The Distributed Design and Fabrication of Metal Parts and Tooling by 3D Printing

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Abstract: Solid Freeform Fabrication (SFF) processes, such as 3D Printing [1], offer many unique capabilities to the design and manufacturing community, such as Local Composition Control (LCC). Experimentation with this new technology, however, is limited to researchers with expertise in the field and access to the machines. To improve access to these processes, our research program is striving to separate design tasks from fabrications issues, permitting the distribution of SFF design tools to a larger group of researchers for the design of parts which will later be manufactured on remote fabrication machines. We intend to demonstrate this concept of Distributed Design and Fabrication of Parts with 3D Printing as the model system, a process capable of producing functional metal parts and tools with LCC. To achieve this goal, we are addressing the technical barriers to achieving a one-way-flow of information from design to fabrication. These barriers include: the design, specification, and processing of parts with LCC, and the anticipation of surface roughness and dimension control. These issues will be addressed by the development of more capable modeling methods, the application of design rules, and the use of simple process simulation. A test bed will be operated at ExtrudeHone for the purposes of: i) testing design tools, ii) realizing creative designs which exploit LCC, and iii) inserting SFF into the undergraduate curriculum at MIT.

Objective:

- Identify and overcome the barriers to the practice of Distributed Design and Fabrication of Solid Freeform Fabrication (SFF) with 3D Printing of tooling as a model application.
- Operate a test bed which will allow designers in the research, educational, and industrial communities to experiment with Distributed Design and LCC Fabrication.

The successful practice of Distributed Design and Fabrication requires the ability for a designer to transmit his design representation to a remote fabrication site with the knowledge that the design can be successfully manufactured. Arguably, a requirement for the practice of Distributed Design and Fabrication is the implementation of a ''clean interface'' between design and fabrication. The concept of the clean interface dictates that all the relevant information about a design can be communicated to those who will fabricate it without discussion between the manufacturer and the designer. Preferably, the information flow should be in one direction only, i.e from the designer to the fabricator with no need for iteration.

Identification of Technical Barriers and Approaches: To achieve the goal of Distributed Design and Fabrication, the barriers preventing direct access to this technology must be removed. In this program, three areas are being addressed: Local Composition Control, surface finish, and dimensional control. It is anticipated that progress in these areas will provide a smoother interface between the designer and the fabrication site. The approach we are taking to capture and communicate the designer's intent to the 3D Printer is shown in Figure 1, taking advantage of existing CAD systems and meshing packages to capture a designer's geometric intent. We are focusing on methods to model objects with graded compositions, design graded compositions, aid designers with the evaluation of models through design rules, and process models into machine instructions to drive the fabrication process.

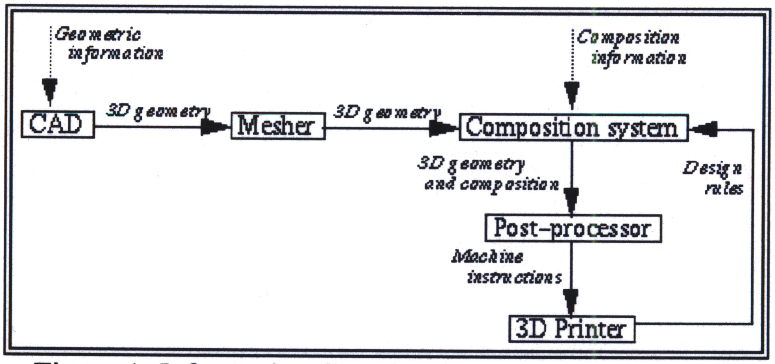

Figure 1: Information flow from the designer to the 3D Printer.

Many SFF processes offer a degree of control over the local composition of parts (LCC), allowing the fabrication of parts with smoothly graded compositions. However, current CAD methods are not suitable for handling models with such compositions, a clear technical barrier to Distributed Design and Fabrication. To address this obstacle, we have first broken it into four areas four areas: the representation of models with graded compositions, graded composition design tools, model processing, and data exchange.

To represent models with graded composition, a solid modeling method based on the cell-tuple data structure is being explored [2]. This structure represents the topology of a model in a graph of cells with each cell representing one topological element of the model (vertex, edge, face, or region). The graph maintains the adjacency information between cells and is capable of representing models subdivided into arbitrary regions. To maintain composition information, a composition function is associated with each cell, allowing a graded composition to be defined over the model's interior [3]. A simple illustration of how topology is represented in this data structure is shown in Figure 2.

