STEREOLITHOGRAPHY PROCESS RESOLUTION

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ABSTRACT

To build smaller parts in StereoLithography (SL) and detect some build errors before fabrication, a good understanding of process resolution is needed. A categorization of resolution factors into process-inherent and software-induced categories is presented in the paper. Results from several experiments testing different aspects of SL resolution illustrate the effects of these factors. A method based on offsetting algorithms is presented to determine as-built part cross-sections and aid detection of possible build errors. A method that will enhance build resolution of SL parts is proposed.

1. INTRODUCTION

StereoLithography is a layered rapid prototyping process in which an UltraViolet (UV) laser is used to cure a vat of liquid photopolymer resin in order to physically make a part from the generated CAD model. SL process accuracy is critical when building small features with intricate cross-sections. Inaccuracies in translation and inability to control the SL process resolution may result in very small features not building accurately or not building at all. One way to ensure building of accurate parts is to understand SL resolution and its limiting factors.

During file preparation and build of a StereoLithography part, the resolution of the process is affected by a number of operations shown in Figure 1 below. Before a part is built in an SL machine, its .stl file is sliced into layers. The slicing is done according to the specified layer thickness in the z direction; and the cross-section is spooled onto a grid in the x-y platform. In addition, during the slicing process, a number of parameters are specified by the user. In the SL process, the UV laser, which is focused below the resin surface, scans the cross section of a layer with a beam diameter size of 200 μm. Typically the thickness of a layer is 100 μm.
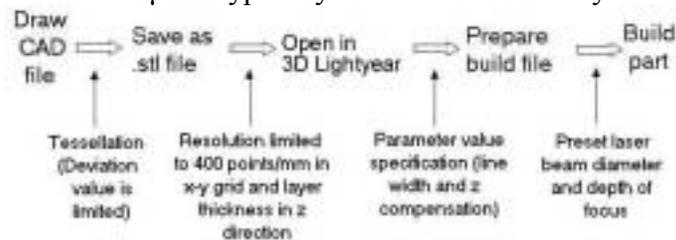

Figure 1. Resolution Issues in SL Build Process

The resolution of the final part is affected with each step along the way. Understanding and quantifying the contribution of each step to resolution of the final shape is a goal of this research.

2. SL RESOLUTION LIMITING FACTORS

SL process resolution is limited by a number of Software Imposed Parameters (SIP) and SL Process Parameters (PP). A distinction should be made between these two categories.

Software-Imposed SL parameters refer to parameters used in commercial CAD software such as ProEngineer for defining surfaces, and parameters used in proprietary 3D Systems Inc. software such as 3D Lightyear and Buildstation to enable preparation and build of StereoLithography parts. Parameters that fall into this category include linewidth compensation, .stl file resolution, layer thickness, z compensation, and StereoLithography grid.

SL Process parameters are inherent to the StereoLithography process. Since StereoLithography is a process that is a combination of physics and chemistry, a number of operations take place at the same time. Properties such as laser beam spot diameter, laser beam focus depth, and layer thickness are inherent to the process.

StereoLithography resolution depends on different variables in the horizontal domain (x-y platform) from the vertical domain (z direction) as shown in Table 1. How each of the factors in Table 1 contributes to the overall SL resolution will be described in this section.

Table 1. Issues StereoLithography resolution is dependent on

X-Y Plane Resolution	Z Resolution
Laser beam spot diameter (PP)	Laser beam spot diameter (PP)
StereoLithography grid (SIP)	Laser beam focus depth (PP)
Resolution of the .stl file (SIP)	Resolution of the .stl file (SIP)
Linewidth compensation (SIP)	Layer thickness (SIP, PP)
	Z compensation (SIP)

2.1 Software-Imposed Parameters

2.1.1 Linewidth Compensation

The linewidth compensation parameter ensures that a cross section is scanned correctly by shifting over the center of the laser beam spot. Linewidth compensation is defined as [1]:

$$L_w = W_o \sqrt{2 C_d / D_p} \qquad (1)$$

where W_o is the laser beam spot radius, C_d is the cure depth and D_p is the depth of penetration. The default value for linewidth compensation is 0.005 inch or approximately 125 μm, which is the half-width of the laser beam diameter. The effect of linewidth compensation is demonstrated in Figure 2 by using a 0.01-inch thick rib, as outlined by the solid line.
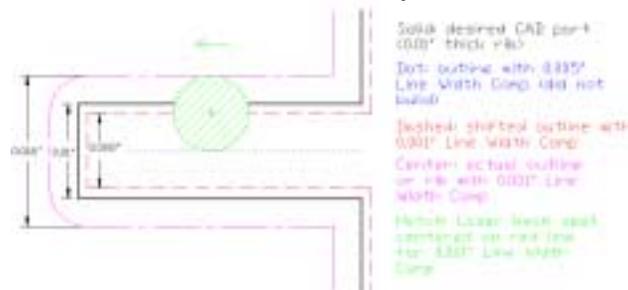

