Compensation zone approach to avoid Z errors in Mask Projection Stereolithography builds

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Abstract

Print-through results in unwanted polymerization occurring beneath a part cured using Mask Projection Stereolithography (MPSLA) and thus creates error in its Z dimension. In this paper, the "Compensation zone approach" is proposed to avoid this error. This approach entails modifying the geometry of the part to be cured. A volume (Compensation zone) is subtracted from underneath the CAD model in order to compensate for the increase in the Z dimension that would occur due to Print-through. Three process variables have been identified: Thickness of Compensation zone, Thickness of every layer and Exposure distribution across every image used to cure a layer. Analytical relations have been formulated between these process variables in order to obtain dimensionally accurate parts. The Compensation zone approach is demonstrated on an example problem.

1. Introduction

Mask Projection Stereolithography (MPSLA) is an additive fabrication process used to build physical components out of a photopolymer resin. The CAD model of the part to be built is sliced by horizontal planes and the slices are stored as bitmaps. These bitmaps are displayed on a dynamic mask and are imaged onto the photopolymer resin surface. When a bitmap is imaged onto the resin surface, a layer corresponding to the shape of the bitmap gets cured. This layer is coated with a fresh layer of resin by lowering it inside a vat holding the resin and the next layer is cured on top of it. By curing layers one over the other, the entire part is built. The schematic of the MPSLA system realized at Georgia Tech. is shown in Figure 1.

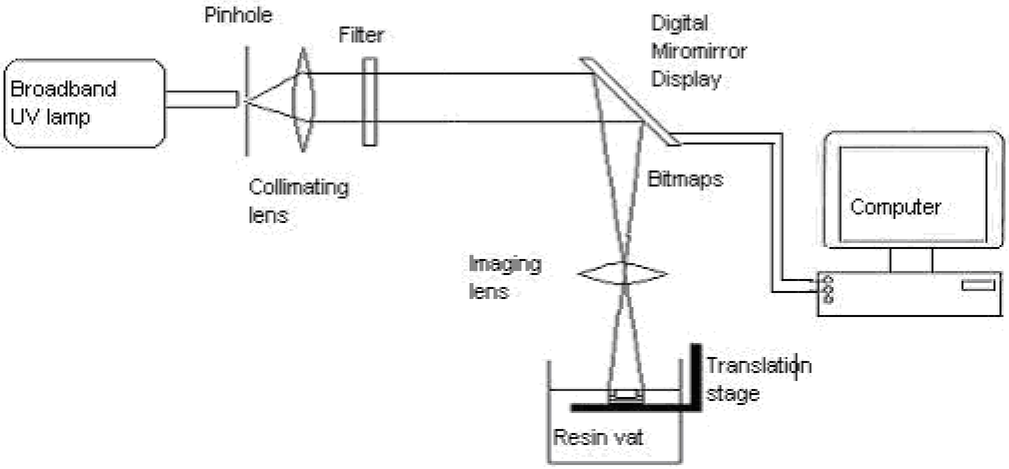


Figure 1 Schematic of the MPSLA system developed at Georgia Institute of Technology

MPSLA can fabricate true 3D geometries as opposed by 21/2D shapes fabricated by other micromachining techniques like silicon etching and LIGA (Madou, 1997) and so, can be a valuable tool to fabricate as well as package MEMS components. The applications like miniature reaction chambers for bio and chemical sensors and micro fluidic devices like micropumps and microvalves have been envisioned in (Tse et al., 2003). In order to realize this potential of the MPSLA process, the process should be able to fabricate accurate microstructures. The MPSLA process needs to be analytically modeled and efficient process planning method should be formulated to fabricate accurate parts.

