CAD and Control Technologies for Computer-Aided Manufacturing of Laminated Engineering Materials

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Abstract

This paper presents recent progress in software, material handling and tangent-cutting control in support of Computer-Aided Manufacturing of Laminated Engineering Materials(CAM-LEM). Progress in CAD focuses on the definition of a new layered file format for describing 3-D solids in terms of thick slabs with ruled-surface edges. For material handling, we present new algorithms for automatic generation of mask hole patterns used in selective-area vacuum gripping, which is required for our laminated assembly process. Finally, we present recent results of object fabrication using thick-slab, tangent-cut layers

1. Introduction

Computer-Aided Manufacturing of Laminated Engineering Materials (CAM-LEM) is a sheet-based approach to Solid Freeform Fabrication being developed at Case Western Reserve University [7, 8, 10, 11]. In this process, layers computed from cross sections of an object's CAD description are laser-cut from sheet material and subsequently stacked and laminated to assemble a part. Such stacks are post-processed to densify the material, fusing it into a monolithic solid. With this approach, we not only realize the original CAD description, but we also satisfy functional engineering properties (e.g. rigidity, strength, thermal expansion, surface finish, etc).

One of the most important characteristics of a part fabricated from a successful SFF system is acceptable surface finish. With few exceptions [e.g., ShapemakerII [1], SDM [2], Stratoconception [3]], current SFF processes build parts from thin, vertically-extruded layers resulting in "staircasing" of the resulting surface. Commonly, one reduces the magnitude of the staircase roughness by reducing the thickness of each layer, but at the cost the fabrication speed.

For our CAM-LEM system, a 5-axis laser cutting platform was built to translate and rotate sheet material under a stationary laser. By cutting contours at the appropriate tangent angles with this platform, it is possible to better approximate an object's surface and/or improve the build rate. However, our process of tangent-cutting and assembling layers presents multiple significant technical challenges. Progress in three of our challenge areas is presented here. First, we describe how to represent the original CAD model in terms of an approximation using relatively thick slabs with ruled-surface edges. Second, we introduce improvements on our technique for extracting desired regions from the cutting table and precisely stacking them on the part assembly. Finally, we illustrate and discuss recent progress in building 3-D objects with our 5-axis CAM-LEM system.

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2. Layered File Format (LFF) Representation of Solids

To exploit the potential advantages of building objects with thick, tangent-cut layers, we must first derive an approximation of our original CAD model in terms of layers that can be fabricated with a practical system. Laser cutting is used in our system, but the same constraints apply to 5-axis CNC machining, 4-axis wire-EDM or hot-wire cutting and 4-axis water-jet cutting of sheet materials. For this geometric processing task, we preferably perform computations directly on the native CAD file, although our approach is applicable to STL format files as well.

In our process, we distinguish "slices" from "layers." We define a "slice" as the 2-D cross section of our model at a given z-height. A slice can be represented in terms of closed contours—"outer" contours enclosing regions of material, and "inner" contours describing punctures within the enclosed regions. Such contour information can be used in an alternative model representation, such as in the contour file formats SLC[4] and CLI[5]. A representation in terms of slices alone is adequate for systems that build with thin, vertical extrusions of layers. For thick, tangent-cut slabs, however, such representation is inadequate; it is also necessary to specify the shape of the edge surfaces of thick slabs. We thus define a "layer" as a 3-D body with planar upper and lower surfaces (slices) connected by edge surfaces. Objects can be defined in terms of stacks of such layers. Technically, such a layered representation can identically redescribe any CAD model. However, the class of layers that can be fabricated by a line-of-sight cutting process is restricted to those with edge surfaces defined in terms of *ruled surfaces* [6]. Layer bodies with ruled-surface edges are simply described by one-to-one mappings of each contour on the upper surface to a corresponding contour on the lower surface. The mapping includes a functional specification of the path of a span—connecting upper and lower contours—swept along the perimeters. The swept path corresponds identically to the cutting-tool path for fabricating the layer, thus guaranteeing feasibility of fabrication.

Since a ruled surface cannot identically match an arbitrary surface, our thick-layer representation with ruled edge surfaces can only approximate an exact CAD model. Since a ruled-surface description joining two contours is not unique, the space of alternative ruled surfaces should be explored to identify the best fit to the original model. An algorithm for performing this computation based on an energy-relaxation technique was introduced in [7] and is further detailed in [8]. Having computed an optimal reconstruction that can be fabricated by a line-of-sight cutting process, the result should be stored in a format that is compact, precise, and efficient to interpret on-line during fabrication. For this purpose, we define a layered file format (LFF), as illustrated in Fig 1.

