FDM Systems and Local Adaptive Slicing

Justin Tyberg and Jan Helge Bøhn

Mechanical Engineering, Virginia Tech
Blacksburg, VA 24061-0238, U.S.A.
tel.: 540-231-3276, fax.: 540-231-9100, e-mail: bohn@vt.edu

Fabrication times for layered manufacturing systems can be significantly reduced by continuously maximizing the build layer thickness, within the bounds of the system's fabrication capabilities and the surface deviation tolerance derived from the part surface geometry. This paper describes how parts and features within a build volume can be adaptively sliced independently of each other such that each is fabricated with distinct build layer thicknesses. This enables significant reduction in fabrication times relative to conventional adaptive build layer thickness techniques. The new approach has been implemented on a FDM 1600 rapid prototyping system, together with a revised system calibration to ensure smooth surface transitions between dissimilar build layer thicknesses.

1 Introduction

Fused Deposition Modeling (FDM) is today the second most common commercial layered manufacturing system. It fabricates parts by extruding molten wax or thermoplastic material through a small nozzle to form a thin bead or "road" that is deposited in a predetermined pattern to complete each build layer, bonding the extrudate to adjacent and previously deposited roads. The motion of the extrusion system operates under three-dimensional computer numerical control (CNC). The extrusion system consists of a small ram extruder in which the spooled filament feedstock pushes molten material through the liquefier with low shear. The feedstock is driven into the extruder by counter rotating rollers as needed under CNC, where it is heated to a manually set temperature, T_L. The extrudate is deposited within a build chamber holding a manually set temperature, T_C. In the FDM 1600 rapid prototyping system, T_L and T_C can be up to 300°C and 70°C, respectively.

The most common build material used with FDM systems is P400 ABS plastic (Stratasys, Inc.), and it is available in several stock colors, including white, red, blue, green, yellow and black. This material is, in the FDM 1600 rapid prototyping system, typically extruded with T_L and T_C set at 270°C and 70°C, respectively, through a 0.012" (0.30 mm) nozzle orifice to form roads that are 0.010" (0.25 mm) thick and 0.020" (0.51 mm) wide, while being deposited at a rate of 0.8 in/s (2 cm/s). This corresponds to a maximum standard deposition rate of 0.6 in^3/hr (9.4 cm^3/hr), that is reduced by delays in starting and stopping of deposition, motion from one build layer to the next, and the fabrication of support structures as needed. This particular combination of hardware, materials and processing parameters has been precisely calibrated by Stratasys, Inc. to enable FDM users to produce some of the most dimensionally accurate parts in the layered manufacturing industry; and it has proven itself particularly useful in the prototype production of functional and semi-functional to-be-injection-molded plastic parts.

As with most layered manufacturing systems, there are two areas in which FDM systems could benefit from further improvements. These are (1) reduction of build times, and (2) improvement of part surface smoothnesses. These needs for improvement are driven by design and marketing personnel's desire to access smooth functional prototype parts within minutes of a design change. This, however, is still beyond the capabilities of current layered manufacturing technologies: Today a prototype part takes hours or days to build—and hours of manual labor to finish—only for it to often be disposed of within minutes of its completion once the quick inspection or test it was intended for has been performed. It is therefore desirable to (a) increase the average material deposition rate to reduce the build time, and (b) reduce the build layer thicknesses to produce smoother parts that require less finishing.

These two objectives can be approached by applying the basic principle of continuously varying the material deposition rate such that, at all times, the maximum material deposition rate is used that satisfies the local surface deviation tolerance across the part being fabricated. This principle has been demonstrated by adaptively adjusting the build layer thicknesses such that they are maximized subject to meeting surface deviation tolerances [1-5], and by increasing build layer thicknesses in the interior of the part [4,6]. As these two approaches are combined, significant improvements in material deposition rates can be realized; limited primarily by the capabilities of the hardware. For instance, in the case of the FDM 1600 rapid prototyping systems building with P400 ABS plastic and using the standard 0.012" (0.30 mm) nozzle orifice, the maximum physical material deposition rate achievable is 4.3 in^3/hr (70.8 cm^3/hr). This corresponds to a 0.030" (0.76 mm) thick by 0.050" (1.27 mm) wide road being deposited at 0.8 in/s (2 cm/s), which is 7.5 times the standard rate. If, in addition, a 0.100" (2.54 mm) air spacing is inserted between the roads interior to the part, then the maximum virtual material deposition rate increases to 13 in^3/hr (212 cm^3/hr), or 22.5 times the standard rate. We therefore see the potential of fabricating parts by FDM in hours instead of days while achieving a surface smoothness equivalent to that of 0.003 - 0.005" (0.07 - 0.13 mm) uniform thickness build layers.