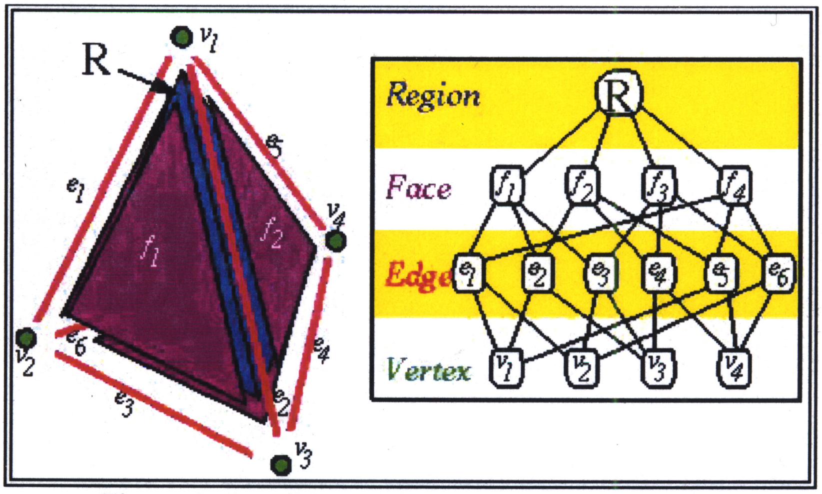

Figure 2. A solid model of a tetrahedron and the corresponding graph of cell.

There are many approaches for the design of compositions. One approach we are exploring is composition design as a function of distance. The designer will first define a variation in composition as a function of distance. Next, a feature is selected, such as a point, line, plane, face, or the entire boundary of the model. Finally, the composition over each cell will be automatically assigned, defining the composition throughout the model as a function of distance from this feature.

To assist with the design of manufacturable compositions, design rules will be established, capturing the inherent limitations of the manufacturing process. These rules, when followed, will guarantee that the model can be satisfactorily manufactured. For the fabrication of graded compositions, two process limitations are currently anticipated: the maximum or minimum allowable concentration of a material and the maximum allowable rate of change of a material in a smoothly varying composition. By informing the designer of anticipated problems at the design stage, corrections can be made without the costly need of manufacturing unsatisfactory prototypes.

To fabricate a graded composition model through LCC, a method to convert from the ''ideal'' continuous model into material primitives need to be established. To accomplish this, we are extending half-toning techniques from image processing to 3D Printing in order to convert solid models into machine instructions for fabrication. This approach will allow the automatic conversion of the model's graded composition into material primitives which are placed in a point-wise fashion by the printing machine.

As we progress in our research, we will develop a method for exchanging models with graded compositions. Based on our experiences, we anticipate being able to suggest extensions to existing model exchange standards with the goal of achieving a neutral exchange of solid models with graded compositions among a wider group of designers, researchers, and manufacturers.

In addition to composition control, surface finish and dimensional control present additional obstacles to Distributed Design and Manufacturing. With respect to surface finish, the effect of the layering inherent in many SFF processes presents a key barrier in many applications. This roughness can be altered substantially by changes in part orientation during the build process and the judicious selection of layer thickness. In addition, the dimensional control of SFF processes, including 3D Printing, is often not good enough for many tooling applications. To compensate for this, the designer must have access to the dimensional capabilities of the machine so that proper allowance can be made for finishing operations. In current practice, control of these parameters is left to the fabricator with the result that the designer is sometimes surprised by the finished parts. In order to provide the designer with the ability to anticipate and to optimize the surface finish of parts, a process simulation tool in envisioned which will allow the designer to visualize the impact of part orientation and layer thickness. To deal with dimensional control, process limitations can be captured in simplified models, establishing a set of design rules for model evaluation. In order to capture part distortion, however, more capable models may involve the 3D treatment of the problem, resulting in models which are more like process simulations.

Project status. The major advances in this project have dealt with the issues relating to LCC. The cell-tuple data structure incorporating composition information has been implemented in C++. The models are visualized using the OpenGL graphics library. Although our representation is sufficiently general to handle arbitrary B-rep models, the initial implementation supports triangulated models subdivided into tetrahedral domains (similar to a finite element mesh). This initial capability is sufficient to represent existing models converted from IGES or STL format into tetrahedral meshes by a commercial meshing system. The components of the modeling system are shown in Figure 3. In addition to representation, we are also addressing issues concerning design, visualization, and processing models for fabrication through LCC.

