Laser Aided Direct Rapid Prototyping

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Abstract

We describe a multilevel design hierarchy applicable to the VLSI-like layered manufacturing technology of Solid Freeform Fabrication (SFF) called Laser Aided Direct Rapid Prototyping (LADRP). We discuss the interfaces between the abstraction levels and the requirements of the standard languages needed for the interfaces. We provide experimental verification for the thickness design rule and indicate other possible design rules applicable to this process. We then present a software tool called a **Slicer** *that takes a three-dimensional description of a solid body and creates 2.5D layers for the SFF process. Our current implementation is based on a boundary representation of solids described by the Unigrafix solid modeler.*

Keywords: Solid Freeform Fabrication, design hierarchy, layered fabrication, solid interchange format, slicer, LADRP (Laser Aided Direct Rapid Prototyping), design rules

1 Structured Design Methodology

VLSI design methodology has exploited multilevel design abstractions (viz. system, function, logic, circuit, and layout), each layer addressing the design issues specific to that layer with its associated synthesis and simulation tools. The communication between two layers takes place through a clean interface that encapsulates the constraints imposed by the lower layer in terms of simple rules to be observed by the layer above it. A "digital interface" between design and fabrication in the form of a set of design rules at the layout level allows processing steps to be defined independent of an object's geometry. For mechanical and electromechanical systems, the multilevel design hierarchy is much more complex due to energy transformation, function sharing of elemental components and because performance considerations are an integral part of the design process [16, 17]. The limits on geometric dimensions of the object and physical attributes of the material as they relate to correct function and performance of the object will be called *design constraints.* The design constraints are process independent and can be derived by experimental methods and mathematical modeling. This terminology is appropriate to distinguish between functionality and manufacturability of a part. For VLSI design, these two considerations can often be merged into a set of conservative geometric *design rules.* In practice, however, an additional set of design rules are followed which guarantees expected performance. An analogous set of design rules must also be discovered for the mechanical fabrication process. For the SFF process, at least four levels of design hierarchy can be identified. Figure 1 shows the design hierarchy beginning at the 3D geometry level.

- **Design level, including function, features, and properties:** At this high level, a formalism is needed to capture the functional behavior of the mechanical system from the physical parts without specifying the geometry information. The emerging international standard STEP [5, 15] will have facilities to specify the design at this high level of product definition.

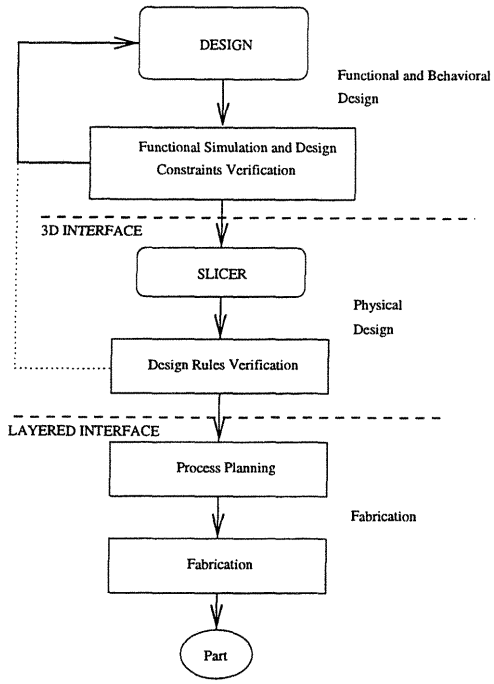

Figure 1: Design Hierarchy for Solid Freeform Fabrication

- **Three dimensional geometry level:** At this level, a completely process-independent representation of the system in terms of its geometrical shape and material in 3D has to be specified. We will call it a *design subsystem* which performs the traditional design by deriving the shape and geometry that achieves the desired functional specification. The design must satisfy a set of design constraints with respect to a set of relevant mechanical and physical properties of the material. The analysis and simulation tools verify the correctness of the design taking into account material strength, volumetric and surface properties, thermal and fluid flow properties if necessary [13].