Figure 2. Linewidth compensation

When the default linewidth compensation value of ½ of laser beam diameter is used, the outline of the rib is shifted to the inside of the feature and it creates a line, as shown by the dotted

line in Figure 2. Since only a line (not a closed profile) is created by this shift, the software would not build the rib with the default 0.005-inch linewidth compensation. By using a smaller linewidth compensation value such as 0.001 inch, a closed profile is obtained, which allows the laser to successfully scan the rib as shown by the dotted line. When the laser scans the cross section, a thicker-than-anticipated part with a thickness of 0.016 inch is obtained, outlined by the centerline in Figure 2. However, this may result in very inaccurate thin features.

2.1.2 Resolution of the .stl file

Stl file format was developed by 3D Systems, Inc. in 1987 to be used in the StereoLithography system. Stl file format has become the de facto RP industry standard for file transfer; however, some issues with .stl files are well documented. An .stl file is an approximation of the surface of a CAD part achieved via tessellation. Tessellation is conversion of surface information into a combination of triangles. Information about the vertices of triangles and facets are recorded in an .stl file. Stl files could be in ASCII or binary format representation. With ASCII representation, the file could be read as text and errors be corrected, however its size is very large. In StereoLithography, the binary format is used. Therefore, if there are any errors in the file, it is usually not possible for a user to detect them.

In order to tessellate a CAD part, the user defines a tolerance value (deviation), which is the distance between the surface of the CAD model and tessellated part. With smaller tolerance values, more accurate .stl files can be obtained. However, the smaller the tolerance value, the larger the .stl file; since the number of the triangles depends on the tolerance value specified [2].

The deviation in an .stl file determines each triangle size of tessellation. The deviation also depends the overall size of the part. For a CAD model that has a maximum dimension of 10 microns, a very small deviation value can be specified. However, for a CAD model that has an overall size of 1mm with a 10-micron rib feature, a larger deviation value must be selected. This is because .stl files do not have double precision; instead they have floating point. This limits the number of decimal points that can be specified for deviation to 6. When working with micron size features, 6-decimal-point deviation values are not enough to represent a boundary model.

An .stl file does not contain topological information, which might result in errors when future changes to the CAD model are made [3]. Numerical round-off due to conversion of real numbers to integers, missing data and the presence of redundant or extraneous data are other causes of errors in .stl files [2].

3D Systems, Inc. also developed the .slc file format, which is a 2.5D contour representation of a model's boundaries. SLC file format might help reduce data loss because of not using tessellation [4]; however, it does not completely eliminate CAD representation problems. Other file formats, which contain more information than just triangle vertices or 2.5D contour representation, could be used to better approximate a CAD model in StereoLithography [3].

2.1.3 Z compensation

Z compensation refers to the z correction applied to a StereoLithography build. Z correction compensates for the estimated build error by omitting a number of initial layers. Z compensation is shown in Figure 3.
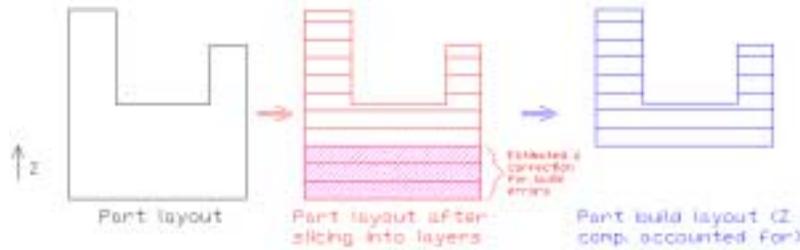
Figure 3. Z compensation effect on a StereoLithography build

Estimated build errors such as print-through and overcure are taken into account when calculating the z correction. Figure 3 shows that after the part is sliced into layers, according to the estimated error, a number of initial layers are omitted by the machine. The StereoLithography machine therefore starts building the part by skipping the initial layers as calculated by z correction.

