# Local Composition Control in Solid Freeform Fabrication

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**ABSTRACT:** This article addresses the central impediment to the wide-spread exploration of the potential of Local Composition Control (LCC) in Solid Freeform Fabrication (SFF), and presents a Feature-Based Design (FBD) approach for modeling complex components with LCC. The approach will allow the designer to simultaneously edit geometry and composition until a satisfactory result is attained. The concise and machine-general procedural representation will be maintained throughout the design process and will be evaluated for the purpose of visual feedback to the designer and for post-processing, i.e., the creation of machine-specific instructions for fabrication.

## 1. INTRODUCTION

One of the great potential benefits of Solid Freeform Fabrication (SFF) technology is the ability to control the internal composition of components, a capability not shared by conventional mechanical manufacturing processes – see Figure 1 and for more detailed information see also `http://www.mit.edu/~tdp/info-flow/`. The capability of Local Composition Control (LCC) [1] has only begun to be explored by the research teams advancing SFF and exploited by the companies commercializing the technologies. While several compelling applications are under development, it is likely that the potential is largely untapped.

Development of methods and tools required to support the representation and design of components with LCC is essential to realize the potential utility of LCC. Most CAD research has focused on the representation of 3D geometry of homogeneous objects, on methods and tools for designers to interact with these representations at a high level, and on derivation of machine specific instructions for machining. Creation of complementary capabilities has not been extensively explored. Several of the current approaches proposed for modeling LCC objects include: (1) Voxel-Based Modeling [5,13]; (2) Finite-Element (FE) Mesh-Based Modeling [14]; and (3) Generalized Modeling Methods such as $r_m$-*sets* [10,11,12] and generalized cellular decomposition approach [7,8,16]. An analysis of these representation methods can be also found in [9].

Current approaches either based on volume meshing or general decompositions are awkward in editing geometric and material composition information simultaneously, because they lack the concept of editable LCC features; in effect, they 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. Also as such, design changes cannot be efficiently propagated.

Tessellation of the volume of a model (e.g., 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: (1) 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; (2) 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; (3) methods for tessellation of a volume into tetrahedral meshes suffer from the general robustness problem in computational geometry relating to inexact computation.

In order to overcome these limitations, we propose an approach which builds on the concept of *feature-based design (FBD)* [4,6,18], which involves the following key concepts: (1) by introducing the concept of editable LCC features, the simultaneous editing of geometric and material information is formalized and simplified; (2) maintenance of an unevaluated exact representation for the geometry and composition for as long as possible along the information pathway, provides a high level codification of the design useful in data exchange and in a general setting not associated with a specific SFF process; (3) evaluation of the above exact representation is performed as needed at later stages of the pathway, e.g., for visualization and design verification at an appropriate resolution corresponding to the visualization parameters or for fabrication only at the resolution printable by a particular process.

## 2. FEATURE BASED DESIGN WITH LOCAL COMPOSITION CONTROL

Our FBD approach for modeling parts with LCC can be characterized as a procedural, unevaluated representation, which becomes evaluated on demand at the resolutions of visualization and fabrication. As such our representation is both compact and exact, avoiding approximations and potentially non-robust geometric algorithms. In comparison with conventional solid modeling, feature-based modeling maintains high level data in the model and relations among them. The high level entities in a feature model provide the user information with engineering significance. Although the current FBD systems carry rich information in terms of features, they only allow users to create multi-material solids with piecewise constant composition using composite structures and assemblies. Due to the nature of FBD, such systems usually cover a limited number of features. In order to address these problems, we propose to extend the definition of features in geometric feature models so as to define the semantics of an LCC feature and extend an existing FBD system to facilitate model creation through LCC features.

**Identification and formalization of LCC features:** The identification and creation of a suite of features for the design of LCC parts is an important component of our work. The basic approach will be to identify potential classes of LCC applications and for each class, identify features, which would be useful in design. For the purpose of allowing users to specify composition variation in the interior of a solid, we define an LCC feature as a construct with two attributes: (1) a generic parametrizable shape and (2) a composition function defined over the shape. In terms of data structure, an LCC feature is composed of two substructures, one providing the representation of generic shape, the other providing the representation of composition profile. Therefore, the LCC feature can be viewed as primarily comprising two sub-features, respectively for geometric shape and composition profile. The geometric sub-feature can be any standard geometric feature or its extension by general user-defined feature (UDF) [6] method, i.e., volume features, transition features, pattern features and user-defined features. Composition profile sub-feature has parameters such as material subspace and constraints on material composition. It also possesses attributes defined through composition functions. Composition is the vector of volume fractions of each material defined over the material subspace and the generic shape of the feature. Composition function is the mapping function from the geometric sub-feature to the material subspace. Composition constraints (design rules) are typically inequalities that specify e.g., what material composition or what gradient of material composition can be fabricated.