This paper reviews recent efforts towards achieving these objectives, and, in particular, that of fabricating smooth-surface parts by FDM in the minimum amount of time. The following sections describe a significant improvement to previous adaptive slicing techniques [7,8], issues that surfaced when migrating this work from computer simulations to actual fabrication, and how these issues were resolved to produce the desired outcome; namely, fast, smooth-surface parts by FDM.

2 Local Adaptive Slicing

Conventional adaptive slicing techniques [1-5] have demonstrated the potential benefit of adaptive slicing, but have not made it out of the laboratory setting. In particular, adaptive slicing has only been applied to simple geometries, one part at a time; a situation that differs substantially from most industry settings where part geometries are often complex and where multiple parts are often fabricated concurrently within the build envelope. Figure 1 illustrates the consequence of applying conventional adaptive slicing techniques to a more complex scenario. It shows how decisions made to satisfy the surface deviation tolerance of one part or part-feature, in this case the sphere, overrule the lesser needs of the more simplistic block. As a result, the block is fabricated with layers that are needlessly thin and valuable fabrication time is wasted.

Figure 2 illustrates a more desirable situation that results from fabricating the same parts independently of one another. A method to achieve this independence has been developed and is described in detail elsewhere [7,8]. Briefly, this new approach, which has been termed local adaptive slicing, consists of a three-step process that is based on stepwise uniform refinement [4,5]. First, all the parts in the build volume are sliced into thick uniform-thickness slabs. Then the contours on the top and the bottom of each slab at a given height are grouped into sub-slabs that

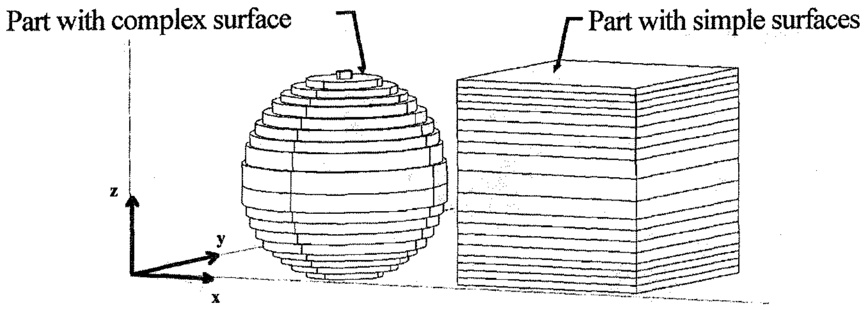

Figure 1 The potential savings of adaptive slicing is lost by conventional slicing methods that slice all parts of a given build volume with the same resolution, regardless of their dissimilar surface characteristics. In this figure, the thin layers necessary for the sphere are imposed unnecessarily on the block.

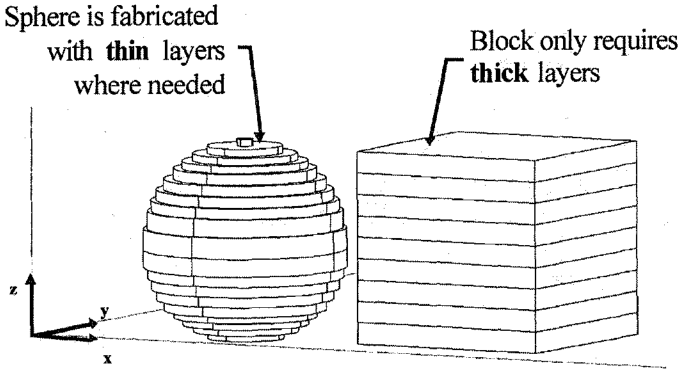

Figure 2 The new approach fabricates individual parts and part-features independently with distinct layer resolutions applied locally as necessary.

reflect that these contours would be physically connected by a surface even if only the sub-slabs at that particular height were fabricated. Finally, each sub-slab is sliced independently into some integral number of uniform-thickness slices to satisfy the surface deviation tolerance of that particular sub-slab. Hence, all sub-slabs are of equal thickness, regardless of how each one is subdivided into thinner build layers, and can therefore easily be processed and fabricated independently of one another.

