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Layered Manufacturing: Current Status and Future Trends

This paper reviews the emerging field of layered manufacturing. This field is little over 10 years old but a significant amount of research has been conducted and results to date are quite promising. We consider three broad topics namely, design systems for heterogeneous objects, layered manufacturing processes, and process planning techniques. Several applications/examples are included in the course of the survey and limitations of current technology identified. We conclude with some possibilities for the future.
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1 Introduction

Layered manufacturing (LM) is a fabrication method whereby artifacts are constructed by depositing material layer by layer under computer control. Also referred to as Solid Freeform Fabrication (SFF), layered manufacturing complements existing (conventional) manufacturing methods of material removal and forming. A host of LM technologies are available commercially. A nonexhaustive list includes: Stereolithography (SLA) by 3D Systems, Selective Laser Sintering (SLS) by DTM Corp., Fused Deposition Modeling (FDM) by Stratasys Corp., Solid Ground Curing (SGC) by Cubital, and Laminated Object Manufacturing (LOM) by Helisys. In addition, several LM processes are under development at various universities such as Carnegie Mellon, Stanford, MIT, University of Dayton, University of Michigan, and the University of Texas.

In industry, layered manufacturing is usually referred to as rapid prototyping (RP) reflecting the most common use. It is used for the rapid fabrication of physical prototypes of functional parts (important in the design stage), patterns for molds, medical prototypes (implants, bones), consumer products, and so on. Rapid tooling is one of the largest application areas of RP today. A unique feature of LM is its ‘‘direct’’ fabrication capability—it does not involve tooling, fixturing, and other peripheral activities associated with conventional manufacturing. Therefore, it is possible to start from a CAD model and create the physical part/prototype in a very short time (that is, hours instead of days and at a relatively low cost).

It is interesting and important to consider the use of layered manufacturing beyond RP applications. When viewed as a fabrication technology, its novelty stems from the layer-wise deposition principle. This offers a range of possibilities including multi-material structures (e.g., copper cooling channels inside a tool steel exterior, objects with embedded electronic components, etc.), direct build of multi-component assemblies, as well as the fabrication of materially graded structures—in density and composition. Layered manufacturing is also an attractive technology for the fabrication of mesoscopic devices. We note, however, that only few LM systems currently possess multi-material and heterogeneous object capability. But, research is underway and commercial development of such machines has begun.

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In summary, layered manufacturing adds a new dimension to product realization by making possible the fabrication of complicated and heterogeneous artifacts that cannot be made with conventional manufacturing techniques. This point is argued strongly in a recent ‘‘industry trends’’ document [1] which says: *Long-term growth in the RP industry will come from applications that are difficult, time-consuming, costly, or impossible with standard techniques*.

In this paper, we highlight opportunities, constraints, and issues related to facilitating this ‘‘long-term growth’’ in the LM field. Two main opportunities that have been realized in recent years are:

- The capability to process material at virtually any point in space-facilitating greatly increased capability for shape and materials complexity.
- Well-defined decomposition methods into manufacturable elements-facilitating design-for-manufacture, process planning and separation of design and manufacturing activities.

To fully realize these opportunities, several constraints must be overcome, including:

- Representation schemes that include geometry and materials and CAD systems that better support part and assembly design for LM.
- Generalized CAD model decomposition methods that suit an increasing variety of LM processes.
- Process planning and manufacturability assessment methods that operate on the CAD representations and decomposed models.
- Design methods that enable exploration of new design concepts that leverage LM’s unique shape and material complexity capabilities.

In the remainder of this paper, we report on the recent progress on design systems for layered manufacturing in Section 2. The LM systems (commercial and under development in universities) are described in Section 3. In Section 4, we provide an overview of process planning issues for layered manufacturing. Data interoperability is an important issue in CAD/CAM systems and in Section 5 we remark on this. Section 6 contains a discussion of novel applications that LM is making possible. Future trends are elaborated in the final section. Since the term solid freeform fabrication (SFF) is used as frequently as layered manufacturing (LM), in this paper, both LM and SFF are used interchangeably.

2 Design Systems for Layered Manufacturing

All layered manufacturing methods require the CAD model of the part to be fabricated. Furthermore, the CAD models are converted to the STL format prior to processing for build. The STL format (i.e., STereoLithography format), developed by the Albert Consulting Group, was put forth by 3D Systems in the early years of this technology and has since become the *de facto* industry standard. The STL format describes the boundary of the object by a list of triangles (i.e., a facetted representation) and each triangle is described by its three vertices and outward pointing normal. Conversion to STL is simple and done by standard triangulation algorithms which are very robust. Some downstream operations such as slicing and orientation are quite easy to perform on the STL model.

However, there is widespread dissatisfaction with the STL format due to a variety of reasons elaborated in [2] and efforts are underway to develop new representation schemes and data formats. Since the fabrication of heterogeneous objects is well suited for layered manufacturing (i.e., by selective deposition of materials) a large number of researchers have focused on representation of heterogeneous objects. By heterogeneous objects we refer to ones composed of different constituent materials exhibiting continuously varying composition and/or micro structure thus producing gradation in their properties. For example, Figure 1 shows a functionally gradient turbine blade with a graded composition between the ceramic exterior and metal interior [3]. The varying material composition resulting in variation in physical properties in different regions of the object can be exploited to achieve multiple and conflicting functionality (e.g., mechanical strength and thermal resistance in the turbine blade example).

It is important to point out that the heterogeneous object fabrication capability is not widespread in current LM systems. It is limited to a few research systems primarily in universities (e.g., Stanford, Michigan, MIT) and national laboratories (Sandia). Nonetheless, the design and representation of heterogeneous objects, dubbed heterogeneous solid modeling (HSM), is increasingly gaining the attention of researchers. Several methods have been proposed and are under development. It is hoped that both technologies, LM systems with heterogeneous capability and HSM, will mature synergistically and their confluence in the not too distant future will open a new chapter in product realization. In the following sections, we briefly describe some methods for creating heterogeneous objects noting that it is only the beginning of a new field and much remains to be accomplished.

2.1 Constructing Heterogeneous Objects

Finite element based methods

Recognizing the similarity between modeling material variation and physical properties, such as stress distribution, it has been suggested that finite element approaches used for analysis could be adapted to the design of heterogeneous objects. Activities of two groups are based on this approach—the tetrahedral mesh-based modeling [4] and quadrilateral element model [5]. In the first, a traditional tetrahedral mesh structure is used. Each tetrahedron, in turn, references four nodes. Each node maintains information about its position in space as well as an associated composition. The shape and composition over each tetrahedron is evaluated as a linear interpolation of the positions and compositions of its nodes. The second approach is based on four-node iso-parametric quadrilateral elements generated over the solid or a feasible region. The material composition within each element is represented by interpolating nodal values with isoparametric shape functions for the four-node quadrilateral element. Adaptive meshing of the domain corresponding to material gradation would be useful for reducing the approximation of material composition.