In an LFF file, a part is represented by successive parallel *layer*s in ascending order in the vertical direction. Each layer is defined by a *bottom slice*, *top slice*, and ruled layer *edge-surface*s between the two slices. Slices are described by the boundary contours, which can be composed of polylines as well as higher-order curves. An LFF file can be generated by slicing CAD models and stitching upper and lower cross-sectional contours with ruled surfaces, or by interpreting reverse engineering data collected by surface digitizing or from Computed Tomography (CT) imaging.

Since our layers describe true 3-D bodies, we can also associate material descriptors with layer bodies. To represent mixed material composition within a layer, we define a layer in terms of a number of regions. Each region is a 3-D body described in terms of a closed (possibly punctured) surface description, and each closed surface contains a labeled material. The regions can be adjacent to each other or disjointed.

Fig. 1 illustrates the format. Layer i is bounded by lower slice-plane "slice i-1" and upper slice plane "slice i." Each slice is defined in terms of closed contours, identified as outer (enclosing material) or inner (defining a puncture). Pairs of contours, upper and lower, are associated through a functional ruled-surface description, specifying the edge surface connecting them. We describe this mapping in terms of a tabulated function of arc-length along the top contour vs. arc length along the bottom contour, specifying endpoints of connecting spans. Edge surfaces that connect upper and lower outer contours occur once for each region within a layer, and we thus associate with this mapping a material tag identifying the material enclosed within the region.

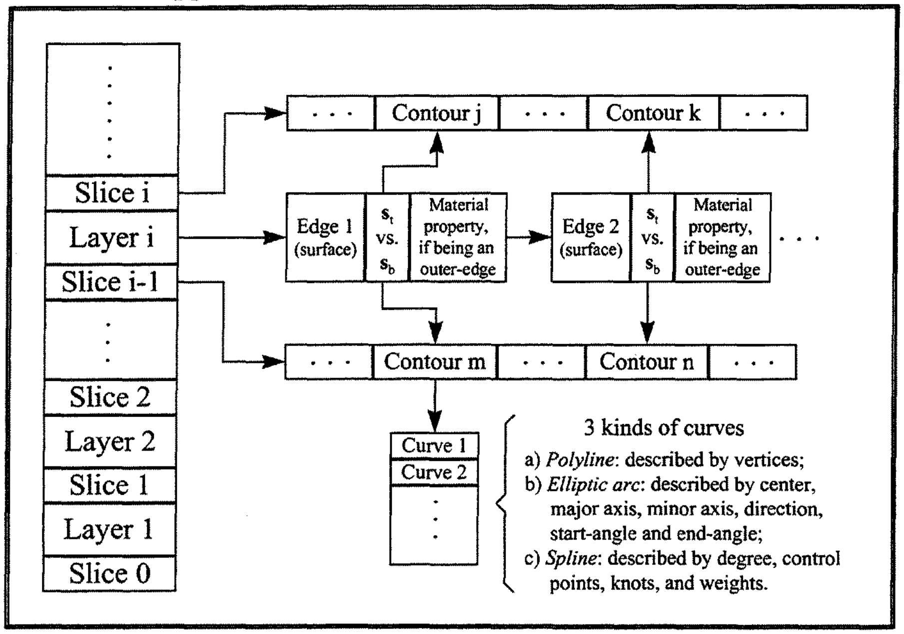


Figure 1 : LFF representation of a solid model

Finally, we encode contour descriptions in terms of "curves." Three types of curve entities have been defined in the current version of the LFF file format. They are the polyline, the elliptic arc, and the spline curve, including Non-Uniform Rational B-Splines (NURBS). Since all contours in our description lie in parallel planes, only 2-D curve descriptors are needed .

A *polyline* is a series of connected straight line segments. A polyline with n segments is defined by its n+1 2D vertices given in x-y coordinates.

An *elliptic arc* is part of an ellipse. It is defined by a center point, a major axis vector, a length-ratio of the minor axis to the major axis, a direction flag, a start-parameter, and an end-parameter (analogous to start and end angles). A circular arc is a special case of elliptic arc when the length-ratio equals 1.0. The elliptic arc is parameterized. Given the center $\boldsymbol{C}$, major axis $\boldsymbol{M}$ and minor axis $\boldsymbol{N}$, a point $\boldsymbol{P}$ on the ellipse can be located by parameter u as $\boldsymbol{P}(u) = \boldsymbol{C} + \boldsymbol{M}\cos(u) + \boldsymbol{N}\sin(u)$.

