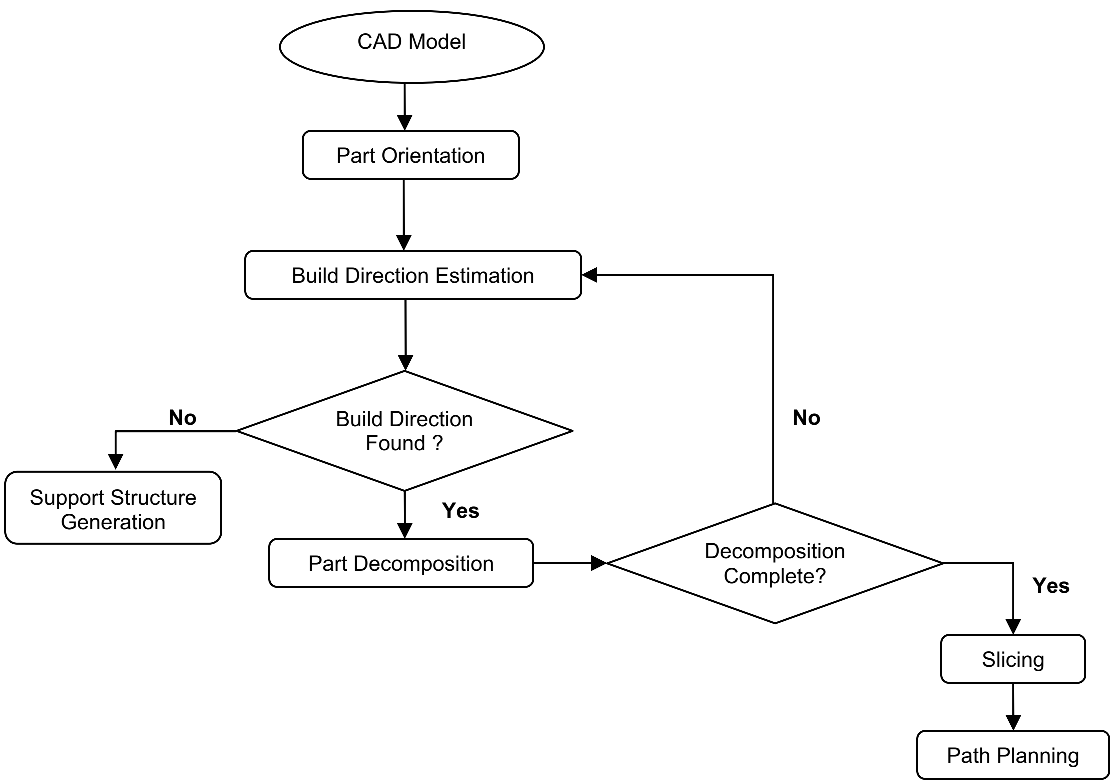


Figure 3: Sequence of Process Planning Operations for MDLD

In the following sections, we review the research in the development of algorithms for the following process planning tasks:

- Part Orientation
- Part Decomposition and Build Direction Determination
- Slicing
- Deposition Path Generation

Where literature is not available, we list the likely computational problems in the solution to the respective process planning task.

4.1 Part Orientation

Part orientation in LM literature refers to the orienting the part relative to the deposition table. The computational challenge in this process planning task is the search for a build direction along which either the build time is minimized or the part's surface quality is maximized. A summary of the literature concerning LM part orientation is provided in [7].

In the context of MDLD, this task is complex due to multiple build directions assigned to smaller part volumes. Setting up metrics such as improved part quality or reduction in build time must take into account the kind of part decomposition algorithms employed. Furthermore, the choice of initial orientation can also influence collisions between the deposited layers and the MDLD mechanism.

Literature concerning MDLD part orientation is scant. One of the efforts is due to Fekete and Mitchell [5] with the object of minimizing the number of build directions. This, according to the authors will improve surface quality at the interface of the part volumes. The computational problem is shown to be NP-hard for 3D parts of genus 0. Factors such as collisions are not considered.

4.2 Part Decomposition

As previously mentioned, in this process planning task the extent of a part volume which can be deposited along any given build direction is determined. The build direction itself is an input. We shall refer to a part volume that can be deposited without supports along a chosen build direction as a *buildable volume*. Various algorithms have been proposed to disjunction parts into buildable and unbuildable part volumes. These algorithms either use a CAD model or slices of a CAD model as input. Before reviewing the research on part volume decomposition, we discuss two relevant process characteristics of MDLD namely the deposition of non-planar slices and the effect of collisions on support-less part deposition.