Voxel-based methods

Spatial occupancy enumeration can also be used as a basis for modeling heterogeneous solids. This is a special case of cell decomposition where cells are cubical in shape and located in a fixed spatial grid. Similar to the tetrahedral model, the shape and material composition of a cube can be formulated in terms of tensor products [6]. Control points and control compositions are formulated using polynomial basis functions such as monomial, Hermite, Bernstein or B-spline. A NURBS-based voxel model is proposed by [7]. Their approach is a combination of voxel-based model and NURBS model since the object is represented by a set of voxels with NURBS representation of surface boundaries.

Generalized cellular decomposition

In Jackson [4,8] the Cell-Tuple-Graph data structure has been proposed as the underlying relational database for capturing the adjacency information. In this approach, the topological entities in the model are considered as cells of the corresponding dimension. Therefore, vertices, edges, faces, and regions can be treated in a similar fashion. The Cell-Tuple-Graph database maintains the adjacency information between the cells. Geometry and material information associated with each cell define the shape and composition of the entire model in a fashion analogous to the B-rep methods.

Constructive Methods

A constructive method for synthesis of heterogeneous objects has been proposed in [9] and implementation described in [10]. It expands on the r_m-object model for representing heterogeneous objects proposed in [3]. A set of modeling operations and functions (e.g. union, difference, intersection, partition, etc.) are defined on r_m-sets for use by the designer. In addition to geometry creation by combining simple primitive shapes, material composition functions can be specified for each in several ways: (a) geometry-independent material functions, where users can choose an appropriate coordinate type (Cartesian, cylindrical or spherical) and specify composition functions; (b) geometry-dependent, in-

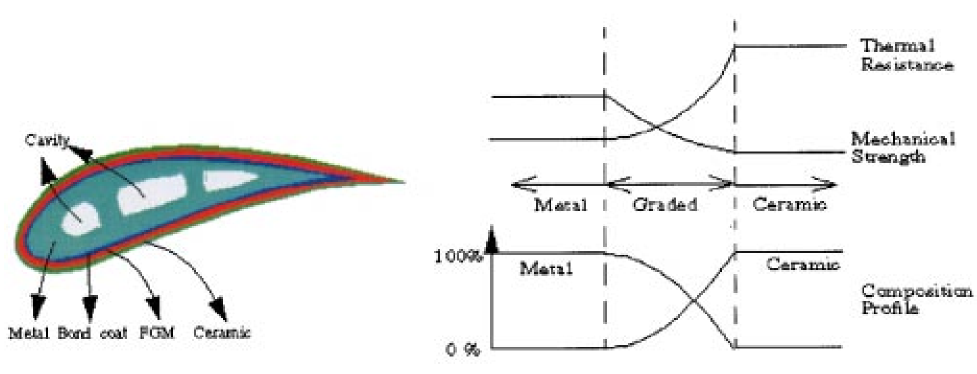

Fig. 1 Use of functionally gradient material in turbine blade [Kumar 99]

Fig. 2 Image data of a bone

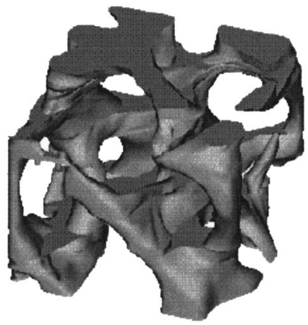

Fig. 3 Converted solid model

cluding the distance-based, sweeping and blending methods for defining material composition; (c) context-specific methods for material definition.

The final object geometry has an associated constructive material composition (CMC) data-structure. The CMC is a binary tree representing the r_m-objects below the root level and retains their material functions, the weight factor for the intersect region, specified boolean operation and the new resultant geometry. This framework is helpful for design changes that might involve geometry and/or material. In the implemented modeler [10] the synthesis process is enabled by the Graphic User Interface. The material distribution functions are input directly by the user or selected from a library. Examples of objects created in the modeler are shown in Fig. 4. Slicing such heterogeneous objects results in geometry and material distribution information for each slice [11].

Heterogeneous Objects from 3D images

Finally, we remark on the inverse problem. In the previous sections we considered the situation where a designer constructs a heterogeneous solid model using a CAD system. The reverse process involves the conversion of image data (Fig. 2) into solid models (Fig. 3). Such data can come from a variety of sources including CT scans, MRI data and automated design output such as in Homogenization Design [12]. It is important and arises in a variety of applications in the medical and engineering domains. In addition to reconstructing the outer geometry for which several methods exist (see [13] for an overview) the challenge here is to capture the material distribution in the interior. Transfinite interpolation methods reported in [14] are promising in this regard.

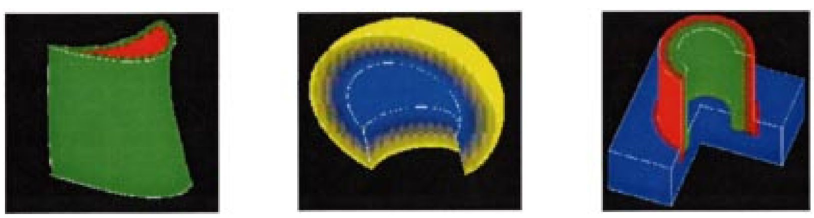

Fig. 4 Some of the examples modeled through HSM

Table 1 LM Process and Characteristics

Process	Build Size	Accuracy	Materials	Heterogeneous Objects
Lithography	up to 500x500x580 mm	±0.05 mm + 0.0015 mm/mm	Photo-polymers	Theoretically capable, but still research topic
Laser Fusion	380x330x460 mm	±0.1 mm	Plastics (PC, nylon, polyamide) and Steel	Under development
Laminated Object Manufacturing	up to 810x560x500 mm	±0.5 mm	Paper, plastic sheet, some ceramics	No
Extrusion	up to 600x500x600 mm	±0.13 mm + 0.0015 mm/mm	ABS, Elastomer, Wax	No
Ink-Jet Printing:	Z Corporation 200x250x200 mm	±0.5 mm	Starch, Plaster, various infiltrants	Under development
	Extrude Hone 305x305x250 mm	±0.13 mm	Stainless Steels with Bronze	No
Shape Deposition Manufacturing		Material and size dependent	Various polymers, ceramics, and metals	Yes
Direct Metal Deposition	900x450x450 mm	500 microns	Any metal	Yes

3 LM Systems

The following section summarizes functionality of several layered manufacturing technologies. No attempt is made to provide an exhaustive overview of existing methods. Those described below include the most widely used systems in industry [15,16]. The methods that can be used for heterogeneous object fabrication are mentioned in Table I.