  The design languages to be used for data exchange at the interfaces must be capable of expressing realistic three-dimensional objects. The SFF research community has given a name SIF (Solid Interchange Format) [11] to such a language. Such a language should probably be based on a solid modeling system such as CSG (Constructive Solid Geometry) or BREP (Boundary Representation), possibly augmented with non-uniform rational B-spline (NURBS) and quadric surfaces [2, 3, 12]. A large number of commercial and research solid modelers have been developed in the past [4] but none of these meet the requirements of SFF technologies.

- **Layered Level adapted to specific SFF technology:** The physical design phase uses specific knowledge of the process and its design rules to specify a layered description of the part. Ideally, like in VLSI which satisfies a layering paradigm with conservative design rules, this stage should be insensitive to an object's geometry.

  The translation of the 3-D geometry to layered geometry has to be done by a *Slicer* that will produce the layers, given its description in SIF. This description will form a digital interface between the physical design and the process planning stage [9, 11]. A key software tool at this level is a *Design Rules Checker*. The design rules specify the geometrical constraints on the dimensions of the layers that will conservatively guarantee reliable production of the part and its three-dimensional geometry (within limits of tolerances) by the underlying SFF fabrication process.

- **Process Planning and Fabrication:** This is the final stage of the hierarchy at the lowest physical level. If the design is validated by simulation and is free from both design constraints and design rules errors, the design is sent down to the process planning stage which generates the information for automatic sequencing of operations for the particular SFF process.

2 LADRP Process

2.1 Experimental setup

Laser Aided Direct Rapid Prototyping (LADRP) is used to develop 3-D metal parts by directly melting base metal powders using the laser source. The fabrication step takes the instructions from the process planning step and manipulates the robot arm to fabricate the part. In the LADRP process, the three main requirements are a laser beam, powder feed, and shielding gas. Experiments were conducted to formulate the design rules for fabrication. The detailed setup is shown in Figure 2. Since laser beams are inertialess and contactless tools, they are readily adaptable to automation. The CO_2 laser was run in CW mode with a maximum power output of 400 W. The laser beam was focused to a 406 micron spot size using a 5 inch lens and was triggered on/off using a controller interfaced with a computer. SS 304 type stainless steel powder of 150 micron size was fed to the focal spot of the laser beam using a volumetric powder feeder. The feed rate of the metal powder is one of the design criteria from the fabrication point of view.

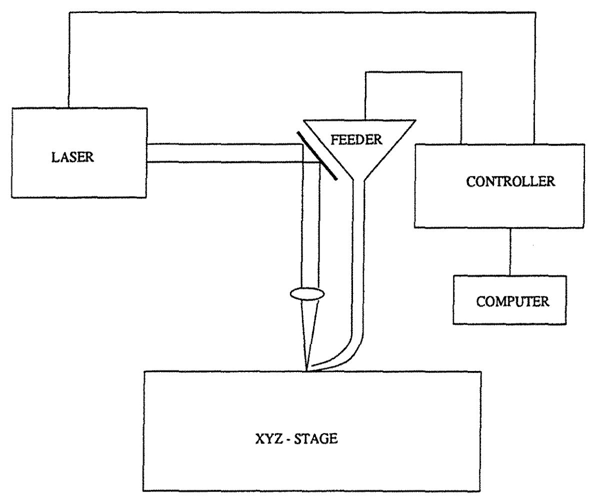

Figure 2: Laser-Aided Manufacturing of Multigraded Components

Three dimensional parts are fabricated by a layer by layer deposition method. The 3-D structure is stored in a computer and is replicated as a real part using a XYZ-Translational stage. The XYZ-stage is linked to the computer through a controller which has its own memory. One layer of the part is deposited as the XYZ stage translates in the XY plane. The next layer is deposited on top by giving an appropriate Z-axis displacement. Likewise the entire structure is formed by layer by layer deposition. The thickness of each layer depends on the speed of the XYZ stage, the Z-axis displacement, the powder feed rate, and the laser power. The interaction of the laser heated material and the surrounding air could cause oxide formation resulting in trapped oxide particles between adjacent layers which is detrimental to material quality. This was avoided using argon at the flow rate of 15 liters/min as a shielding gas. There are two outlets for the shielding gas, one through the laser head which also helps cooling the lens and the other through the powder delivery system which acts as a carrier gas for uniform powder deposition.