**Development of LCC feature creation and editing techniques:** Using feature-based parametric design methods, we will develop tools for LCC composition profile design and editing of LCC features via extending a current feature-based design system.

**Development of generic feature-based representation of LCC objects:** We propose a feature-based LCC object modeling approach based on an existing feature-based modeling system. As demonstrated in Figure 2, feature data in such a model are structured into five levels: an assembly model, a LCC feature model, a part (component) model, a feature model and a generic model. The assembly model is the model at the highest level. Hatched arrows in Figure 2 represent the mapping of elements of higher level model to that of lower level models. The generic model is the lowest level model. Its nodes are the topological or geometric entities or parameters that represent a feature. Topology constraints and geometric constraints are the linking relations in the graph. Features are mapped to sub-graphs of the generic entity graph and feature relations are mapped to a set of entity relations. Feature model is composed of features that serve for design applications and their relationships. Features contain the geometric, parametric or functional description of a feature. Feature relations include relative positions, orientations, parametric dependencies between features, etc. Parts are mapped to sub-graphs of the feature graph and part relations are mapped to a set of feature relations. Parts are also mapped to a body data structure via a B-rep solid modelling kernel. The mapping is the procedure of derivation of part shape from features. Part relation usually specifies geometric or non-geometric relation between two parts in an assembly. Some systems implement special part relations, such as part derived from another part through external references, and the one illustrated with red dotted arrow, part referencing a specific component, within a specific assembly. In the implementation of our system via extension of an existing feature Model, the “LCC geometric sub-feature” is a component that maps to part and features. An LCC feature also maps directly to features in the feature model, because certain composition profile sub-feature of the LCC feature will be parametrized with respect to specific feature(s) in the model. Those specific features need to be referenced by the LCC feature. Such reference features could be features of the component of the LCC feature, or features that belong to components of other LCC features. Some LCC features that reference other LCC features for composition profile design require additional LCC feature dependency. For example, LCC features that serve as volume transition between LCC features will depend on the two adjacent LCC features compositions as well. At the highest level is the assembly model. Assembly is a tree with nodes representing assembly features and edges representing the assembly order. Assembly features contain the assembled components and the semantics of the relations between components. Assembly relation is mapped to associated components and the relations between entities of the bodies of the components. Entities are faces, edges or vertices.

**Efficient and robust evaluation of LCC object at different levels of resolution for both visualization and fabrication:** Evaluation of LCC object for visualization and SFF fabrication is an important part of the work. Considering different types of rendering methods and different required resolutions, appropriate intermediate models will be constructed. For example, issues related to 3DP process will be taken into account to accommodate the downstream processing, i.e., machine instruction generation. Efficiency and robustness are very important requirements for the evaluation of LCC object especially when there are a large number of queries to make for the intermediate model and large number of features in the LCC object or the composition profile is very complicated. Composition evaluation algorithms could be customized for different types of LCC features. For example, given an LCC model, where the composition is defined as a function of the minimum distance to the boundary of the model, efficient Euclidean digital distance transform algorithm [17] could be used to approximate the minimum distance at the voxel level.

**Implementation:** A feature-based LCC modeler described above has been partially prototyped. LCC feature data structure has been completed and the class of composition features that represents material composition as a function of minimum distance to the user-defined or user-specified features is developed. Simultaneous editing of both geometry and composition feature is achieved. As an example, Figure 3 demonstrates a tooling part that is made of two materials and designed such that the material compositions around the cooling channel are both function of the minimum distance to that cooling channel. The users can input the lower and upper limit of the distance values and the type of mathematical function. The geometry of this part is constructed by a sequence of feature attachment, among which the cooling channel is a sweep cut feature that is generated by sweep-cutting one closed sketch along a sketch of a path. Here is the LCC feature is mapped to the part and the sweep cut feature and its material composition function is parametrized with respect to the minimum distance to the sweep cut feature. Figure 4 demonstrates the material composition is a combined result of different functions of the minimum distance to different set of user-specified features. When the domains of different distance functions interfere with each other, the material composition is a proportional blend of the involved functions. The blending is efficiently computed via using a binary subdivision tree and classifying dither cells. In this example, there are three materials, and for each material there are two composition profiles with respect to different set of features imposed. One composition profile is parametrized with respect to the distance to the sweep cut feature, the other profile is parametrized with respect to the minimum distance to the union of three features (well, well fillets and the dome). The volume ratio of the material colored with yellow increases linearly from 0 to 100% into certain distance from the two sets of features. And the volume ratio of the material colored with green decrease from 100% to 0% into certain distance from the sweep cut feature, so does the material colored with red with respect to the other set of features. As a special usage of this class of LCC feature, user can define the composition ratio as a function of the minimum distance to the part boundary that is composed of a set of surface features as demonstrated in Figure 5. Efficient evaluation of this class of LCC feature(s) is also developed at required resolutions.