Photolithography (resin-based) LM systems build shapes using light to selectively solidify photocurable resins. There are two basic approaches: laser photolithography and photomasking. The laser photolithography approach depicted in Fig. 5 is currently the most popular used SFF technology for rapid prototyping in industry.

Laser photolithography creates acrylic or epoxy parts directly from a vat of liquid photocurable polymer by selectively solidifying the polymer with a scanning laser beam. Parts are built-up on an elevator platform which incrementally lowers the part into the vat by the distance of the layer thickness. To build each layer, a laser beam is guided across the surface (by servo-controlled galvanometer mirrors, for example) drawing a cross-sectional pattern in the *x-y* plane to form a solid section. The platform is then lowered into the vat and the next layer is drawn and adhered to the previous layer. These steps are repeated, layer-by-layer, until the complete part is built up.

With laser photolithography, features with gradually changing overhangs can be built up without support structures. Large overhanging features, however, require supports since the initial thin layers which form them can warp or break off as the part moves down into the liquid. The supports are typically built up as thin wall sections which can easily be broken away from the part upon completion. Photolithography has been commercialized by several companies, notably 3D Systems, with their stereolithography line of machines (http://www.3dsystems.com).

In contrast to ''drawing'' out each cross-section with laser photolithography, it is possible to image an entire cross-section in a single operation using photomasks as depicted in Fig. 6. Each cross-section may be imaged onto an erasable mask plate produced by charging the plate via an ionographic process and then developing the image with an electrostatic toner (e.g., like the Xerography process). The mask is then positioned over a uniform layer of liquid photopolymer and an intense pulse of ultra-violet light is passed through it to selectively cure the material. Uncured photopolymer is removed from the layer and replaced with a low melting point, water-soluble wax which serves as the sacrificial support. After the wax has cooled, the layer can be milled to produce a flat surface. The Solid Ground Curing technology, from Cubital Ltd., is the best known commercial example of this method (http://www.cubital.com).

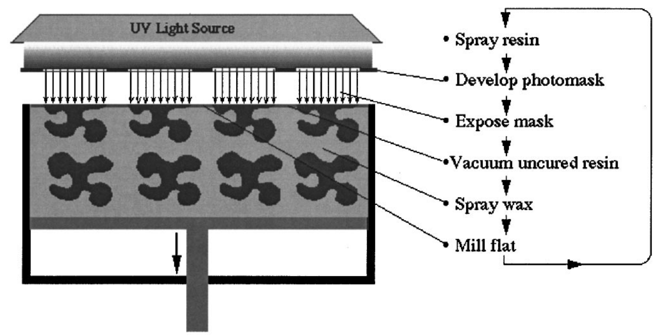

Fig. 6 Photomasking

In **laser fusion** systems, high powered lasers selectively fuse powdered material to build up shapes. The ''selective laser sintering'' approach, depicted in Fig. 7, was originally developed at The University of Texas at Austin, now available commercially in the U.S. through DTM Corp. (http://www.dtm-corp.com). In this system a layer of powdered material is spread out and leveled over the top surface of the growing structure. A CO_2 laser then selectively scans the layer to fuse those areas defined by the geometry of the cross-section; the laser energy also fuses subsequent layers together. The unfused material remains in place as the support structure. After each layer is deposited, an elevator platform lowers the part by the thickness of the layer and the next layer of powder is deposited. Several types of materials are available including plastics, waxes, and low melting metal alloys, as well as polymer coated metals and ceramics for making ''green'' preforms.

Laminated Object Manufacturing (LOM) is a lamination method which builds shapes with layers of paper or plastic (Fig. 8). The laminates, which have a thermally activated adhesive, are glued to the previous layer with a heated roller. A laser cuts the outline of the part cross-section for each layer. The laser then scribes the remaining material in each layer into a cross-hatch pattern of small squares (see Fig. 8), and as the process repeats, the crosshatches build up into tiles of support structure. The cross-hatching facilitates removal of this tiled structure when the part is completed. LOM builds up large parts relatively

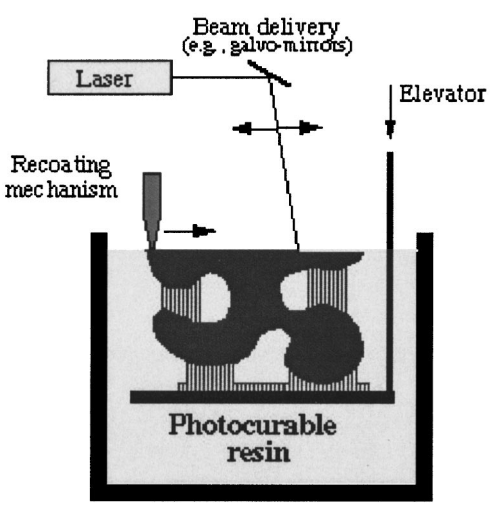

Fig. 5 Laser photolithography

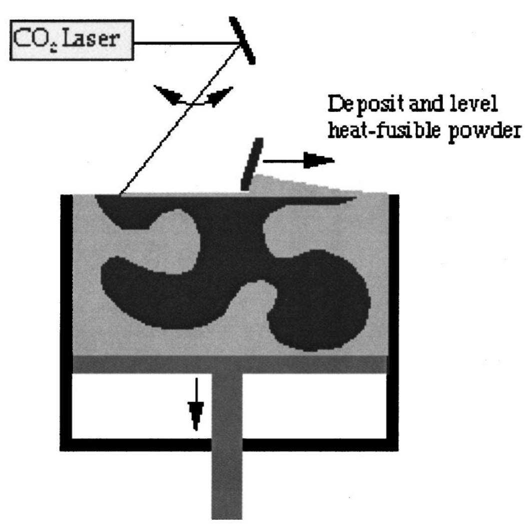

Fig. 7 Laser fusion

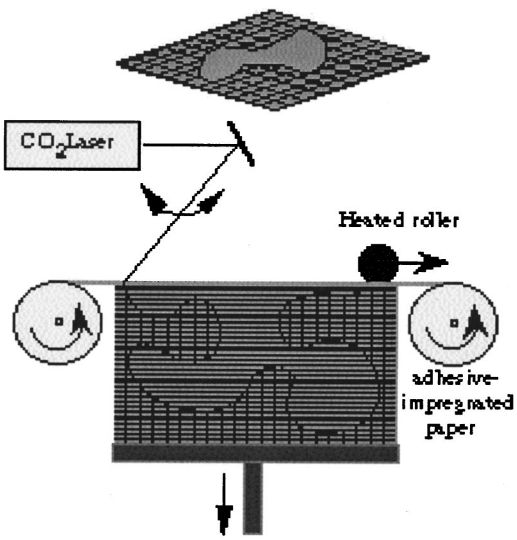

Fig. 8 Lamination systems

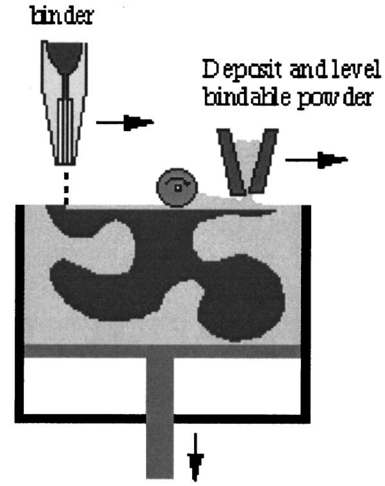

Fig. 10 Ink-Jet printing systems

rapidly because only contours are scanned. In the U.S., LOM systems are available commercially through Helisys, Inc. (http://www.helisys.com).

