LASER ADDITIVE MANUFACTURING PROCESS PLANNING AND AUTOMATION

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Abstract

This paper presents a Laser Additive Manufacturing Process Planning (LAMPP) being developed at the University of Missouri-Rolla. The off-line planning recognizes difficult-to-build features from an STL file, selects optimal part orientation and building directions based on the skeleton information of the object geometry, and optimizes the sub-process sequences for deposition and machining. During the optimization of the sub-part building processes, collaboration between the deposition process planner and the machining process planner is needed to check the deposition availability and machinability. As a result, tool paths for both the laser head and the machining head are automatically generated.

Introduction

Currently, most freeform fabrication processes can not produce fully functional parts. The materials for these processes usually are thermoplastics, resins, etc. Parts made of these materials can not be used to test if the design of parts meet the mechanical property requirements. Therefore, to satisfy the demand in industry for fast, accurate and fully functional renditions of designs, a freeform fabrication process based on laser cladding is investigated and reported here.

For metals, it is hard to find a suitable support material that can be easily separated from the build material in the post process. Also, time used in building many support structures is substantial in the overall build time. To resolve these issues, a five-axis process is proposed. The process can utilize the flexibility of the five-axis motion to greatly minimize the support structures. For example, the part in *Figure 1* can be built in three phases with different build directions and orientations without any support structures as shown in *Figure 2*. The part is decomposed into three subparts as shown in *Figure 3*. The build sequence is from subpart1 to subpart2 to subpart3. The build directions for them are along the z-axis, x-axis, and z-axis

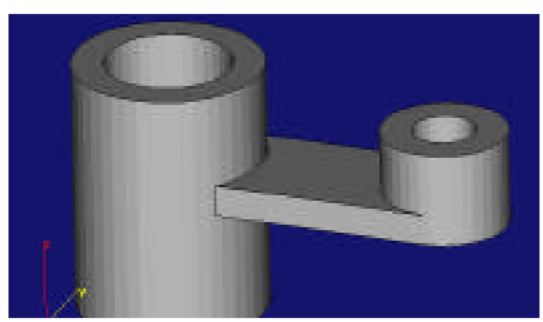


Figure 1 An example part to be built

respectively. Another advantage is that the five-axis motion provides the possibility to build the 3-D layer. An example of 3-D layers is shown in *Figure 4*. It is different from a traditional planar 2-D layer.

