Techniques for Improved Speed and Accuracy in Layered Manufacturing

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Abstract

The ability to improve the construction accuracy and/or the build speed for layered manufacturing techniques is demonstrated using a series of new techniques: (1) Parts can be decomposed into sections which are constructed in parallel and then assembled. This reduced the build time and material waste for a sheet foam process. (2) A more accurate interface based on direct slicing of the CAD model can be used to eliminate the need for the intermediary tessellation file. (3) The layer thickness can be adapted based on the part's geometric complexity to increase the surface quality, build speed, and z-axis accuracy.

Introduction

During the past three years, the focus of the research in the area of Solid Freeform Fabrication (SFF) conducted at the Manufacturing Processes Laboratory at the University of Utah has been on developing new Layered Manufacturing techniques. The results of this work are two technologies that address unique aspects of the Layered Manufacturing market.

Shapemaker I (SM I)(now commercialized as JP System 5 Desktop Rapid Prototyping by Schroff Development Corporation of Mission, Kansas) is a desktop prototyping technology dramatically less expensive than all other existing SFF technologies. SM I uses a plotter equipped with a cutting tool instead of a pen to create layer cross sections from adhesive backed materials. A software package allows the user to import, manipulate, and slice stereolithography format (.stl) files. The layers are registered and stacked manually using a construction table provided with registration pins. Materials used currently are: paper, foam, and vinyl sheet attached to a backing layer. The sheets are readily available in various sizes. The plotter cuts each slice, penetrating only as deep as the construction material layer. The layers are stacked on the construction table by matching the registration holes cut by the plotter on each sheet with the registration pins. After each individual layer is stacked, the backing layer is peeled off, thus exposing the adhesive and providing a bonding surface for the next layer. Once construction is completed, the parts are coated to improve their rigidity and aesthetic appearance and to cover any exposed adhesive.[1]

Shapemaker II (SM II) addresses another seldom approached aspect of Layered Manufacturing: the fabrication of large scale objects. While existing SFF devices are reportedly limited to a 39" x 31" x 20" volume [2], SM II allows the construction of large scale prototypes (up to 4' by 8' by any reasonable height). It consists of an electrically heated wire driven by a four-axis motion control device, a custom software package that allows the user to import, manipulate, and slice .stl files, a pre-processing stand alone device that ensures the flatness and thickness accuracy of the foam material used, and a construction table provided with registration pins. The build material is foam, which is readily available in sheets of various thickness and sizes since it is commonly used for insulating buildings. The heated wire cuts the contour of each slice as well as the internal registration holes. The layers are stacked on the construction table using the registration pins and are bonded together by applying a thin and uniform layer of adhesive on one face of each slice.[3]

This paper discusses several techniques that have been implemented or are in the process of being implemented and are aimed at improving the build speed and the overall accuracy of components manufactured using the processes described above. While all of the techniques described in this paper have been used exclusively in conjunction with the Layered Manufacturing processes developed at the University of Utah, their realm of applicability can be extended to other processes.

Hierarchical Model Decomposition

Inherent to the nature of the SM I process is the ability to decompose an object into sections that can be built simultaneously. This allows the operator to save paper and dramatically increases the build speed. In fact, when building objects that are significantly smaller than the machine's build volume and consist of mostly solid geometry, SM I can be significantly faster than many existing SFF technologies.

In order to complete this decomposition, the software first evaluates the maximum number of part cross sections that can be built on a single sheet of construction material. Next, the part is sliced into a number of equal thickness sections and these sections are spread out to fill the construction sheet. Then, these sections are sliced to the thickness of the construction material. The result is a series of plot files, each containing several cross sections. The number of stacking operations that need to be performed when building an object is a function of the total number of layers, and the number of parallel sections. A theoretical minimum number of operations is achieved when these parameters fit the "square root" model. For example, on a stereolithography machine a 64 layer part would require 64 sequential operations to construct. If this part can be decomposed into 8 sections, the part can be built in a total of 16 operations. (8 operations simultaneously building 8 sections and 8 operations to put the sections together).

In addition to savings in time and materials, parallel decomposition of parts results in less need for support structures. If a part has a cantilever overhang, the operator can define a section break at the level of the overhang. This puts the overhanging material flush with the construction platform during the first stage build. During second stage build the sections are thick enough to be self supporting and do not require supports. The ability to custom define and manipulate sections has helped improve the accuracy of parts built.