Since the process is quite new, most work on it is experimental in nature. MPSLA systems have been realized by (Bertsch at al., 1997, Chatwin et al., 1998, Beluze et al., 1999, Chatwin et al., 1999, Farsari et al., 1999, Monneret at al., 1999, Bertsch et al., 2000, Farsari et al., 2000, Bertsch et al., 2001, Monneret et al., 2001, Hadipoespito et al., 2003, Limaye and Rosen, 2004). Most of the research presented in these papers is experimental. In (Limaye and Rosen, 2004) we have presented the MPSLA system realized at Georgia Tech. The system comprises of broadband UV lamp as the light source, a Digital Micromirror Device (DMD) from Texas Instruments as a dynamic mask and an automated XYZ stage from ASI imaging. We cure parts out of the DSM SOMOS 10120 resin with our system. In (Limaye and Rosen, 2004) we have modeled the lateral dimensions of a layer cured using our MPSLA system in terms of the process parameters. The irradiation of the resin surface has been modeled using the ray tracing approach (Smith, 1990). The curing characteristics of the resin have been empirically modeled by plotting its working curve. In (Limaye and Rosen, 2005), we have used these models to formulate a process-planning method to cure a layer with the required lateral dimensions. This method is used to generate the bitmap to be displayed on the DMD and compute the time for which it should be imaged onto the resin surface to cure the desired layer. Using this process planning method it is possible to cure layers within 3% error in their lateral dimensions.

The vertical dimension of a MPSLA part built by curing dimensionally accurate layers over one another is not equal to the algebraic summation of the individual layer thicknesses and involves some errors. These errors are a result of unwanted curing occurring due to Print through (Section 2). In Section 3, a method called "Compensation zone approach" is proposed to compensate for this unwanted curing. Analytical relations between the various process parameters are derived to avoid the Print through errors using the Compensation zone approach. The Compensation Zone approach is applied to an example problem in Section 4.

2. Print through error

Whenever a layer is cured, radiation penetrates beyond its intended thickness and ends up exposing the resin underneath it. As the radiation propagates through the resin, it gets attenuated according to the Beer Lambert's law of absorption. The exposure received by the resin at a depth z from the surface is given by

$$E(z) = E_0 e^{-z/D_p} \qquad (1)$$

where $E(z)$ is the exposure at the depth z in resin,

E_0 is the exposure at the resin surface,

D_p is the depth of penetration, which is a resin constant.

The resin beneath a MPSLA build gets exposed due to radiation penetrating to it from all the layers cured above it. Exposure being additive, a point is reached when the exposure received by the resin underneath the MPSLA part equals the threshold exposure for polymerization (E_c).

This unwanted curing causes an increase in the vertical dimension of the part. This error is called as the Print through error. The source of Print through error is depicted pictorially in Figure 2.

Commercial Stereolithography machines offer the user an option called "Layer compensation" to compensate for Print through (3D Systems user manual). In this approach, the bottom most layer of a part is skipped to compensate for the increase in vertical dimension that would occur due to Print through. This is an ad-hoc approach, which assumes that the increase in Z dimension due to Print through is always equal to the thickness of the lowermost layer. Also, by skipping the lowermost layer, the details at the bottom of the part are lost. Furthermore, the approach can be used to control errors occurring only on horizontal down facing surfaces and is ineffective in controlling the errors occurring in slanting and curved down facing surfaces.

