Process Planning for Solid Freeform Fabrication Based on Laser-Additive Multi-Axis Deposition

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Abstract

This paper describes a new approach for rapid prototyping based on volumetric skeletonization. Contrary to most of the popular techniques for Solid Freeform Fabrication (SSF) based on 2-1/2 -axis layering as planar slices, this approach suggests the growth of the component along all three coordinate axes. While this approach offers many advantages in terms of the elimination of the support structures for the reduction of the staircase effects and the elimination of various post processes for the functional parts, this approach also offers challenges towards process planning. For various complicated shapes it may not be possible to generate the required shape using this approach; however, a hybrid approach which also incorporates the deposition by layers, may offer an optimum solution. Preliminary results are based on the successful laser-based additive deposition along multiple g-vectors. The material properties and the problems of possible porosities are still to be investigated. Advantages, process planning, applications, experimental results, and the challenges of this new method are the subject of this paper.

Introduction

Recent approaches for rapid prototyping assisted by flexible machines like a CNC, [1,2] robot [3-8] and promising results of the laser-based metal powder deposition, which allow material deposition from any direction [11] have inspired researchers to look forward to the multi-directional deposition for Rapid Prototyping. Another advantage inherent to the laser-based metal powder deposition is that the volume of material deposited can be controlled using different parameters, primarily the laser head speed, the laser power, the size of laser focal point, and the metal powder flow rate. Contrary to most of the Rapid Prototyping techniques that are based exclusively on the 2-1/2-axis planar layer deposition approach, the multi-direction material deposition approach offers many advantages.

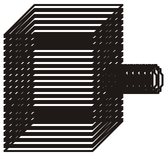


Figure 1. Multi-directional Slicing

In a traditional 2-1/2-axis planar layered deposition, the slicing of a branching structure may yield disconnected islands. The islands usually require supporting structures. A large number of disconnected path elements for different islands render more turning points and path elements; therefore the total time and process complexity are increased. Different methods such as growth from the skeleton, progressive decomposition, and a hybrid approach can be used to exploit multi-directional material addition for part fabrication. Similar to the phenomenon of crystal growth that can be visualized as the growth of a solid from its tree-like dendritic skeleton, the slender parts can be fabricated by growing a part from its skeleton. An approach suggested by Singh et al. [9,10] which is based on the progressive decomposition of the part into sub-volumes, can be used such that each of the sub-volumes can be completely built along a certain direction in layers (Figure1). A hybrid approach that involves skeleton generation for support and the bulk of material added by 2-1/2-axis planar layered deposition process provides an alternate approach to optimize the part fabrication.

(a)Skeleton of the part

(b)Part after deposition of first layer

(c)Part grown from skeleton

Figure 2. Part grown from its skeleton

(a) Part

(b) Support required when 2-1/2 Rapid Prototyping method is used.

Figure 3: A part fabricated using 2-1/2-axis approach that requires support

This paper describes the approach for building a slender part from its skeleton. The approach is based on the thinning of a solid model to generate the skeleton of the component followed by regeneration of the solid from the skeleton (Figure 2). Various disadvantages of the traditional solid freeform fabrication techniques based on layered deposition that the proposed new method seeks to address are:

1. Staircase effect.
2. Requirement for support structure (Figure 3).
3. For various geometries, the trade-off between the material deposition rate and the mimimization of the support structures that govern the choice of part-build orientation.
4. The complexity of the process due to the treatment of rapid prototyping and the corresponding solid model of the component as a uni-directional layered structure.

5. Requirement for various post processing steps of the part.

Other advantages of fabricating a part form its skeleton include the ability to fabricate two loosely fitting components simultaneously. Multi-directional material deposition allows repairing a part without the need for relocation or reorientation. The use of freeform curves in space to deposit the material and the control of the material volume during deposition reduces the staircase effects.

The limitations that can be attributed to the Multi-directional material deposition approach include:

1. The geometry of the part may not allow the material deposition head to access all of the points.
2. A layer-by-layer technique is usually more suitable for the parts that have simple geometry and /or have an aspect ratio close to unity and have many branching structures.