2.1.4 StereoLithography Grid

StereoLithography grid (slice resolution) is the conversion factor used with .stl or .slc files when converting from CAD space to slice space [5]. For a StereoLithography system, the slice resolution in the pre-build software is 40 to 400 slice units per millimeter in the x-y platform [1]. The slice resolution value can be specified by the user. The use of the SL grid is shown in Figure 4 below.
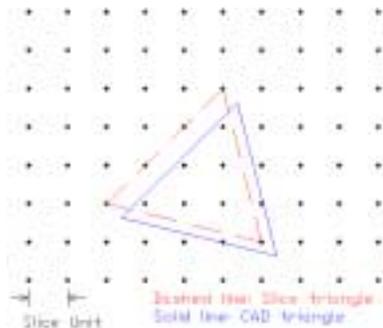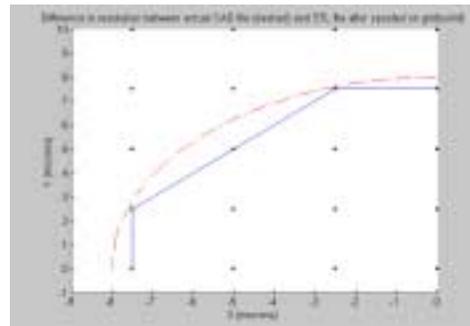

Figure 4. (a) Stereolithography Grid   (b) Effect of grid on circular cross-section

The .stl file triangle vertices are snapped onto a horizontal "grid" in the SL build software, which are used by the UV laser to scan a cross-section. The smallest grid spacing allowed is 2.5 μm (when 400 units/mm used). In Figure 4(a), the .stl file triangle vertices are spooled onto the *closest* grid point in the x-y platform. Since the triangle vertices are snapped to the closest grid point, the shape of the cross section might become different from the actual shape for micron size features. This is shown in Figure 4(b), where a quadrant of a 16 μm-diameter circle is plotted with a grid point spacing of 2.5 μm. In Figure 4(b), the circular cross-section cannot be approximated accurately since the grid spacing is too large for a micron-size part.

2.2 StereoLithography Process Parameters

2.2.1 Laser Beam Spot Diameter

The laser beam diameter is fixed at 200 μm on the build surface for most SL systems. In theory, this is the absolute limiting size of a feature that can be built. However, because of the

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scanning patterns, the smallest feature that can be built is around one-and-a-half times the laser beam diameter, around 300 μm. In high resolution systems such as the 3D Systems' Viper Si2 machine, the laser beam spot diameter is 75 ± 15 μm, and features as thin as 80 μm have been built using this spot size.

With the smaller spot size capability come added parameters such as *Small Feature Preservation*, which provides linewidth compensation without eliminating small features, and *High Resolution Spatial Tolerance*, which helps smooth "notched" surfaces only on highly tessellated parts [6]. Though these improvements help increase SL accuracy, they do little to improve the process resolution.

2.2.2 Laser Beam Focus Depth

In the z direction, the cure depth of a layer is a function of the focus depth underneath the resin surface [7]. The attainable layer thickness is inversely proportional with the cure depth, hence the depth of focus of the laser beam. The laser beam is focused beneath the resin surface in order to increase the Rayleigh range [8] and the accurate build platform size. The focus distance is typically 8 mm below the resin surface.

2.2.3 Layer Thickness

Thickness of one layer is inversely proportional to the depth of focus of the laser beam under the resin surface. However, layer thickness is mainly limited by the recoating mechanism and resin viscosity. StereoLithography machines use a blade to sweep the excess resin from the top of the build before a layer is built to ensure that the build surface is flat. The Zephyr™ blade limits the thickness of each layer. This blade is necessary because SL resins have high viscosities, approximately 180 – 2000 centipoises [9]. Currently the smallest layer thickness that can be obtained in the StereoLithography process is 0.001 inch (25 μm). Layer thickness affects the surface texture, the accuracy in the z-axis and the build speed [1].

3. OUR APPROACH

Our approach to better understanding and controlling StereoLithography resolution consists of analyzing the aforementioned different aspects of SL resolution. The overall goal is to be able to predict what the SL part cross-section of a given CAD model cross-section would look like *before* building it using a StereoLithography machine. A method is needed, as shown in Figure 5 below that will take the SL grid, stl file tessellation, offsetting, and build parameters into account when predicting a cross-section. This method should also be able to highlight resolution issues on areas of the build where problems might arise.
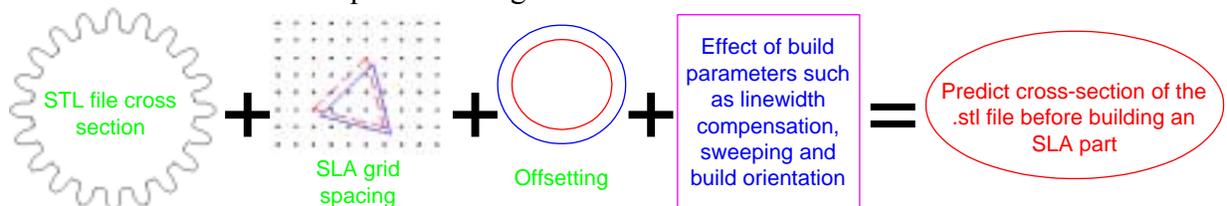

Figure 5. Information needed to display .stl file cross-section before it is built in SL machine

3.1 Experiments to quantify build parameters' effect on resolution
     In order to quantify individual contribution of resolution issues, a number of experiments were performed. The results of these experiments are discussed below.

