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maxel framework for representing and process planning of Functionally Graded Materials.

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Abstract

Functionally Graded Materials (FGM) are characterized by variation in material composition or density per the required functionality. Inherent ability of various Solid Freeform Fabrication techniques to access bulk volume of part makes it a amenable to fabricating range of functionally graded materials. However, most of the Solid Free Form fabrication follow 2-1/2 additive process. In SFF manufacturing methods the tool path for each layer follows a Zig-zag or similar profile that necessarily is not most optimal path for material delivery. This may led to process inefficiencies. This paper presents a framework based on the *maxel* representation of materials to enable more efficient and accurate manufacturing of FGMs.

Introduction

SFF enables control of material composition and fabrication of hidden geometric features. Most popular SFF techniques are based on deposition of the material in the form of layers. Layered material addition allows process planning to be independent of part morphology. The path for the material deposition end effector along each layer is based on the distribution of two-dimensional curves. Majority of parts fabricated by SFF, layered deposition and the subsequent independence of the process with respect to the part morphology is acceptable. Most of the deposition processes are based on the delivery of material in a discrete amount, which limits the accuracy of the geometry. The post processing such as machining is done in order to remove unwanted material and get a precise geometry. Material composition on the other hand must be controlled very precisely during addition because it is not possible to alter the material composition once the material has been deposited. Recent developments in technology such as computer-based geometry representation and the very precise control of electric drives have allowed the fabrication of a variety of FGM. A FGM part may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. Materials can be designed for a specific function and applications. Various approaches based on the bulk (particulate processing), preform processing, layer processing, and melt processing are used to fabricate FGMs [1].

As described in Figure 1 any SFF based FGM implementation system would comprise of four fundamental units:

1. Material Feeders.
2. Mixer
3. Spatial Manipulator
4. Deposition head
5. Controller

The material feeder feeds different materials in desired composition. The mixer prepares a uniform blend of individual components, and the spatial manipulator delivers the material at a desired location. The controller controls the manipulator and material feeder to provide and form and material distribution.

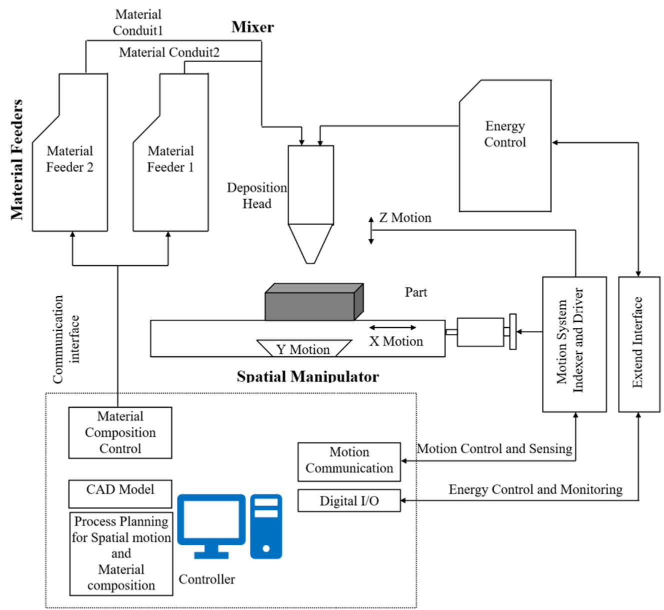


Figure 1 : SFF based FGM fabrication system

The *maxel* as a basic unit of material composition representation was introduced in 2005 [2,3]. The attributes of *maxel* include the location and volume fraction of individual material components. A laser based direct metal deposition (LBDMD) used *maxel* framework for processing planning [3].

This paper describes the *maxel* framework for a general-purpose implementation for fabricating functionally graded materials. System also describes a preliminary implementation of stepper motor based material feeder on a commercial Fuse Deposition 3D printer.