In lamination systems, internal cavities are hard to form since it is difficult to remove the sacrificial material from internal regions. To address this issue, Case Western Reserve University and CAM_LEM, Inc (USA) are developing a lamination system using green tape castings with a separate supporting material fugitive tape. Each section is individually cut with a laser and then stacked in-place. The fugitive tape is then burned out during the final firing and sintering process.

Extruding freeform shapes (Fig. 9) is practiced by a method called Fused Deposition Modeling (FDM), commercialized by Stratasys, Inc. (http://www.stratasys.com). In this technique a continuous filament of a thermoplastic polymer or wax is deposited through a heated nozzle that moves on a *x-y* table. The material is heated to slightly above its flow point so that it solidifies relatively quickly after it exits the nozzle. Therefore, it is possible to form short overhanging features without the need for explicit support. In general, however, explicit supports are needed which are drawn out as thin wall sections.

Several SFF processes have taken advantage of **ink-jet printing** technology to print layers of structures. The Three-Dimensional Printing (3DP) process, depicted in Fig. 10 was developed at M.I.T. as a method to form ''green'' preforms for powdered metallurgy applications. Powder (e.g., alumina) is dispensed from a hopper above the bin, and a roller is used to spread and level the powder. An ink-jet printing head scans the powder surface and selectively injects a binder (e.g., colloidal silica) into the powder. The binder joins the powder together into those areas defined by the geometry of the cross-section. The unbound powder becomes the support material. When the shape is completely built up, the ''green'' structure is fired, and then the part is removed from the unbound powder. 3DP of metal powders, such as stainless steel bound with a polymeric binder, is also being explored; subsequent infiltration of the matrix is then required for densification. Ink-jet printing machines are available commercially through Z Corp. (http://www.zcorp.com) and Extrude-Hone (http://www.extrudehone.com).

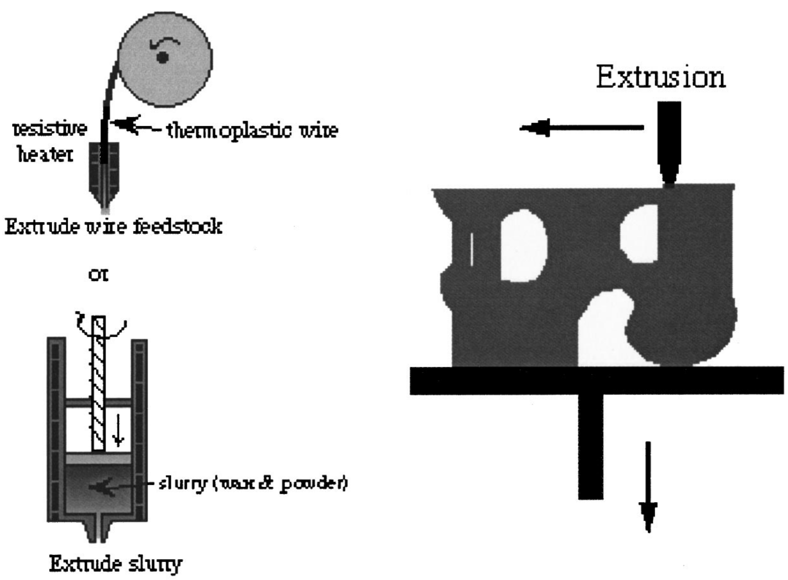

Fig. 9 Extruding freeform shapes

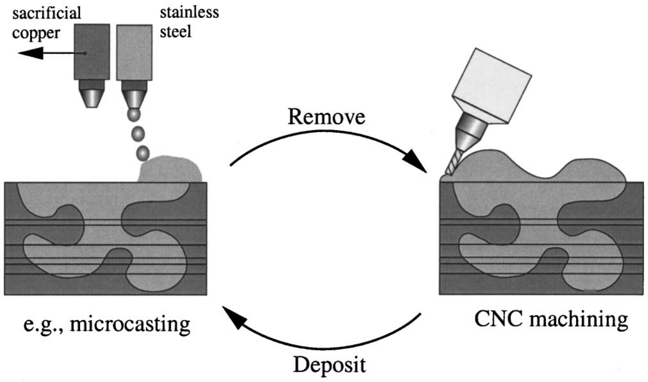

Fig. 11 Shape deposition manufacturing

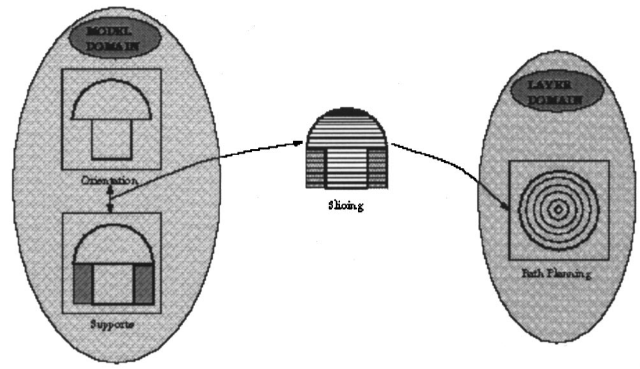

Fig. 12 LM process planning tasks in model and layer domains

There are efforts to investigate combining the benefits of material additive processes (i.e., simplifies planning) with the benefits of material removal processes (i.e., for accuracy and surface finish). Carnegie Mellon and Stanford universities are developing an addition/removal process, **Shape Deposition Manufacturing** (SDM), which incorporates support structures [16]. In SDM, a CAD model is first sliced into 3D layered structures. Layers segments are then deposited as near-net shapes and then machined to net-shape before additional material is deposited (Fig. 11). The sequence for depositing and shaping the primary and support materials is dependent upon the local geometry; the idea is to decompose shapes into layer segments such that undercut features need not be machined, but are formed by previously shaped segments. SDM can use alternative deposition sources, such as microcasting, which deposits discrete, super-heated molten metal droplets in order to build up fully dense, metallurgically bonded structures. For example, stainless-steel is deposited as the primary material and copper as the sacrificial material. Other types of deposition processes which are being investigated include laser welding, gelcasting, UV curable systems, and 2-part epoxy mixtures. Laser−cladding process can make heterogeneous parts and is being commercialized [80].