Spline curves, rational and non-rational, are also parameterized. A spline is defined in terms of a specified degree, control points, knots, and (for rational splines) a set of weights. (see [9] for details).

Our LFF file format achieves our stated objectives. It can represent contour descriptions within a slice plane precisely and compactly through the use of higher-order functions. It can also encode material information throughout the volume of a body. It represents tangent information for edge surfaces in terms of a compact representation (scalar functions defining ruled surfaces) that encodes the full precision achievable by a line-of-sight cutting process. Finally, and most importantly, the format guarantees that each layer can be fabricated using a line-of-sight cutting means, and the specification decomposes efficiently for real-time interpretation for machine control. We consider this format to be ideal for sheet-based processes, including our CAM-LEM system.

3. Selective-Area Material Handling of Layers.

A second technical challenge of the CAM-LEM approach is material handling. Since we cut each layer individually, the desired regions must be extracted from the cutting table and assembled precisely to form the desired part. For this task, we utilize a novel masked vacuum gripper technique (see [10] for details). In previous work, we demonstrated that it is feasible to extract selective regions using a vacuum gripper masked by a selectively-punctured, non-porous material. In recent progress, we have improved and automated the mask-hole pattern definition, we have extended the mask design to automated computation of multi-purpose masks, and we have proposed a means to extract tangent-cut regions from waste material.

Our procedure for automated mask generation is described here. Consistent with our LFF layer descriptions, we refer to the closed contours defined on the upper slice plane of each layer. (Only the upper slice plane will come in contact with the vacuum gripper). This slice consists of one or more *outer* contours, each possibly enclosing one or more *inner* contours. In our mask generation process, simply stated, each outer contour is successively eroded, each inner contour is successively dilated, and mask holes are defined at fixed intervals along the resulting contours. Ideally, this results in a sequence of closed, non-intersecting contours describing a uniform distribution of mask holes that can be punched along efficient trajectories.

While conceptually simple, complications occur with this approach. For a non-convex contour, erosion eventually leads to self-intersecting contours, as illustrated in Fig 2. (A similar problem can occur with dilation of inner contours). To resolve this problem, we analyze each eroded contour to test for self intersections. Self intersections define multiple closed loops. Each such closed loop is tested for its direction of rotation. If the direction of rotation is consistent with the direction of rotation of the original contour, then the resulting loop is retained. Reversed circulations indicate contours to be deleted. In a similar manner, the problem of intersections among multiple eroded/dilated contours is solved by locating the points of intersection of one contour with another and then retaining those inner/outer contours consistent in direction , as illustrated in Fig 3. Incorporating these considerations, our algorithm is capable of generating correct mask-hole distributions for arbitrarily complex regions, resulting in fill patterns along concentric, closed contours. The corresponding mask production time is faster and more precise than a raster scan, analogous to the comparison between vector graphics and raster graphics. (This same algorithm may be applicable to efficient scan patterns for point-wise SFF building techniques as well.)