3 Design Rules for LADRP

The design rules specify a set of simple geometrical rules that a CAD designer must follow in a geometrical model so that the product is reliably produced by the process. Generic design rules such as VLSI's λ-based rules specifying minimum dimensions of transistors, separation and width of interconnecting wires [8], do not seem to exist for SFF processes. This can be attributed partly to the dependence of the functionality of the part on the particular material, geometry and fabrication technique used to produce the part. The dependence of the functionality of the part with its 3D geometry can be expressed in terms of a set of *design constraints* which are derived by designers using mathematical modeling of material properties and functional specification. Let us take a simple example of designing a bracket. It has a general shape but its actual dimensions will depend on the load specification. The same load-bearing capability of the bracket can be achieved by using various types of materials such as aluminum, iron, plastic, etc. But in each case, the dimensions will be different since the mechanical strengths of these materials are different. However, for all these materials, the strength and dimensions can be related by the same equation [14]. The next step is to verify whether the given manufacturing process is capable of fabricating the part. The limitations imposed by the process parameters on the manufacturability of the part are referred to as *design rules.* In a recent paper, Kar and Mukherjee [6] presented design rules that relate part dimensions with process parameters such as laser power, wire feed rate, temperature and thermophysical properties based on energy balance equation [1]. One of these rules, the thickness rule, states that given a set of process conditions and material, the thickness of a layer is proportional to the square root of the product of laser power and energy utilization factor. We will provide experimental verification of this design rule.

3.1 Experimental verification

The important process variables that affect the design rules are discussed below.

- Laser power - affects the energy input to the material.
- Laser beam radius - determines the radius of the material feed that can be melted. The beam radius depends on the focal length of the lens. The theoretically achievable smallest beam radius is given by the diffraction-limited spot size. For a given laser machine and beam focusing system, the beam radius can be computed by considering the propagation of the laser beam.
- Material (powder) feed rate - influences the rate of manufacturing the part. This process variable is usually selected on the basis of economic considerations.

The proposed thickness rule theory is verified using the experimental setup for LADRP shown in Figure 2. The various parameters like translational speed of the XYZ stage, the focal length, spot size, powder feed rate, and the shield gas were kept constant and the laser power was varied. The variation of layer thickness is plotted against the square root of laser power as shown in Figure 3. The linearity between the two quantities is evident. The same figure shows the linearity of the maximum thickness and the theoretical thickness for the various power levels. The various process parameters used are: Laser source - CW CO_2 Laser Maximum power level 400W: Focal Distance - 5 inch; Spot size - 460 micrometer;

Translational speed - 0.51 cm/sec; Shielding gas - Argon; Shielding gas flow rate- 15 l/min; Power level variation - 340 to 380 watts.

3.2 LADRP Fabrication Limits

Various process parameters like the spot size of the laser, the resolution of the XYZ translation stage, surface tension of the molten metal and orientation of the 3-D structure with respect to its fabrication

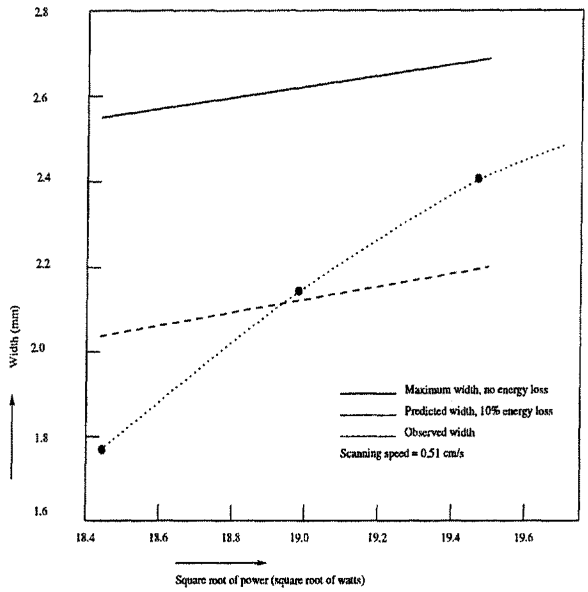

Figure 3: Experimental verification of the thickness rule

determine the limitations of the process. In our present work three kinds of limitations have been considered, namely angular resolution, cone tip resolution, and supportless structure formation.

