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Solid Freeform Fabrication with Local Composition Control

W. Cho, E.M. Sachs, and **N.M. Patrikalakis,**
Massachusetts Institute of Technology (Cambridge, MA)

One of the great potential benefits offered by solid freeform fabrication (SFF) technology is the ability to create parts that have composition variation within them. Such local composition control (LCC) has the potential to create new classes of components. Material composition can be tailored within a component to achieve local control of properties; for example, index of refraction, electrical conductivity, formability, magnetic properties, corrosion resistance, hardness vs. toughness, and so on. By such local control, monolithic components can be created that integrate the function of multiple discrete components, saving part count, space, weight, and enabling concepts that would be otherwise impractical. Controlling the spatial distribution of properties via composition will allow for control of the state of the entire component (the state of residual stress in a component). Integrated sensors and actuators can be envisioned, which are enabled by LCC (bimetallic structures, in situ thermocouples, and so on). Devices that have (as their function) the control of chemical reactions are possible. The utility of mesoscopic parts made by SFF will depend strongly on the ability to locally control composition.

Realizing the potential utility of LCC in SFF is a many-faceted challenge requiring developments in the: (1) information technology and design tools required to support the design of parts with LCC; (2) extension and characterization of the range of materials that can be deposited with local control (SFF technology specific); (3) design of materials systems with locally varying composition that can be successfully treated in operations subsequent to the SFF process itself (densified in a furnace firing operation); and (4) exploration of specific applications of LCC.

The work reported in this article focuses primarily on the issue of information technology and design tools. The absence of knowledge, methods, and tools in this area presents an absolute bar to the exploration of materials systems and applications. Developments in these areas will allow a wider community to contribute to materials and applications.

Information technology and design tools may be divided into two categories: (1) tools that are generic and (2) tools that are specific to a given SFF process. Generic electronic representations must be developed to allow for electronic specification within a component. There must be a suite of tools that allows a designer to communicate with this representation using high-level features that are sensible to a designer. The designer must be able to visualize and interrogate the evolving model. The model must not allow the designer to request that which cannot be made. Process specific tools include methods to render desired continuous composition profiles in the discretized form required by a specific process and the generation of machine-specific fabrication instructions.

Wherever possible, our work is generic and applicable to a broad range of SFF technologies. However, in the cases where the outcome is process specific, 3D printing is used as the prototypi-

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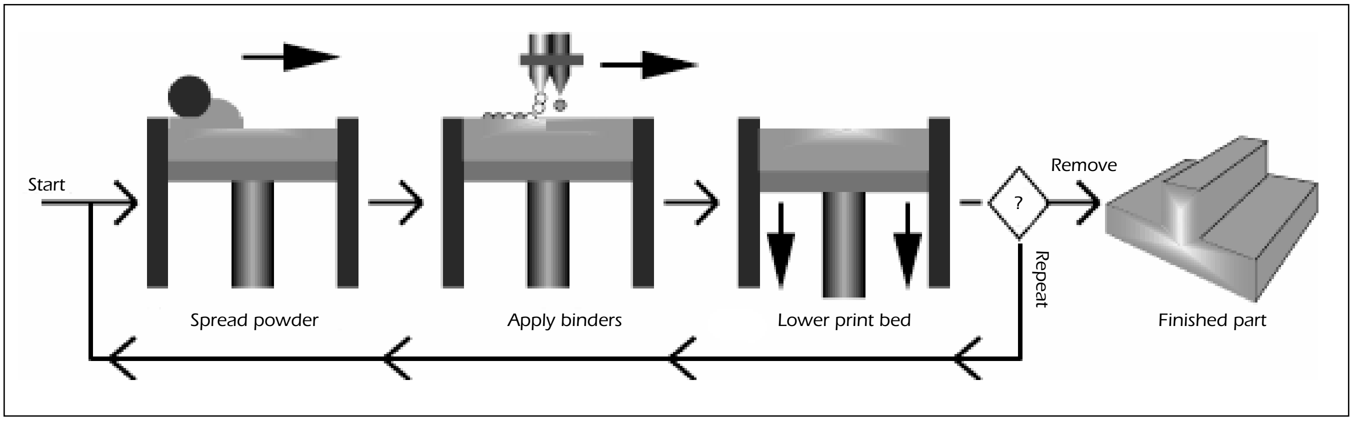