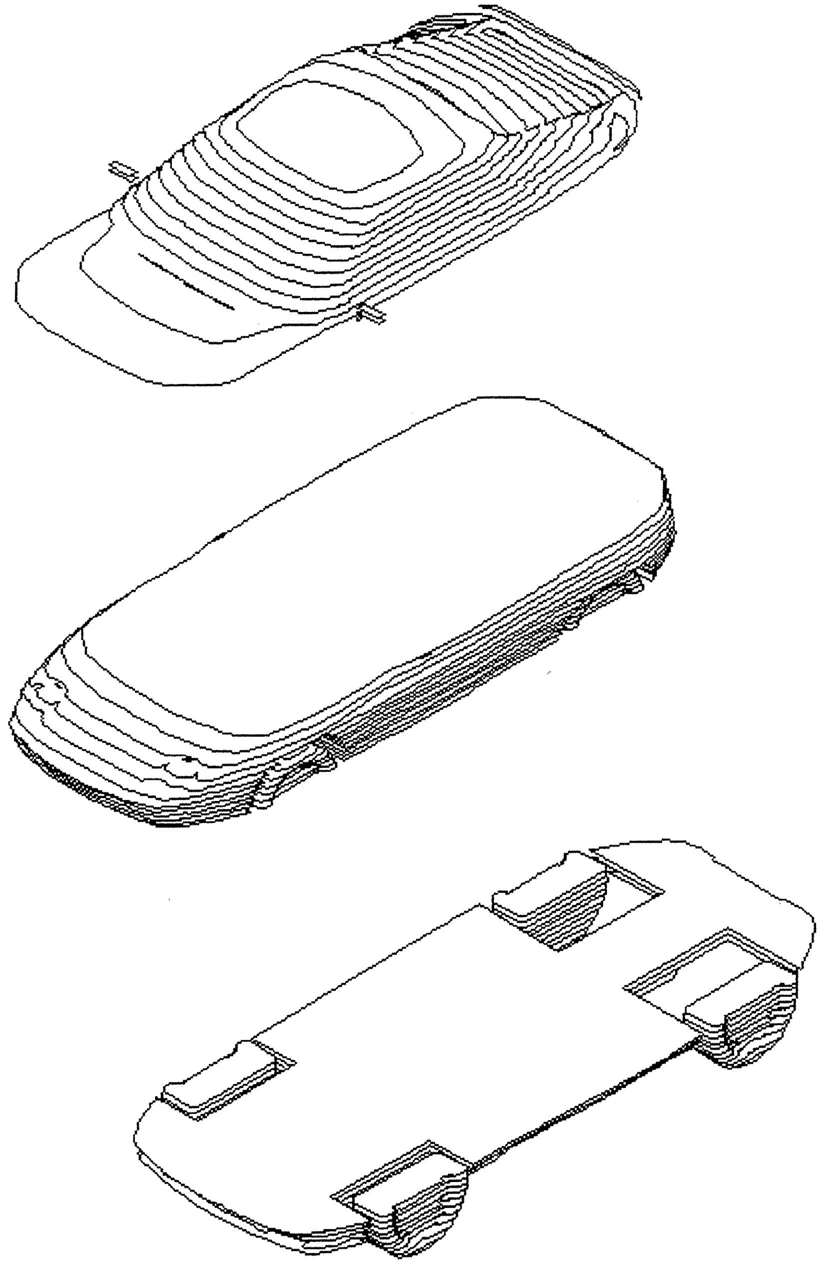

Figure 1. Hierarchical model decomposition with user-defined sections. The overhangs (mirrors) are built from largest cross-section up as part of the top section.

Section Orientation Mirroring

The cantilever effect associated with overhang features is an issue common to all Layered Manufacturing technologies. While most processes address this issue by constructing supports for the overhang features, SM I and II eliminate the need for support structures by decomposing the model in sections and mirroring the sections as necessary. As described above, all objects being built are first decomposed into sections with the user having full control of this process.

The software also allows the user to mirror the orientation of any section such that all sections are built from their largest cross-section up.(see Figure 2) This unique solution which allows the elimination of all support structures is a critical time saving feature.