1. **Angular resolution**. The large number of parameters influencing the process makes it difficult to formulate a mathematical expression for angular resolution. We have chosen instead to experimentally establish angular resolution criteria by building structures in the shape of triangles with various corner angles and determining the resolution of the angle by the quality. When using this technique, the measured values are affected by the XYZ stage resolution. The resolution of the XYZ stage was independently determined and was compared with the resolution of the process and the least of the two accounted for the observed value. The XYZ was found to have a resolution of about 1.71° below which it becomes difficult to distinguish between the lines with normal eyesight. The actual process has a much smaller resolution of about 11.3° only and hence structures with corner angles below this value become difficult to fabricate. For any two walls of thickness r meeting at an angle θ the length of the cross section is given by $\frac{r}{\sin\frac{\theta}{2}}$. Hence as the angle decreases the length of common region between the two walls increases. Below the angular resolution there is an overlap of the layers. In addition to this, at the corners the XYZ stage temporarily comes to rest. This results in more melting at the corners thus forming lumps. This can be avoided by reducing the powder feedrate at the corners or in similar positions where the stage experiences a temporary rest.

2. **Cone tip resolution**. Sharp points may be difficult to fabricate. This is due to the fabrication method of layer by layer deposition because corners tend to be more of a point than a layer. Various structures involve solid angles like a conical tip. Limitations of fabricating such features are established using the thickness rule criterion as discussed before. In case of a hollow cone the fabrication process starts from the base and a circular ring of thickness $2r$ forms the first layer. The second layer is deposited on top of the first with a slight offset and with a smaller diameter ring which accounts for the slant angle of the cone. The thickness $2r$ of the layer is determined by the thickness criterion. Again the slant angle is another design criterion fixed by surface tension of the liquid metal. Layer by layer deposition results in the conical structure of fixed dimension. The topmost layer decides on the tip resolution for the cone. Since the thickness of the layer is $2r$ which is the width of the layer w, the final top surface of the cone can be formed with no center gap i.e., with a diameter of $2w$. Hence the topmost surface of a

cone will have a finite area A_c and not a point as in case of an ideal cone. The area of the top cone surface is given by $A_c = w^2$ where w is the layer thickness given by the thickness criterion.

3. **Supportless structures**. For example, dome like structures can be fabricated without internal support with certain limitations on the angle of tilt of the dome. Only a certain maximum angle of tilt is allowed which is decided by the surface tension of the molten metal balanced by the weight of a single layer. Formation of supportless structures involves depositing layer by layer with a calculated offset which accounts for the angular dimension. However there is a limit to the extent of offset which is determined by the surface tension forces that act between the already solidified layer and the new liquid layer getting deposited. The area of interaction of surface tension forces are determined by the Z axis displacement of the stage and the translational speed. The surface tension forces balance the cosine component of the weight of the new layer being formed.

4 Slicer

In our project, we have chosen Unigrafix as a baseline for our 3D modeling language. Unigrafix (UG) is a boundary representation solid modeling language developed at the University of California at Berkeley [10]. UG uses simple BREP for its objects. This makes it easy to obtain the needed data for our slicer. Also it lends itself well to the joining together of the slices into a single unified object file. We are currently developing the 2.5D slicer so that we may express objects in an L-SIF language as described earlier.

The goal of this algorithm is to decompose a solid model into "slices" that can be suitably described to a Solid Freeform Fabrication system for manufacturing. Intuitively, the slicer we have implemented uses a "space-sweep" algorithm. The main idea is to sweep a plane oriented parallel to either the yz plane, xz plane, or xy plane (i.e., along the x, y, or z axis, respectively) through the solid model of the object. The plane stops at event points for processing. A sweep data structure is maintained that provides local information about the portion of the solid that has been swept so far that contributes to the current slice.

The inputs to the algorithm include the solid model (in Unigrafix boundary representation format), the axis (α) for the plane to sweep along (x, y, or z), and the width of each slice. Our initial implementation uses variable but prespecified slice widths; however, the implementation is easily extended to allow adaptive slicing by allowing an external process to supply slice widths.