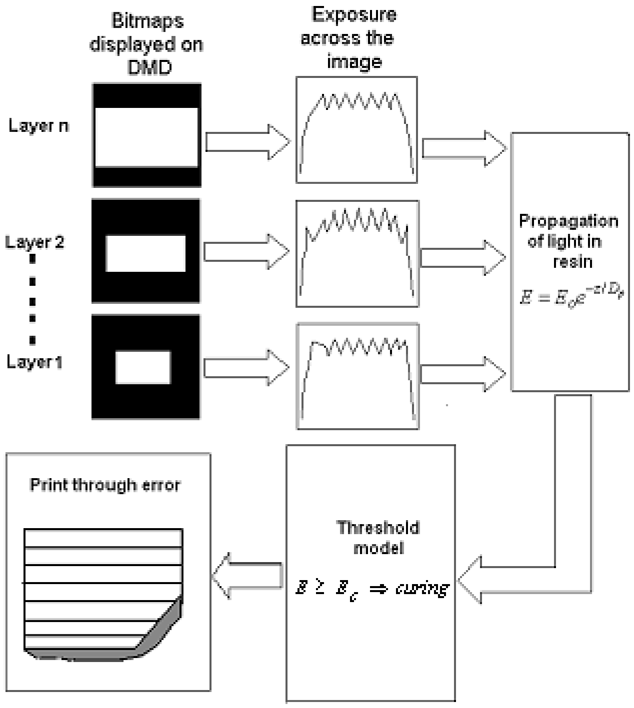


Figure 2 Print through error

3. Compensation zone approach

In this paper, we propose a method we call as the "Compensation zone approach" to avoid Print through errors in MPSLA builds. This method entails subtracting a tailored volume (Compensation zone) from underneath the CAD model in order to compensate for the increase in the Z dimension that would occur due to Print-through. By controlling the process parameters, including the thickness of the Compensation zone, it is possible, in theory, to eliminate the Print through errors completely.

The following are the process variables, i.e. process parameters under user control.

- Thickness of the Compensation zone, given by the function $Z_c(x,y)$
- Thickness of every layer given by the function $LT_k(x,y)$, where $LT_k(x,y)$ is the thickness of the kth layer.
- Exposure supplied to cure every layer, given by function $E_k(x,y)$

The fixed process parameters are the resin properties:

- Threshold exposure of polymerization E_c
- Depth of penetration D_p, which is a measure of the attenuation of light as it passes through the resin.

3.1 Relation between layer thickness $LT_k(x,y)$ and exposure $E_k(x,y)$

The exposure $E_k(x,y)$ supplied to cure the k^{th} layer should cure the layer to a depth greater than or equal to the thickness of the layer $LT_k(x,y)$ so as to ensure that the layer does not float away. In other words, $E_k(x,y)$ should be such that the exposure at the depth $LT_k(x,y)$ should equal to E_c. In order to minimize the Print through error, and thereby the thickness of the Compensation zone, this exposure should be as low as possible. Assuming the Beer Lambert's law of absorption for radiation attenuation and the threshold model for resin cure (Jacobs, 1992), equation (2) can be derived.

$$E_k(x,y) \geq E_c e^{LT_k(x,y)/D_p} \tag{2}$$

3.2 Relations between layer thickness $LT_k(x,y)$ and Compensation zone $Z_c(x,y)$

When the k^{th} layer is cured, radiation would penetrate beyond its intended thickness and expose the bottom surface of the part. Assuming that the radiation is attenuated according to the Beer Lambert's law, the exposure received by the bottom surface due to radiation coming from the kth layer will be given by equation (3).

$$E_{bk}(x,y) = E_k(x,y)e^{-(\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y))/D_p} \tag{3}$$

where the exponential term $\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y)$ is the height of the top of the kth layer from the bottom surface.

The bottom surface would receive exposure penetrating to it from all the n layers cured above it. So, the total exposure received by the bottom surface will be given by

$$E_b(x,y) = \sum_{k=1}^{n} E_{bk}(x,y) \tag{4}$$

where n is the number of layers the part is made up of.

Substituting the value of $E_{bk}(x,y)$ from equation (3), the exposure received by the bottom surface is given by equation (5).

$$E_b(x,y) = \sum_{k=1}^{n} E_k(x,y)e^{-(\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y))/D_p} \tag{5}$$

The exposure received by the bottom surface should be equal to E_c in order to have accurate vertical dimension, i.e.

$$E_b(x,y) = E_c \tag{6}$$

From equations (5) and (6),

$$\sum_{k=1}^{n} E_k(x,y) e^{-(\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y))/D_p} = E_c \tag{7}$$

Substituting the value of $E_k(x,y)$ from equation (2) into equation (7),

$$\sum_{k=1}^{n} E_c e^{LT_k(x,y)/D_p} e^{-(\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y))/D_p} = E_c \tag{8}$$

Canceling the term E_c in equation (8), we get the first relation between the layer thickness $LT_k(x,y)$ and Zone of compensation $Z_c(x,y)$ as given by equation (9).

$$\sum_{k=1}^{n} e^{LT_k(x,y)/D_p} e^{-(\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y))/D_p} = 1 \tag{9}$$

The height of the part is the algebraic summation of the thickness of every layer and the thickness of the Compensation Zone. The height of the part can be readily obtained from its CAD model as $h(x,y)$, and will be given by equation (10). This is the second relation between the layer thickness $LT_k(x,y)$ and Zone of compensation $Z_c(x,y)$

$$h(x,y) = \sum_{k=1}^{n} LT_k(x,y) + Z_c(x,y) \tag{10}$$

In order to build a MPSLA part with accurate vertical dimensions, process parameters should be selected so that equations (2), (9) and (10) are satisfied. The Compensation Zone approach can be represented as a problem of solving simultaneous equations as follows.

