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DOUBLE SIDED LAYERED MANUFACTURING

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ABSTRACT

Many layered manufacturing technologies require building a sacrificial structure to support overhanging geometry during part fabrication. Often this support structure accounts for a significant fraction of the build time and raw materials used. In this paper, we introduce a new "double-sided" paradigm for layered manufacturing with the potential to significantly reduce the time and material requirements for building the support structure for a large class of geometries.

KEYWORDS

CAD/CAM, layered manufacturing, rapid prototyping, solid freeform fabrication, fused deposition modeling, support structures, computer aided process planning.

INTRODUCTION

Designers who want to make prototypes of solid three-dimensional parts directly from CAD descriptions are increasingly turning to a class of technologies collectively referred to as layered manufacturing or solid freeform fabrication (SFF). These technologies include stereolithography (SLA), 3-D printing (3DP), fused deposition modeling (FDM), selective laser sintering (SLS), and laminated object manufacturing (LOM) (4). In all these processes, a triangulated boundary representation (b-rep) of the CAD model of the part is sliced into horizontal, 2.5-D layers of uniform thickness. Each cross sectional layer is successively deposited, hardened, fused, or cut, depending on the particular process, and attached to the layer beneath it. The stacked layers form the final part.

For additive SFF technologies such as SLA and FDM, a sacrificial support structure must also be built to support overhanging geometry. Building this support structure can take a significant amount of time and material, in some cases almost as much as is used for the part itself. Furthermore, manually removing it from parts with complex geometries can take hours. Experienced machine operators reorient parts to reduce the amount of support required, as shown in the 2D example in Figure 1, but often it is impossible to find an orientation that makes a significant improvement, as shown in Figure 2.

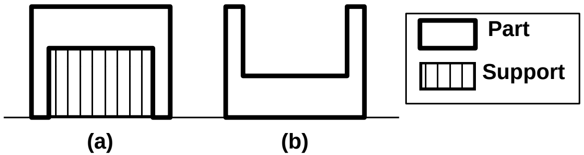

Figure 1. *This part requires a significant amount of support material in orientation (a) but no support in orientation (b).*

Related Work

Many theoretical results have been obtained related to minimizing support structures in layered manufacturing, but the majority apply only to a subset of possible part geometries or a simplified version of the problem. Majhi et al. (6) present algorithms for finding the orientation of a 2D polygon that minimizes the

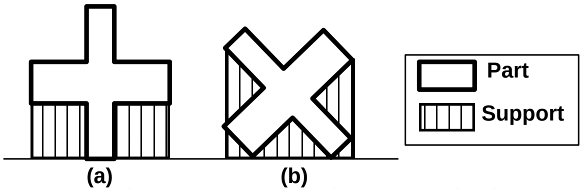

Figure 2. *This part requires almost exactly the same amount of support material in orientations (a) and (b), or any other orientation.*

length of the contact between the support regions and the part, or that minimizes the support regions' area. In three dimensions, Majhi et al. (7) have developed $O(n^2)$ algorithms for minimizing the contact area and volume of supports for convex polyhedra with n vertices. Agarwal and Desikan (1) describe more efficient approximation algorithms for solving the same problem for convex polyhedra. For the general case of a non-convex polyhedron, they show that the set of build directions that minimize the total area of faces that need support can have as many as $\Omega(n^4)$ connected components in the worst case, suggesting that solving the minimization problem for general polyhedra may be quite expensive. Allen and Dutta (2) present an algorithm that attempts to minimize the support contact area, but it only considers a subset of possible orientations and hence does not always find the optimal solution; furthermore, the approximation error cannot be bounded, as shown in (6).

The earliest work in the computational geometry literature that considered layered manufacturing, by Asberg et al. (3), presented an $O(n)$ algorithm for determining if a polyhedron with n vertices can be built without supports using stereolithography. Their algorithm searches for an orientation, if one exists, that eliminates overhanging geometry. Fekete and Mitchell (5), who call a polyhedron that admits such an orientation a histogram, propose decomposing a non-histogram polyhedron into a small number of histograms that can each be built without support and then gluing them together to form the final prototype. Unfortunately, finding a decomposition that minimizes the number of pieces is NP-complete, they show.

Motivation

For a geometry designed to be mass produced from a two part cavity mold with a planar parting line and opposite draw directions (see Figure 3), however, we observe that a decomposition into histograms can be trivially accomplished by cutting the geometry with the parting plane. For most parts this will divide the part into two histograms, the minimal number. When designing a moldable part the designer must identify the parting line and draw direction a priori in order to add an appropriate draft angle to vertical walls to facilitate ejecting the final part from the mold. Therefore, for such a moldable part no additional processing will be needed to determine where to cut the part to decompose it into histograms, making decomposition an attractive approach for eliminating support requirements when prototyping these parts.