In the FDM 1600 rapid prototyping system, the build volume is subdivided into 0.030" (0.76 mm) thick slabs, that correspond to the thickness of the maximum flow rate roads described in Section 1. This facilitates the fabrication of the interior of each sub-slab using these roads and the exterior using thinner roads that satisfy local surface deviation tolerance requirements [4,6]. Each sub-slabs' exterior regions are subdivided into an integral number of uniform thickness build layers, α_{slab}, using the criteria developed by Dolenc and Mäkelä [1] and refined by Sabourin *et al.* [4,5], but limiting the points of consideration to only those that are associated with a particular sub-slab when determining the optimal subdivision for that sub-slab:

$$\alpha_{sub-slab} = int\left(\frac{L_{max}}{C_{max}} max\{n_z\}\right), \quad \alpha_{sub-slab} \in \left[1, \alpha_{max}\right], \quad \alpha_{max} = int\left(\frac{L_{max}}{L_{min}}\right) \tag{1}$$

where L_{min} and L_{max} are the minimum and maximum build layer thicknesses available, respectively; $C_{max} \geq L_{min}$ is the maximum permissible surface deviation error; and $\{n_z\}$ is the set of unit normal z-components for all the points along all the contours of the sub-slab. The build layer thickness used to fabricate this particular sub-slab therefore becomes

$$l_{sub-slab} = \frac{L_{max}}{\alpha_{sub-slab}} \tag{2}$$

The FDM 1600 has a Z-stage resolution of 0.0005" (0.013 mm) and a proven quality fabrication capability with P400 ABS plastic for build layers with thicknesses in the range of 0.005" to 0.015" (0.13 - 0.38 mm); the 0.030" (0.76 mm) layers produce overly rough part surfaces. Therefore, it is reasonable to limit α_{slab} to integers between 6 and 2, inclusive, which corresponds to fabricating with 0.0050", 0.0060", 0.0075", 0.0100", and 0.0150" (0.13, 0.15, 0.19, 0.25, and 0.38 mm) build layers. Hence, these are the only layer thicknesses for which we need to determine and manage flow rates.

3 Implementation Issues

The above fabrication procedure was implemented using an FDM 1600 with a 0.012" (0.30 mm) nozzle orifice and P400 ABS plastic. The software developed reads any CAD model described in the .STL file format, generates the contours on each build layer, and exports them as an .SSL file complete with layer thickness and flow rate information. QuickSlice 5.0, the FDM post-processor by Stratasys, Inc., can then use this information generate the actual roads that are described in the .SML file format for control of the FDM 1600.

The software appears to be robust and it generates .SML files with values that are identical to what would be generated if this process had been executed manually. Unfortunately, the initial fabricated parts were not satisfactory. While the part surfaces where the build layers were constant were smooth, including across sub-slabs, there was a small but noticeable discontinuity wherever there was a change in build layer thickness, and particularly when there was a change between the 0.005" (0.13 mm) and 0.015" (0.38 mm) build layers. In addition, the thinner layers tended to delaminate and thus further reduced the resulting surface quality.

The smooth part surfaces where the layer thickness was constant indicated that it is within the capability of the hardware and material to consistently produce high-quality part surfaces. This led us to suspect that the discontinuity problem was a function of poor calibration. A closer examination of the calibration tables used by QuickSlice 5.0 strengthened this hypothesis. As shown in Figure 3, the calibration curves for several of the layer thicknesses used, are composed of several C^0 discontinuous, piecewise logarithmic curve segments. This is contrary to what one would expect since there is no discontinuity or sharp change in the flow characteristics of ABS plastic at these flow, pressure, and temperature levels. Therefore, if the transitions along a constant layer-thickness curve are imprecise, the transitions from one build-layer-thickness curve to the next would also have to be imprecise, and this latter imprecision would explain the discontinuities that were experienced on the part surfaces when changing from one build layer thickness to another. The standard FDM calibration tables for P400 ABS plastic should therefore be revised to accurately reflect actual material behavior so smooth, adaptively sliced part surfaces can be fabricated.