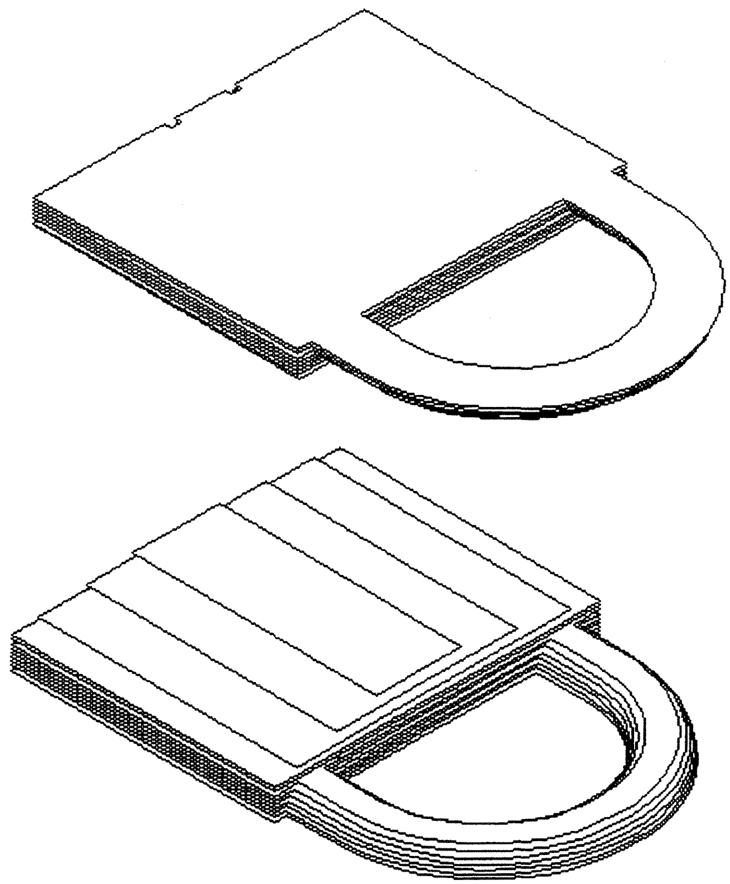

Figure 2. The need for support structures for this section of a lock pad (top) can be eliminated by mirroring the section and building from the largest cross section up (bottom)

Most SFF processes are accompanied by software packages which, among other functions, automatically generate the necessary supports. These automatically generated supports are often too few - causing inaccuracies or too many - slowing down the build time. The SM I and II solution eliminates at least three steps that are required by most other SFF processes: the generation of support structures in the slicing software, their physical creation, and their removal in the post-processing phase.

Direct Slicing

All SFF processes use as input an electronic file generated using a 3D Computer Aided Design (CAD) system. Since the CAD industry thrives on non-compatibility, a common interface had to be developed so that SFF and CAD could become fully integrated technologies. This interface is based on the principle of tessellation or mapping a triangular mesh over the surface of the solid model. The current standard interface (the stl file format) was developed by 3D Systems, the inventors of the first SFF technology, Stereolithography. [4] SM I and II accept stl files as input for generating the slices.

This intermediary step between the CAD model and obtaining the cross sections that are used to manufacture the object layer by layer yields a loss of accuracy since the tessellation of any complex shape is an approximation. Therefore, there is much to be gained by eliminating this step and creating the slices directly from the CAD model. Such an interface was developed at the University of Utah to work with Layered Manufacturing processes such as SM I and II. This new C++ based interface called SLICE uses an HPGL (Hewlett Packard Graphics Language) compatible format to represent each cross-section. The HPGL format is used because it is already supported by all CAD systems. The output file created by SLICE contains information on all the slices of the object as well as any other information required to build and define the object completely. The following example illustrates how a slice of the object is represented by SLICE:

```
object OBJECT_NAME
        SOLIDS solid1,AL;solid2,Polystyrene;solid3,steel
        scale 1
        slice #x of x
                Z position 1.0500
                solid1
                        80,-60;80,90;-70,90;80,90;80,-60;
                solid2
                        100,0;120,0;120,-20;100,-20;100,0;
                        .......
                solid3
                        .......
                hole1
                .......
        endslice
        .......
endobject
```

Each cross section represented in the SLICE format is divided into a number of closed loops sorted clockwise. Each loop is represented individually and it could be made up of any specified material. If a loop is empty, the designated word "hole" will indicate that there is no material inside the loop.[5] A detailed description of SLICE will be published in [6].