1. 3D printing illustrating LCC.

cal SFF technology. Among the SFF processes, 3D printing is particularly well-suited to the fabrication of parts with LCC. Three-dimensional printing creates parts in layers by spreading powder and then ink-jet printing materials into the powder bed [13-18]. In some cases, these materials are temporary or fugitive glues, but in many cases, these materials remain in the final component. Examples of the latter include: ceramic particles in colloidal or slurry form, metallic particles in slurry form, dissolved salts (which are reduced to metal in the powder bed), polymers in colloidal or dissolved form, and drugs in colloidal or dissolved form. 3D printing has been extended to the fabrication of LCC components by printing different materials in different locations, each through its own ink-jet nozzle(s). *Figure 1* illustrates this conceptually with two different colors, each representing the printing of a different material into the powder bed with local control of position. 3D printing is thus capable of fully 3D control of composition.

MIT's 3D printing website can be found at *www.mit.edu/~tdp/*. The research menu selection brings you to a description of the research programs now under way, including the LCC program, a listing of our publications, and illustrative examples of our work.

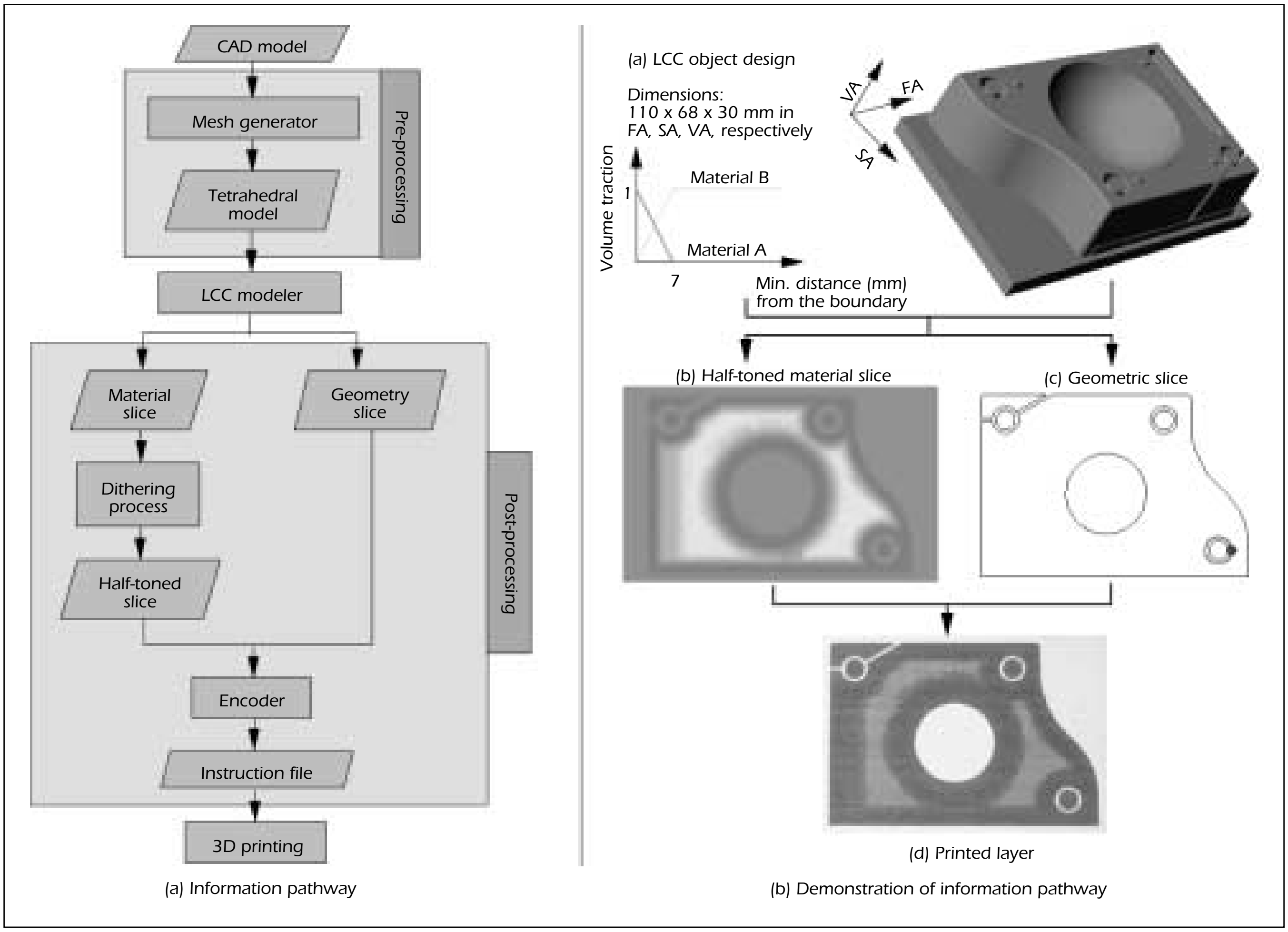
LCC Information Pathway

The LCC information pathway enables a designer to design a part with LCC, send it electronically for fabrication, and have a part returned that conforms to expectations without the need for iteration. Our program has sought to identify and overcome the barriers to such information flow and to demonstrate accomplishment with parts made by 3D printing.

Overview. The LCC information pathway with 3D printing begins with a designer interacting with a standard CAD system to define the shape of the object, as shown in *Figure 2a*. Therefore, the created solid model is then exported from the CAD system in a standard exchange format such as STEP [2] or IGES [5].