The delamination problem, on the other hand, was not due to inaccurate calibration, but to insufficient material weld time. The low material volumes and flow rates associated with thin

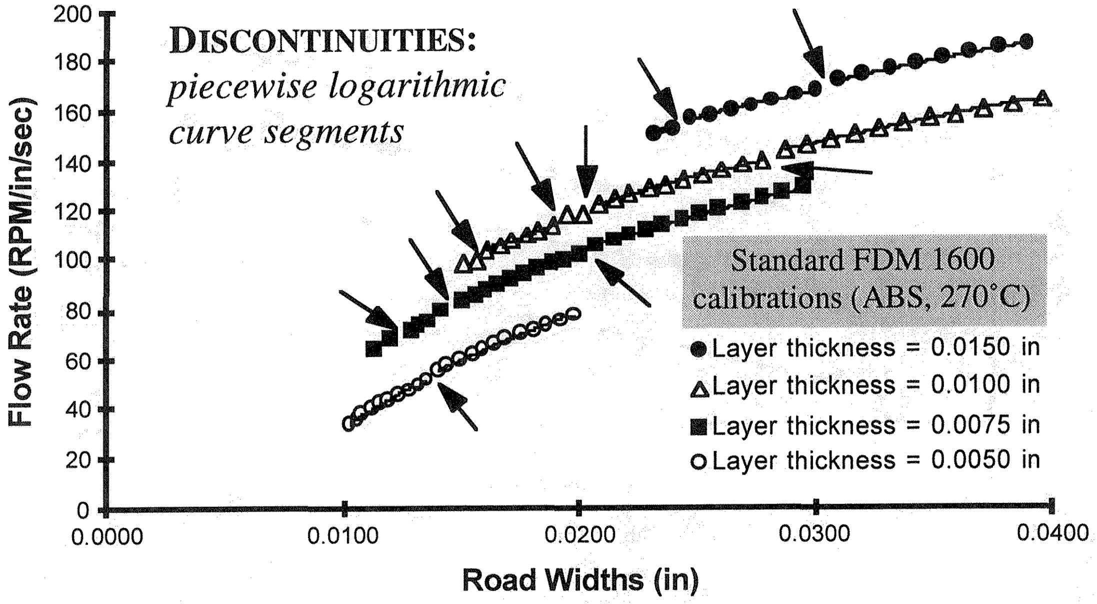

Figure 3 Standard FDM 1600 calibration values for P400 ABS plastic extruded at T_L = 270°C through a 0.012" (0.30 mm) nozzle orifice into a T_C = 70°C build envelope.

roads cause the extrudate to cool down too fast for it to weld sufficiently to the previously deposited material. This weakened weld often breaks under the pulling force exerted by the liquefier as it traces across the build plane. When this occurs, the newly deposited road will be free to lean in the direction of the motion of the liquefier, which will change the road's location and disrupt the steady-state material flow rate, and, ultimately, distort the part geometry.

The effective weld time can be extended, to increase the strength of the weld, by increasing the extrusion temperature, T_L. Stratasys, Inc. recommends increasing T_L to 290°C and lowering T_C to 50°C when fabricating with 0.007" (0.18 mm) build layers in the FDM 2000 [9]. We therefore duplicated these temperature changes in the FDM 1600, and we found that it effectively eliminated the delamination problem while still allowing fabrication with the thicker build layers. This observation is important because the temperature settings are set manually, and, therefore, all build layer thicknesses must be fabricated at the same temperature configuration. However, since the material flow rate is affected by changes in temperature, and the standard calibration tables are based on a different T_L / T_C combination, a change in processing temperatures called for a revision of the calibration tables, at the new T_L / T_C combination, to enable accurate and smooth part-surface fabrication.

