The Globalization of Manufacturing in the Digital Communications Era of the 21st Century: Innovation, Agility and the Virtual Enterprise

Proceedings of the Tenth International IFIP WG5.2/5.3 Conference PROLAMAT 98

#45

Towards STEP-based data transfer in layered manufacturing

D. Dutta, V. Kumar,
University of Michigan, Ann Arbor, Michigan, USA
Tel: +1 (313) 936-3567, Fax: +1 (313) 747-3170
E-mail: [dutta/vinodk]@engin.umich.edu

M.J. Pratt and R.D. Sriram
National Institute of Standards and Technology
Gaithersburg, MD, USA
Tel:+1 (301) 975-3951, Fax: +1 (301) 975-4482
E-mail: [pratt/sriram]@cme.nist.gov

Abstract

This paper discusses the informational requirements of layered manufacturing (LM). The most common industrial use of LM today is for rapid prototyping, but we take a wider view of it as a flexible fabrication technology. Its use in building functional metallic parts under computer control has already been demonstrated in the research context. Commercial LM machines for building production parts are in prospect. We report on a study of current and proposed data formats for communication between the various stages of the LM process. They are compared, and attention is given to the issue of their extensibility to meet future needs. In this last respect, particular emphasis is given to materials-related and other non-geometric information needed for fabricating multi-material objects and objects with graded material properties. One conclusion is that the best way forward is the creation of a new Application Protocol for the international standard ISO 10303, specifically to handle layered manufacturing information.

Keywords

Layered manufacturing, rapid prototyping, solid freeform fabrication, standards, STEP, ISO 10303, data exchange, information technology

1 INTRODUCTION

Layered manufacturing (LM), also known as solid freeform fabrication (SFF) or rapid prototyping (RP), is an additive manufacturing process in which objects are constructed layer by layer, usually by a series of parallel planar laminae approximating their cross-sectional shape. Many LM processes currently exist, using different materials and layering methods (Burns 1992). The classes of methods are

- Photopolymer solidification (e.g., stereolithography, solid ground curing), in which a liquid resin is hardened layer by layer with a laser or ultraviolet lamp.
- Material deposition (e.g., fused deposition modelling), in which drops or filaments of molten plastic or wax are deposited to construct each layer.
- Powder solidification (e.g., selective laser sintering, three-dimensional printing), in which powdered material layers are solidified by adding a binder or by sintering with a laser. Parts can be built from ceramics, nylon, polycarbonate, wax or metal composites.
- Lamination (laminated object manufacturing and solid ground curing). The first of these methods uses lasers to cut layers from sheets of paper, cardboard, foil or plastic, stacks them and bonds them together. The second uses a cut mask to expose regions of resin to be solidified by an ultraviolet lamp.
- Weld-based approaches. Currently still at the research stage, these use welding and cladding techniques to build metal parts (Mazumder et al 1996).

LM processes were initially used for rapid prototyping to help the designer verify part geometry, but are now increasingly used to make molds for castings. They also have significant potential for the manufacture of one-off and small batch production parts. LM processes can be used to build very complex artifacts, having intricate geometry, internal voids or multiple assembled components, without any special tooling. However, because LM objects are built layer by layer, their surfaces often have a staircase appearance. They may also have inferior material properties when compared with objects manufactured by other means. Poor surface quality is sometimes overcome by performing finishing operations, such as grinding or polishing, after an object is built.

A major emerging use of LM is the manufacture of heterogeneous objects. These may be made of more than one material, have varying microstructure, have graded material properties, or contain embedded devices. LM, unlike conventional manufacturing processes, in principle permits complete 3D control over material properties. New design methods such as homogenization for structural topology design (Bendsoe et al 1993) specify varying material properties throughout the volume of the designed object; LM provides a means for producing such artifacts.