In the course of our work, we implemented an LCC modeler based on tetrahedral mesh data structure. This finite-element-based LCC modeler can be thought of as a special instance of our generalized cellular decomposition approach to LCC modeling [7,8,15]. It was chosen as a convenient method to demonstrate the information pathway and to explore the issues associated with LCC. Once the geometry of the model is fully defined, it is loaded into a finite-element mesh generator via a neutral format and then meshed into a set of tetrahedra. This process is referred to as pre-processing in *Figure 2a*. The composition of a part is established by specifying the composition values at the vertices of each tetrahedron and interpolating between them. As an exemplar of a design tool, we developed a method to specify a composition profile normal to the surface and applied this profile to an entire object [10,11].

Post-processing then converts the designed LCC model into instructions [22] for the 3D printing machine. Post-processing takes place on a layer-by-layer basis along two parallel paths: (1) the accurate definition of the surface (geometry slice) and (2) rendering the composition of the body (material slice). The continuous-tone material composition is rendered into printable discrete information using half toning (or dithering) algorithms. The boundary and composition information is recombined to produce the drop-by-drop instructions that are loaded onto the 3D printing machine. Special attention is given to reconciling conflicts that occur at the boundary where the designer's intent in both composition and surface finish must be recognized.



2. Information flow for LCC with 3D printing (from prior work).

The complete information and 3D printing pathway has been tested and demonstrated [3] with a part of representative complexity, as shown in *Figure 2b*. The part is an injection molding tool, and the design challenge is to place hard phases in a designed composition profile near the surface. In this demonstration, two colors of ink were printed (magenta and cyan) with the condition that the sum of the materials was everywhere constant. The bottom image in *Figure 2b* shows a photograph of a layer of the actual printed part. This can be compared with the material and geometry information above it, which become merged to produce the instructions, which led to the printed part.