SFF system for FGM fabrication

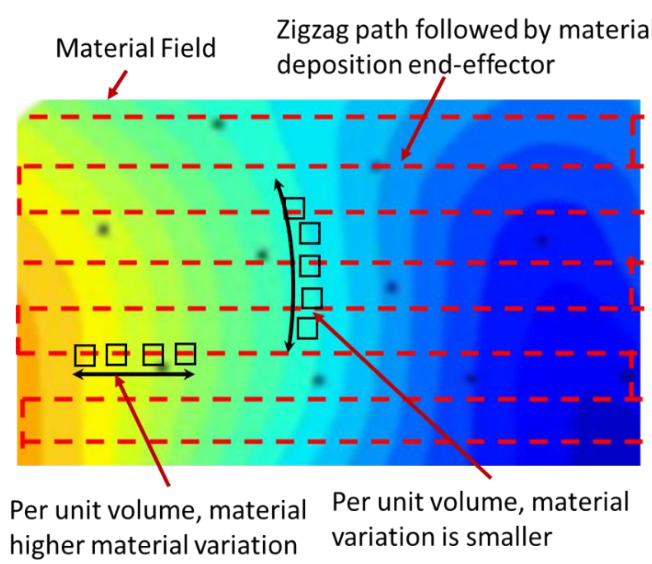


Figure 2 : Material field vs actual material deposition path

For FGM parts, fabrication setup limits the accuracy of desired composition of the part due to frequent variation of composition of material. As described in the Figure 2, usual material deposition by a SFF equipment is some variant of zigzag path. The zigzag path may necessarily not align with the material field. Issues inherent towards getting the desired composition include time lag between the asking for a given composition and when the composition is actually injected at the point of delivery [4]. The most significant parameters that affect the accuracy of material delivery will be (1) the volume of material mixing area (2) the heating rate of material (3) Controllers. When the composition of metal powders is changed, preexisting material in the material mixing area must be removed. This imposes a requirement for a suitable process planning that minimizes variation in composition of material being added during material addition process.

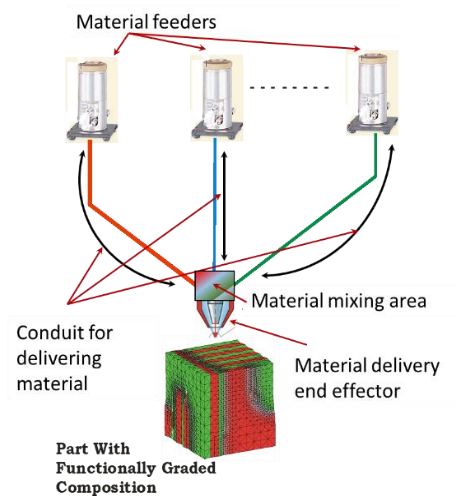


Figure 3 : Material composition adjustment due to distance of the material carrying conduit from the end effector

Method suggested in this paper uses *maxel* framework to optimize the material addition and delivery to minimize the frequency of variation in metal composition during the delivery. Process planning approach also suggests an analytical model for the determination of time for discharge of unwanted material when material deposition end effector moves from one region to another. It also suggests the approach for time determination before the flow of material and subsequent composition becomes uniform.

maxel **based material field representation**

The desired composition of a part made of functionally graded material is governed by the material distribution function of the part. While certain regions of the part have a non-varying material composition, other regions have a varying multi-material composition. Based on the distribution of material composition, the composition is represented by a vector field such that a vector corresponding to the composition of material is attributed to every point in the space as it changes from point to point. FGM material can be expressed by the material vector-space of order m where each coordinate corresponds to a constituent material. The geometric topology of the FGM is expressed by the underlying manifold $M3$of the Eucledian space of order 3 corresponding to the $x-$,$y-$, and $z-$ coordinates. The concept of manifold-and-material space, in essence, captures the intent of spatial-and-material composition continuity. The projections of the manifold-and-material function in the material space along the individual coordinates provide the input for process implementation.
The approach based on establishing a one-to-one correspondence between the spatial regions inside the solid and the composition of the constituent materials result in an undesirable $C0$ continuity. Introducing the time as a parameter so as to express the process model as phase spaces, models the process as a high-dimensional manifold with a vector field indicating how the system changes over time. The inclusion of time to express the spatial motion of the metal deposition end effector and material composition as a function of time ensures a higher order of continuity across the part domain. Also, the time derivative of the spatial function determines the velocity or the input for the spatial manipulator. Similarly, the arrangement of iso-composition curves in the order of composition variation allows for continuity in the state of the drives that control the delivery of

material. For all practical purposes, the manifold *M3* is a topological manifold. A manifold χ is a topological manifold if:

1. χ is locally Euclidean with constant local dimension 3 in the present case.
2. χ is second countable
3. χ is a Hausdorff space.