Along with accuracy improvements, direct slicing also speeds up the process of converting the 3D CAD model into a physical object. Time compression is achieved through the reduction of pre-processing time and the elimination of the all too common process of "repairing" the stl file, which becomes necessary because of the inconsistent implementation of the stl translators within the CAD systems available on the market. Direct slicing also produces files that are generally dramatically smaller than those produced through tessellation because the latter format incorporates much redundancy since information about each triangle is recorded and shared ordinates are repeated over up to five times. The reduction in file size is another incentive for pursuing direct slicing as an alternative to the stl file format.

Adaptive Slicing

Currently, the focus of our research is on integrating adaptive slicing capabilities into SLICE, the direct slicing interface discussed above. It is envisioned that by adding this feature to the interface the user will be able to optimize the layer thickness for accuracy as well as build speed. The interface will make use of the cusp height concept, which is similar to the chord height concept used by the tessellation based approach. The cusp height is a measure for the deviation of the surface of a part built in layers from the true surface of the 3D CAD model. The cusp height is defined by the maximum gap measured in the normal direction of the true surface.[7] Using this new interface, for a given input value for the maximum allowable cusp height, the object will be sliced using a small layer thickness to preserve the accuracy of sections that contain complex surfaces and a large layer thickness to improve the build speed of sections where there are no cross sectional changes in the direction of build. (see Figure 3)

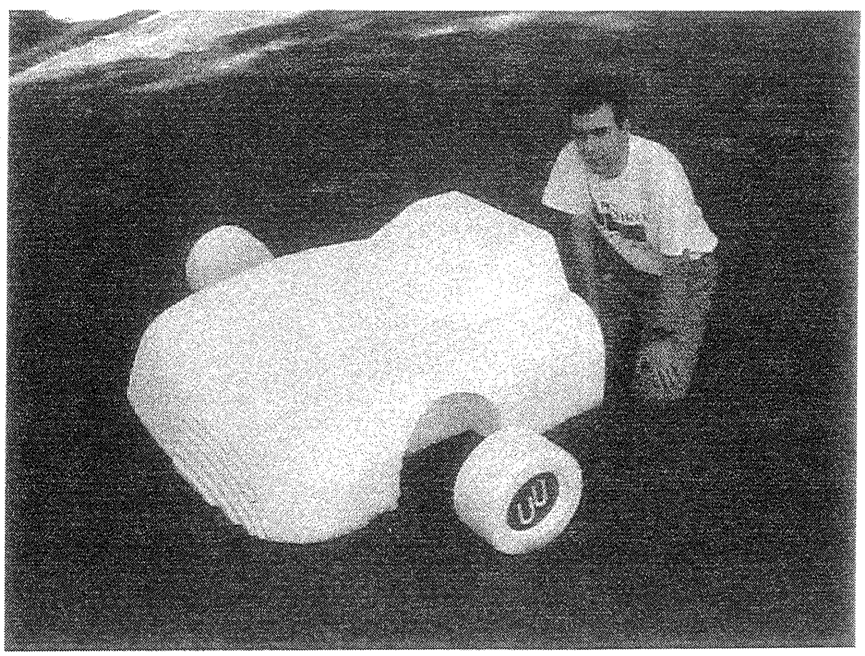

Figure 3. An object built with SM II using variable thickness layers.

The fabrication of large scale objects using a Layered Manufacturing process presents a unique set of challenges as far accuracy is concerned. The limiting factor for accuracy in the build direction for most Layered Manufacturing processes is the thickness of the slices used. This problem is due to the use of constant layer thickness. If the distance between the end of the last layer and the end of the CAD model is smaller than the layer thickness, the physical object will be incomplete. This problem can be addressed through the use of variable thickness slices.