## Applications:

Gradient index lenses: Gradient index lenses refract light by gradients in the index of refraction, rather than by external geometry. Such lenses can provide the functionality normally associated with multi-component ground optics at lower cost and in a smaller space. A cylindrical gradient index lens with composition gradient can be created by extrusion of a 2D closed circle, while the composition function is parametrized with respect to the local cylindrical coordinates as shown in Figure 6. In this application, composition feature that represents analytical functions of user defined cylindrical coordinates needs to be developed. The analytical functions can also be B-spline interpolations of user input. Design rules are to be introduced at the specifics of the GRIN lens, which are represented as mathematical inequalities. In case that the composition is only a function of radius, higher level tool will be developed so that the user can specify the lens in terms of its focal length. Assuming the focal length is large in relation to the lens height, ray tracing methods will be developed that will allow the derivation of the required local index of refraction as a function of the radial coordinate in order to achieve a specific focal length. In this way, a high level functional specification of a part will become possible for the first time in this context.

Parts with wear resistant surfaces: Parts with wear resistant surfaces can be made via 3DP LCC. Hard phases such as TiC can be printed near the surface of a tool for increased wear resistance. A specific feature that represents composition variation from a subset of the boundary that users are interested toward the interior of the body will be developed. Composition function is either an analytical or a B-spline interpolated function of the minimum distance to the target surface. Efficient methods for the evaluation of composition at different resolutions based on spatial subdivision and digital distance transform techniques will be developed for this purpose.

## 3. POST-PROCESSING

Our FBD approach for modeling solids with LCC is generic and applicable to a broad range of SFF technologies. However, in the cases where the outcome is process specific, Three-Dimensional Printing (3D Printing) [15] (see also Figure 1) is used as the prototypical SFF technology. 3D Printing has made it possible to print continuously varying multi-material composition by the simultaneous use of multiple printheads. Post-processing is required to convert the LCC model created by the FBD process into machine instructions for its realization via 3D Printing. In this context, there are two major issues: (1) an intermediate representation scheme should be provided which converts the continuous-tone composition variation into printable, discrete information throughout the volume of an LCC object, to serve as link between design and fabrication stages; (2) as a result of such conversion, the transformed boundary may only approximate the boundary of the LCC object and accordingly, it would lead to difficulty for the precise specification of geometry and composition near the boundary.

A solution to the former issue would be a conversion of the LCC feature model into a voxelized representation, where we note each voxel will correspond to our *3D dither cell* [3]. A 3D dither cell consists of $n_f \times n_s \times n_v$ bi-level sub-voxels for each material in fast, slow, and vertical axis of the 3D Printing device, where fast (slow) axis denotes high (slow) speed raster-scan direction of the machine, respectively, and the vertical axis denotes the direction normal to the layer plane. A set of those 3D dither cells will optimally simulate continuous-tone graded composition of the LCC model in a point-wise fashion as detailed in [3]. The size of a 3D dither cell is in fact arbitrary, which will determine the resolution and hence storage cost of the intermediate voxelized representation. We also note that our dithering approach is generic in terms of LCC modeling/fabrication methods, and can be applied to various kinds of LCC modelers/point-wise fabrication processes in SFF. For example, Figures 7(a,b) show a dithered layer using 3D dithering with a mold example (about half-way up the part). Physical dimension of the bounding box of the part is 6.5*cm* x 4.3*cm* x 1.3*cm* in fast, slow, and vertical axis, respectively. We set the width of an equivalent PEL to be 30μ*m* and its aspect ratio to be 6 – see [3] for the further information. The composition for the object is designed as a function of minimum distance from the object's boundary to place hard phases in a designed composition profile near the boundary surface by locally controlling the volume fraction of two materials. In this example, the composition grades linearly over the region within 3.25*mm* of the object's boundary with the condition that the sum of volume fractions of two materials is everywhere one, creating a skin of designed composition.