3.1.1 Effect of Linewidth Compensation, Sweeping, Build Orientation on Build Resolution
     Parts with very thin walls were built by using the 3D Systems Viper Si2 machine High Resolution build style with Cibatool SL 5510 resin. The experiment part was a 1-inch by 1-inch square block with 2 mm thickness that had grids with 50 μm thick walls and 700 μm spacing in between the walls. This part is shown in Figure 6 (a) below. Figure 6 (b) shows the different part orientations used in the vat. As shown in Figure 6 (b) below, the 45-degree orientation evenly distributes the effect of blade sweeping in x and y directions.
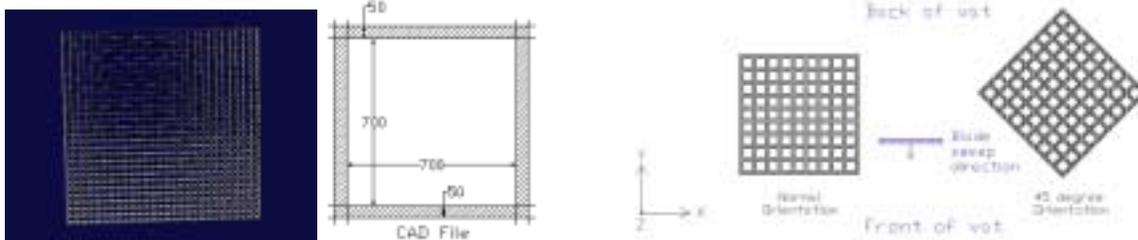

Figure 6. (a) Original test part and detail of a grid   (b) Part Orientation in vat

     The parts had different build parameters turned on/off during a particular build. This is shown in Table 2 below. The z compensation was turned off for all experiments in order to eliminate errors that may be caused by compromising the first few layers of a build.

Table 2. Build parameters used for test parts 1-5

Build	Linewidth comp. (in)	Z compensation	High Resolution Spatial Tolerance	Small Feature Preservation	Sweeping	Orientation
1,2	0.0001	Off	On	On	On	Normal
3	0	Off	On	On	On	Normal
4	0	Off	On	Off	On	Normal
5	0	Off	On	Off	On	45 degrees

     Due to symmetry of top and bottom surfaces, initially only the top surface was measured. A representative grid was analyzed from the top surface of each of the builds using data taken by Zygo NewView 200 white light interferometer. However, it was realized that due to overcure, the top surface of the parts had thinner walls than the bottom surfaces. Studying the vertical profile of the walls under a microscope revealed that the walls indeed have a cone shape. This is true for every test part built. The vertical cross-section for part 3 is shown in Figure 7.
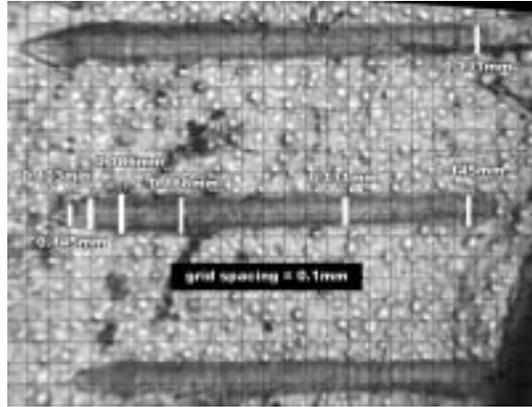
Figure 7. Vertical cross-section of grid walls

The left side of Figure 7 is the top of the wall, and the right side is the bottom of the wall. It can be seen that the walls are much thicker at the bottom than the top, and the very top of the wall looks like a cone. The test part, whose vertical cross-section is shown in Figure 7, was built in the normal orientation with sweeping on and linewidth compensation turned off. It can be said that turning linewidth compensation off for a thin part may result in a thicker part. Sweeping gives better control on distribution of resin on the top surface and may improve the resolution during scanning. When the parts are oriented in a 45-degree fashion, similar thicknesses could be obtained in the x and y directions.