The limitations, while governed by the geometry and material deposition technique employed, also depend on the orientation of the part. Different methods are investigated for the part fabrication by multi-directional material addition. The initial part of the paper discusses the different methods used for volume skeletonization. Also discussed is how the skeletonization algorithm is used for the process planning for material deposition. In the later part of the paper, the experimental results are discussed.

Volume skeletonization and process planning

A technique selected for the volume skeletonization should be able to address the following issues:

1. The skeleton must maintain the fundamental topology and geometry of the part.
2. The process planning should allow re-growth of the part from its skeleton.

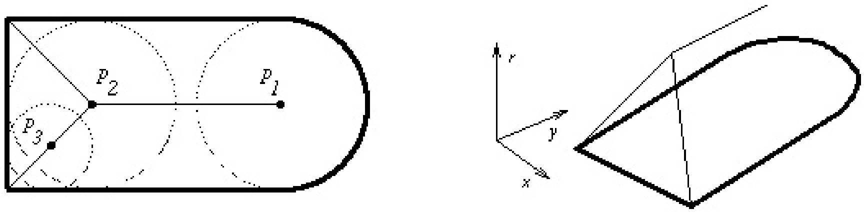
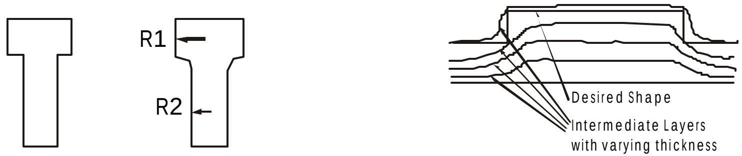


Figure 4 : Maximal inscribed sphere.[13]

The medial axis transform (MAT) is a shape representation method that describes an object by a lower-dimensional skeleton together with a local thickness [14]. MAT is defined by associating to each axis point $\boldsymbol{p}$ along the skeleton the radius $r(\boldsymbol{p})$ of the maximal inscribed sphere (Figure 4). The Voronoi diagram is a similar fundamental construction in computational geometry[14]. The Voronoi diagram captures the proximity structure of a collection of elements in space. Consider a fixed, finite set of points $\{s_i\}$in Euclidean space. The points $\{s_i\}$are called *sites*. An arbitrary point $\boldsymbol{p}$ is said to lie in the Voronoi region of $\{s_i\}$ if $\boldsymbol{p}$ is closer to s_i than to any other site s_j. The Voronoi diagram divides space into regions according to the closest site. Attali et al. have [15] suggested the use of polyballs to approximate shapes and skeletons. The method suggested by Eric et al. [16] suggests an approach to the reconstruction of branching shapes that exploits the relationships between the skeleton of an object and the Voronoi graph of its boundary points. Their method is based on the division of space based on a set of points. The Voronoi graph and the skeleton may be approximated as the subset of the Voronoi elements that are completely included in the object. Gagvani et al. [17] have reported a technique for skeleton computation for articulation that can be used in an animation program. They (Gagvani et al.) suggested a method for voxel arrangement to generate a skeleton-tree from the volume. The method is based upon the distance transform, and the distance transform values are stored and used for regrowing the object from its skeleton.

For a solid X, which is a closed subset of R^3, its interior is defined as $p \in X$ and its exterior is the complement $p \notin X$ .The boundary of the solid is defined as $p \in \partial X \subset X$ that is the subset of solid where any neighborhood contains non-members. The distance transform maps the solid to its equivalent distance field. The corresponding distance field [18] is the scalar field associated with solid X, $F : R^3 \rightarrow R$ that maps a point in space to the distance from that point to the closest on ∂X .

$$F(p) = \begin{cases} -\min_{\forall q \in \partial x} (|p - q|) & p \in X \\ 0 & p \in \partial X \\ \min_{\forall q \in \partial x} (|p - q|) & p \notin X \end{cases}$$



(a) Thin part built by one sweep

(b) Large part made by multi layer deposition.

Figure 5: Part fabrication by varying material volume

During the material deposition, the distance transform value of the skeleton is converted to the amount of material deposition at the location. The speed of laser head, the powder flow rate, the laser power, and the size of the focal point are the primary parameters that control the rate of material volume deposition. By controlling these parameters, the desired shape of the object is generated. For small or thin components, the part is generated by a single sweep of the laser head [Figure 5 (a)]; however, the larger components need a multilayer deposition [Figure 5(b)]. For every layer, the thickness of the deposited layer is manipulated such that the final shape is obtained as the linear sum of intermediate layers [Figure 5(b)]. Process planning converts the distance transform values to the linear constant multipliers for the process parameters.