As observed in Figures 7(a,b), the ordered dither inevitably produces blurred/coarse boundary or surface finish. Special attention needs to be given to reconciling conflicts which occur at the boundary where the designer's intent in both composition and surface finish must be recognized. In 3D Printing, the issue of boundary reconciliation is taken care of in the encoding stage. Although the encoding scheme is beyond the scope of this article, we briefly describe major techniques associated with surface finish in 3P Printing. 3D printing uses continuous-jet printing with a capability of proportional deflection [15]. In proportionally deflected printing, droplets can be steered to any position within the maximum deflection range in the slow-axis direction. The use of proportional deflection offers significant potential to improve the quality of the printed parts with no compromise in production rate. To achieve an accurate composition/geometry near the boundary, an algorithm is required which identifies the necessary boundary droplets to be printed and the amount of their proportional deflections. Especially, the algorithm should guarantee the concentration $C_b$ of the sum of all binder materials satisfies a required amount $C_\tau$ at the boundary. Such required amount will vary from system to system, however, would typically be between 10% - 50% of full saturation. At present [2,3], $C_\tau$ is forced to be 100% and the amount of proportional deflection is computed from the geometric boundary information. A general scheme is under development, which guarantees sufficient binding at the surface to satisfy the geometric design intent with the minimum possible deviation from the composition design intent.

## 4. CONCLUSION

The major barrier to the wide-spread exploration of the potential of LCC in SFF is due to the lack of electronic representations and design tools for objects with LCC. Most CAD research has focused on the representation of 3D geometry of homogeneous objects, on methods and tools for designers to interact with these representations at a high level, and on derivation of machine specific instructions for machining. Current approaches proposed for modeling LCC objects are awkward in editing geometric and material composition information simultaneously. In effect, they permit sequential editing (i.e., first of geometry and then composition), which is not flexible and limits the designer's options. Current LCC models are also limited to low level data and operators and do not allow for the symbolic representation of the designer's intent with respect to composition. Also as such, design changes cannot be efficiently propagated. In order to address these limitations, our proposed approach builds on the concept of feature-based design (FBD) and extends it from a geometric domain to simultaneous material and geometric editing of features. Key issues involved in our FBD approach to LCC modeling include: identification and formalization of LCC features; development of LCC feature creation and editing techniques; a generic feature-based representation of LCC objects; and their efficient and robust evaluation at different levels of resolution for both visualization and fabrication purposes. An unevaluated exact representation for the geometry and composition is maintained for as long as possible along the information pathway, which provides a high level codification of the design useful in data exchange and in a general setting not associated with a specific SFF process. Evaluation of the exact representation is performed as needed at later stages of the pathway, e.g., for visualization and design verification at an appropriate resolution corresponding to the visualization parameters or for fabrication only at the resolution printable by a particular process. Conversion of an LCC model created by the FBD process into machine instructions is performed via post-processing for its realization via 3D Printing. A voxelized representation relying on the optimal volume dithering is used to serve as an intermediate representation scheme which converts the continuous-tone composition variation into printable, discrete information throughout the volume of an LCC object. As a result of such conversion, the transformed boundary may only approximate the boundary of the LCC object. To achieve an accurate composition/geometry near the boundary, a general scheme will be developed, which guarantees sufficient binding at the surface to satisfy the geometric design intent with the minimum possible deviation from the composition design intent.

## ACKNOWLEDGMENT

NSF under grants DMI-9617750, DMI-0100194.