The composition vector field is a vector each of whose components is a scalar field; that is, a function of spatial and time components expressed as:

$$M(x,y,z,t) = m_1(x,y,z,t)e^\wedge 1 + m_2(x,y,z,t)e^\wedge 2 + m_3(x,y,z,t)e^\wedge 3 + \ldots m_n(x,y,z,t)e^\wedge n \qquad (1)$$

Where M represents the vector field , x, y, z correspond to the spatial coordinates of the part, t is the time and m_1 , m_2.... Represent the spatial function of the part material fraction in the composition at the point of consideration. One of the conditions that must be satisfied is that the material fraction at a given point must add to unity:

$$\sum_{i=0}^{n} m_i(x,y,z,t) = 1 \qquad (2)$$

Equation 2 above in essence is a *maxel.* At a given point defined by position x,y,z and time t. In context of the layered deposition using SFF. Similar to the pixel and voxel based quantization for the image processing and computer graphics, respectively, let us define a term maxel. A maxel corresponds to the quantized material-composition attributed to a sampled 3-dimensional volume. The assignment of material attributes, to the quantized volume is done based on composition averaging over the unit volume of each maxel. maxel-based quantization is expressed as:

$$f_s(x,y,z) = \sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{n=1}^{N} f_{av}(m\triangle x, n\triangle y, p\triangle z)\delta(x - m\triangle x, y - n\triangle y, z - p\triangle z) \qquad (3)$$

Where Δx, Δy and Δz correspond to the sresolution of the material deposition end effector. For every layer, the variation along the z− axis is ignored. The f_{av} is the composition averaged over one *maxel* area such that:

$$f_{av}(x,y,z) = \frac{1}{\triangle x \triangle y} \int\limits_{x-\frac{\triangle x}{2}}^{x+\frac{\triangle x}{2}} \int\limits_{y-\frac{\triangle y}{2}}^{y+\frac{\triangle y}{2}} f(x,y,z)dxdy \qquad (4)$$

Note, that the quantization scheme suggested in the equation 4 ignores the variation of the material composition along the $z-$ direction. Figure 4 shows a sampled and quantized transformation model of a FGM. The Figure is obtained by sampling of the FGM over a minimum resolution volume as provided by material deposition end effector.

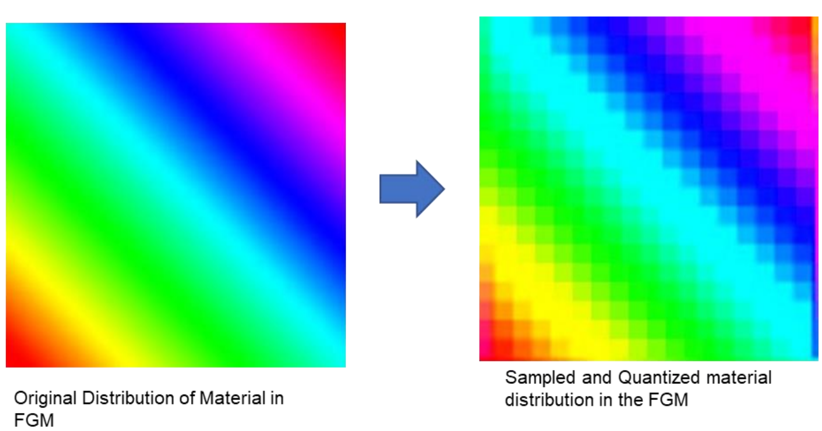


Figure 4 :Sampling and quantization of FGM

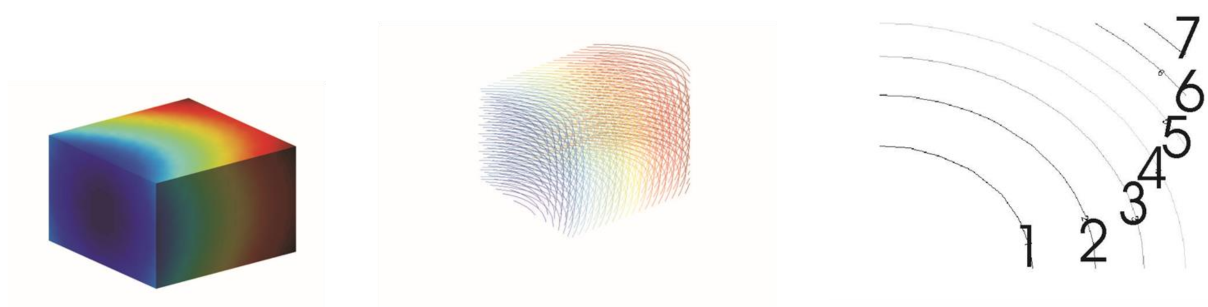
Process planning using *maxel* framework