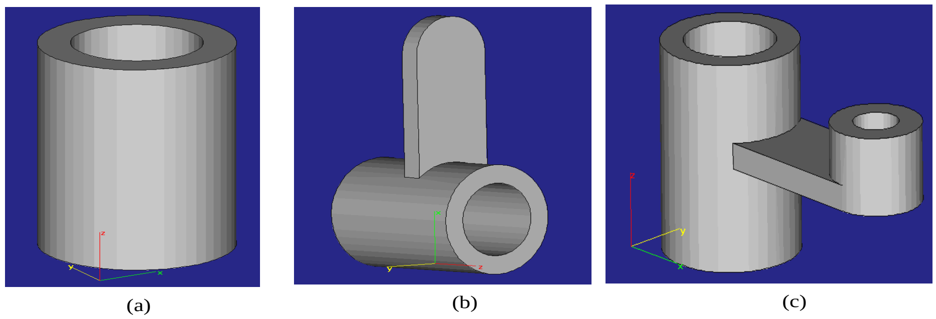


Figure 2 Non-support building steps and the associated orientations

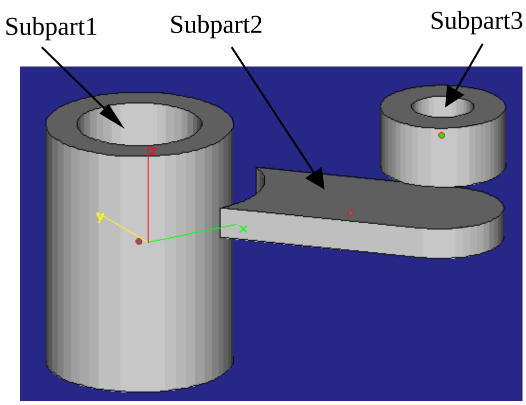


Figure 3 Part Decomposition

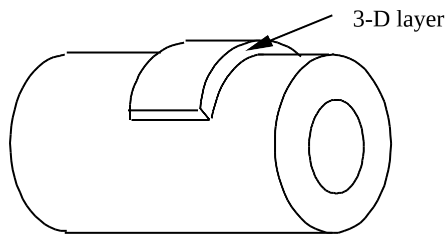


Figure 4 An example of a 3-D layer

Due to the complexity of the part geometry, some parts can not be built without support structures even if the process has five-axis capability. In order to keep the flexibility of the system, the building material is also used as the support material. The extra materials will be removed in a machining process. By combining laser deposition and machining processes, the resulting hybrid process provides more build capability and better accuracy and surface finish. The hybrid process can build some features that are difficult to build in the pure deposition processes.

Certainly, a five-axis integration process is more challenging in process planning. The automation of the part decomposition and build direction searching is more complex. To be able to build a part with freeform surfaces, the skeleton of the part is used for the geometry reasoning. The skeleton of a 3-D object can be defined as the locus of the centers of all the interior maximal spheres of the object (a maximal sphere is a sphere that is not contained by any other interior sphere). From the definition, the skeleton represents the fundamental nature of the part shape. Therefore, along the skeleton, the maximal possibility of the non-support building is expected.

The skeleton possesses characteristics that are important in many engineering applications. These characteristics include the following:

- Uniqueness: There is a unique skeleton for a given object,
- Invertibility: Given a skeleton, its corresponding object can be reconstructed,
- Dimensional reduction: The dimensionality of a skeleton is lower than that of its object,
- Topological equivalent: A skeleton is topologically equivalent to its object.

In the hybrid process, the cooperation between the deposition planning and the machining planning is a new approach, which involves a lot of research issues such as the optimization of the deposition time and machining time, the optimization of the machining time and the part accuracy, and the selection of the best processes for specific features.

Process Planning Overview

The LAMPP uses STL models as input and generates a description that specifies contents and sequences of operations. The objective of the process planning is to integrate the five-axis motion and deposition-machining hybrid processes. The results consist of the subpart information and the build/machining sequence. The build/machining sequence is a sequence of build and machining operations in the order so that all operations can be executed without any tool collisions. The decomposition and the sequence generation are related to each other. In order to satisfy the depositability and machinabiliy of the part decomposition and the build/machining sequence, a communication tool is needed between the deposition planner and the machining planner. Basic planning steps involve determining the base face, extracting the skeleton, decomposing a part into subparts, determining build sequences and build directions for subparts, checking the feasibility of the build sequences and build directions for the machining process, and optimization of the deposition and machining. The system architecture is shown in *Figure 5.*

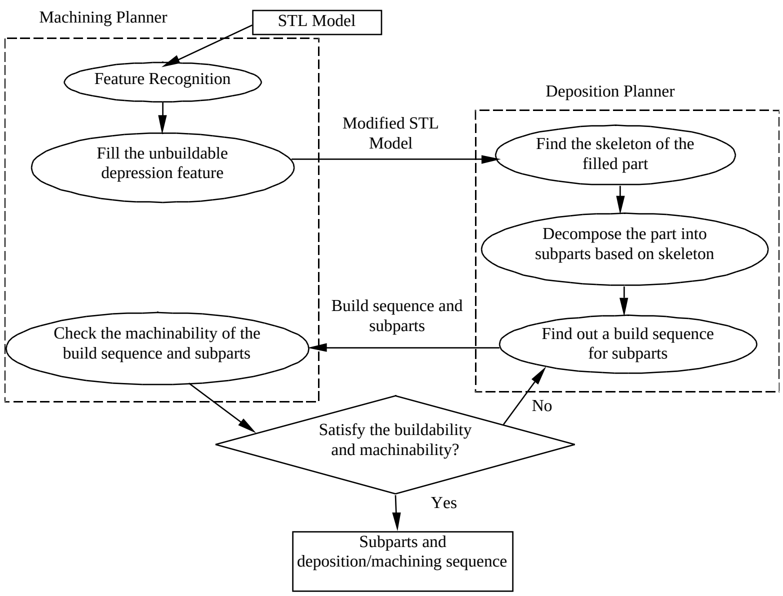
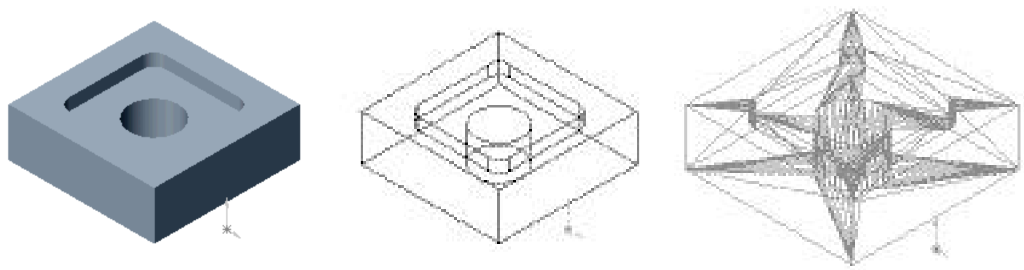