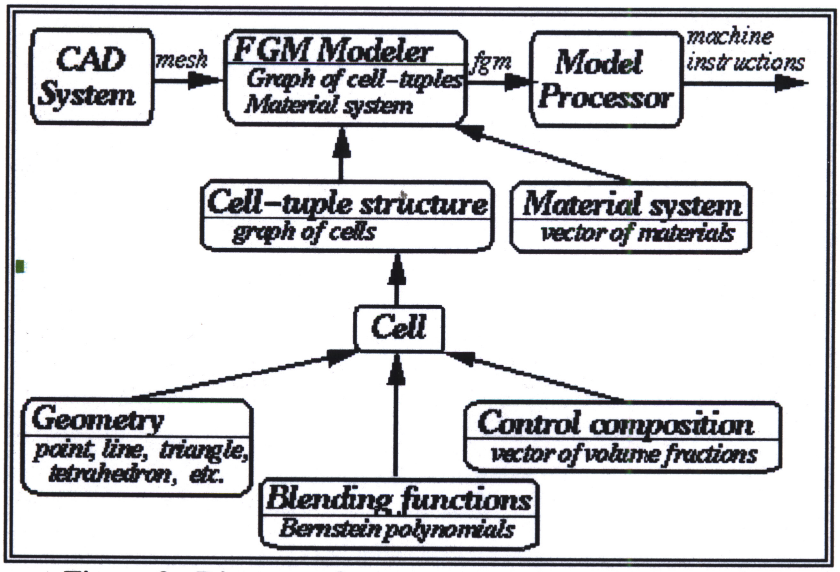

Figure 3. Diagram of components of modeling system, illustrating how information is represented and processed.

To represent the variation of composition over each tetrahedron, the composition is defined in terms of a set of *control compositions* and *basis functions* (Bernstein polynomials) [4]. Conceptually, the composition at a point can be considered as a blend of the control compositions with the influence of each determined by the value of its basis function.

With each control composition representing a degree of freedom in our model, ''design tools'' to automatically assign composition values for large models are being developed. The methods currently implemented assign values to the control compositions as functions of distance from a point, line, plane, or the model's boundary. In each case, the value of the control composition is determined as a function of its minimum distance in space to the reference feature. An example of how the design of a composition as a function of distance from a line is illustrated in Figure 4 in which the carbide concentration in a pulley is optimally distributed to resist wear.