In Table 1, we summarize the capabilities of these technologies with respect to build size, materials, accuracy, and capability to build heterogeneous objects.

4 Process Planning for LM Fabrication

As in conventional manufacturing, an essential task in layered manufacturing is the planning of the fabrication, commonly referred to as process planning. Process planning tasks for layered manufacturing include orientation determination, support structure determination, slicing and deposition path planning. As shown in Fig. 12, orientation and supports are tasks essentially in the 3D model domain, while path planning is a layer-domain task. These layers are obtained by slicing, which can be thought of as a mapping from the (3D) model domain to the (2D) layer domain.

The existing literature can be divided into two categories: algorithmic and decision-support. The first refers to geometric methods that operate on the CAD model. A significant amount of work has been done in this area and a survey can be found in [2]. The decision support approaches seek to quantify trade-offs among competing goals during process planning. Techniques from multiobjective optimization and heuristics are used to quantitatively relate process variables to the objectives. In the remainder of this section, we first describe the algorithmic methods for process planning tasks and then consider decision-support methods. As in the earlier section, no attempt is made to be exhaustive.

4.1 Orientation Determination. The task in planning for layered manufacturing is the determination of the orientation in which the part will be built (see Fig. 13). Various factors can be considered important during the part orientation selection. The height of the part (in the build direction) for many processes is directly related to total build time. Part orientation impacts the quality of the part surfaces as well as the amount of support structures used during fabrication. Finally, mechanical properties can also be affected by the chosen orientation since the fabricated parts are orthotropic.

Orientation determination involves analysis on the 3D model (either the STL file or the native CAD model) and several approaches have been reported. The task is to determine an orientation that is optimal with respect to some user defined criteria e.g., reduce support structures [17,18], minimize trapped volume [19], improve part quality and engineering properties [18–21], etc. If all factors need to be considered concurrently, multi-criteria optimization can been used [22,23].

4.2 Support Structure Determination. When a part with overhanging features, in a given orientation, is to be built

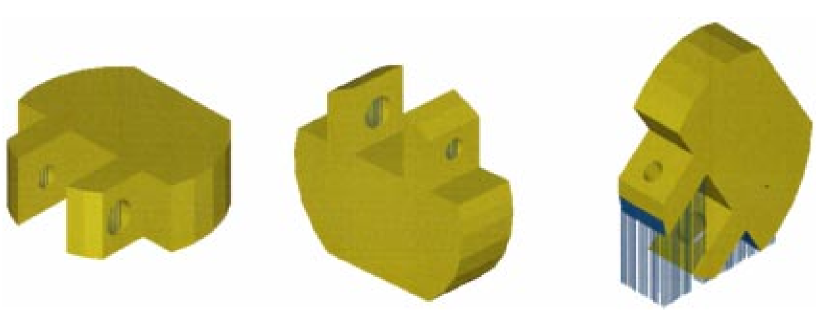

Fig. 13 Determining orientation and support structures for layered manufacturing

Fig. 14 Adaptive slicing of heterogeneous objects

by depositing material layer by layer, it is necessary to determine *apriori* which surfaces need to be supported from below (see Fig. 13). Once this is known, the support structure has to be fabricated along with the part and removed as a post processing operation. In certain LM methods such as in laser fusion, ink-jet printing and lamination systems, the supports are intrinsic (i.e., provided by the powder-bed or paper) and not necessary as an extra planning step.

Supports can be internal or external. External supports are needed to support overhanging features, while internal supports are necessary for top surfaces of hollow parts. Supports can be generated from either the STL file facets [24–26], the original CAD model [17] or by using slice data [26–28]. STL models provide an easy way (based on facet normals) to determine facets that require external support. When using a 3D CAD model, a gaussian map of the surfaces indicates the regions that need support. However, computing the Gaussian map for freeform surfaces is a difficult problem. A method for selective thickening of walls of a hollow object to eliminate the need for internal support has been explored [29].

4.3 Slicing. Slicing is a fundamental task in layered manufacturing process planning and is required for all LM processes. In this step the 3D model (or the associated STL file) is intersected with a horizontal plane to determine the planar contour inside which the material is to be deposited. The output from the slicing procedure is the layer thickness values of the individual slices and the contour profile for each slice for the manufacture of the part.

Initial approaches for slicing used the STL file [30–32]. Later methods focused on a variety of advancements including adaptive slicing to improve surface quality [33–38], robust intersection methods [39–41] as well as slicing of heterogeneous solids [42] as shown in Fig. 14.

Recent advances in hardware have resulted in layered manufacturing machines that can deposit along multiple directions. These machines can build parts with better surface quality and reduce (or completely eliminate) the need for support structures. A progressive volume decomposition scheme that yields slices along multiple directions (based on user defined criteria) has been reported in [43]. The method iteratively computes the regions (subvolumes) of the part that can be built without any supports for a given build direction (initialized with the *z*-direction). New build directions are chosen for the decomposed volumes by a Gauss map computation. Figure 15 shows an example of the volume decomposition for multi-directional deposition (all volumes except the horizontal cylinder in to be built in direction-1, the initial *z*-direction). The sliced volumes are shown in Fig. 15(c).

4.4 Deposition Path Planning. In layered manufacturing, path planning for material deposition consists of two components—interior and exterior. Exterior paths refer to the material deposited in the neighborhood of the part outer surface and hence directly affect the surface quality. Interior path planning requires determining the trajectory and the associated process parameters for filling the inside of the contour with material. For most processes, there is a preferred geometric pattern (cross hatch, zig-zag, etc.) as in conventional CNC, in which material is deposited inside the layer. The geometrical problem of path layout and spacing is similar to CNC cutter path planning. The difference lies in the process physics whereby the thermal history and material bonding are considered; this remains an area for further research. For rapid prototyping speed is of prime importance and methods have been reported in [28,30,44,45] to optimize the speed for various LM processes. For functional parts, however, part properties and material density/microstructure are possibly of higher priority. Several investigations have been conducted on this topic [36,46–52] relating deposition patterns and process parameters to desired part properties.

Exterior path planning controls the accuracy of the external geometry of the manufactured layer and typically the paths are offsets of the outer contour [53–57]. Model bonding/adhesion characteristics have also been studied [58–60]. Feature-based methods for fabrication have also been reported [61]. A concept of ''feature interaction volume'' is proposed to decompose the object into sub-volumes and reduce the overall staircase effect in the part.