Alternative Representations and Evaluation. We have presented and analyzed various data structures for modeling objects with LCC [3,6]. In modeling LCC parts efficiently, any such method should provide a concise and accurate description of all of the relevant information about the part with an affordable cost in terms of storage. Because both the voxel-based modeling and finite-element mesh approach approximate design intent, trends for the sizes of the voxel lattice or mesh were then established in terms of the desired geometric and material accuracy of the representation. These trends were based on the nature of the intended design and include properties such as rate of material variation, surface curvature, material curvature, and minimum feature sizes. The storage costs of the generalized B-rep data structures are constant with the desired accuracy of representation, and grow with the number of features in the model.

We summarize below our view of the limitations of existing approaches (including our own) for the representation of LCC parts: current approaches either based on volume meshing or cellular decompositions are awkward in editing geometric and material composition information simultaneously; in effect, they only permit sequential editing (first of geometry and then composition), which is not flexible and limits the designer's options. Current LCC models are limited to low-level data, and operators and do not allow for the symbolic representation of the designer's intent with respect to composition. As such, design changes cannot be efficiently propagated.

Tessellation of the volume of a model (via tetrahedral meshing) early in the design and fabrication pathway, although expedient for testing of ideas, does not provide a long-term solution for the following reasons:

- tessellation implies both approximation of surface geometry and material composition, which is undesirable in general, and for realistic accuracies of approximation leads to verbose evaluated representations that are unattractive for general LCC modelers;
- tessellation approximation accuracy for surface geometry and material composition can be improved via adaptive meshing procedures; however, these are difficult to implement robustly and efficiently; and
- methods for tessellation of a volume into tetrahedral meshes suffer from the general robustness problem in computational geometry relating to inexact computation.

Design Methods and Visualization. In this work, we assume that the input geometry is a single solid represented via a boundary representation, including tessellated and curved models obtained from a CAD system and exchanged via a standard file format such as STL [1], IGES [5], or STEP [2]. The first algorithm developed allows specification of the locally controlled composition at a point as a piecewise polynomial or rational function of the minimum distance d of the point from the entire boundary surface. To design composition as a function of d, an efficient distance transform (DT) is necessary. Among the approaches for an efficient DT, space division via a rectangular lattice is particularly useful and easy to implement. Specifically, the approach for improving efficiency of DT includes pre-processing the model with bucket sorting [4] and digital distance transform of the buckets [10,11]. Complexity analysis of the algorithm outlined above and experimental results demonstrated effective performance of the method. With the composition function evaluated effectively, the visualization of the composition may be performed through various computer graphics techniques. The methods implemented include color-coded point sets, color-coded planar sections, cuberilles, and ray casting of the composition [6,11].

Volume Dithering. In the information flow for LCC with 3D printing, a dithering algorithm plays an important role as it converts the continuous-tone LCC representation into a discrete (point-wise) version of machine instructions. Motivated by the fact that 3D printing is analogous to ink-jet printing, our dithering algorithm is based on the classical digital half-toning technique [21] but adapted to attain optimal dithering patterns for LCC models. We note that the undesirable low frequency textures of composition are minimized not merely layer wise but throughout the volume of the LCC model [3,22]. Compositions over the layers are sampled and compared with 3D threshold matrices. A binary representation, approximating the original, continuous-tone values, is output, which is then translated into machine instructions for fabrication. Peculiarities of the 3D printing machine, including anisotropic geometry of its picture elements (PELs) and uncertainties in droplet placement, are addressed through modifications of the standard digital half-toning algorithm. Our algorithm accounts for technical limitations in the machine, only generating lattices that can be represented within the memory limits of the current hardware.

Encoding and 3D Printing. Once the geometry slicing and composition dithering are complete, the geometric and material information is merged through the encoding process. In 3D printing, each nozzle prints a droplet inside a raster segment. With the raster segments generated from the geometric slice, we match each segment with the associated composition information resulting from the dithering process. Such recombined information is then encoded into machine instructions based on the pattern capability of the 3D printing machine; for example, the ALPHA machine at MIT, where nozzles are allocated to different materials in a pair-wise manner. 3D printing with LCC is being accomplished on the MIT ALPHA machine, which has an eight-jet continuous jet printhead and defines the part by raster scanning over the powder bed. The eight-jet printhead was configured with two banks of four jets each, one for each color.