Figure 5 Process Flow of the

Hybrid Process Planning

Feature Recognition and Depression Features Fill

In order to generate the skeleton of a part to decompose the part into subparts and find the building direction, depression features have to be recognized. Usually, feature recognition starts with B-reps format data; however, in the process planning, the STL format is taken as input data for the following reasons:

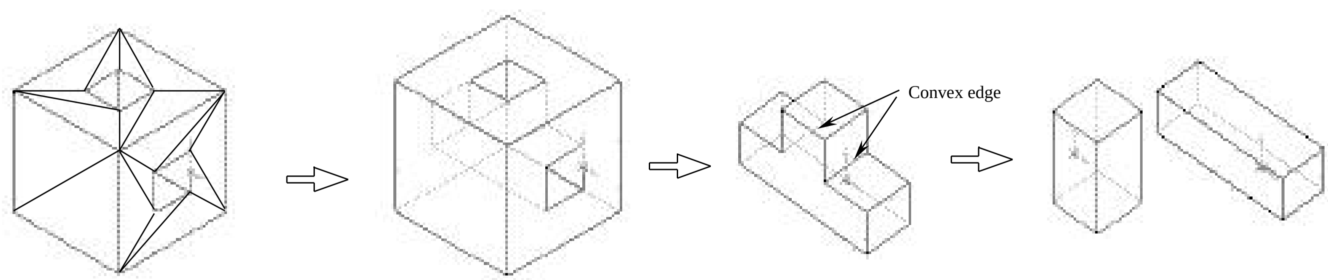


(a) The part (b) B-reps (c) STL representation

Figure 6 A part in solid model, STL and B-reps formats

- STL is the initial input data format for LAMPP and very easy to slice.
- The depression features will be filled to find skeleton, which is based on tessellated data.

Figure 6 shows a part in solid model, STL and B-reps formats. In *Figure 6 (b)*, the hole is represented in four half-circular edges and two linear edges. In *Figure 6 (c)*, only linear edges exist in STL format to represent the hole, therefore more steps are needed to extract features from a triangulation file. Some basic features such as holes, steps, pockets and slots are commonly used in the industry, the present work is focusing on their recognition.



(a) STL representation (b) After merging triangles (c) Feature Extraction (d) Feature separation

Figure7 Feature recognition process

In the LAMPP, the B-reps information is reconstructed based geometry information of triangles. Using rebuilt B-reps information to generate the face adjacent graph (ADG), in which each node represents a face and an edge marked “concave” or “convex” represents adjacent relationship among faces. All the features including intersections are extracted by searching sub-graph in the ADG and matching them with ADG of predefined features, [1][2][3]. Then the convex edges are searched in those features to separate basic features from intersections. *Figure 7* shows the process to extract and separate features.