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## FIGURES

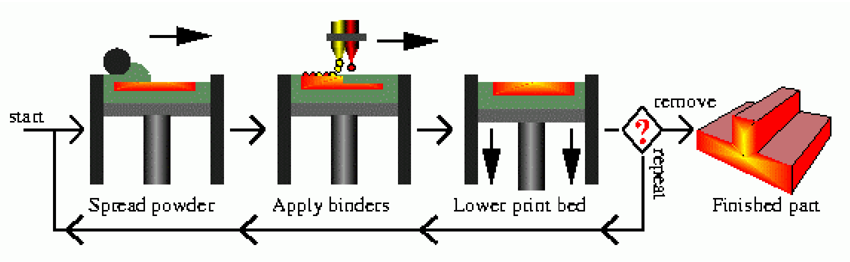

Figure 1: Illustration of Local Composition Control via 3D Printing

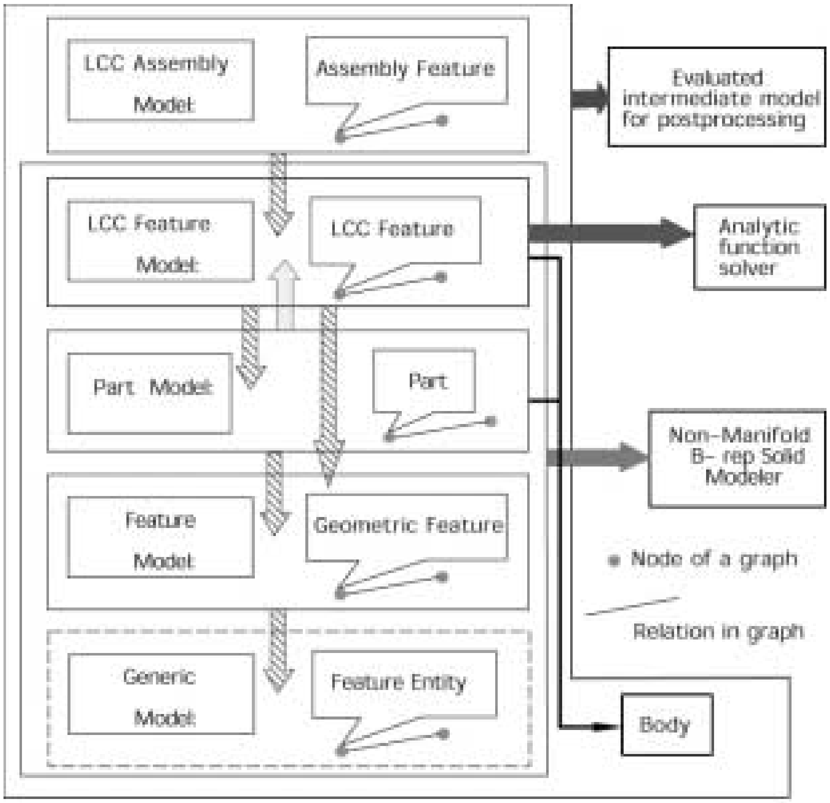

Figure 2: LCC object modeler

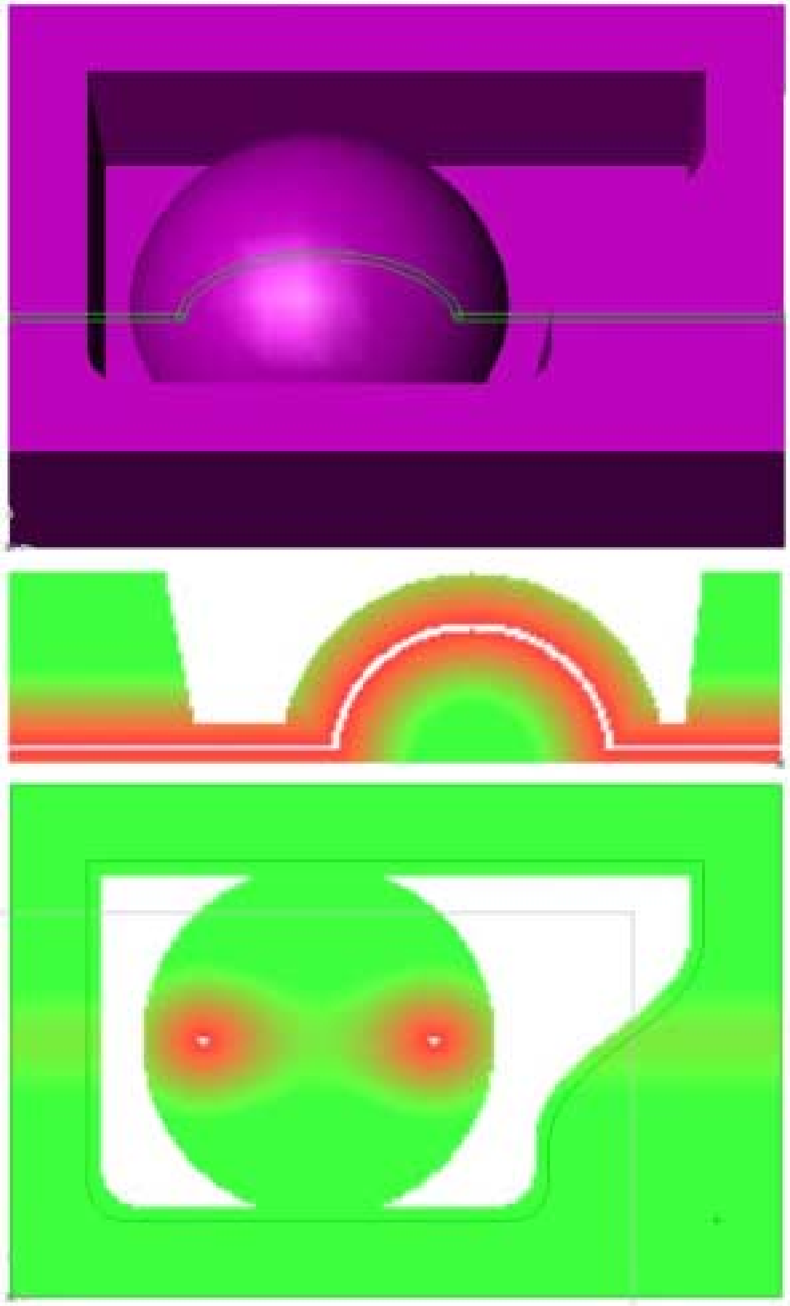

Figure 3:  Implementation: a tooling part – composition around surface feature