In order to minimize the point to point material composition variations, parameters that must be taken into account during the process planning includes the volume of the region where constituent material mix and melt. Sufficient time must be provided unless the composition of the material becomes homogeneous and the rate of flow is consistent. Therefore, the geometry of the path should be such that it follows the direction of least gradience of the composition. For certain regions, a smooth variation of composition may allow part fabrication by a coordinated control of electric drives. The same may not be possible for other regions where change in the composition of material is discontinuous. A shift of regions and discontinuity in metal deposition enforces the inclusion of a sufficient time to discharge the metal already present in the material mixing region and the time required before another set of materials or composition becomes stable. Another factor associated with material variation is that the material composition requires a change in the settings of drives for the powder feeder and spatial movement. The above discussions suggest the following list of factors the path planning method can address:

1. The path should be directed along the direction of minimum decent of the composition variation.
2. Determination of the time required before the delivery of the desired composition of material becomes uniform.
3. The time before excess material is removed when shifting from one region to another.
4. The geometric and the material parameters must be represented by a finite amount of data.
5. The distance between the path segments must be able to take into account the geometry corresponding to the size of the material deposition resolution and the allowable overlap between the depositions.

The first step towards part fabrication by SFF is slicing the computer model of a solid into a set of layers. The next step is to generate a path for each layer. The path planning technique for fabricating FGM must take into account the requirements for geometry as well as the material composition. The existing approaches of path planning are based on the trivial assumption of material homogeneity. This imposes the requirement of path planning for FGM to be viewed from entirely different point of view.

The existing strategies for path generation may be classified into evolving curves, which include the zig-zag type and contour type, spirals, and the space filling curves [5,6,7]. The same idea may be extended to the path planning for FGM with certain modifications.



(a) Functionally Graded Solid (b) Sliced FGM and iso-contours for the slices (c) Ordered iso-contours for a slice

Figure 5 : Slicing and derivation of iso-composition contours for a FGM Solid

Let us define the iso-composition contour, which is widely used for the implementation of the process. The iso-composition contour corresponds to a two-dimensional curve that connects points with a similar composition. Figure 5(a) shows a FGM solid, Figure 5(b) is the sliced model and the subsequent iso-composition contours derived for each of the fields. Figure 5(c) depicts a set of iso-composition contours derived from a 2D field arranged in the order of variation of the composition.

Contrary to the popular methods of representation that are based on the subdivision of volume of the original solid into a set of sub volumes and attributing the material to each sub volume, we propose an algorithm based on the representation of the solid by spatial curves corresponding to the torch path and attributing the material

properties to each curve. The algorithm may be described as:
Step 1 Slice the solid.
Step 2 For each slice, segment the area of the slice based on the boundaries that depict a sharp variation in the metal composition.
Step 3 For every region connect the points of similar composition to generate iso-composition contours. The distance between the iso-composition contours is governed by the minimum allowable distance in deposition.
Step 4 Arrange the order of build for each curve based on the minimum variation of the material composition.
Step 5 When the distance between two iso-composition contours is more than the allowable distance, generate the intermediate curves by interpolation.

Experimental setup for FDM based multi-material feeder
Taubert[8] successfully demonstrated multi-color extrusion using FDM on a RepRAP pltatform and is limited by First In First Out.   Design of a common extruder is still in development therefore authors used an approach similar to one used by Carton. Et al [9]. However, instead of sustaining same feeder rate as used the authors actively controlled the material feed rate for each extruder to obtained a cumulative same material flow.

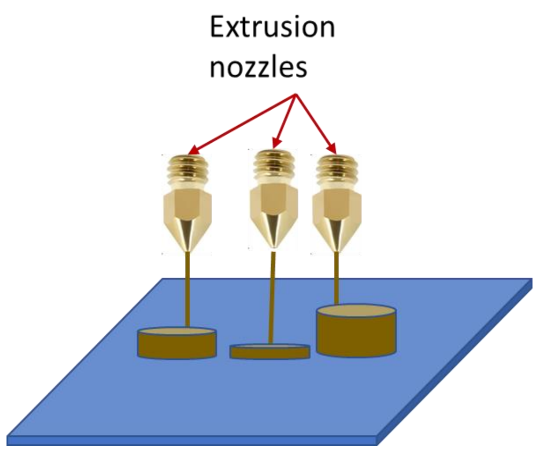


Figure 6 : Schematic for multi-extrusion setup for experiment

The scope of this work includes testing *maxel* based approach to deposit material in a required composition from a set of material feeders to a common extruder. Figure 6 describes the schematic of the material deposition. Three extruders are actuated using multiple stepper motors as described in Figure 7.