4.5 Decision Support Approaches to Process Planning. Decision support approaches have been investigated that seek to

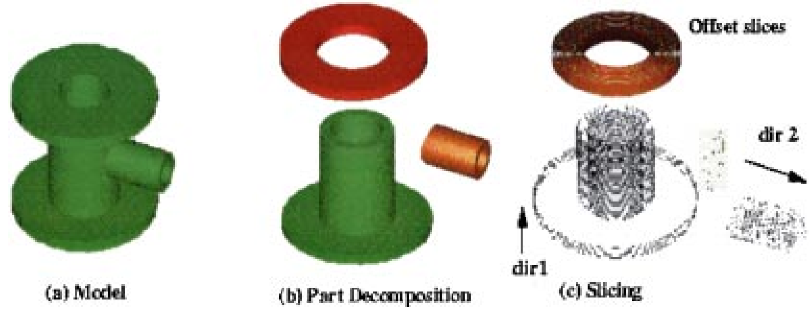

Fig. 15 Multi-direction slicing

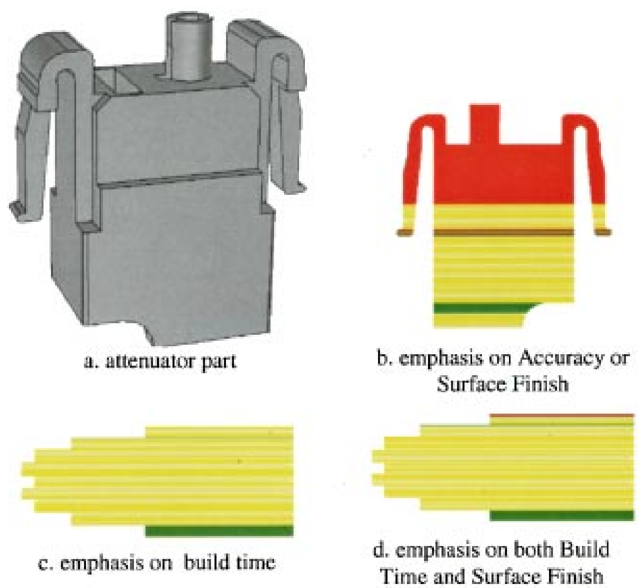

Fig. 16 Attenuator process plans

quantify trade-offs among competing goals during process planning. Given a part to be fabricated via LM, the designer may have different preferences for build time, surface finish, and accuracy, depending upon the purpose of the physical part. For example, people would probably prefer to have concept prototype models built as quickly as possible, even though it may result in a rougher surface and less accuracy than the LM process is capable. These process planning methods were adapted from multiobjective optimization and utilized empirical data [62,63], analytical models, and heuristics [64]. A key idea in the usage of multi-objective optimization is the specification of preferences among the objectives.

A decision support based process planning method for stereolithography was developed that integrated empirical tolerance and surface finish models with an adaptive slicing method [65,66]. This process planning method orients the part, adaptively slices it, and selects values of SLA process variables to best meet build time, accuracy, and surface finish objectives. Different preferences among these objectives will result in different process plans. Hence, the intent of this process planning method is not to develop the optimal process plan for the fabrication of the prototype, but rather, to assist the SLA process planner in quantifying the tradeoffs between the three build goals.

The specific multiobjective optimization formulation utilized for CABSS is the compromise Decision Support Problem (cDSP) [67]. To support the method, a formulation of the process planning problem is presented that is based on a series of three cDSP's for selecting part orientations, slicing schemes, and SLA parameter values, respectively. The optimization method seeks to minimize an aggregate measure of deviation from accuracy, surface finish, and build time targets in each of the cDSP's. The variables to be found during optimization include part orientation, layer thicknesses, and SLA process variables (scan and recoat variables). Mathematical models of constraints and goals are presented for each cDSP. Empirical models are presented for each goal as a function of SLA process variables. Constraints include the effects of support structures and large horizontal planes.

In each cDSP, each surface finish and geometric tolerance (accuracy requirement) is evaluated separately, after which overall composite evaluations measure how well the finish and accuracy goals are being met. By using a set of response surface models [62] that relate four build process variables (hatch and fill overcure, sweep period, and *z*-level wait) with a specific type of geometric tolerance and a surface type, the obtainable accuracy for that tolerance may be predicted. Six types of geometric tolerances were considered: positional, flatness, parallelism, perpendicularity, concentricity, and circularity. A total of thirty-six different response surfaces were developed based on the type of surface, the orientation of that surface, and the type of tolerance. Tolerances can be affected by SLA process variables due to resin shrinkage, residual stresses, warpage, and other process effects [68]. Given the tolerance type, orientation of the tolerance surface, and the values of the layer and recoat parameters, predictions of the achievable accuracy for every geometric tolerance can be made.

CABSS was demonstrated on a fiber optic attenuator housing, shown in Fig. 16a [66]. Several sets of preferences were investigated. Process planning results are shown in Fig. 16b–d, where the darkest shading represents 0.2032 mm layers, the medium shading represents 0.1016 mm layers, and the lightest shading represents 0.0508 mm layers. When the designer preferred accuracy over surface finish and build time, the process plan in Fig. 16b resulted. In this case, the part was built vertically with smaller layers in areas of high curvature and detail. The same result was obtained when surface finish was most preferred. When build time was emphasized, the process plan changes completely to that shown in Fig. 16c. Build time preference would be common for concept models, for example. When both build time and surface finish are emphasized, a process plan results that is a modification of that for build time emphasis—the only change is that smaller layer thicknesses are used near the top of the part. Other combinations of objective preferences gave other intermediate process plans (e.g., Fig. 16d).

5 Data Standards and Interoperability

A major bottleneck confronting users of all CAD/CAM systems is data interoperability. As mentioned earlier, there is growing dissatisfaction with the STL format in the RP industry. Furthermore, it is not suitable for heterogenous object representation, a necessity if LM systems are to be effectively utilized for their fabrication. While extensive research on heterogeneous object representations is underway, the standardization of data formats for layered manufacturing has not received much attention. That is not surprising since even in the conventional (and mature) CAD/CAM industry, problems related to data transfer and compatibility between commercial systems are paramount.