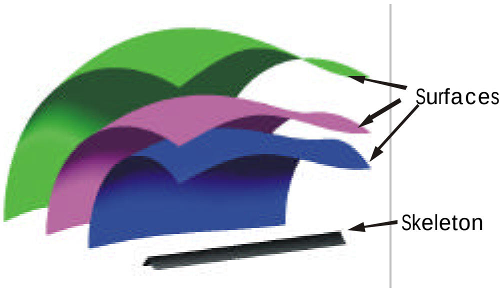


Figure 6. Tool path surfaces

The solid to be built is defined by the boundary $F(p)=0$ such that $p \in \partial X$. The trajectory for the m^{th} layer $g_i(p)$ of the process function is defined as:

$$F(p) = \sum_{i=1}^{m} (c_i + v_i + l_i) g_i(p)$$

c_i, v_i and l_i are the process parameter constants that correspond to the powder feed rate, laser head traverse speed, and the laser power feed rate. The process parameter-constant values are determined experimentally. Movement of the tool takes place along the surfaces described by the process function (Figure 6).

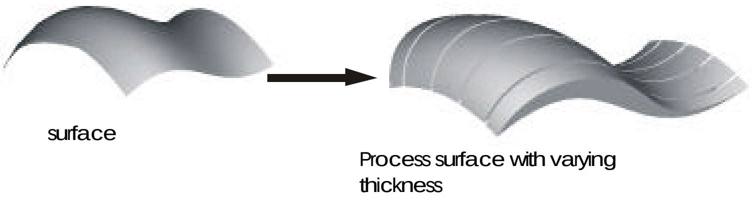
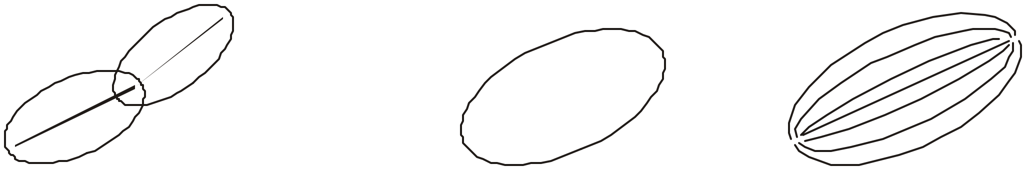


Figure 7. Mapping surface to process surface

The surfaces are homotopes of the intermediate material layers such that the variation in thickness of each layer is stored. The intermediate layers manufactured by material deposition are referred as process surfaces. Each surface, in turn, is comprised of closely spaced curves in the space. The thicknesses of the surfaces correspond to the material volume controlled by process parameters, and the space curves represent the deposition head path trajectory. As shown in the Figure 7, the geometric surface provides the trajectory for the deposition head; whereas, the process surface is obtained by attributing the material thickness to the trajectories. The process planning allows the varying volume of material to be deposited along the trajectories to obtain the final component.

Another approach for multi-directional material deposition is based on ellipsoid fitting. The ellipsoid fitting method can be used to approximate the shape of an object by providing important and useful attribute sets. However, it does not provide an accurate description of the shape. The ellipsoid fit provides global measures for geometry. However, this attribute is a crude (first order) approximation of the shape [19].


(a)Skeleton and ellipsoid approximation

(b) Unit Ellipsoid

(c) Path for Unit ellipsoid


(d) Overlapped Paths

(e)Final Path

Figure 8. Path generation for part based on ellipsoid approximation.

In the case of machining after the material is deposited, in order to remove extra material, the shape approximation by ellipsoids can be used for process planning. The task of material deposition for a complex component is subdivided into the subtasks, where material deposition is performed for individual ellipsoids. A Boolean equivalent union of all the sub-paths of the ellipsoids renders the final path. Figure 8(a) depicts the skeleton of an object and its ellipsoid approximation. Figures 8(b) and 8(c) show a unit ellipsoid and the corresponding path for material deposition, and Figure 8(d) shows the overlapped paths for the ellipsoids used to approximate the solid. Figure 8(e) represents the equivalent of a Boolean union of the paths for individual ellipsoids to generate the final path.