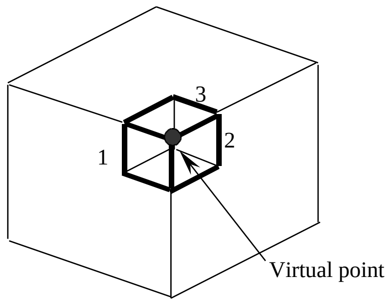


Figure 8 Virtual faces for blind step

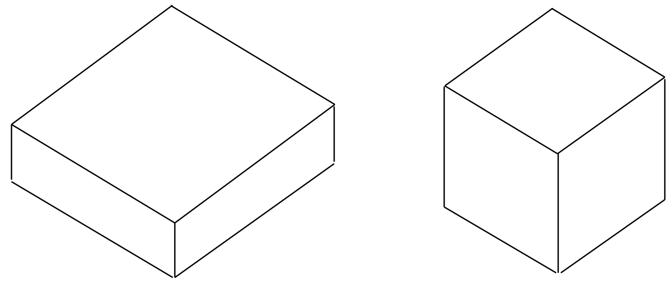

(a) Fill result for part in figure 6 (b) Fill result for part in figure 7

Figure 9 Fill result

Once the depression features are recognized, a fill operation is performed to obtain the skeleton correctly for part decomposition. In the fill process, different strategies are used for different kinds of features. For depression features cutting out the boundary of part, virtual faces and point are necessary for filling the depression features, however they are redundant for nested depression features. For example, one virtual point is generated in order to build three virtual faces for a blind step, shown in *Figure 8*. *Figure 9* shows the results for parts *in Figure 6* and *Figure 7* after fill. The process of computing skeleton will be discussed in the later section.

Skeleton Computation

Most of the 3-D algorithms in existence (such as the ones above) are fundamentally discrete algorithms. Few continuous approaches have been proposed, largely due to the computational complexity involved. Related papers [4] [5] reported the exact representation of the bisectors that appear as skeleton branches in the skeleton of simple CSG objects bounded by planes, natural quadrics, and torii. Reddy and Turkiyyah [6] proposed an algorithm for determining the skeleton of a 3-D polyhedron based on the generalization of the Voronoi Diagram. The algorithm can explicitly determine certain critical points of the skeleton, but does not contain accurate representations of the curves and surfaces making up the skeleton. STL model is a polyhedral approximation of the 3-D geometry of the part. An algorithm for computing the skeleton of 3-D polyhedron is needed. Therefore, the algorithm proposed by Sherbrooke et al.[7] is adapted. The algorithm is based on a classification scheme for points on the Medial Axis. The continuous representation of the Medial Axis is generated with associated radius functions. Because it is used as a geometric abstraction, the skeleton is trimmed from the facets that touch the boundary of

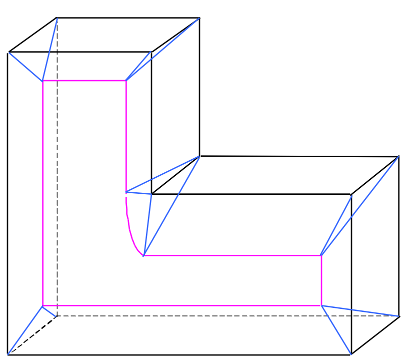


Figure 10 Skeleton of a “L” shape

the object along every boundary edge for which the interior wedge angle is less than π rad. The skeleton of an L-shape part is shown in *Figure 10*.

Part Orientation

The determination of the base face from which the building process of the part starts is very important. The base face works as the function of the fixture in the machining process. Therefore, when in the machining process, it must provide enough resistance force against the cutting force. The maximal resistance force depends on the area of the base face. The base faces have to satisfy the following conditions:

- Located on the convex hull of the part.

The condition makes all the other faces at one side of the base face. Because the base face contacts with the working table, all the other faces are above the working table.

- Certain amount of contact area

To function as the fixture, the base face must have a certain contact area with the working table. The amount of contact area required depends on the geometry and weight of the part

Part Decomposition and Building Direction

The objective of part decomposition is to divide the part into a set of subparts which can be deposited and machined. The topology of the part can be obtained from the skeleton. Each branch of the skeleton corresponds to a subpart. The partition process for the example in *Figure 1* is shown in *Figure 3*. One of the partitions that are preformed is along a non-planar surface. Therefore, close to the partition area, 3-D layers are needed to build the connection between two subparts. For example, the joining deposition of subpart 2 on subpart 1 in *Figure 3* will need a 3-D curved layer.

The build direction of a subpart may not be constant. It changes when the part is built layer by layer so that for two adjacent layers, the later layer can be deposited based on the early layer without any support structures. To achieve the non-support build, the build directions need to be along the skeleton.