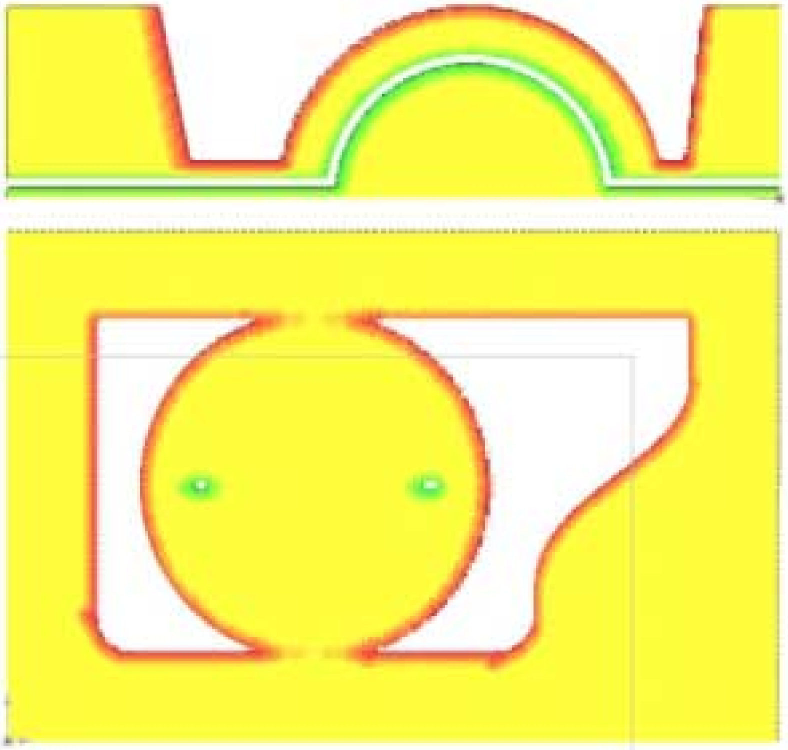

Figure 4:  Implementation: a tooling part – different composition profiles around different surface features

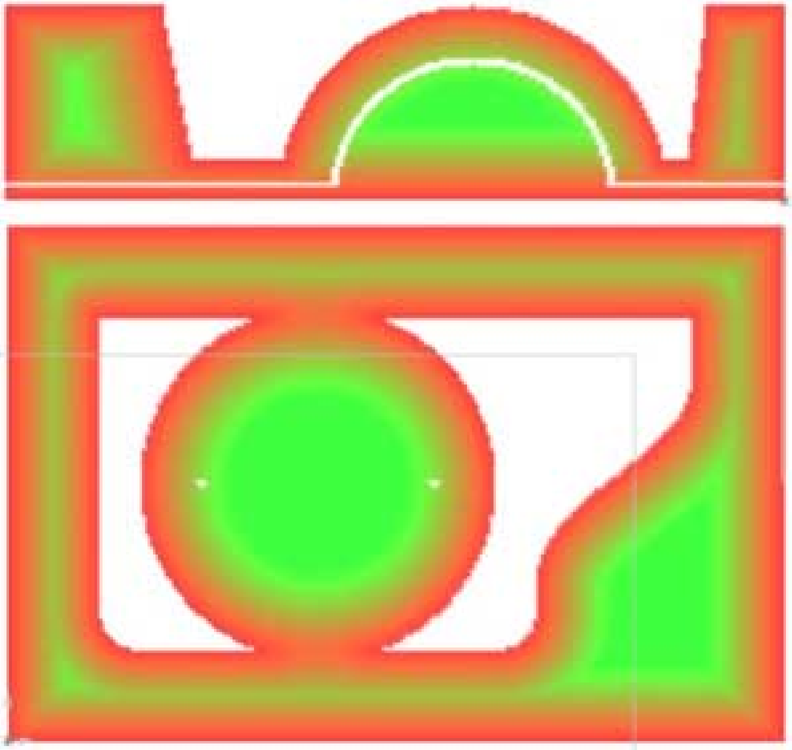

Figure 5:  Implementation: a tooling part – composition ratio as a function of distance to boundary