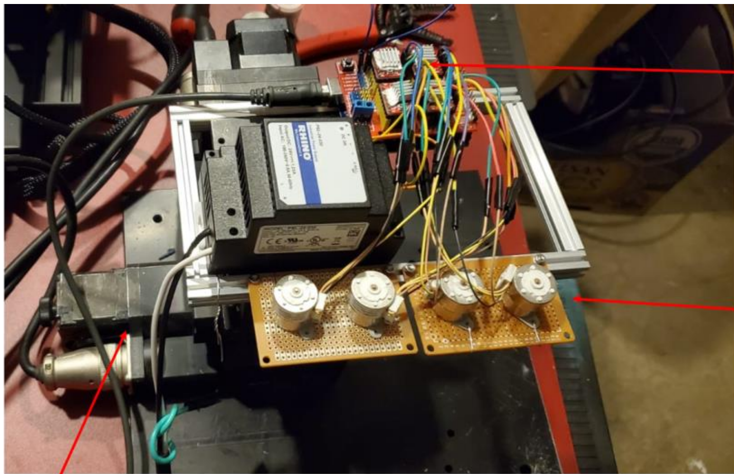


Figure 7 : Experimental setup for multi material deposition end effector

PLA 1.75mm was used for deposition and the orifice diameter for each extruder is 0.4mm. Three PM25L-024-HHC5 permanent magnet bipolar stepper motors are used to feed the material. The stepper motors are high torque small form factor to enable uniform material flow. Three stepper motors are actuated with max speed 18rpm. The stepper motors are controlled using an open-source Arduino CNC module. Combined extrusion volume is approximately 16mm^3 per second. The heating requirement for all three filament feeders is higher than the one available therefore, material is accumulated on a common substrate and weighed for effectiveness of the material feeding. The manipulation platform is a repurposed 3 axis goniometer based on Suruga-Seiki K332 8N with a positional accuracy of 10μm at a speed of 10mm/sec.

Table 1 : Experiments for material flow

	Speed rpm				Results	
Experiment	Stepper 1	Stepper 2	Stepper 3	Effective	Speculated Weight (g)	Observed wt (g)
1	0	9	9	18	2.4	1.9
2	3	3	12	18	2.4	1.75
3	6	12	0	18	2.4	1.92
4	9	9	0	18	2.4	1.87
5	12	3	3	18	2.4	1.87
6	15	3	0	18	2.4	1.92

For a cumulative effective speed of 18rpm, three motors are actuated at different speed as described in Figure 8 and Table 1. For a speculated total material weight of 2.4 g observed total material weight is 1.75g-1.92g. Other than experiment 2 that shows a total weight of 1.75g material, the variation in the weight is within 0.05g. Experiment 2 also has significant speed variation (3rpm vs 12rpm) between the motors.

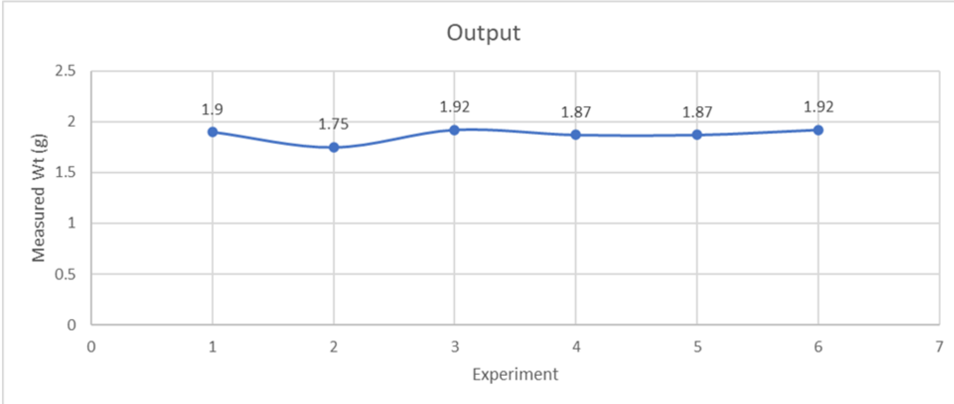


Figure 8: Material variation

Conclusion/Summary/ Future work

A *maxel* framework based multi-material addition process is described. A set of experiments are performed with 1.75mm PLA. For a three extrusion material deposition end effector, the *maxel* based material addition show a maximum variation of 0.17g however ignoring the outliar, the variation is observed within 0.05g. Additional experiments will be performed to determine the root cause. For an expected total weight of 2.4g the output weight is observed to be 1.75g -1.92 g. the speculated reason is variation between estimated weight vs the stepper motor drive. Additional experiments are required for stepper rate vs material feed rate caliberation.
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Resources:

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