Anne et al. [20] have suggested an algorithm for the construction of skeletal curves from an unorganized collection of scattered data points lying on a surface. A neighborhood graph is constructed over the set of points to compute geodesic distances between the root point and the other points. Connected level sets of the distance map are then extracted and organized in a tree structure. The root of the tree is an input to the algorithm. The centers of these levels sets constitute the skeletal curves.


(a) Part

(b) Surface points

(c) Tool Path curves

(d) Path curve, top view

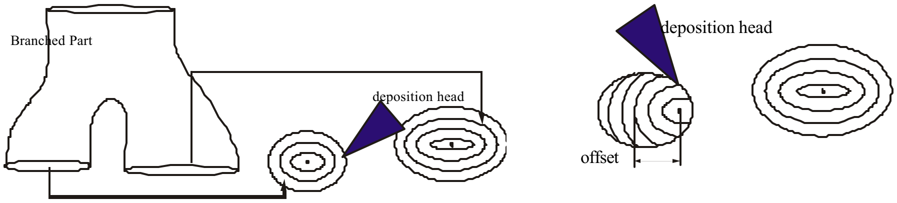
Figure 9 Path generation from the scattered data points along the surface

To use the method based on skeletal curves for rapid prototyping, a solid model is represented as coaxial layers of surfaces. Since the part geometry is known *a priori*, the coaxial surfaces and the surface points are generated (Figure 9). The surface points are joined to build the skeletal curves. The skeletal curves should be built close enough to allow continuous surfaces. Simple and unbranched curves provide the path for the material deposition head; therefore, the steps for branching and center-extraction for the skeletal curves are eliminated. The points on each surface are connected to get unbranched skeletons to generate the path for the material deposition head. The component is fabricated by depositing the material from the innermost surface to the outer surfaces.

The Process Planning:

The process planning for part fabrication should be able to address the requirements and limits of the material deposition process. The method used for skeleton generation must capture the topology of the part and store enough information for the process planning. Other issues include the determination of a suitable orientation of the skeleton such that the growth of the part should not only allow the accessibility to all the points while the part is being built, but should also maintain the stability of the part during the growth such that the requirement of the support structures is eliminated or minimized. The selection of orientation must minimize the requirements for the support structures. The number of turning points and path segments increases the heat accumulation and the process complexity due to the frequent direction changes of the material deposition head. Therefore, a reduction in the total number of turning points and the path segments should be another criterion for path planning.

The material deposition for the thin structures is accomplished by a single sweep of the material deposition head. Variations in part thickness regulated by changing various process parameters. For the thicker structures, however, material is deposited as coaxial surfaces with varying thicknesses around the skeleton.



(a) Branched Part and deposition head inaccessibility

(b) Deposition head accessibility due to skeleton offset

Figure 10. Skeleton offset for accessibility

For branched and intricate geometries, the accessibility of the part by tool might be limited [Figure 10(a)]. A modification in the skeletonization approach such that the skeleton is offset is suggested [Figure 10(a)]. The offset distance of the skeleton depends on the dimensions of the material deposition head.

Experimental Results:

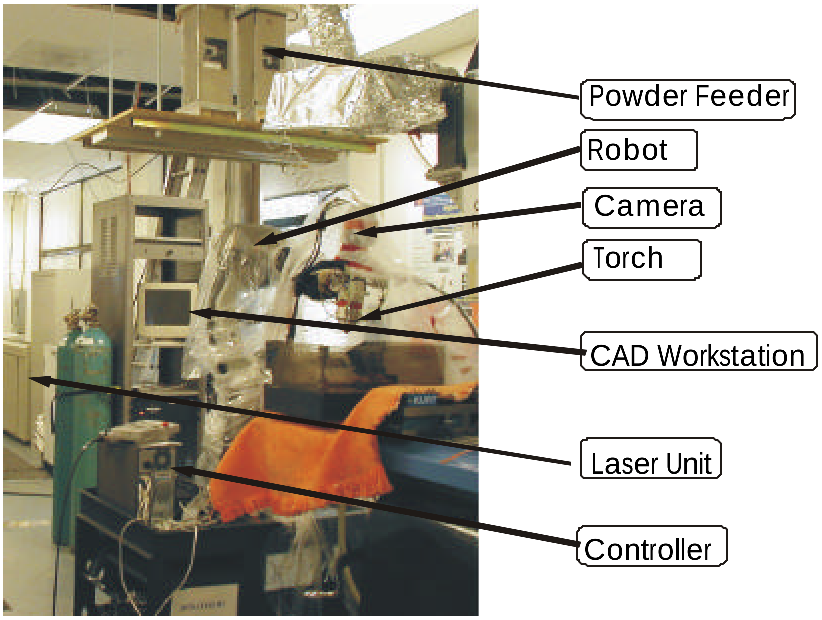
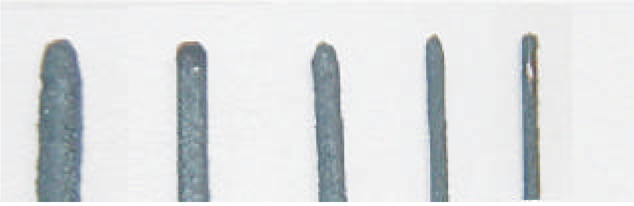


Figure 11. Experimental Setup

The experimental setup is a 6-axis robot with a laser deposition head mounted at its end effector (Figure 11). Nd-YAG laser unit is used for the laser power source. The controller unit controls the shutter on/off position, the laser power, and the powder feeder in real time. The CAD workstation generates the model file of component and the job instruction file for the robot. The material deposition head has four powder delivery nozzles arranged coaxially. The quantity of the powder delivery can be controlled by the powder feeder. Experiments are performed with H13 metal powder.



Bead Diameter	3.6mm	3.2mm	2.6mm	2.3mm	2mm
Laser Power	200W	190W	190W	160W	120W
Powder feed rate	90Hz	90Hz	80Hz	70Hz	60Hz
Head Speed	1mm/s	1mm/s	1mm/s	1mm/s	1mm/s

Figure 12. Variation in cross-section thickness with respect to the power and powder feed rate (Note: The rate of powder deposit is 0.05g/Hz of the powder feeder motor frequency)

A code was developed in (Visual Basic for Application) VBA for AutoCAD for simple cylindrical components. Different experiments were performed to study the influence of the process parameters on the material volume. This influence includes the variation in laser power, the powder feed rate, and the deposition head speed. The material is deposited by vertical movement of the material deposition head such that the laser head moves away from the just deposited material, and the molten pool is formed at the focal point of the laser.

It is observed that there is an increase in the material volume deposited with the increase in the powder feed rate, the speed of torch movement. However, the volume is further limited by the size of the molten pool, which in turn depends on the laser power. Figure 12 shows the variation of part thickness that corresponds to the material deposition rate for different parameters.

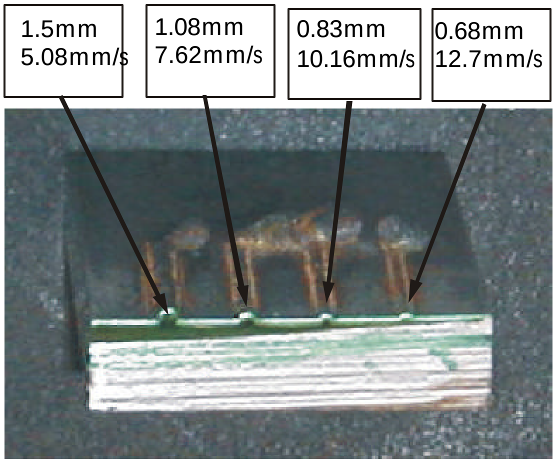


Figure 13. Variation in cross-section size with respect to the head speed
(laser power = 380W, powder feed rate at 200Hz)

Figure 13 shows the dependency of the part thickness on the head speed. A single bead of the material is deposited at different speeds for the same rate of the powder feeding, and the laser power. The material deposition is done along the horizontal direction.