In the U.S., the National Institute of Standards and Technology has taken the lead by organizing several workshops on the topic and initiating preliminary work proposals on RPLM standards in the international STEP meetings [69,70]. STEP (STandard for the Exchange of Product model data) is an international standard (ISO 10303) for the computer representation of product data for various engineering tasks. In industry, there is interest in the standardiza-

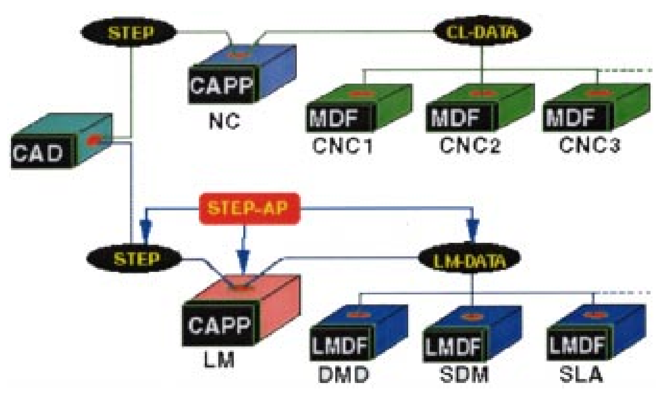

Fig. 17 A STEP based architecture proposed for data interoperability

tion of the slice format for layered manufacturing for which not even a *de facto* standard exists at present. Toward that end, preliminary work has begun [71] focusing on determining the informational requirements for supporting layered manufacturing. A (STEP) Data Planning Model is under development to represent the geometric and material information at the slice level. It is prudent to include heterogeneous objects in the development of standards for the slice format. While existing STEP resources can be used for representing geometry as well as material type and tolerances, new STEP entities will have to be developed in order to support modeling of graded material composition in heterogeneous objects. An EXPRESS representation of a heterogeneous slice is partially shown below. The full model can be found in [71].

```
#1001=COMPONENT(″,#1002,1);
#1002=MATERIAL_SOLID_MODEL_REPRESENTATION(″,1003);
#1003=MATERIAL_SOLID_REPRESENTATION_ITEM(‘‘RMSET1’’,2,#1004,#1005,#1006);
#1004=MANIFOLD_SOLID_BREP(‘RSETGEAR’, . . . );
#1005=MATERIAL_REPRESENTATION_ITEM(‘MAT1’,#1010,#1011,#1023);
#1005=MATERIAL_REPRESENTATION_ITEM(‘MAT2’,#1010,#1024,#1027);
```

Interoperability of data for layered manufacturing has also been considered. In [72] a LMData format is investigated in the context of an architecture for data interoperability (Fig. 17). The intent is for the LMData to be generated by the process planning systems and used by different LM machines after postprocessing. The idea is borrowed from the CNC domain. That is, the LMData has several features that exist in the CNC cutter-location data format. In particular, the LMData describes the deposition head configuration and its movement. A machine definition file (MDEF), as in the CNC domain, contains the LM machine specific commands and parameters and is used to postprocess the LMData into machine specific commands. Two commercial machines, Stratasys FDM and Sanders ModelMaker are considered in [72] to demonstrate the LMData concept.

6 Applications of Layered Manufacturing

In this section, we highlight selected emerging applications of LM using representative examples. We describe the application area, highlight the fundamental attributes of devices and parts that make them challenging or unique, and identify the primary roadblocks to improved solutions to these application areas. Successful development of solutions for these application areas will require adoption and/or improvement of the heterogeneous modeling capabilities outlined in this paper, as well as improvements in design and CAD technologies, process planning, materials, and processing.

To data, the most widely recognized advantage of layered manufacturing methodology is the relative ease of automatically planning and executing the fabrication of complex geometric shapes. However, as we argue in this paper, shapes using selective material deposition/fusion processes will have a second, far-reaching advantage. They enable designers to create heterogeneous structures. A heterogeneous structure might include multi-material regions and/or pre-fabricated devices embedded into the growing shapes, surfaces with micro-geometric textures and internal structures or features. These type of designs would not be practical, perhaps might be impossible to fabricate with conventional techniques. One example of a heterogeneous structure is the injection molding tool depicted in Fig. 18. This tool includes conformally shaped heating/cooling channels, formed using sacrificial material. The interior of the tool is made of copper, for fast and uniform heating/cooling, while the outside shell would be steel for strength. Such examples require the fabrication of shape or material structures 5–7 orders of magnitude smaller than typical part dimensions. This is a challenging materials processing challenge, as well as a heterogeneous modeling challenge.

The shape complexity capability of LM technologies enables the fabrication of complex structures and devices that were heretofore difficult or impossible to construct. Truss structures are one method of achieving complex internal shapes that offer the potential to fine-tune dynamic properties, such as inertia or natural frequency, of devices. Much of the inspiration for internal trusses comes from natural geodesic structures in living organisms. An example usage of truss structures to reinforce a sculpted external shape is shown in Fig. 19 [73]. A tetrahedral truss was used to fill the interior while conforming to the external shape. By modeling the object using 3-parameter solid volumes, it is straightforward to generate such truss structures. This particular model utilized two tri-cubic Bezier volumes with G^1 continuity between them, as shown in Fig. 20. If the diameters of the trusses and the truss density were varied, it is possible to optimize the object shape and structure for improved strength, stiffness, weight, resonant frequency, and other characteristics. These models were fabricated with stereolithography, but could have been built on most LM technologies where parts are self-supporting or where support structures are easily removable. The larger challenges are in designing optimal shapes and structures to satisfy needs, while ensuring manufacturability. For the selected LM technology and material, features cannot become too small, too closely spaced, or require accuracies beyond the technology's capability.

Truss structures can be considered examples of complex shape distribution. Other distributions are also enabled by LM technologies. When material composition is distributed, heterogeneous

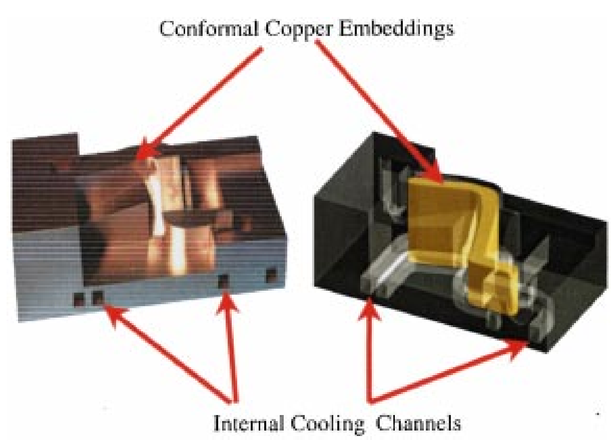

Fig. 18 Tooling for injection molding

Fig. 19 Truss structure model

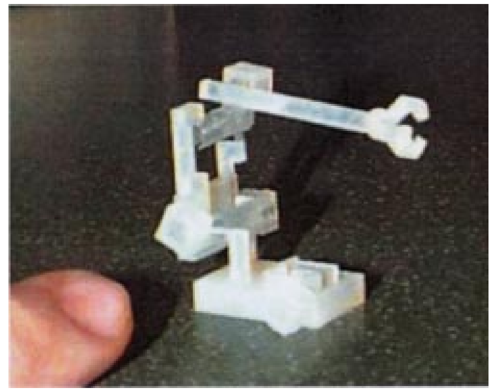

Fig. 21 Robot with split-tube joints

material structures arise. It is possible to distribute mechanical properties, such as compliance, using one material. For example, in stereolithography, it is possible to tune compliance by varying the energy that different points in a part cross-section receive. Realizing the potential of such mechanical property distribution will require improvements in process planning and material processing, and may require extensions of current heterogeneous modeling. Successes enable a wide variety of devices and structures, such as compliant mechanisms and prosthetics.