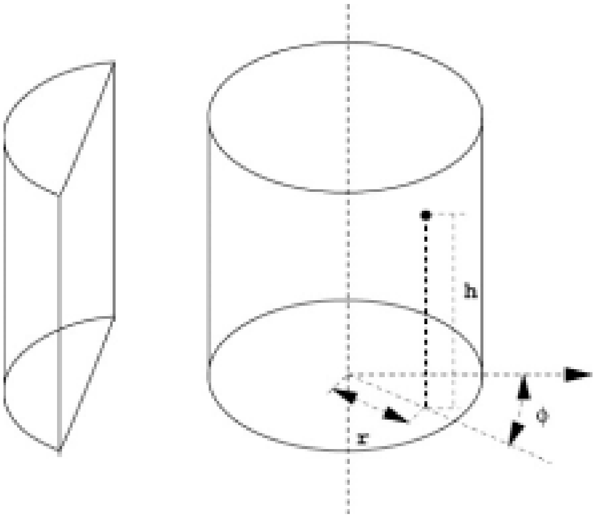

Figure 6: GRIN lens with composition as a function of $(r,h,\phi)$

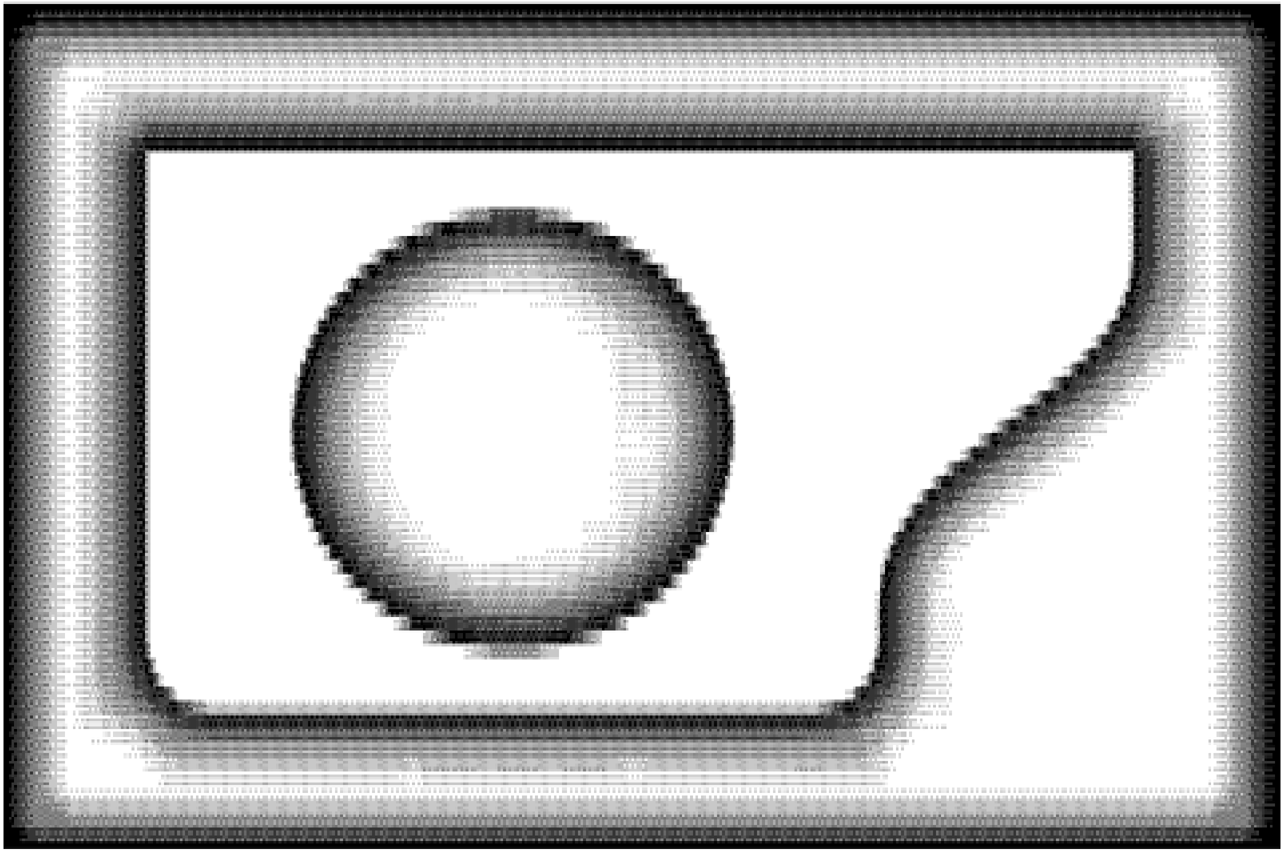

Figure 7(a): A dithered layer for the first material using 4 by 8 by 2 3D