MDLD processes have the ability to deposit non-planar slices. These are offsets of a base surface and are parallel to each other. Figure 4 shows the geometry of these slices. Figure 4a show the base surface in red. The part is deposited using offsets of this base surface (ref. Figure 4b). The build direction is along the surface normal. Such slices are referred to as transitional walls [18], conformal layers [12] or offset slices [13][14] in literature.

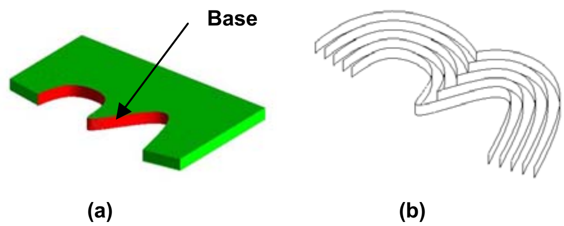


Figure 4: Non-planar slices – offsets of the base surface

The second process characteristic of MDLD is the effect of collisions during the deposition process. Collisions occur due to the finite volume of the MDLD apparatus and limitations in machine kinematics. To avoid collisions, especially for smaller part sub-volumes, support structures are deposited. Most research efforts employ concepts such as the visibility maps of surfaces [6] to detect collisions.

4.2.1 Review of Part Decomposition Algorithms

Part decomposition for 2.5D LM machines retrofitted for MDLD is discussed in [11] and [17]. In [11] the part is deposited in two opposite directions and consequently there are two part sub-volumes. The part is decomposed using a plane. The need for supports is determined using the castability analysis [3] for 2 mold parts. The MOD process [17] has two nozzles mounted perpendicular to each other. The part decomposition algorithm in MOD uses a sliced CAD model as input. The computation of unbuildable slice regions is accomplished by performing the Boolean difference operation between two successive layers. If the overhanging region (result of the Boolean difference) exceeds the process specific overhang angle it is termed as a macro-overhang and is deposited using offsets of the base surface. The process is shown in Figure 5. The authors do not account for collisions during the deposition process.

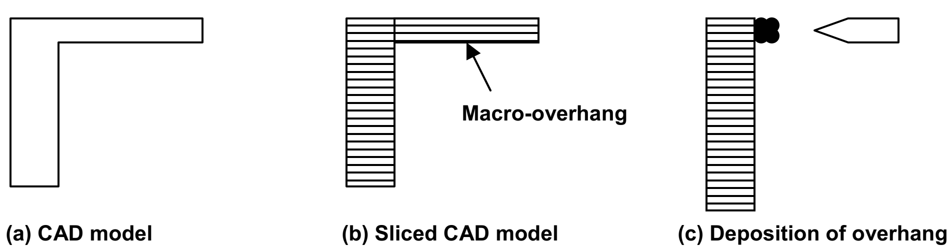
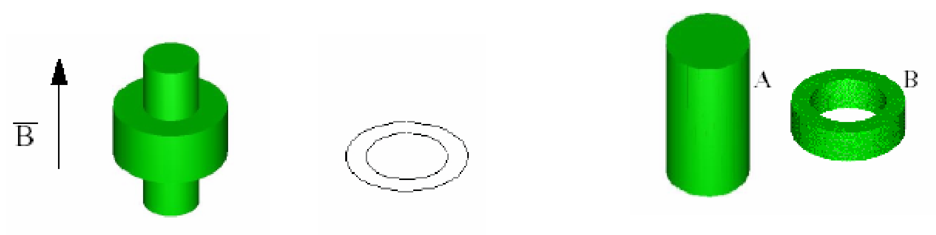


Figure 5: Deposition of Macro-overhangs in the MOD process [17].

Part decomposition algorithms and associated analysis for processes specifically designed for MDLD can be found in [5][13][14][18]. In [13] the authors assume a deposition nozzle mounted on a generic 6-axis manipulator. The part decomposition algorithm uses the CAD model and the build direction (B) as inputs. The overhang is restricted to 90 degrees. Silhouette edges associated with the negative of the build direction (-B) on the faces of the CAD model bound regions which are unbuildable (based on the overhang criterion). The surface regions bounded by the silhouette edges are swept along the build direction to create a (swept) volume. The unbuildable volume is obtained by intersecting the swept volume with the input CAD model; the difference gives the buildable volume. Figure 6 demonstrates an example of the approach taken in [13]. The silhouette edges of the part along $-\overline{B}$ are identified (ref. Figure 6b) and the resultant buildable and unbuildable part volumes are shown in Figure 6c.



(a) CAD Model (b) Silhouette Edges (c) A -> Buildable Vol., B -> Unbuildable Vol.