1.1 Process planning for LM

Each LM process uses specialized equipment. However, in most of them, a tool is moved under computer control to add material to the part. Process planning for

LM determines the tool paths and process parameter settings for the manufacture of a particular object from a given material by a particular LM process (Marsan and Dutta 1997). The common steps required are:

- Choice of part orientation during the build process. This affects the time taken to build the part, aspects of its material properties, surface quality and the need for support structures.
- Support structure design. Supports are needed with certain LM processes, when the object being built has overhangs or internal voids, in which case part of any layer may have no underlying layer to build it on. Supports are usually built together with the part, and are later detached and discarded.
- Slicing the part into 2D contours. With the orientation chosen and the support requirements established, this gives the shape of the layers to be laid down.
- Path planning within contours. This affects both processing time and material properties in the finished artefact.

These tasks are common to most forms of LM. In Section 2 their informational needs are analyzed to establish the possibility of standardizing LM data transfer.

Other planning tasks in LM include process parameter selection, a very method-specific task, less suitable for a standard approach. Further, most LM techniques require post-processing of the built part (e.g., finishing operations to improve surface quality, or curing following stereolithography to remove unsolidified material). Such process-specific activities are not currently automated and involve no electronic data transfer, so are not further considered here.

1.2 Requirement for data transfer protocols

The designer and manufacturer of an LM object are often different people, working in separate organizations. Hence it must be possible to transfer design data to the manufacturer so that process planning can be performed and the part built. Additionally, the input to the path planning phase requires slice data in all cases. Thus there is a need for one or more data transfer protocols to ensure the efficient transfer of data, without ambiguity or loss of information. Since a single organization may manufacture parts using several different LM technologies, a unified set of data transfer protocols is desirable for the entire class of LM processes.

2 DATA REQUIREMENTS FOR LM PROCESS PLANNING

The informational requirements of the various common stages of LM process planning listed earlier are as follows:

- Choice of part orientation during the build process. This requires a knowledge of the three-dimensional part shape to enable minimization of support requirements and optimization of surface quality (freedom or otherwise from staircase effects in functionally important regions). Further, the structural properties of the part are affected by the orientation of the layers within it, since the LM process gives rise to material inhomogeneity. The output of this task is simply a transformation to orient the part model appropriately for some weighted combination of optimality criteria.

- Support structure design. This again requires information regarding the 3D part shape. Support regions for any orientation can be found by comparing slice shapes with the "shadows" cast by the object on the slicing planes.
- Part slicing. Given the oriented part model and its support volumes, this is a purely geometrical process. Its output is a set of 2D slice contours.
- Path planning within each slice. The input to this stage is the shape of the slice, and details of the path planning strategy if any choice is available. For lamination methods as described earlier, it is only necessary for the path to traverse the boundary of the slice. For other methods, an area fill strategy must be used, with or without a boundary traversal. The path planning output is a geometric representation of the generated paths. Criteria for path planning may include minimization of build time and requirements on part stiffness and strength – different scan strategies give different material properties.

Another effect of path choice concerns post-manufacture distortion; in some processes, molten or unsolidified material shrinks as it hardens on top of a previously solidified layer. Because the layer below is already hardened, this generates residual stresses and consequent distortion of the part. A suitable choice of tool paths can minimize this effect. Finally, the structural properties of the part are affected by tool paths because the bonding strength between newly deposited material and previously hardened material depends on tool path spacing and the time interval between their traversal by the tool.

2.1 Geometry-related process planning input

The most basic input to a LM process planning system is a description of the shape of the object to be manufactured. Additionally, tolerance information, surface finish, material data, etc., should ideally be used in performing certain process planning tasks. However, most LM process planning systems currently accept only shape information. Several types of shape representation exist:

- Computer aided design (CAD) models are usually surface models or boundary representation (Brep) solid models (Hoffmann 1989). Both are composed of bounded regions of different surfaces forming a larger composite surface. The solid model usually has three distinguishing properties. First, it defines a *closed* object boundary. Second, topological information is used to specify how the surface regions are connected. Third, and most importantly, solid modelling systems provide automatic validation of shape models. Both types of model may use planar and/or curved surfaces. A specialized type of model uses only planar surfaces, representing the composite surface by a mesh of polygonal facets. If only triangular facets occur, the model is consistent with STL, the most commonly used input format for LM process planning systems. Most CAD systems can compute and output such approximate triangulated boundary representations (e.g. STL files), the chord-height deviation between the actual object surface and the triangular facets being controlled according to the user's requirements on approximation accuracy.