Given

- Geometry of the part *h(x,y)*
- Resin properties: Depth of penetration D_p and Threshold exposure of polymerization E_c

Find

- Thickness of all layers $LT_k(x,y)$
- Thickness of Zone of Compensation $Z_c(x,y)$
- Exposure supplied to cure every layer $E_k(x,y)$

Satisfy

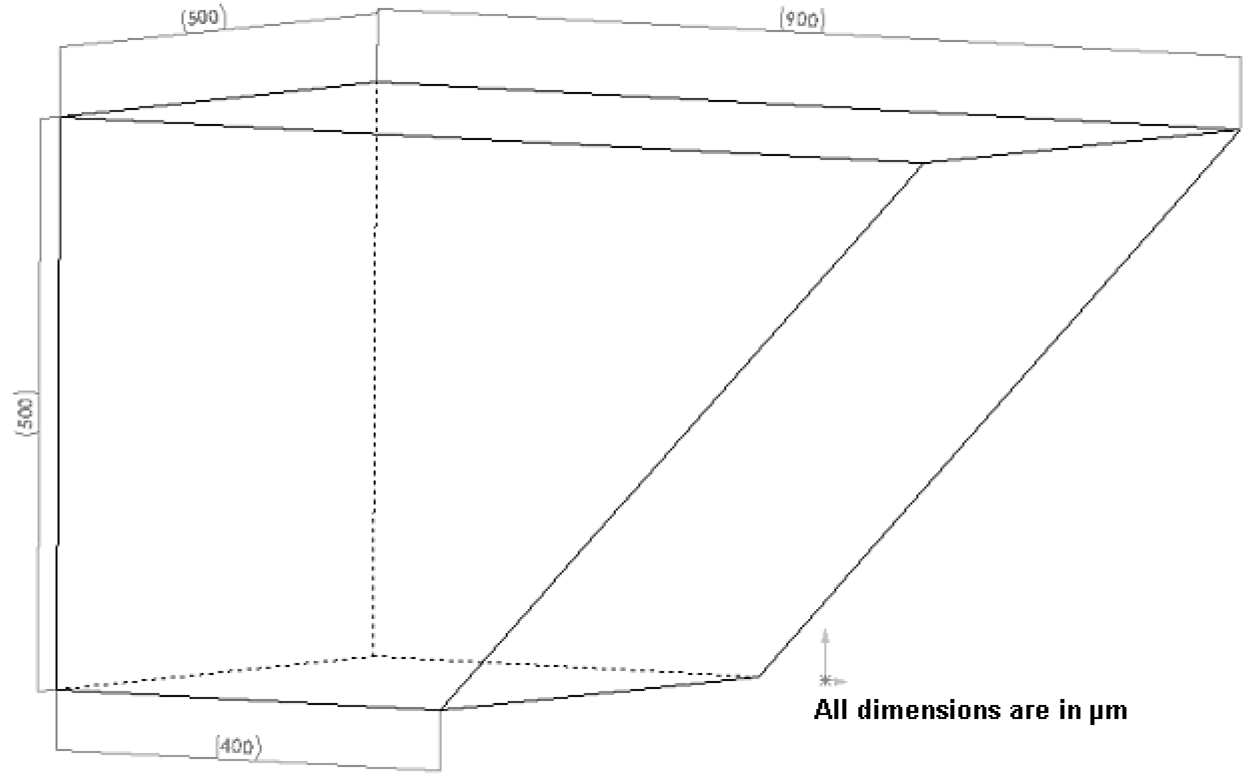
- $E_k(x,y) \geq E_c e^{LT_k(x,y)/D_p}$ (Equation (2) in Section 3.1)
- $\sum_{k=1}^{n} e^{((LT_k(x,y)+OC_k(x,y))/D_p)} e^{(-\sum_{m=1}^{k} LT_m(x,y)+Z_c(x,y)/D_p)} = 1$ (Equation 9 in Section 3.2)
- $h(x,y) = \sum_{k=1}^{n} LT_k(x,y) + Z_c(x,y)$ (Equation 10 in Section 3.2)

The above problem has more variables than equations and is thus an under-constrained problem with multiple solutions. So, additional constraints, like those on vertical resolution, build time etc. can be imposed on the process planning.