Another problem common to all Layered Manufacturing processes is due to the finite thickness of the layers. This problem occurs when trying to reproduce a curved surface and is referred to as the stair stepping effect or 3D aliasing. Slices as thin as 0.002", or about the diameter of a human hair, have been reportedly used in order to improve the accuracy in the build direction. [8] Clearly such thin layers would be impractical for manufacturing large scale objects. Extensive use of SM II has demonstrated the need for using slices thinner than the current 1" standard thickness in order to improve the accuracy with which objects containing curved surfaces are reproduced. SM II is capable of producing ruled cuts - not just stepped cuts, an implementation which has diminished the stair stepping effect (see Figure 4). Custom angled edges are cut on each layer, forcing the top of the layer to match the specified upper cross section and the bottom to match its corresponding cross section.[9] While this has improved the accuracy of the object being constructed, it hasn't eliminated the need for variable thickness slices.

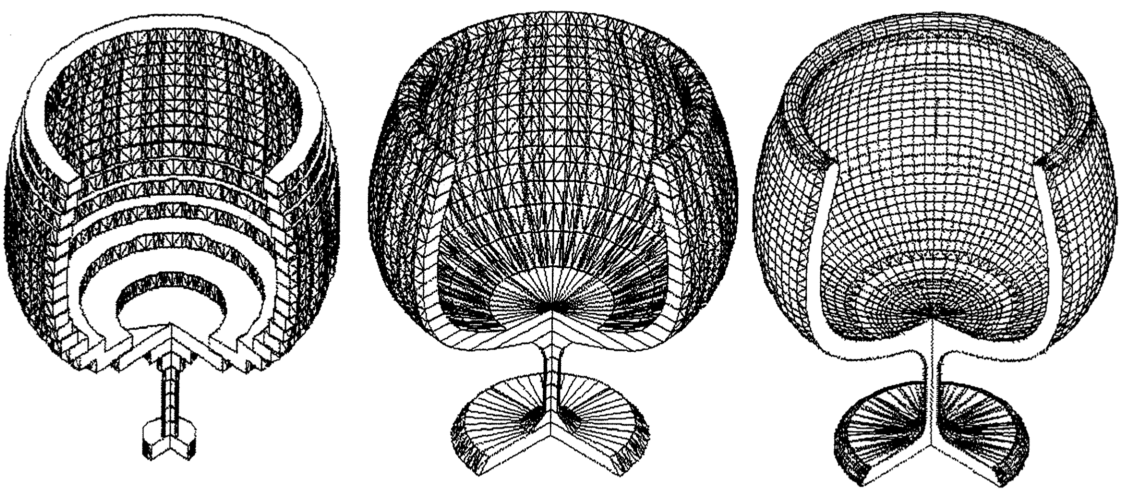

Figure 4. Current commercial systems produce layers with vertical edges (left). Shapemaker II produces layers with ruled surface edges (middle). Shapemaker III will produce layers with curved edges (right).

Future Work

Our future plans for enhancing the Layered Manufacturing processes discussed in this paper include the implementation of software as well as hardware changes that would support the use of non flat and non parallel layers. Objects will be sliced not only along a flat but also along a curved direction. The object will then be built around a non flat platform. The use of non parallel layers will improve the accuracy and build speed of curved objects. For example, a torusshaped object would be reproduced more accurately using wedge-shaped non parallel layers rather than the conventional flat layers.

Conclusion

The efforts aimed at improving the accuracy and the speed of construction of objects manufactured using the Shapemaker technologies have yielded promising results. These improvements have been achieved through software that allows hierarchical model decomposition and section orientation mirroring for SM I and optimization of direct slicing for SM II (the optimization process is still under development). Future improvements are to be achieved through implementation and use of non flat and non parallel layers.

Cost, versatility, accuracy, and speed of construction are the top four concerns with all SFF technologies. The order of importance of these factors depends upon the intended end use of the technology. SM I was designed with cost as the most important parameter. The price of the commercial system based on SM I is $7500. This price is by far the lowest in a market where most systems sell for six digit figures. SM I and II cover a dimensional range unprecedented with any other Layer Manufacturing techniques, proving to be highly versatile. Parts less than 1 in^3 have been built using SM I, while parts exceeding 90 ft^3 have been built using SM II. When building objects with mostly solid geometry SM I has proven to be faster than most existing SFF processes, while building large scale objects using SM II is faster than using conventional fabrication techniques.

Acknowledgment

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