Building Sequence

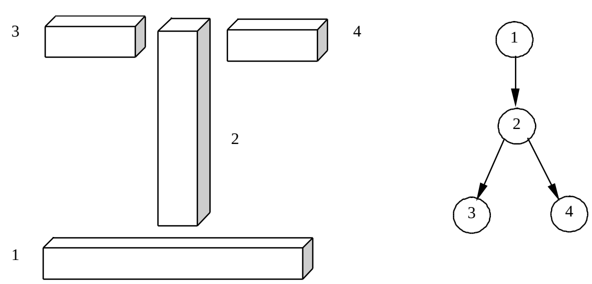


Figure 11 Adjacent Graph

The results of decomposition are recorded in an adjacency graph where nodes represent subparts, and edges represent the adjacency relationship between connected nodes. After considering part building order, a directed graph that represents the precedence relationship among subparts can be constructed. From the precedence graph, one can identify in what order the subparts can be built. With the precedence graph, a set of alternative building plans can be generated. Each plan represents a possible building sequence on the decomposed geometry and can be chosen optimally depending upon machine availability or other criteria such as minimum building time, etc. The adjacency graph, precedence graph, and the building alternative tree of a part are shown in *Figure 11*.

Machinability Check

The main purpose of machinability check is to choose an optimal building sequence from the sequence set. Local and global collision checks are operated first to choose acceptable sequences since the building direction is different in each sequence. If any kind of collision happens or an under cut plane appears, the corresponding sequence will be discarded. For the rest of the building sequences in set, the buildability check and machining time computation is performed to find an optimal building sequence. The purpose of buildability check is to find whether the depression feature can be built by deposition rather than machining. *Figure 12* shows the difference between two building directions. The pocket can be deposited under direction A but is not buildable under direction B. Time spent on machining time is computed for different sequences. The minimum constructing time is required for the optimal sequence. After choosing the sequence, the virtual point and virtual faces will be removed in case that a depression feature can be deposited for the final chosen building sequence.

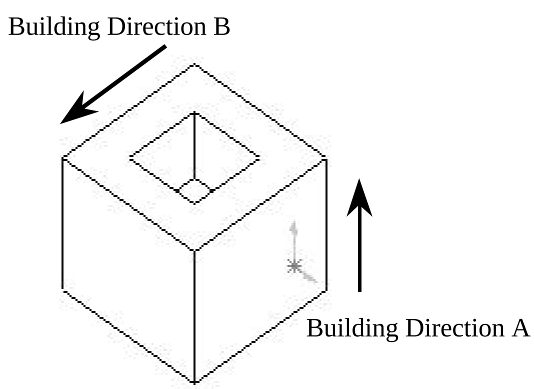


Figure12 Difference between different building direction

Toolpath Generation

From the 3-D finite element model analysis, the pattern used to deposit a layer of material has a significant influence on the deflection of the manufactured part. Usually two scanning patterns are used: raster pattern and spiral pattern as shown in *Figure 13*. A raster pattern with lines oriented 90° from the beam's long axis produces the lowest deflections for a beam substrate. The spiral pattern scanned from the outside to the inside produces low and uniform deflections for a plate substrate.

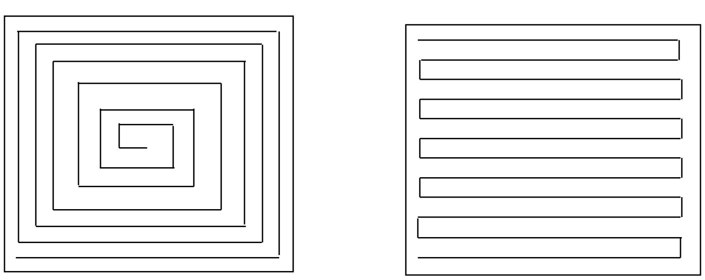


Figure 13 Decomposition scanning patterns

The method by Pi et al. [8] is adapted for surface cutting. For depression feature cutting, they are clustered by machining direction and cutting tool. Machining toolpath is generated for each clustered feature group.

Conclusion and Future Work

A process planning for five-axis laser metal deposition system is discussed in this paper. The LAMPP offers automated toolpath generation for five-axis layer building and machining. The integration issues between layer building and machining are discussed. Algorithms for each subtask such as featured recognition, skeleton searching, building sequence generation, part decomposition etc. have been presented.

Further work will include the development of more efficient ways to find the skeleton of a part and general methods that can decompose the parts with complex geometry such as freeform surfaces. A more robust feature recognition method is needed to further improve the later system.

Acknowledgements

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