In the first stage of the algorithm, an event queue is constructed using the solid model and the slice widths. Two types of events are added to the event queue: *vertex events* and *slice events*. Events are placed in the queue in increasing order of their corresponding values along the α axis (ordering of multiple events with the same α axis value is described below).

Vertex events are added to the event queue for each α axis value corresponding to a vertex in the solid model. Along with vertex events in the queue is a list of vertices that share the same event.

Slice events are added to the event queue at the location of each slice in the solid model. These locations are calculated by starting at the smallest vertex α value and adding successive slice widths. Note that although the current implementation fixes all slice widths before building the event queue, we only need to fix the width of one slice at a time; as a slice of the model is cut, we may request the next slice width and dynamically add a corresponding slice event to the queue.

If a slice event occurs at the same α axis value as one or more vertices in the solid model, then the slice event is placed after the vertex event for that α axis value.

In the second stage of the algorithm, the plane is swept along the α axis, stopping at each event point. A sweep data structure containing a boundary representation of the current slice of the solid is built as the plane sweeps through the solid. The processing at each event point is summarized below.

Vertex Event. In this case, all vertices at this α axis value are added to the sweep data structure along with any edges of the solid incident to these vertices that are not already within the slice model.

Slice Event. In this case, the sweep plane is intersected with the sweep data structure by intersecting it with the appropriate edges in the structure. The resulting "slice" is output by the algorithm. The top of the slice (the part cut by the sweep plane) is stored as the base of the next slice. The vertices within the sweep data structure that are below the sweep plane are removed, along with any edges below the sweep plane that have endpoints in vertices corresponding to this event.

An alternate algorithm is suggested in [7]. As part of our continued work, we intend to compare our approach with the algorithm given in [7] in order to develop a fairly general and efficient slicer.

4.1 Error Checking in Sliced Structures

All calculations within Unigrafix, and in particular the slicer, are done using floating point numbers. The properties and errors associated with floating point numbers are well known. These properties brought up the question of the potential for *gaps* within adjacent slice structures (i.e., a non-seamless intersection of a slice's ceiling and the floor of the slice above it).

The method used to find gaps was based on the following concept: The ceiling points of slice A should be identical, within some error range, to the floor points of the adjacent slice B, for all slices within the structure.

The floor/ceiling points of the respective slices are determined as being any points within some ϵ_1 of the floor/ceiling of the slice. When a slice is created, its floor points are determined and stored. If there exists a set of ceiling points from a previous slice, then a series of comparisons is made. Essentially, every new floor point is checked to see if it has a match in the corresponding ceiling. If a match is not found, then a gap has occurred between the two slices. A point (x, y, z) is tested as follows:

$$||x| - \lceil x\rceil| \leq \epsilon_2 \quad \text{and} \quad ||y| - \lceil y\rceil| \leq \epsilon_2 \quad \text{and} \quad ||z| - \lceil z\rceil| \leq \epsilon_2 \tag{1}$$

If the above condition is false, then a gap has occurred.

This test was run on a variety of structures with different epsilons. Sample ϵ_1 values were 0.5 to 0.1. Sample ϵ_2 values were 0.01, 0.001, 0.0001, 0.00001, and 0.000001. Sample structures included cubes, pyramids, dodecahedrons, and mixtures of several other forms. The results for all epsilons on all structures was 100% accuracy with no gaps.

These results are expected and are easily explained. When calculating line intersections, the same standard line equations were used for all slices. Also, only the original points from the slice are used for these calculations (i.e., no derived points are used to derive more points). And finally, the same precision was maintained throughout the code for all floating point numbers.

We expect to incorporate information about materials into our solid models in the near future. This will likely be done using tags indicating the type of material used for different parts of the solid. This presents several new constraints for the slicer algorithm, including how to slice an object made up of multiple materials (a consideration that may be important for some SFF processes) and anisotropy in density.

Our goal is to make our slicer general enough to be used with several different SFF processes. Although our current work is focused on one process (the LADRP process), we will attempt to make the output from our slicer conform to emerging standards and convey this output to other SFF sites.

5 Acknowledgment

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