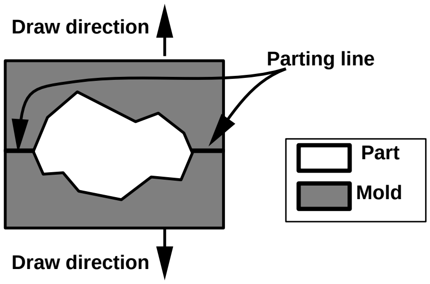

Figure 3. *A two part mold with a planar parting line*

However, "gluing" the histograms together has the disadvantages of inaccuracies that will result from manually positioning the parts during the gluing, and reduced strength across the glued region. To address these issues, we introduce a new "double sided" paradigm for layered manufacturing of decomposed parts.

OVERVIEW

In our double-sided building process, we orient the part to align the draw directions with the z axis, then divide it into two regions with the horizontal parting plane. Each of these regions can be manufactured with no supports when the top section is build right-side up and the bottom section is built upside-down. We first manufacture the bottom section upside-down, then flip this section over and continue adding the layers for the top section *directly* onto the surface formed by the intersection with the parting plane. We have successfully built parts using this paradigm with fused deposition modeling (FDM). We have found bonding between the two sections to be excellent, comparable to the strength of the bond between any other two layers, provided the bottom section is brought up to temperature before depositing the layers for the top section.

In order to fixture the bottom of the part for the second stage of the build, we add small tabs of a standard height and width protruding along the parting plane during the first build stage (Figure 4 a). These tabs, supporting the attached inverted portion of the part, are placed into small jigs, also built by the FDM machine, for the second build stage (Figure 4 b). The jigs are left attached to the build platform between runs so that they can be re-used. Since the machine builds the jigs itself, the coordinate systems for the two stages of the build are automatically aligned without the need for any manual re-alignment or zeroing.

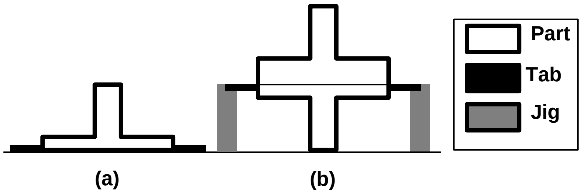

Figure 4. *First we make what will ultimately be the lower section of the part, with tabs (a). Then we flip it over, place the tabs in the jigs, and build the top section directly on top of it (b). No support material is needed for overhangs.*

IMPLEMENTATION

We have experimented with this approach using a fused deposition modeling (FDM) machine, the FDM 1650, from Stratasys, Inc. In fused deposition modeling the part is built up in layers formed by extruding melted ABS plastic, polycarbonate, or wax. The modeling material is supplied as a thin filament that feeds off of a spool into the FDM head. Inside the FDM head, the filament is heated to just above its melting temperature and then pumped out through a nozzle. Meanwhile, the head, controlled by an NC tool path, moves to trace out the cross section of the layer. The melted material adheres to the platform for the first layer, otherwise to the previous layer, hardening in about a tenth of a second. After each layer has been deposited, an elevator adjusts the distance between the platform and the FDM head so that the next layer can be deposited on top of the previous layers. Every other layer, the head lifts off the part and retracts to the back of the machine to clean itself on a brass brush.

Support structures are crucial for FDM. Since there is no liquid photopolymer (as in SLA) or powder bed (as in SLS or 3DP) to help support the top layer being deposited, supports will be required anywhere that a layer extends more than minimally over the profile of the previous layer. The FDM 1650 uses two extrusion heads: one to deposit ABS for the part, and one to deposit the support. Both materials bond more strongly with themselves than with each other, which facilitates support removal. We make use of this characteristic when designing our tabs and jigs.

The tabs are built out of the support material so that they can be snapped off easily after the entire part is complete. The bottom half of the part along with the tabs, like standard FDM 1650 parts, is built on a base composed of a few layers of support material that extend slightly beyond the part silhouette (including the silhouette of the tabs in this case). This base serves as a smooth surface to build on and allows the part and support to be easily removed from the foam build platform. After the build is complete, the base is pried off the foam build platform and then grabbed by the edge and peeled back from the part. The tabs are positioned to rest directly on this base during this first build stage, since otherwise they would need supports of their own. However, the bottom layer of the tabs is built with a loosely packed layer of the *part* material, not support material like the rest of the tab structure, to ensure that the base can be peeled off without also pulling off the tabs.