- Other shape representations (including "point clouds", image data generated by computer tomography or magnetic resonance imaging) usually require postprocessing into faceted surface representations for input to LM.

In addition to the overall shape of the artifact to be built, two-dimensional representations of the individual slices are also needed as input for the path planning stage. At present, path planning is usually performed in the same system that calculates the slice shapes, so that there is no need for a standardized representation for the slice data. However, as will be shown, there is motivation for performing the slicing and path planning functions in separate systems. In this case there is a requirement for a standardized slice format.

2.2 Non-geometric process planning input

Apart from shape models, two other types of input data are desirable. These are related to shape tolerances and materials. Neither can be handled by currently used data input formats, but both are clearly required for the future, particularly when LM reaches the status of a regular production technology.

Tolerance information

For future purposes, tolerance information may be taken to cover the standard forms of engineering tolerances as associated with various elements of the model. These include tolerances of size, location and form, together with associated datum elements where appropriate. However, a more important form of tolerance information in the present state of the art is concerned with surface finish. In the LM context this relates particularly to the "staircase" effect resulting from building the object as a set of layers with (nominally) perpendicular edge faces.

Good surface quality on an LM part requires minimization of the staircase effect. Most LM systems deposit material in only one direction, and reduction can in principle be achieved by slicing the part at smaller intervals. This has little effect on the accuracy of vertical or near-vertical faces, but may significantly improve the surface quality elsewhere. More generally, the slice thickness may be varied non-uniformly during the build process to get the best results, an approach known as adaptive slicing. This is well suited for parts with

- horizontal faces – which can then be built at their nominal design height rather than at an approximate height determined by a uniform slicing strategy;
- thin horizontal protrusions – which may lie between uniform slicing levels and hence be missed entirely.

Adaptive slicing requires a shape model of the part, plus information on the desired minimum cusp height on the manufactured part. This height may vary from region to region of the part, depending on its functional requirements. Particular LM machines usually have a maximum and a minimum allowable slice thickness, which may vary from one material to another. Thus, both method-specific and material-specific constraints may have to be imposed on the calculations. When adaptive slicing is not available, it is still necessary to determine the uniform slice thickness that best meets the surface finish criteria required on the part.

In general, scan strategies that include a boundary traversal in addition to a fill pattern give a better finish, because they avoid the occurrence of the secondary staircasing in the slice contours that may arise (for example) from simple zigzag scanning. This effect results from the finite width of the LM tool. Other scan strategies in use include paths that are offset inwards from the slice contour by multiples of the tool radius. This has advantages in the manufacture of hollow structures, because it requires many fewer reversals of tool direction than a conventional raster fill strategy. There are consequent savings in the time taken for tool repositioning (during which material deposition or solidification is not taking place) and in acceleration and deceleration for direction changes.

Material information

Material information, not available in any LM data transfer format in current use, will be needed in the future for a variety of purposes:

- Knowledge of material properties and process characteristics is required for slicing calculations because the minimum and maximum allowed layer thickness varies for each process and often for each material.
- If the object to be built is composed of discrete regions with different material properties, boundary and slice models of those regions are also needed.

The technology is already available for *selective deposition* of materials on a given layer. This allows the manufacture of multi-material (or, as a special case, multi-color) parts. Furthermore, there is current research on the deposition of materials with variable density, for use in the manufacture of optimal product shapes having non-homogenous material distributions. One missing element in this product design and layered manufacturing environment is the capability to create a 3D CAD model that can represent a product's solid interior, in terms of material micro-structure or continuously variable material properties. The authors believe that no standard representational scheme provides such a capability. Research is needed to fill this technology gap, which may otherwise raise a barrier to important new developments in LM technology.