Conclusion

Most CAD research has focused on the representation of 3D geometry, on methods and tools for designers to interact with these representations at a high level and on derivation of machine specific instructions for machining. This work develops complementary capabilities in the area of LCC and SFF. It is hoped that the availability of such tools and methods will be the key ingredient needed for the community to explore the potential of LCC.

This article has described our recent work on local composition control in solid freeform fabrication via 3D, printing which enables a designer to create a design, send it electronically for fabrication, and have a part returned that conforms to expectations without the need for iteration. Our work has sought to identify and overcome the barriers to such fabrication methods and to demonstrate accomplishment with parts made by 3D printing. The major barrier is the inability of designers to exploit LCC due to the lack of electronic representations and design tools.

At this time, it is difficult to predict the eventual impact of LCC on the practice of engineering.

SFF processes must become broadly used for manufacturing and not just prototyping (an active area of research within the 3D printing project). Materials systems that can be processed to produce finished components with locally varying composition without distortion must be developed. Compelling applications must be demonstrated.

Encouragement can be taken from the fact that in the 3D printing project, several promising applications are under active development. Drug delivery devices are being created by printing different drugs at prescribed locations within the interior of a pill or implantable device. These drugs are then released into the body according to designed release profiles [9,12]. A new program has just begun on gradient index lenses (GRIN), which refract light by gradients in the index of refraction, rather than by external geometry. Such lenses can provide the functionality normally associated with multicomponent ground optics at a lower cost and in a smaller space. The drug delivery and GRIN applications are for high value-added devices that are small in size and thus can reasonably be manufactured by 3D printing. LCC is also being applied to the fabrication of tooling by 3D printing. Hard phases, such as TiC, are being printed local to the surface of a tool for increased wear resistance. Tools with local control of porosity (for venting of gases) are being fabricated by printing a material, which acts to block the infiltrant during furnace densification. Although large in size, tooling applications can be economical because small quantities are required.

While one may not hope to match the impact of VLSI fabrication methods on engineering and society, the parallels are intriguing. VLSI and SFF are layer processes. VLSI depends on local control of composition, and SFF is capable of the same. Perhaps, as in the case of VLSI, we will find that designers, given the proper tools, will find uses not now imagined for LCC in SFF.

Acknowledgment

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References

References for this article can be found at *www.sme.org/rpa*.■

NEWSLINE

Rapid Preforming Developed for Metal Matrix Composites

Metal matrix composites (MMCs) are often better than metal alloys because of lower weight, higher stiffness, and improved fatigue and wear resistance. But MMCs—whether reinforced with continuous fibers or discontinuous fibers or whiskers—are expensive due to high processing costs. Traditionally, a uniformly porous ceramic shape was made via injection molding or powder compaction using costly hard tooling or patterns. Metal Matrix Cast Composites Inc. (MMCC, Waltham, MA) has developed a new affordable process called 3-Dimensional Printing (3DP™), similar to RP, that quickly produces a porous ceramic preform. Silicon carbide or alumina powder is evenly spread over a discrete area inside a closed cabinet and "printed" through computer control with an organic binder to form a 2D layer or slice. Repeated 2D layers produce the 3D preform shape, which is then sealed using a proprietary technique called the Tool-less Mold. The encapsulated preform is then surrounded by a medium similar to that used in investment casting, and pressure forces molten metal into the preform/mold. The company claims the process produces a near-net-shape component, even for complex shapes in a matter of days—without the need for tooling. MMCC has produced an aluminum-based, half-scale prototype oxygen turbopump housing for Marshall Space Flight Center, for use in rocket applications, replacing nickel-based superalloys such as Inconel 718. *www.mmccinc.com*■

From the RPA/SME Board to You...