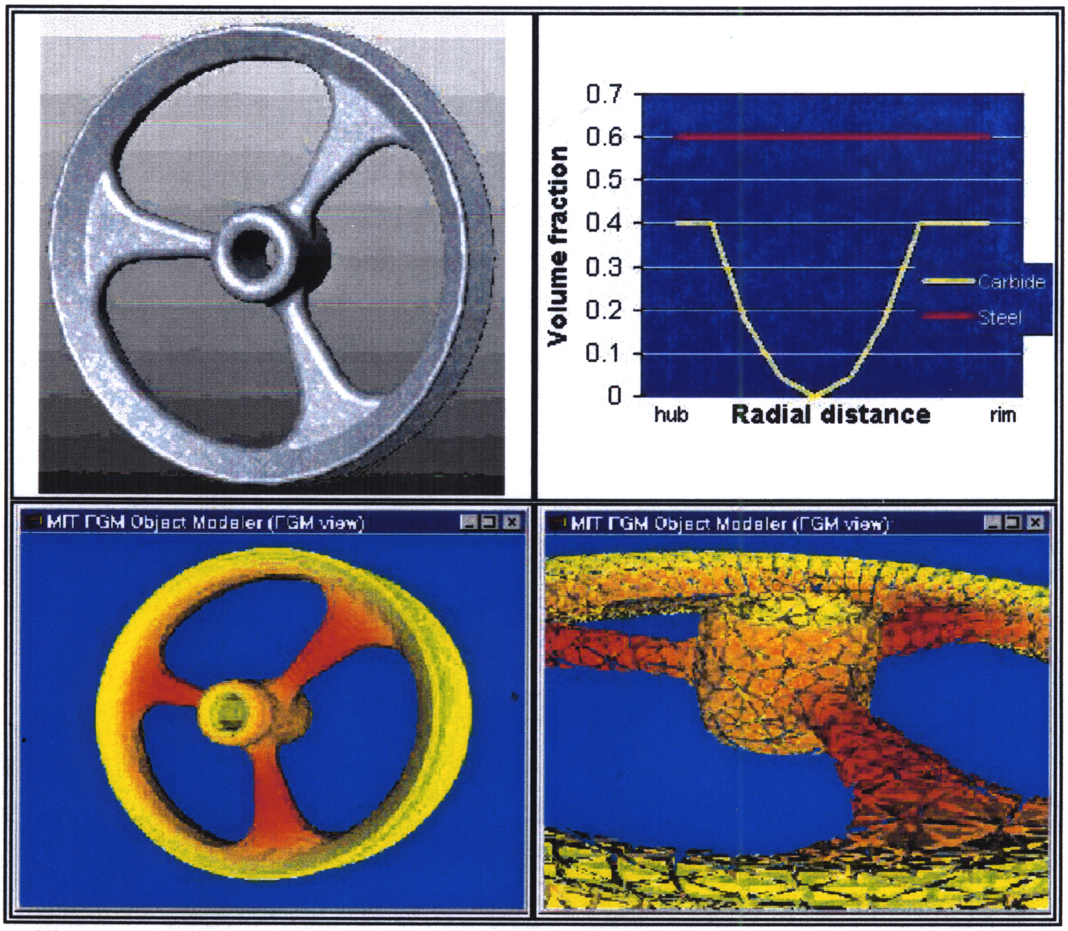

Figure 4. Pulley with graded composition designed to resist wear. The initial design is shown at the top left and the desired concentration of carbide is shown to its right. The compositions are applied to the model, as shown in the bottom views of the pulley.

In order to efficiently determine the distance of a control composition to the model boundary, an efficient algorithm to evaluate the minimum distance from a given point inside a 3D model to its boundary surface has been developed. This algorithm avoids the costly global calculation of the distance between every point-facet pair in the model by sorting the boundary facets into buckets. The problem then reduces to searching only the buckets nearest a point until the closest facet is found. One possible application for composition design as a function of distance from the model's boundary is the design of a drug delivery system, as shown in Figure 5. The release of medicine from the pill can be controlled by tailoring the distribution of the drug throughout its interior [5].