dither array with AR of PEL = 6 (for even number layers)

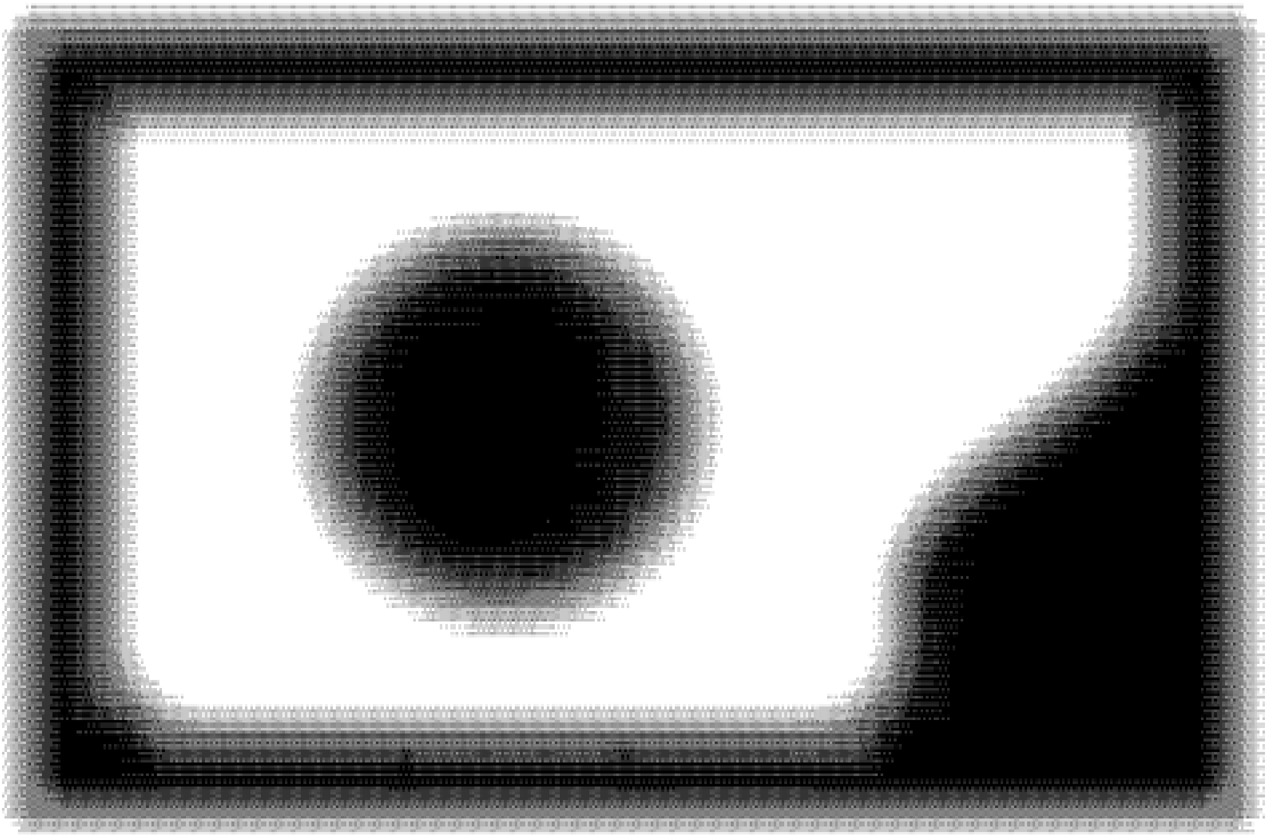

Figure 7(b): A dithered layer for the second material using 4 by 8 by 2 3D dither array with AR of PEL = 6 (for even number layers)