3 EXISTING AND PROPOSED LM DATA TRANSFER PROTOCOLS

We now turn to the topic of information transfer into a LM process planning system, which must be efficient in terms of data volume and free from errors or ambiguity. Data transfer is an increasingly critical issue as accuracy requirements in LM become more stringent (Dolenc and Mäkelä 1995). In what follows we discuss some existing and proposed formats for LM data transfer.

3.1 The STL format

Although it was developed specifically for the stereolithography process, STL has become the *de facto* industry standard for the transfer of data to LM process planning systems. It represents a 3D shape in terms of a triangulated approximation of its boundary. Each planar facet is defined in terms of its vertices and a normal direction pointing outwards from the interior of the object (Burns 1992, Bøhn 1993). The ordering of the vertex data is significant, because it provides a second indication of the direction of the normal vector of the facet.

The triangulated format used by STL has certain advantages:

- It is conceptually simple, and is easy to generate from a wide range of other forms of shape representation, using robust and reliable algorithms. The approximation accuracy is easy to control, and few types of degeneracy arise.
- The algorithm for slicing a triangulated boundary representation is also simple (but not necessarily efficient) as it involves processing a list of triangles, and only plane-plane intersections need be computed.

STL also has significant disadvantages, however:

- Curved surfaces are approximated in terms of planar triangular facets. There is a clear tradeoff between number of facets and approximation accuracy.
- STL is highly redundant. The facet normal information is unnecessary; it can be calculated from the vertex data. Further, each vertex is multiply specified, once for each facet it appears in. It would be more efficient to specify a vertex once only and to point to it from each owning facet. This would also avoid mismatched physical locations of vertices that are logically identical.
- The numerical data are represented by single-precision real numbers. Also, STL requires the entire object to be located in the positive octant, i.e., all coordinates must have positive values. Taken together, these characteristics can exacerbate the absolute value of truncation errors, because coordinate values are larger than they would need to be if negative coordinate values were allowed.
- Processing of STL files is inefficient because they contain no information concerning connectivity between facets. For efficient slicing, the topology or connectivity of the model must first be determined so that the slicing software is aware of inter-facet adjacencies and can hence "march" from one face to the next in a logical manner.
- It is easy for facet normal directions to be computed with reversed senses during the generation of the STL data, in which case they are inconsistent with the orientation of other neighbouring facets. Also, explicitly specified facet normals may be inconsistent with the normals computed from facet vertices. Both problems occur frequently in practice, causing confusion during the generation of slice data.

Several types of problems can also arise during the generation of an STL file:

- Gaps: individual triangular surface facets are sometimes erroneously omitted from the STL facet list. Further, inaccuracies in the calculation of vertices sometimes lead to mismatches in triangle edges, giving rise to narrow gaps in the composite surface. In either case, when a faceted model with gaps is sliced, the slices contain non-closed contours, and computed scan path vectors extend beyond the boundary of the desired object so that the part is built with unwanted protrusions. Poor modelling practice by CAD system operators is often responsible for this type of problem.

- Internal walls and structures: these may be caused by poor user practice in constructing a surface model, or be generated inadvertently in the correction of gaps in a faceted model. They can cause discontinuities in the solidification of the material as the object is built.
- Degenerate facets: facets may be degenerate, having zero area and therefore no defined surface normal. There are two kinds of facet degeneracy:

  Topological Degeneracy: Two or more vertices of a facet coincide. This does not affect the geometry or connectivity of remaining facets and the degenerate facet can therefore be discarded.

  Geometric Degeneracy: All the vertices of a facet are distinct, but they are collinear. Such a facet has no normal, but it contains implicit topological information on the connectivity of neighbouring facets and may not be discarded.
- Incorrect intersections: facets may intersect incorrectly (i.e., other than at their edges), giving rise to interpenetrations between them.