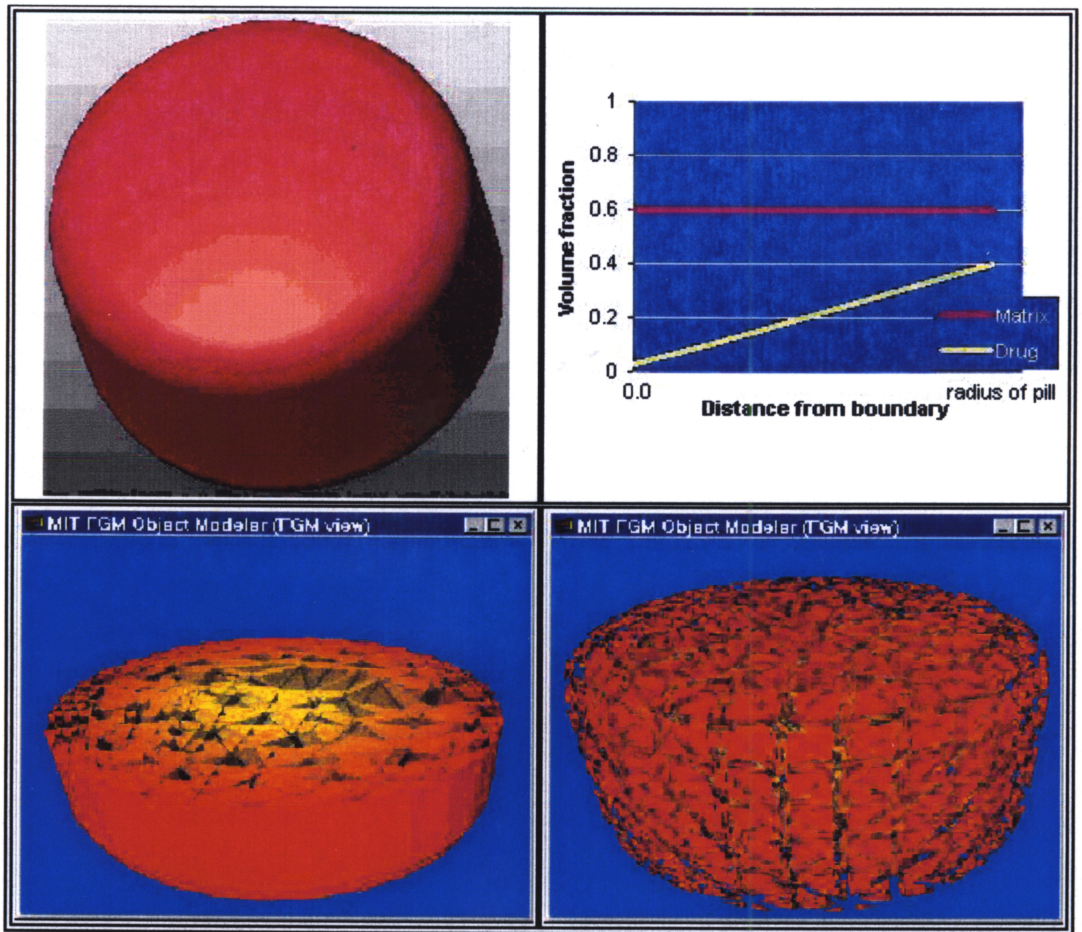

Figure 5. The design of a pill for controlled drug release. The initial pill model on a commercial CAD system is shown in the upper left. Next, a composition profile is defined (top right). The profile is then assigned throughout the pill, as shown in the sliced and tetrahedral views.

Approaches to processing graded composition models into machine instructions are being evaluated. Currently, the 3D Printing machine fabricates parts by applying binder in a drop-by-drop fashion into a powder bed (see Figure 6). By using a print-head with multiple nozzles and associating a different material with each nozzle, the placement of each material can be controlled on the scale of the droplet diameter (on the order of 100 microns). In order to fabricate models with continuous compositions from droplets of material slurries, two issues are being addressed: a ''half-toning strategy'' and a method to convert the half-toned model into machine instructions.

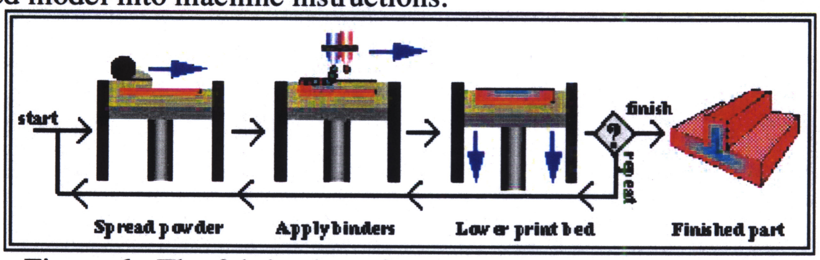

Figure 6. The fabrication of a part with graded composition through 3D Printing and LCC.

Digital half-toning is a method of rendering the illusion of continuous-tone images on displays that are capable of producing only binary picture elements (PEL) [6]. Since most hardcopy devices render images as binary or discrete tones, half-toning is used to convert a continuous, ideal image within a computer representation into a form capable of being rendered on the hardcopy devices. As 3D Printing builds objects in a point-wise fashion, in an analogous fashion to printing ink on paper, a logical starting point for achieving LCC is to extend digital half-toning methods to 3D Printing. Instead of defining dither matrices to determine a color scheme which approximates the continuous-tone images, two-dimensional (within a layer) or three-dimensional composition dither matrices can be defined which would determine the placement of different materials to accurately control the composition represented in the computer model. Currently, we are developing an optimal dithering pattern that avoids low frequency textures and guarantees the minimum run-length imposed by the 3D Printer's memory.

With a small model potentially requiring billions of droplets for its fabrication, explicit instructions for each droplet will result in enormous files, beyond the memory limitations of the printing device. To overcome this obstacle, two possible avenues for encoding information into machine instructions are being evaluated. The first involves sampling the continuous model at a lattice of points over a few layer at a time, applying a half-toning scheme to the values, and then compressing the resulting digital representation into machine instructions using run-length encoding. The second approach involves thresholding the continuous model into regions of uniform composition at levels reproducible by the printer. Surfaces of constant composition bounding these regions will be found through a tracing algorithm. This thresholded model will then be sliced into layers and printing patterns corresponding to each region's threshold level will be used to fabricate the model. The choice of which method we pursue depends on which one we find to be the most efficient and flexible, allowing us to experiment with as wide a variety of half-toning strategies as possible.

- **Operate Test Bed:** A key element of this program is the operation of a test bed facility at the ExtrudeHone Corporation of Irwin, PA. This test bed will be used to verify the efficacy of the representations, design rules, and simulations developed under this program. It is expected that other university research groups will use this fabrication service to design and create parts which exploit the freedom of composition possible with 3D Printing and it is hoped that new classes of applications emerge from this work. University groups can test both MIT's design tools as well as design tools that they have developed. Industrial designers will also be offered access to the test bed and this will serve both as a test of design tools and an opportunity for creativity. Finally, 3D printing of tooling will be brought into the undergraduate curriculum at MIT by having some of the students in the Junior level class in Design and Manufacturing class create and use the tooling.

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