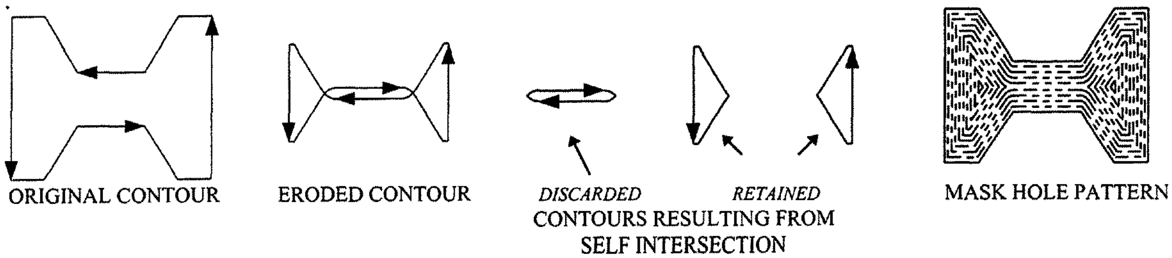


Figure 2

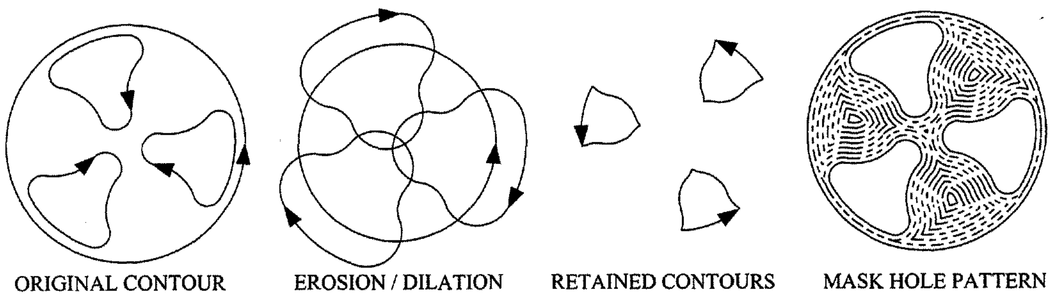


Figure 3

A limitation of our masked vacuum gripper technique is that production of masks can be too time consuming if a separate mask is required for each layer. In a recent extension, we automatically generate masks applicable to multiple layers. The motivation is obvious for gradually changing layers, since the corresponding masks would also be similar. However, multi-use masks can also be employed for surprisingly dissimilar layers. The procedure for generating multi-use masks is illustrated in Fig 4. The first two shaded regions are the desired areas to be grasped. The third image shows the Boolean intersection of the two desired regions. The mask pattern applicable for grasping both regions, the fourth image, is generated by our generic technique, but based on the contours of the intersection of regions.

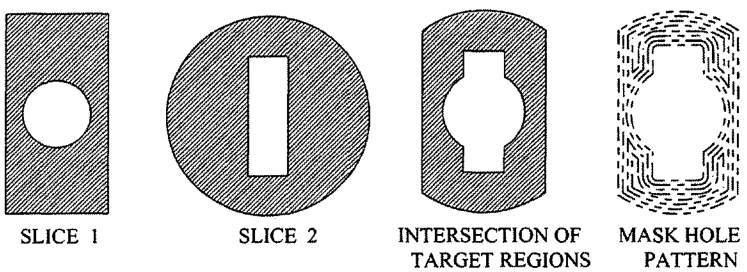
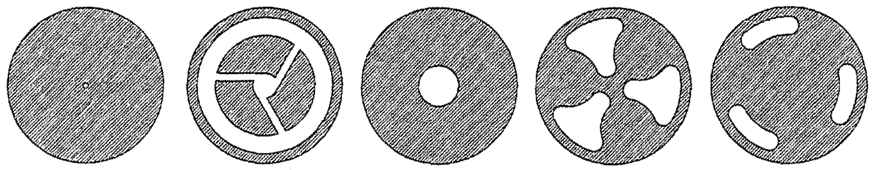


Figure 4

A multiusable mask once generated should be checked for feasibility. An analysis of the force exerted by the gripper on the part is done by solving for Newton's force balance and Euler's moment balance equations . The analysis requires the gravity force on the slice, the centroid, suction force per mask hole, the location of the mask holes and the number of mask holes, which are all known. The only unknown is the reaction pressure distribution between the grasped part and the mask . The space of the possible reaction pressure distributions is approximated by a finite number of hypothetical concentrated reaction forces distributed over the interior of the target region . In proposing reaction force coordinates, there is no penalty for including an excess number of locations. To assure a complete flooding of candidate reaction force locations the same mask generating algorithm is employed. The result is used as input to a linear programming equation solver, which solves for force/moment equilibrium feasibility.



FIVE SLICES OF A FLUIDIC DEVICE

Figure 5

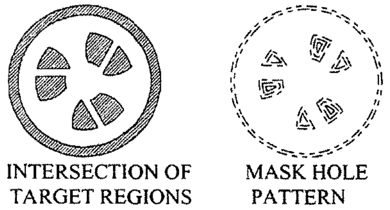


Figure 6

The above method was employed to test the feasibility of a multiusable mask for five slices of a fluidic device, shown in Fig 5. The multiusable mask for the five slices, shown in figure 6, was fabricated and tested, and it successfully picked up each of the five layers while leaving the waste material behind in all cases.