The RPA/SME Board of Advisors is always looking for ways to bring you, RPA/SME members, the latest, most up-to-date information on rapid prototyping that you can use and apply now. These websites, therefore, are noted by the Board:

www.vr.clemson.edu/credo/rp.html

http://ltk.hut.fi/~koukka/RP/rptree.html#SL

www.cc.utah.edu/~asn8200/rapid.html

www.rapid-discussion.com

If there are any websites that you feel may be of interest to other members/the Board, please forward them to Dianna Helka at *helkdia@sme.org*. We will be happy to post them in future editions of ***RAPID PROTOTYPING***. Stay tuned for further updates...

3D Solid Models

3D solid models of many of Jergens, Inc.'s (Cleveland) standard jig and fixture components are available free of charge through the company's website, *www.jergensinc.com*. Presented in both Step and Solid Works® formats, the models can be used with most popular CAD packages, including Catia®, Pro/Engineer®, Unigraphics Solutions®, and Cadkey®. Files are continually updated with engineering changes and improvements. The addition of 3D solid models complements Jergens' existing FixturePro™ 5.1 fixture component software, which is available free via CD-ROM or the Internet. The FixturePro software part library includes 2D drawing and 3D wire frame versions in DWG, DXF, and IGES formats. *info@jergensinc.com*

Rapid Micro Product Development

Miniaturization is not an end in itself but a means that is meaningfully marketable. For the long term, direct benefits can be achieved through miniaturization, such as new diagnosis and therapy facilities in medical technology; more safety and comfort in the automobile industry; high savings of energy in the aviation and space industries; and better handling in the area of consumer end products. Manufacturing processes without tooling ensure cost savings in production, especially in the area of micro technologies, and it is important to avoid further assembly processes whenever possible to achieve a high manufacturing accuracy through CIM. With the advent of rapid micro product development (RMPD), developed by MicroTEC (Duisburg, Germany), there is now a process available for prototyping in the area of micro structures and micro systems technology, as well as for very fast mass production with no tooling required. The basis of RMPD is the CAD/CAM installation for the design and fast production of microstructures of almost any desired shape. The virtual CAD model is realized either as a real prototype or produced by parallel batch production. In both cases, a liquid monomer is polymerized by a laser. In this manner, it hardens the liquid photoresist by photoinitiation. The accuracy can be up to 1 mu layers or better with RMPD special. The speed depends on the volume; for example, the wind wheels can be produced within 20 minutes. The materials used are acrylics and epoxies. More information on this new manufacturing process can be obtained by visiting *www.microTEC-D.com*.

Data Translation

For companies with occasional data translation needs, Delcam International's (Windsor) PC Exchange offers a service that allows the CAD model to remain in the user's

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RP&M 2001 Conf. & Expo Agenda