Much time and effort is currently spent in correcting faulty STL files and generating topological information from the facet lists in STL. It has been estimated that about 90% of STL files generated from surface models have flaws, and about 10% of those generated from solid models (Miller 1994).

3.2 Alternatives to STL

Despite its proprietary origins, STL now serves as a neutral (system-independent) format for the transfer of LM shape models. Nevertheless, its drawbacks as described above, together with the more stringent requirements imposed by developments in LM technology, motivate the development of alternative LM data transfer formats. Several suggestions have been made for such formats (Kumar and Dutta 1997), but none has met with enthusiasm from the LM community. The situation has recently been changed, as will be shown, by the availability of a new standard for shape representation with strong potential for application in LM.

3.3 STEP – STandard for the Exchange of Product model data

STEP, or more formally ISO 10303 (ISO 1994, Owen 1993), is an international standard for the exchange of product life-cycle data, covering design, analysis, manufacture, maintenance and disposal. STEP has been built on experience gained with earlier computer graphics and product data transfer standards, and its scope is continually expanding to cover new classes of products and new phases of the product life-cycle. At present STEP is most highly developed in the area of mechanical artifacts, but it is intended eventually to cover a wide range of manufactured products, from microelectronics to cars and ships.

STEP has a three-level architecture, with conceptual, application and physical layers. The conceptual layer contains Integrated Resources (IRs), which are sets of related data entities that can be specialized to describe different domains of interest. For example, one IR (ISO 10303-42 – Geometrical and topological representation) contains entities for describing the geometry and topology of an object. In the application layer, subsets of the IR data entities are specialized for particular product classes and life-cycle stages. This results in a series of Application Protocols (APs) that prescribe the scope and representation of the data that can be exchanged for that purpose. The third (physical) layer of STEP architecture defines how the data elements are mapped into a physical file format (ISO 10303- 21), or how it may be accessed in a data repository (ISO 10303-22).

An AP specific to LM has not yet been developed, but the STEP IRs provide the means for this to be done. Specifically, ISO 10303-42 defines geometrical and topological facilities that allow the capture of geometric models of several different types, as detailed below. As an example, the AP ISO 10303-203 (Configuration controlled design) uses ISO 10303-42 to specify the requirements for the exchange of mechanical engineering design data between different types of CAD systems, a common need in multi-tier supplier situations. The types of model representation supported include wireframes and surface models with or without topology, faceted boundary representations, and advanced boundary representation solids (with curved surfaces). The faceted boundary representation capability includes that of STL, but adds topology and omits the redundant surface normal information. The wireframe facility could also be used in LM, for slice contours.

Three further STEP IRs are also relevant to LM. ISO 10303-45 ("Materials") provides representations for material properties, covering requirements identified earlier. ISO 10303-47 ("Shape variation tolerances") covers another of the desired LM capabilities. ISO 10303-49 ("Process structure and properties") provides a basis for the transfer of process-related information in LM.

3.4 Slice Formats for LM

The use of models with exact rather than faceted geometry allows increased accuracy. This implies that slicing may best be done in the CAD system where the design model originates, because that provides all the necessary capabilities for geometric computation. In this case, a neutral format is needed for the transfer of the resulting slice data from the CAD system into the LM process planning system.

A slice format must enable the capture of all the geometrical data of the layer, including the layer thickness. Also, it must have provision to store material and process-related information, if necessary. Although there is currently no formal or industry standard for slice data, a few proposals have been made in this area:

- Common Layer Interface (CLI) and Layer Exchange ASCII Format (LEAF) – these were developed by two European consortia as system-independent slice formats. Both define layers in terms of closed bounding contours and a thickness, and both also represent hatch patterns for the definition of support and filling structures. CLI defines only line-based geometric information. LEAF is more comprehensive; it includes keyword definitions and vendor or machine-specific details, together with such things as the radix of the number system used, units, and ranges of values. LEAF describes layer contours in terms of 2D polylines and circular arcs.