4 Calibrations

Both the apparent inaccuracies of the standard FDM 1600 calibration tables and the change in processing temperatures made revising the calibration tables necessary to facilitate accurate and smooth part-surface fabrication using adaptive slicing techniques. The actual road widths that result from various constant build layer thickness / material feed rate / T_L / T_C combinations had to be measured. These measurements were obtained by building several series of vertical walls. Each wall was 2.0" (50 mm) long, 0.25" (6.4 mm) tall, had the width of a single bead, and was assigned a flow rate value of even number between 2 and 254 (RPM/inch/sec) [10]. Each series

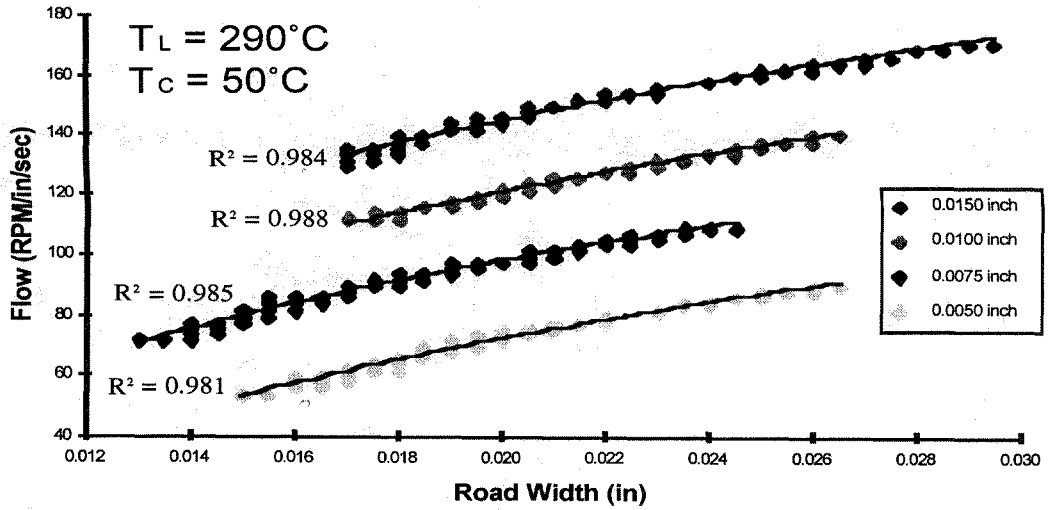

Figure 4 Revised FDM 1600 calibration values for P400 ABS plastic extruded at T_L = 290°C through a 0.012" (0.30 mm) nozzle orifice into a T_C = 50°C build envelope. Continuous logarithmic curves are fitted to data points that represent measured road widths for given flow rates at fixed build layer thicknesses.

contained up to 21 parallel walls that were given sequentially increasing flow rates and were located about 0.4" (10 mm) apart on a single support material base. This base was placed in the center of the build chamber, and its walls were oriented in the direction of the heated air flow in the build chamber, to provide near uniform material cooling.

12 series of walls were fabricated using a nozzle orifice diameter of 0.012" (0.30 mm); T_L / T_C settings of 270°C / 70°C, 290°C / 70°C, and 290°C / 50°C; and build layer thicknesses of 0.0050", 0.0075", 0.0100", and 0.0150" (0.13, 0.19, 0.25, and 0.38 mm). The flow rates comprised all even numbers between 50 and 90, 70 and 110, 112 and 140, and 130 and 170, for the 0.0050", 0.0075" 0.0100", and 0.0150" (0.13, 0.19, 0.25, and 0.38 mm) build layer thickness, respectively. The head speed was kept constant at 0.8 in/s (20.3 mm/s). The external ambient conditions were measured with a thermometer and hydrometer on top of the FDM 1600. The temperature measured between 78°F and 80°F (25°C and 27°C), and the relative humidity measured between 25% and 32%.

Five measurements were taken from each wall using a caliper with a 0.0005" (0.01 mm) resolution. All measurements were obtained from the central regions of the lines to ensure that only steady-state deposition was being measured. These measurements were graphed using Microsoft Excel 7.0 and fitted with a single continuous logarithmic curve for each build layer thickness / T_L / T_C combination (Figure 4). The functions described by these curves where then used to revise the calibration tables used by QuickSlice 5.0.