Monday, May 14	Tuesday, May 15	Wednesday, May 16	Thursday, May 17
MORNING ➢ Check-in/registration	MORNING 8:30-8:45 A.M. ➢ Welcome & introductions 8:45-9:30 A.M. ➢ Keynote address: Speed Kills—In About an Hour Dave Browne, retired CEO of LensCrafters, shares how "speed" in the business world, and in particular within LensCrafters, is truly one of the only killer strategies available in today's reality. The address will provide thought-provoking, real-life examples of how LensCrafters has applied, and how you can directly use, "speed" as an advantage and challenge you to help your customers "speed up." 9:30-10:15 A.M. ➢ State of the Industry Executive Summary Break: 10:15-10:30 A.M. 10:30-11:30 A.M. ➢ Industry Panel Discussion Lunch: 11:30 A.M.-1:00 P.M.	MORNING 8:30-11:30 A.M. Concurrent sessions ➢ Materials for RP ➢ Direct Metal Fabrication Break: 10:00-10:15 A.M. Lunch: 11:30 A.M.-1:00 P.M.	MORNING 8:30-11:30 A.M. Concurrent sessions ➢ Rapid Technologies for Plastic Tooling Applications ➢ Alternative Approaches to Mold Making Break: 10:00-10:15 A.M. Lunch: 11:30 A.M.-1:00 P.M.
AFTERNOON Noon-4:30 P.M. Tours ➢ Morris Technologies Inc. ➢ Univ. of Dayton RP Development Lab ➢ Ethicon Endo-Surgery Inc.	AFTERNOON 1:00-2:30 P.M. Concurrent sessions ➢ Rapid Production ➢ Use of CNC w/RP ➢ Innovations in Reverse Engg. Applications	AFTERNOON 1:00-2:30 P.M. Concurrent sessions ➢ New Products: Niche Applications ➢ Fast Castings 3:00-4:30 P.M. ➢ R&D Initiatives ➢ Advances in RP Machines	AFTERNOON 1:00-2:30 P.M. Concurrent sessions ➢ Process Improvement ➢ The Future of RP (Panel Discussion)
EVENING 6:00-9:00 P.M. ➢ Tutorials ➢ Understanding RP Materials & Selecting the Right Process ➢ Funds. of RP & Tooling ➢ Intro to Mfg. Processes: Casting & Plastic Molding ➢ Collaborative Engg. Tools	EVENING 5:00-7:00 P.M. ➢ RP&M Networking Reception (Hyatt Regency Ballroom) Food, Fun, Entertainment, and Door Prizes! Theme: Cruisin' on the River Visit the SME "riverboat" and meet and interact with your RPA/SME Board of Advisors, RP&M attendees, exhibitors, and speakers.		

Using rapid manufacturing technologies to achieve faster product development while maintaining high quality and low costs is the focus of this conference. This event covers the full range of design, RP technologies, additive processes used throughout the rapid product development process, and rapid processes for rapid production. RP&M 2001 features companies displaying the latest innovations in products and services for RP and rapid manufacturing. Included are materials, equipment, and software for RP and rapid tooling as well as evaluation of products that reduce costs and produce high-quality parts quickly.

computer. Because the translation is stored in the user's computer, there is no need for time-consuming upload and download of CAD files. Both the speed with which data translation can be made and the security of the system are dramatically improved. To use the service, the user simpler obtains a real-time authorization from Delcam's website (*delcam.com*). This approach gives much faster results because transferring a short authorization code is much quicker than transferring a complex CAD model. The translation typically would not take more than a few minutes. Uploading and downloading a typical CAD model in contrast would take hours—even with a fast Internet connection. Because the model file remains in the user's own computer, there is no chance of sensitive information being intercepted or mailed to an incorrect address. There are no upfront charges and use is on a "pay-per-translation" basis. To test the new service, simply download the PX-Exchange software from Delcom's website and register to participate. Ph: (519) 974-8088, *Machine Tools Online*, 10/19/00.

Events

Funds. of Injection Molding
Apr. 23-24 (St. Charles, IL)
RP&M 2001 Conf. & Expo
May 15-17 (Cincinnati)
Injection Molding Funds.
May 21 (Springfield, MA)
Designing Plastic Injection Molds
May 22 (Springfield, MA)
Funds. of Moldmaking Technology
May 22 (Springfield, MA)
GD&T Level 1
May 22-24 (Springfield, MA)
Plastic Injection Molding: Mfg. Startup & Mgmt.
May 23-24 (Chicago)
SME

Reaction Injection Molding
May 24 (Dearborn, MI)
SME

3DIM2001
May 28-June 1 (Quebec City, Canada)
NRC
www.vit.iit.nrc.ca/3DIM2001/

Funds. of Magnesium Injection Molding
June 5 (Dearborn, MI)
SME

12th IEEE Int'l Workshop on Rapid System Prototyping
June 25-27 (Monterey, CA)
IEEE
www.rsp-workshop.org/

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Associate Editor
Dianna L. Helka
helkdia@sme.org

Graphics Support
Barry Sloan

Publisher, Director of Publications
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Nancy Berg

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