- SLC formats – these encompass several different proprietary slice formats, all using polyline approximations to represent slice contours.
- STEP – the STEP Integrated Resources provide all that is needed for defining contours and fill patterns, using polyline approximations or exact geometry. STEP also has relevant non-geometric capabilities, as mentioned above.

Although there exists no widely used format for 2D slice data to supplement the almost universal use of STL for 3D models, LEAF and STEP as described above are the most complete proposals in that they provide the means for transmitting additional information beyond geometry.

3.5 Motivation for abandoning 3D data transfer in LM

Some researchers have suggested that a standardized 2D slice format could be used to replace STL (Donahue and Turner 1991). Such a departure from current methodology would require slicing to be performed in the CAD system, rather than in the LM system as is usually the case at present. The suggested reasons for jettisoning the 3D format include the following:

- CAD systems provide powerful geometric capabilities that are directly applicable to the determination of a good build direction, the generation of support structures and the calculation of slice data.
- These operations could be performed directly on a CAD model using a precise geometry representation. This would generate slice data without the loss of precision inherent in STL, leading to accurate parts with improved surface finish. It may also lessen the time taken for process planning, because similar accuracy using STL would demand a fine level of discretization, requiring very large files and increasing the chance of errors in triangulation and slicing.
- The powerful geometric capabilities of CAD systems can be used to optimize the slicing algorithm and validate its results automatically. This will avoid the creation, storage, and possible need for correction of an STL file.
- In most cases, correction of faulty geometry is easier in sliced data.
- A slice format may be better for use with parts defined by scanned or image input data, because it avoids the difficult task of creating a full 3D model.

Two disadvantages in replacing the 3D format by slice data are that

- Once the model is sliced, changing the build orientation is impossible.
- Most current LM technologies fabricate parts in layers, but some deposit material in 3D, and they clearly demand some approach other than slicing.

4 CONCLUSIONS

Process planning for LM involves multiple tasks with specific data requirements. Various file formats are in use or have been proposed for transferring data between those tasks. Most are restricted to the exchange of geometry data, though there is an increasing need for the transfer of additional types of information. STL, the current *de facto* standard, allows the transfer of approximate 3D shape information alone. This is inadequate for the future, because non-shape information is growing increasingly important in LM and the STL approximation puts limitations on its potential uses. In the authors' view, extending the STL specification will not give a good long-term solution. The ultimate survival of STL is called into question by

- The prospect that LM will become suitable for production use (apart from its current applications for molds and dies) in the medium-term future. Such use will place a premium on the transfer of exact product geometry from the CAD system, together with information on tolerances, surface finish and materials.
- The possibility that some phases of LM planning will migrate into the CAD system, raising the need for an alternative standardized slice format.
- The prospect of using LM for the generation of parts with embedded electronic or other components, multi-material parts, or parts in which the material properties vary in a continuous manner. These parts will demand completely new capabilities in LM data transfer.

These considerations lead us to urge development of a STEP Application Protocol for LM process planning. Existing STEP resources provide most necessary types of data, including material specification, process parameters, tolerances and surface finish requirements. 3D shape data can be transferred using STEP's faceted boundary representation (a direct replacement for STL), or as an advanced Brep solid with topology information and general curved surfaces. Additionally, STEP resources can be used to represent slice contours in terms of lines or general curves; thus both 3D and slice data can be defined in the same standard. The major required capability lacking in STEP is that for modelling inhomogeneous materials, but a resource suitable for this purpose is currently under development.

The clinching argument, however, is that many of the existing parts of STEP are already components of an international standard that is increasingly used by industry. Most of the capabilities needed for the new AP already exist, have been tested and refined in practical use, and can be adopted wholesale for the new AP. We believe that these considerations strongly support our recommendation.