The jigs are built from the part material, with blind slots of the width and depth of the tabs to hold them in a clearance locational fit. (While an interference fit might provide more secure fixturing, the risk of detaching the jigs from the build platform when removing the part from them rises with a tighter fit.) After the bottom section of the part with tabs attached has been flipped and positioned in the jigs, an additional fixturing layer of support material is deposited over the edges of the tabs and overlapping the jigs to further secure the part. This is necessary to prevent part movement in the positive z direction which would otherwise occur when the head lifts off of the part and retracts for cleaning between layers (the tensile strength of the extruded semi-molten filament attached between the part and the head needs to be counter-acted so that the filament will break before lifting the part). Again, different materials are used to prevent strong bonding, in this case between the jigs and the overlapping fixturing layer, so that the latter can be easily removed while leaving the jigs in place. Then the top section of the part is built directly on the "platform" provided by the bottom section at the parting plane.

RESULTS

For a test geometry, the part shown in Figure 5 was used. It was divided along the parting line shown to perform the double-sided build, using two support tabs.

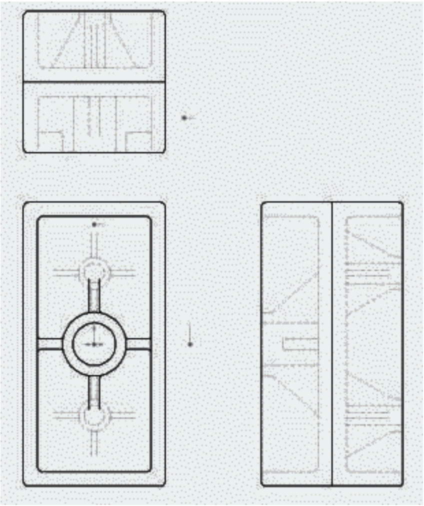

Figure 5. *Multi-view drawing of our test geometry, showing the parting line in the top and right views.*

Figure 6 shows the part inside the machine after the build was completed.

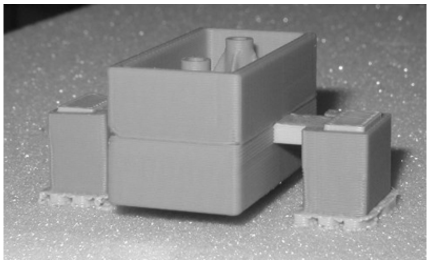

Figure 6. *The test part inside the FDM machine after the entire build is completed.*

Figure 7 shows the part, with its tabs still attached, after it has been removed from the jigs. Note the loose layer of the darker part material on top of the tabs that allowed them to be cleanly and easily removed from the original base.

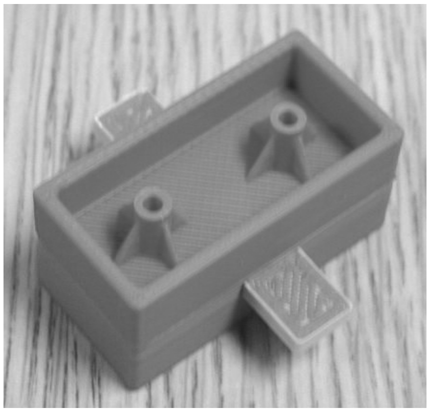

Figure 7. *The test part with tabs attached after it has been removed from the jig.*

The final part, with its tabs removed, is shown in Figure 8. A small amount of support material from one tab can be seen on the top of the part, due to too much overlap between the part and the tab. We are continuing to experiment to find the optimal parameters.

CONCLUSIONS

This double-sided build paradigm shows promise for prototyping moldable parts with fused deposition modeling. The jigs can be re-used through multiple design iterations or even for completely new parts which fit within their envelope, amortizing their cost over many runs. For a typical geometry designed to be moldable with a planar parting line and opposite draw directions, the entire support structure that would normally be built is replaced by as few as two tabs and the re-usable jigs.

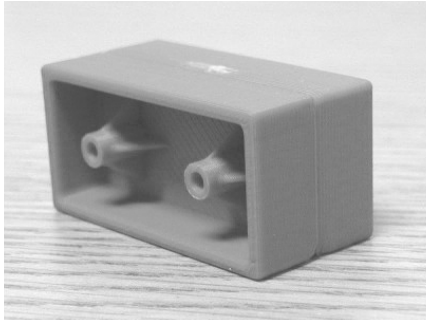

Figure 8. *The final part after the tabs are broken off.*

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