5 Results

With the revised calibration tables installed, the part surface quality produced by the FDM 1600 rapid prototyping system noticeably improved. The former discontinuities that occurred at transitions between dissimilar build layer thicknesses can no longer be observed visually or by human touch (ref. arrow in Figure 5). The only remaining sign of these transitions are the line density changes reflecting off the part surfaces.

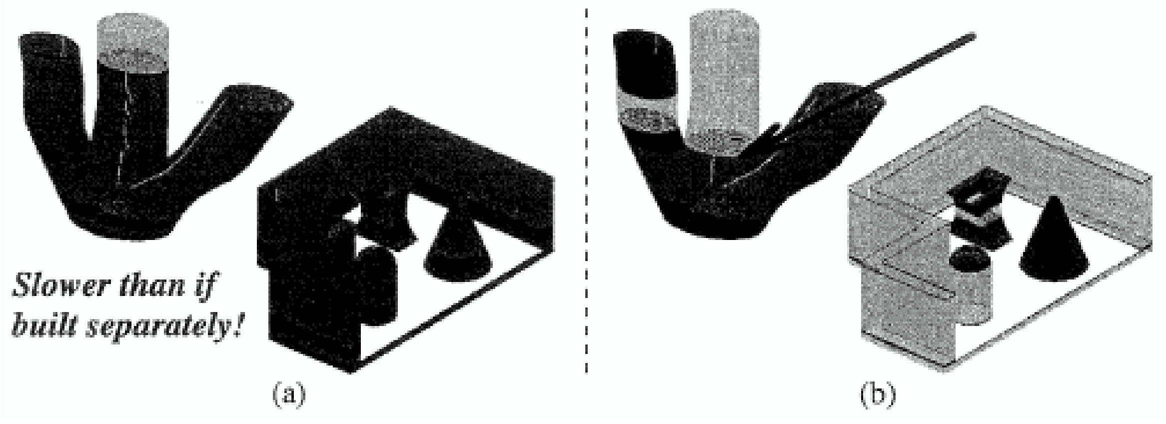

Figure 5 Two parts with a number of individual features were fabricated concurrently in a single build volume using (a) conventional adaptive slicing and (b) local adaptive slicing. Both sets hold the same overall surface tolerance, but set (b) requires 37% less fabrication time. The medium, dark, and light gray areas are 0.0050", 0.0075", and 0.0150" (0.13, 0.19, and 0.38 mm) build layers, respectively. The arrow shows the location of the approximate 0.005" (0.13 mm) discontinuity before revising the calibration tables.

The potential time savings from adaptively slicing each part-feature independently are substantial. In Figure 5, the two parts were adaptively sliced with C_{max} set to 0.0035" (0.09 mm) and fabricated with 0.0050", 0.0075", and 0.0150" (0.13, 0.19, and 0.38 mm) build layer thicknesses. With this configuration, local adaptive slicing reduced the fabrication time by 37% compared to conventional adaptive slicing. This case illustrates how the performance of conventional adaptive slicing degrades as the number of parts and part-features increase: In Figure 5(a), the right-most "finger" of the left part requires thin build layers, and these thin layers are imposed onto the two other fingers and the vertical walls on the part to the right. Hence, when using conventional adaptive slicing, it takes 12% longer to fabricate the two parts concurrently than sequentially. Local adaptive slicing, on the other hand, does not carry a penalty for concurrent fabrication; instead, in the case shown here, there is a 4% reduction because fewer vertical layer-to-layer movements are needed during concurrent fabrication.

6 Conclusions

A new effective approach to adaptive slicing has been developed. It fabricates all parts and part-features independently of one another. Therefore, its effectiveness does not deteriorate as part complexities and build volumes increase. Conventional adaptive slicing techniques, on the other hand, do deteriorate under such conditions, and are therefore impractical in an industrial setting.

To implement local adaptive slicing on FDM 1600 rapid prototyping system, it was necessary to (1) increase the extrusion temperature to prevent delamination when fabricating with thin build layers, and (2) revise the calibration tables to enable accurate and smooth part-surfaces.

Acknowledgement

FDM® is a registered trademark of Stratasys, Inc. of Minneapolis, Minnesota, U.S.A., Reg. No. 1,663,961.

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