A third recent advance in our material-handling challenge is the extension of our masked-gripper technique to manipulating tangent-cut sections. Figure 7 illustrates the potential problem of extracting a desired section of material when tangential cutting is employed. The figure represents a side view of a layer of a tilted cylinder cut from sheet stock, still surrounded by waste material. It is not possible to extract the desired section vertically without interfering with the waste material, nor is it possible to first extract the waste material vertically without interfering with the desired region. To solve this problem, we propose a second pass cutting trajectory in which the laser cuts the waste material as shown in the top view of Fig 7. The second-pass cut is oriented vertically, and it follows the upper contour of the desired region over those path segments bounding "overcut" regions (sections for which the surface normal of the layer's tangent-cut edge surface has a downward-facing component, thus blocking waste material from vertical extraction). The second pass cuts only through waste material. The result is that the waste material exposed to the top surface is then extractable vertically without interfering with the desired region. After the waste is extracted and discarded, the desired region is removable by vertical extraction without interference. The target slice can then be easily extracted, and what remains on the cutting table is discarded. This technique is still under development and testing, but it appears to be general enough to handle arbitrarily complex cases.

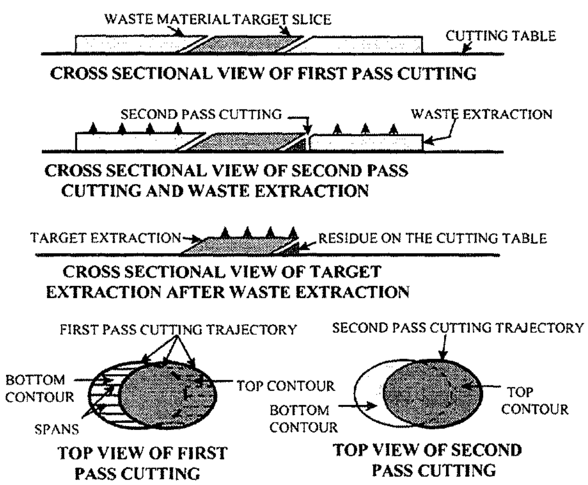


Figure 7

4. Tangent-cut Parts Fabrication

Our CAM-LEM tangential cutting system is comprised of 3 parts: a cutting tool, a cutting platform and a material handling module. Our cutting tool is a 50W CO_2 laser mounted vertically above the cutting table. The cutting platform consists of 3 translational axes (x,y,z) and two rotational axes (roll and pitch). This mobility enables the mechanism to position an arbitrary point on its cutting surface at an arbitrary orientation (within joint constraints) at the laser focal point. Our 5-axis mechanism carries a cutting table that clamps sheet feedstock to an aluminum honeycomb cutting surface by drawing a vacuum beneath the cutting surface. Material handling (loading, picking-up and stacking) is executed by 3-axis motion of a Cartesian robot with our selective-area vacuum gripper design as its end-effector.

Recent results of tangential cutting performance based on thick-slab, ruled-surface layered approximations of solid objects are presented here. Figure 8 shows the fabrication of a geometric test object consisting of the union of a 60mm-high cone with a 30mm-high rectangular prism. The object was defined in a CAD modeller, sliced at 11 slice planes, and redefined in terms of 10 layers with ruled-surface edges. The functional relationship defining the ruled-surface edges was used to define the path of the cutting tool. Motion of the cutting platform was derived from this tool path through inverse kinematics, as described in [11]. The ten layers were cut from 6mm sheets of polystyrene foam. (Our models were assembled by hand, since our automated material-handling concept for tangent-cut layers has not yet been implemented in our system).

Since each layer of the test object was defined in terms of ruled edges, a feasible tool path was guaranteed. Each ruled surface was approximated in terms of interpolation between more than 500 tabulated spans. Although this data constituted a feasible and accurate model, some trajectory modifications were required at run time. In particular, some of the spans near complicated regions required high joint velocities and accelerations to maintain a constant material removal rate. To avoid dynamically-undesirable or infeasible joint commands, the prescribed paths were preprocessed before execution to identify problem conditions. Cutting speeds were scaled down linearly (preserving the same path shape) in such regions to satisfy dynamic constraints. A consequence of this time scaling is that it was not possible to maintain a constant material removal rate, yet the laser power remained fixed. As a result, some overcutting (excessive erosion) occurred in regions where the trajectory speed was reduced. This problem should be relieved by coordinating laser-power modulation with cutting speed.

A second test part, a 22-layer reconstruction of a head, is shown in Fig 9. The tangent-cut layered head is compared to the corresponding 22-layer reconstruction using vertically-cut layers.