5 ADDENDUM – RECENT DEVELOPMENTS

Two workshops were recently held at the US National Institute of Standards and Technology (NIST) to discuss standardization issues in LM, with participants from industry, academia and government. A resulting consensus White Paper recommends improving STL to meet short-term LM requirements and developing a new STEP Application Protocol for LM in the longer term (Jurrens 1998).

As a separate development, two meetings of a STEP Interest Group on LM have been held since June 1998. This group is likely to pursue the development of a new STEP Application Protocol for LM, as recommended in this paper.

6 ACKNOWLEDGMENTS

The authors recognize financial support from NIST and from the US Defense Advanced Projects Research Agency (DARPA).

7 REFERENCES

Bendsoe, M.P., Diaz, A. and Kikuchi, N. (1993) Topology and generalized layout optimization of elastic structures, in *Topology Design of Structures* (eds. M.P. Bendsoe and C.A. MotaSoares). Kluwer Academic Publishers, Amsterdam.

Bøhn, J.H. (1993) Automatic CAD-Model Repair. PhD Thesis, Rensselaer Polytechnic Institute, Troy, NY.

Burns, M. (1992) Automated Fabrication. Prentice Hall, Englewood Cliffs, NJ.

Dolenc, A. and Mäkelä, I. (1995) Rapid prototyping from a computer scientist's point of view, Proceedings of Rapid Product Development Conference, Stuttgart, Germany, May 8-9, 1995.

Donahue, R. and Turner, R. (1991) CAD modeling and alternative methods of information transfer for rapid prototyping. *Proc. 2nd International Conf. on Rapid Prototyping*, University of Dayton, Ohio, June 1991.

Hoffmann, C.M. (1989) Geometric and Solid Modeling. Morgan Kaufmann, San Mateo, CA.

ISO (1994) *Industrial automation systems and integration – Product data representation and exchange, 1994* (International Standard ISO 10303).

Jurrens, K.K. (1998) Rapid prototyping's second decade. *Rapid Prototyping* (quarterly newsletter of the SME Rapid Prototyping Association), **4**, 1, 1-4.

Kumar, V. and Dutta, D. (1997) An assessment of data formats for layered manufacturing, *Advances in Engineering Software*, **28**, 3, 151-164.

Marsan, A. and Dutta, D (1997) A survey of process planning techniques for layered manufacturing. In Proc. 1997 ASME Design Technical Conferences, Sacramento, CA, August 1997.

Mazumder, J., Koch, J., Nagarathnam, K., and Choi, J. (1996) Rapid manufacturing by laser aided direct deposition of metals, Technical Report, University of Illinois, Department of Mechanical Engineering.

Miller, J.F. (1994) Tutorial notes on CAD requirements for rapid prototyping. From conference *Rapid Prototyping and Manufacturing '94*, Society of Manufacturing Engineers, Detroit, MI, 1994.

Owen, J. (1993) STEP: An Introduction. Information Geometers, Winchester, UK.

8 BIOGRAPHIES

Debasish Dutta is an Associate Professor in the Department of Mechanical Engineering and Applied Mechanics (MEAM) at the University of Michigan in Ann Arbor. He has a PhD from Purdue University, and currently heads the CADCAM Group in the Design Laboratory of MEAM. Vinod Kumar is a PhD candidate in the same department; he gained his bachelor's degree at the Indian Institute of Technology, Madras, India, and his master's degree at Rutgers University, NJ.

Mike Pratt is a Senior Research Associate with Rensselaer Polytechnic Institute in Troy, NY, and is currently working as a Guest Researcher at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. He was formerly Professor of Computer Aided Engineering at Cranfield University in the UK. He has a master's degree from Oxford University and a PhD from Cranfield. Ram Sriram leads the Engineering Design Technologies Group at NIST, having previously been an engineering faculty member at MIT. He gained his bachelor's degree from the Indian Institute of Technology, Madras, and his master's and PhD from Carnegie-Mellon University in Pittsburgh, PA.