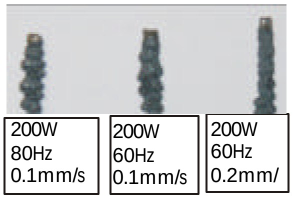


Figure 14. Irregular bead formation due to surface tension

The combination of laser power, torch speed, and powder feed rate determines the surfaces smoothness. The surface tension of the molten metal and the formation of spherical droplets can cause the formation of a rough surface. Figure 14 shows three columns with rough surfaces. An increase in the speed of the torch and the corresponding lowering of the heat accumulation improves the surface quality. One of the most important factors that must be taken into account is the possible melting of the skeleton at any instant due to excessive heating. The determination of the optimum power is extremely important because excessive heat may melt the structure, and insufficient heat does not allow the formation of a proper of molten pool for the material welding.

By controlling the process parameters, various three-dimensional structures can be built. Experiments were performed to build slander parts and surfaces. The material addition is done for different g-vectors.

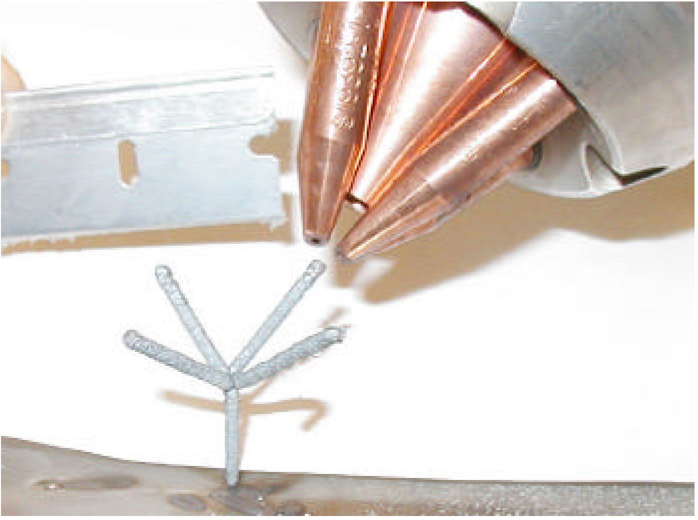


Figure 15. A branched structure made by laser cladding

Figure 15. shows a branched structure that is generated by laser cladding. The branched structure includes a vertical segment onto which four other segments each at an angle of 45 with respect to the x,y and z axes are added.

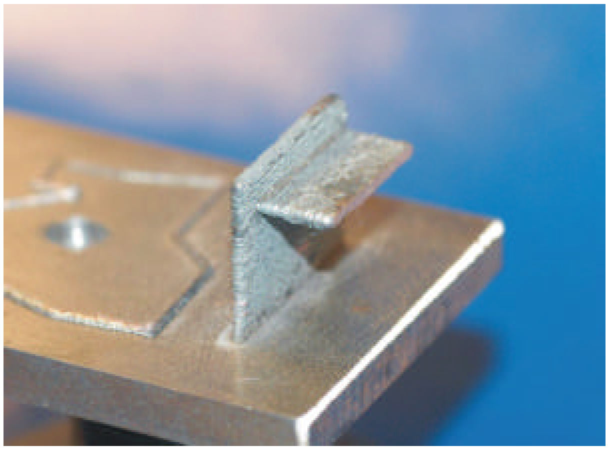


Figure 16. Surfaces created in space by laser cladding

Figure 16 shows surfaces made in the space by laser cladding. The surface thickness is equal to a single bead width. The surfaces are generated by depositing material, perpendicular and horizontal with respect to the gravity.

Conclusions

The variation in the material deposition rate by changing various process parameters: the powder feed rate, the laser power, and the laser head speed in laser-based metal powder deposition allows the fabrication of complex geometric skeletons. Different algorithms can be used for the process planning to fabricate a solid part based on the reconstruction of a solid from its skeleton. The process can be optimized and controlled by obtaining various process parameters experimentally. The experimental results have demonstrated the ability to manufacture complex and branched structure without the support structures inherent to the traditional techniques.

A hybrid technique that involves incorporation of the 2-1/2-axis deposition technique along with the fabrication of a part from its skeleton needs to be developed to create a more efficient process that combines the best of both of the methods.

A mathematical model for dependence of the material volume and the properties of the laser cladding on different parameters like the speed of laser head, the laser power, and the powder feed rate, is required.

Acknowledgements

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