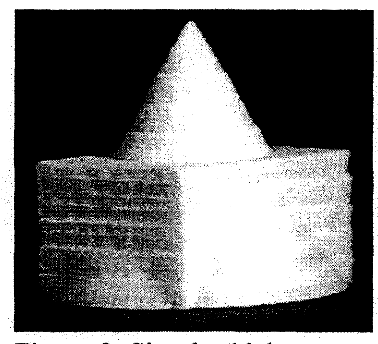


Figure 8: Simple, 10-layer geometric test part

The fabrication parameters for both of the tangent-cut test parts shown are summarized in Table 4.1. The present examples deliberately illustrate exaggerated cases of the advantages of tangent cutting. All 22 layers of the more complex test part (the head) could be cut in under 15 minutes using the quoted parameters (but ignoring material-handling time). In practice, thinner layers would be used to achieve greater precision, with corresponding increases in build time. Nonetheless, significant advantages in build speed can be expected relative to SFF systems employing point-wise build techniques. More importantly, the CAM-LEM tangent-cutting process is applicable to a wide variety of materials in sheet form. We are currently working with tape-cast advanced ceramics (alumina and silicon nitride) and sheet-based powdered metals.

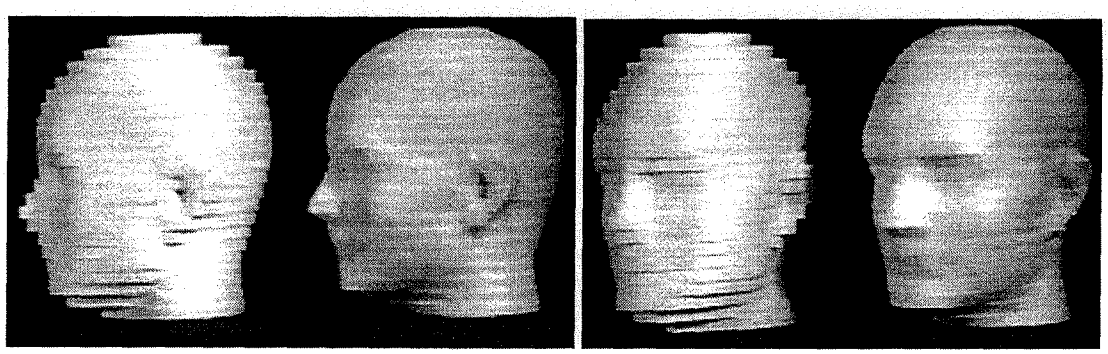


Figure 9: A 22-layer Model of a Head; vertical-cut layers vs tangent-cut layers

	part 1(Fig 8)	part 2(Fig 9)
max. cutting speed (mm/sec)	10.0	10.0
min. cutting speed (mm/sec)	2.5	1.8
max. tangent angle (degree)	34.280 (from vertical : in 1st slice)	71.562 (from vertical : in 1st slice)
part size (mm × mm × mm)	57.05 × 57.05 × 60.10	117.83 × 89.77 × 132.22
material (thickness : mm)	polystyrene foam (6.01)	polystyrene foam (6.01)
# of layers	10	22
# of spans at each layer	600	800
laser power (W)	36	30

Table 4.1 : Cutting Parameters and Part Specifications

5. Summary and Conclusions

This paper has presented our recent progress in CAM-LEM. We have emphasized the value of approximating solids in terms of relatively thick layers with ruled-surface edges, as such a description compactly captures the full model resolution achievable by line-of-sight type sheet cutters. At the same time, such a description guarantees the feasibility of fabrication of each layer using a line-of-sight cutter. This realization leads to a natural file format, which we have described as our "Layered File Format" (LFF). We argue that an LFF representation is optimal for sheet-cutting processes in terms of compactness, precision and ease of conversion to machine control.

We have also described our advances in automated mask generation for our masked vacuum gripper material-handling technique. Our new algorithm for mask design results in concentric, closed contours, leading to a uniform distribution of mask holes as well as an efficient trajectory for punching mask holes. The gripper technique is further extended to multi-use masks. Experiments verified the value of the approach using significantly dissimilar layers.

Finally, we have shown recent results from our 5-axis laser-cutting CAM-LEM system. Examples illustrate the value of tangent cutting, either in terms of surface finish or in build speed. Although the examples shown were fabricated from styrofoam, the process is applicable to engineering materials. In ongoing work, we are developing procedures for fabricating tangent-cut, laminated objects from advanced ceramics and powdered metals.

Acknowledgments

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