4. Implementing the Compensation Zone approach

The problem formulated in Section 3 involves more variables than equations. So, the simultaneous equations would have multiple solutions. In order to have a unique solution, additional constraints would have to be imposed on the process. The solution can then be computed using a root finding algorithm. In this section, the approach is explained by considering an example.

Example: The micro part with dimensions as shown in Figure 3 is to be built in a resin with known values of E_c and D_p. The height of the part is 500µm. The part has a horizontal and a slanting down-facing surface. The slanting down-facing surface is at an angle 45° to the horizontal plane. Determine the thickness of every layer, the exposure to be supplied to cure each of these layers and the thickness of the Compensation Zone that has to be subtracted from the beneath the part, in order to cure the down facing surfaces accurately.



All dimensions are in µm

Figure 3 MPSLA part built to validate the Compensation Zone approach

Solution:

The following simplifying assumptions are made in order to solve the problem.

- The thickness of every layer is constant and equal to 100µm except near the edges of the part. By this assumption, only the layer just above the compensation zone will have a thickness other than 100µm, while all other layers will have a thickness equal to 100µm. Mathematically, this can be represented as

For any point (x_1,y_1),
$0<LT_t(x_1,y_1)<100$, *then*
$LT_k(x_1,y_1) = 0$ *or* $LT_k(x_1,y_1) = 100$, *for all k from 1 to n but k not= t* (11)
$LT_m(x_1,y_1) \geq LT_n(x_1,y_1)$ *for all m>n*

- This thickness of the Compensation zone is to be kept to its minimum. For this, each layer would have to be supplied with the minimum possible exposure.
For any point (x_1,y_1),
$E_k(x_1, y_1) = E_c e^{(LT_k(x_1,y_1)/D_p)}$ (12)

With these two assumptions, the problem now has a unique solution. The simplified problem is shown in Figure 4.

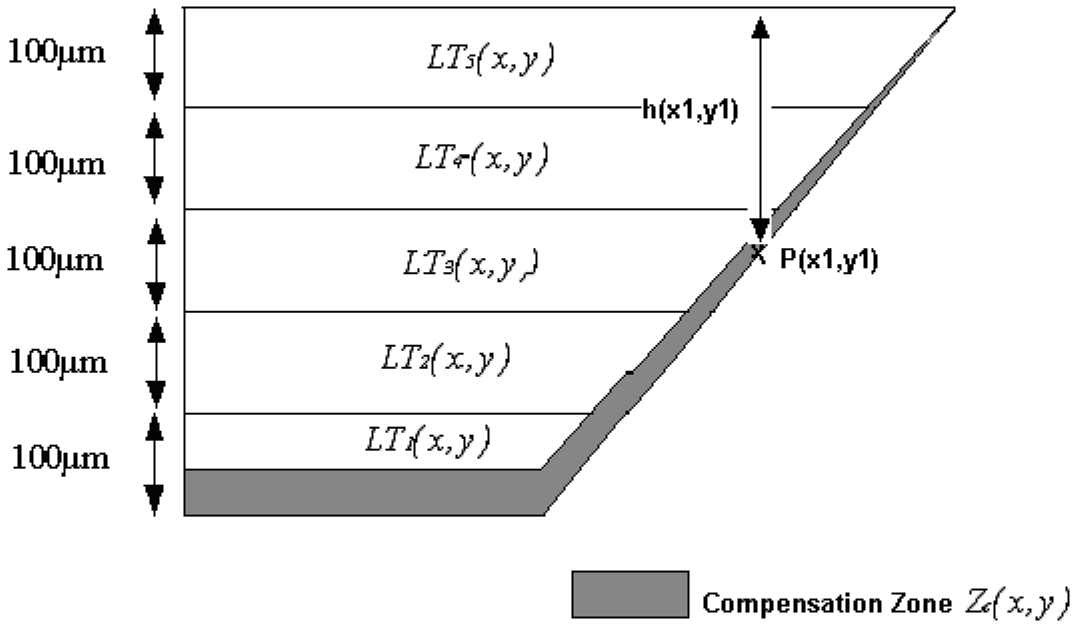


Figure 4 Simplification of the example problem

The simplified problem can be expressed as follows

For any point $P(x_1,y_1)$ on the part in Figure 4:

Given

- $h(x_1,y_1)$

Find

- $LT_k(x_1,y_1)$
- $Z_c(x_1,y_1)$
- $E_k(x_1,y_1)$

Satisfy

- $0<LT_t(x_1,y_1)<100$, then
  $LT_k(x_1,y_1) = 0$ or $LT_k(x_1,y_1) = 100$, for all k from 1 to n but k not= t
  $LT_m(x_1,y_1) \geq LT_n(x_1,y_1)$ for all $m>n$
- $h(x_1,y_1)=\sum_{k=1}^{n} LT_k(x_1,y_1)+Z_c(x_1,y_1)$
- $\sum_{k=1}^{n} e^{LT_k(x_1,y_1)/D_p} e^{-(\sum_{m=1}^{k} LT_m(x_1,y_1)+Z_c(x_1,y_1))/D_p} = 1$
- $E_k(x_1,y_1)=E_c e^{LT_k(x_1,y_1)/D_p}$

The first two constraints in the Simplified problem formulation create a one to one correspondence between $Z_c(x_1,y_1)$ and the combination of layer thickness values $LT_k(x_1, y_1)$. The value of $Z_c(x_1,y_1)$ which would converge the function

$$\sum_{k=1}^{n} e^{(LT_k(x_1,y_1)/D_p)} e^{(-\sum_{m=1}^{k} LT_m(x_1,y_1)+Z_c(x_1,y_1)/D_p)}$$

to its desired value, i.e. 1, can be determined by binary search. To start the binary search, the minimum value and maximum values of $Z_c(x_1,y_1)$ are assumed to be 0µm and 100µm respectively. Once the values of $Z_c(x_1,y_1)$ and $LT_k(x_1,y_1)$ are determined by binary search, the values of $E_k(x_1,y_1)$ can be determined using the fourth constraint.

The XY extents of the example part are 900µmX500µm. These extents were discretized into 18X10 grid of points. At each of the points, the values of Z_c and LT_k and E_k were determined. The grid was kept this sparse to reduce the computation time. In theory, the separation between grid points can be made as small as the size of a pixel irradiated by a single micromirror on the mask. 18X10 matrices for the Zone of compensation, the layer thicknesses and the exposures to be supplied to the layers have been generated. The profile of the part that would be cured has been simulated. As shown in Figure 5, the Compensation zone to be subtracted at the horizontal down facing surface of the part is 14.7µm. The Compensation zone to be subtracted from underneath a layer varies depending upon the distance of the layer cured on top of it. For example, the Compensation zones denoted A and B in Figure 5 receive the same exposure from layer 3. However the layers 4 and 5 are situated closer to Compensation zone A than B and so, A receives more radiation penetrating from them than does B.

5. Conclusions

The Compensation Zone approach ensures that the bottom most surface of the part being built receives an exposure exactly equal to the threshold exposure of polymerization (E_c). This approach however is based upon certain assumptions. It assumes the threshold model of exposure, i.e. there is no partial curing, it assumes that the attenuation of radiation as it passes through liquid resin and cured layers are the same. Further, the approach also assumes that the exposure is additive. Due to these assumptions, the Compensation Zone approach is unlikely to eliminate the Print through error completely.

The Compensation Zone approach can be adopted to reduce the problem of stair stepping to create layers conforming to slanting and curved part boundaries. For example, in the Figure 4, the stair steps are of size 50µm. The size of the stair-steps can be further reduced by increasing the density of the matrix used to populate the part near its edges. This can improve the surface finish on the down facing surface of the part further.