Combining the shape and material complexity capabilities of LM systems enables a wide variety of new applications. Mechanisms require joints or compliance to produce relative motion. Several researchers have explored the fabrication of kinematic joints and mechanisms in Fused-Deposition Manufacturing [74] and Stereolithography [75]. Others have used inserted components for joints, and have included actuators as well [76,77]. Although kinematic joints are an achievement, greater benefits can be achieved through the use of compliance for small mechanisms. Several variations of revolute joints have been investigated, based on a split-tube design as shown in Fig. 21 [78,73]. By taking advantage of LM's capabilities, these joints can be placed virtually anywhere and at any orientation within a mechanism to yield complex motions. Simple two-joint miniature robot arms have been used to demonstrate the concept, utilizing shape-memory alloy wires as actuators. Improvements in materials are critical to extending the suite of applications outlined here, particularly for production, rather than prototyping, usages.

Device miniaturization offers many advantages and challenges. One example is the fabrication of miniaturized mechanisms. Beyond a certain degree of miniaturization it is no longer cost-effective to manufacture the links and joint elements as single components and assemble them afterwards in an additional operation to form a complete system [73]. Additionally, applications are emerging for devices that integrate sensing, actuation, control,

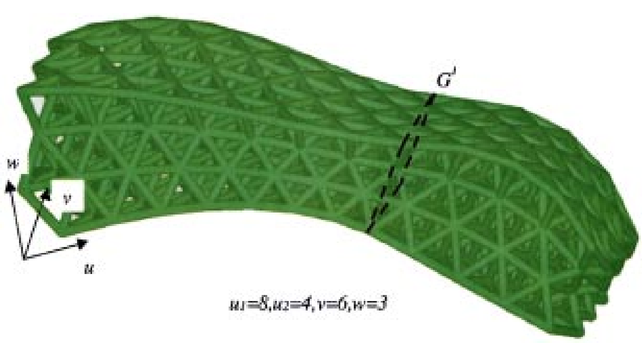

Fig. 20 Truss structure from two tricubic Bezier volumes

and intelligence. Recent research advances have utilized compliant mechanisms as motion amplifiers and transmitters for these applications, often amplifying inputs from piezoelectric actuators [79]. Hence, *in-situ* assembly provides a promising solution. Considerable progress has been made in designing, modeling, process planning, and fabricating devices for *in-situ* assembly using LM technologies [76], however, challenges remain. Designers need tools to help them in designing devices with complex heterogeneous material compositions and embedded components. Furthermore, tools are needed to analyze the functional behavior of such devices, to assess their manufacturability via an increasing spectrum of LM technologies, and to perform processing planning for those technologies.

7 Future Trends and Possibilities

Design Systems

LM technologies provide the potential for placing any material, anywhere in space, and processing it to yield desired properties. Incremental fabrication of material structures, layer by layer, or almost pixel by pixel will further increase the spectrum of development and production tools available at the fingertips of next generation designers.

The challenges in design and CAD technologies are to enable designers to explore new design spaces and to ensure the feasibility of devices that designers generate. New methods of defining and manipulating geometry and material are needed for designing complex devices. Representation and reasoning methods for heterogeneous materials remain a topic for further research, despite the progress that has been made. Feature-based methods must be explored in the heterogeneous domain since designers transitioning from the conventional solid modeling domain will expect such high level tools. Furthermore, modeling and representation of micro and nanostructures is an area that has not been researched but will need to be focused upon. Finally, it does not good to synthesize complex material structures if they are not physically or chemically feasible. After heterogeneous devices are designed, they must be analyzable. Interfaces to CAE tools will have to be established. Computational methods to analyze complex material structures in a physically meaningful manner will be necessary. Data standards for interoperability deserve much more attention in the coming years if the pitfalls of the CNC domain are to be avoided.

LM Systems

New layered manufacturing techniques are being pursued in research laboratories around the world and some are starting to become commercially available. There is considerable research underway in developing new materials for LM systems as well as new machines with better tolerances and speed, multi-axis deposition and wider range of materials.

The synthesis of deposition and material removal techniques is being explored and is likely to provide fabrication power hitherto unachievable. The Shape Deposition Manufacturing process is a good example of this synthesis. For small scale structures, several material deposition processes appear promising, including electrodeposition and Laser Chemical Vapor Deposition (LCVD). These processes have the potential to fabricate complex devices and very complex material structures in size ranges of tens of nanometers to several millimeters. Integration of such wide-scale fabrication capability is a challenge.

Process Planning Systems

As LM design technologies and fabrication techniques improve, it will be incumbent upon the research community to provide tools for their digital linkage. Communicating complete designs electronically has long been practiced in VLSI design and fabrication. In the past, similar attempts in the mechanical domain have failed since manufacturing difficulties related to part-specific tooling and fixturing could not be anticipated. Realistic 3D simulations will significantly help to envision downstream problems. However, decomposing parts into thin subsections and eliminating fixturing requirements all together due to the embedding of parts into sacrificial support structures is also considered a crucial step towards de-coupling design specifications from fabrication processes.

Process planning methods must deal with increasingly complex geometries and materials. Improved and more general 3-D decomposition methods are needed for the increasing range of LM fabrication techniques. Quantitative models that relate process variables to device quality characteristics must be available. This is particularly important when working with complex heterogeneous materials. Such models enable the process planning system to better meet product development objectives, including cost, timeliness, and quality. Reasoning about the fabrication of heterogeneous objects in an integrated material deposition-removal environment is a complex problem, one that will have to be addressed if such fabrication facilities are to be fully utilized.

Closure

We anticipate that design and manufacturing will be conducted by globally distributed, multi-corporate teams that reconfigure rapidly to generate and fabricate new products. Limitations regarding functional decoupling will frequently determine the degree to which design tasks can be geographically distributed.

Once a design is completed, effective communication for prototyping or manufacture over the internet will be crucial. High speed and bandwidth connections are likely to be available. 'Over night' prototypes can significantly influence the design direction that a team intends to pursue. We anticipate an even larger impact on product development, once functional prototypes can be delivered within days rather than weeks or months which are common in today's development environments.

Increasingly, research and development efforts are targeting production, rather than prototyping, as a realistic objective. Production applications will likely be in small volume areas that take advantage of LM's unique capabilities, such as multiple and graded materials and customized geometries. These may include one-off medical devices, customized consumer electronics, high temperature structural applications (turbine blade, combustors), small electro-mechanical devices, etc. The societal impact of this new technology is likely to come from the medical devices (implants and tissues) and educational enhancements (3D printing artifacts off-the-internet can significantly enhance elementary/high school experiences).

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