Figure 6: Part decomposition approach taken in [].

The analysis in [13] assumes planar slices. An extension to offset or conformal slices is presented in [14] which is restricted to extruded part geometries.

In [18] the authors present a process planning framework for the 5-axis Rapid Metal Forming process. This is an additive-subtractive MDLD process [19]. The authors use an adaptive slicing algorithm in which the slice planes are not parallel to each other. Consequently, the slices have non-uniform thicknesses (ref. Figure 7). The slice planes are chosen to conform to the geometric continuity of the part. Regions between two slice planes are the buildable part volumes. The associated build direction is the normal to the lower slice plane. The deposition of such slices is done in two stages. First, slice(s) of uniform thickness are deposited with extra material. These are then shaped using a 5-axis CNC machine. This ensures that the final part has increased accuracy as surfaces of the final part are a first order (tangent) approximation of the CAD model.

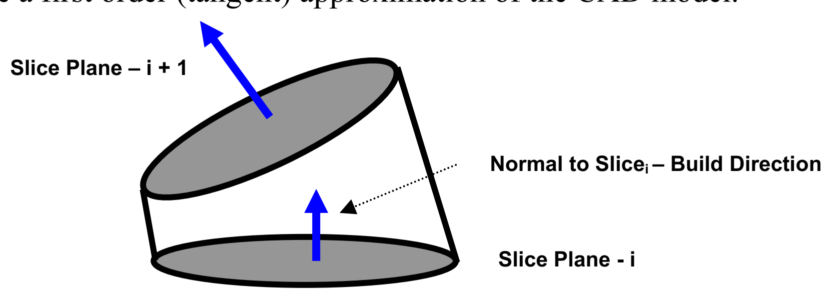


Figure 7: Deposition of Slices with non-uniform thickness [18]

In the case of large overhangs, such as shown in Figure 5, the authors deposit the part using transitional walls (offset slices).

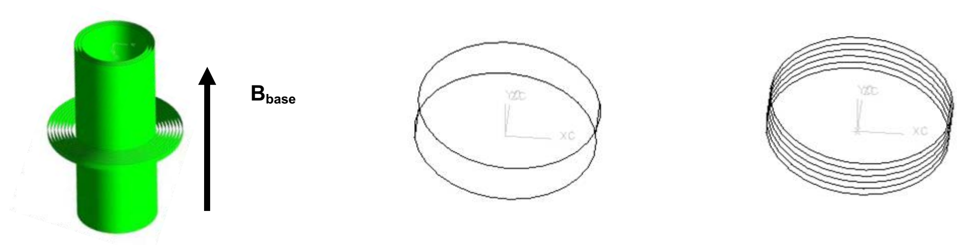
4.3 Build Direction Determination

This process planning task assigns a build direction to an unbuildable part volume. Unbuildable part volumes result from part volume decomposition. In [11][17], where only a limited set of build directions is possible, this process planning task is trivial. In processes specifically designed with MDLD capabilities, all feasible build directions must be identified. If the angle between a vector and all surface normals of the (unbuildable) part boundary is less than the overhang angle it is considered to be a feasible build direction. In [13][18] the authors use spherical maps [6] to represent the set of all feasible build directions. The best build direction is chosen by minimizing metrics such as the average weighted cusp height [1].

4.4 Slicing and Deposition Path Generation

Multiple degrees of freedom in MDLD permit the deposition of both planar and non-planar slices. Planar slices are deposited along their respective build directions. The path planning for material deposition proceeds along the same lines as in 2.5D LM. The reader is referred to [9] for more details.

As mentioned in Section 4.2, non-planar slices are offsets of a base surface and are parallel to each other. The slice thickness is measured along the surface normal. [12][13][14][18] propose to use the deposition direction of the base substrate to generate the deposition patterns for offset slices. Figure 8 shows the approach using an example part. The build direction for the base surface (B_{base} in Figure 8a) is pre-assigned. The deposition paths for an offset slice (ref. Figure 8b) are generated by intersecting it with planes aligned along the build direction of the base surface. The distance between two contiguous planes is equal to the slice thickness. The number of the planes depends on the span of the base surface along its build direction.



(a) Offset Slices of a CAD model

(b) Deposition Patterns for an offset slice

Figure 8: Deposition Path Planning for Offset Slices

5.0 Summary

In this paper we have reviewed literature on the process planning tasks involved in multi-direction layered deposition. Some of these processes are still being developed and the associated process planning methodologies are being actively researched. MDLD consolidates the advantages offered by layered manufacturing by limiting the need for supports. Further development is likely to be driven by the need for fully functional, custom manufactured metal parts.

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