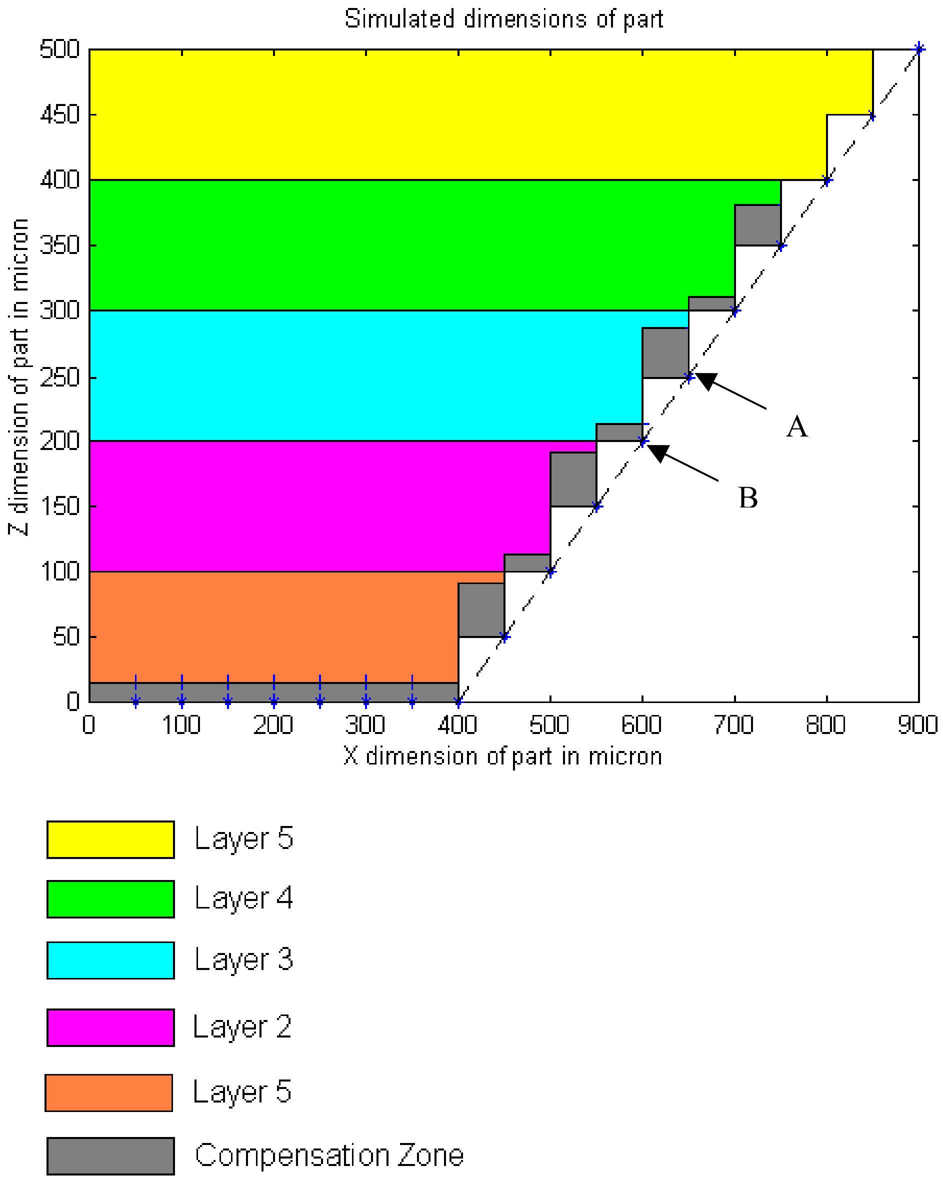


Figure 5 Simulated profile of the part that would be built using the Compensation zone approach

6. Future Work

The Compensation Zone approach shall be used to build the example part on the MPSLA machine at Georgia Tech whose dimensions shall be compared with those of the simulated part.

The MPSLA process needs to be made robust against changes in resin properties E_c and D_p caused by unwanted radiation (e.g., ambient light, print-through) that can cause partial polymerization. A method to compute the values of the process variables so that the process becomes robust against change in resin properties shall be formulated.

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