3.1.2 Effect of .stl file resolution on circular surfaces

Choosing the correct surface deviation value when generating an stl file is important in obtaining an accurate part, especially if the part has circular surfaces. An effective way to obtain good surface finish for such a part can be achieved by expressing the resolution as a factor of the radius of curvature of the surface and deviation value from the .stl file:

$$C_{res} = \delta / R \qquad (2)$$

where C_{res} is the circular resolution, δ is the deviation value of the .stl file, and R is the radius of curvature for the surface. Since radius of curvature is known for a given part, if a suitable circular resolution value can be obtained, the deviation value that will give acceptable surface finish could be calculated.

A CAD model of an optical lens with a 10 μm radius of curvature was designed using SolidWorks software. This CAD model and its .stl representation are shown in Figure 8 below.
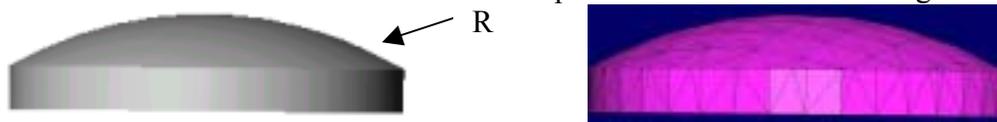

Figure 8. Lens CAD model on the left and .stl file on the right

It can be seen from the .stl file in Figure 8 above that the tessellation, even with the lowest deviation value possible, is not be enough to accurately display the boundaries of this lens.

Larger lenses were built using StereoLithography apparatus. Acceptable surface finish was achieved with the 52 mm radius of curvature lens and 0.00177 mm deviation. This gives a C_{res} *value of 0.000034*, which could be used as a guide when designing circular surfaces for SL parts.

3.2 Conclusions from experiments

The grid parts have a vertical cross section similar to a cone, because the top layers do not have the effect of overcure due to scanning. Turning linewidth compensation off for a part with such thin walls causes the walls to become much thicker than intended. Turning sweeping on is recommended so that the build surface will be even. In addition, 45-degree orientation minimizes directional discrepancy.

A C_{res} *value of 0.000034* could be used as a guide when designing circular surfaces for SL parts. The corresponding deviation value can be calculated when exporting an .stl file, so that acceptable surface finish will be obtained for the finished StereoLithography part.

4. USING OFFSETTING TO PREDICT A CROSS-SECTION

Our approach aims to display a cross-section and possible issues that might arise with it. This can be achieved by employing offsetting algorithms to a cross-section in order to simulate the effect of vector tracing by the laser beam spot on the x-y plane.

4.1 Offsetting Operations

The mathematical definition of an offset is given as "a constant specified distance from an object" [10]. For a line, the offsetting equation [11] is given as

$$O(t_o) = C(t_o) + d \cdot N(t_0) \qquad (3)$$

where $O(t)$ is the offset curve, $C(t)$ is the parameterized curve, d is the offset distance, $N(t)$ is the normal to $C(t)$, and t is the parameter.

When implementing offsets, a number of problems such as discontinuity, cusps and loops may arise. The issues resulting from offsetting operations are shown in Figure 9 below.
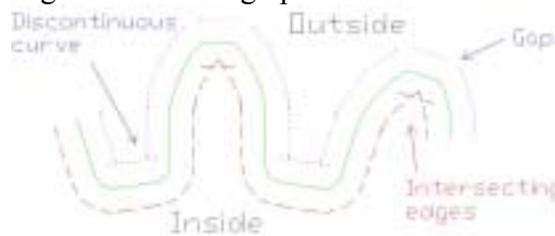

Figure 9. Inside and outside offsetting profiles for gear teeth

In Figure 9, an offset to the inside of gear teeth profile is denoted by the dashed line and has intersecting edges. An outside offset profile is drawn by using a dotted line, and has gaps and discontinuous curves.

4.2 Offsetting method to predict cross-section in StereoLithography

Predicting what a cross-section would look like can be achieved by a number of steps:

1. The coordinates of the cross-section are obtained from the .stl file triangle vertices, recorded in a counterclockwise fashion, and displayed.
2. The outline of the cross-section is spooled onto the StereoLithography grid.
3. Areas of the build where vertices cannot be snapped directly onto a grid point are highlighted. This is achieved by calculating the distance between the original outline coordinate and snapped point coordinate. If this distance is larger than a certain value (can be specified), the area is highlighted.
4. The outline of the cross-section is offset to the inside by the laser beam spot radius (default linewidth compensation value).
5. The cross-section is offset to the outside by the laser beam spot radius. At the end of step five, the as-built cross section is obtained.

For the last 2 steps (Steps 4 and 5), there are different offset values that are taken into account in order to obtain the best possible as-built cross-section. The offsetting values considered are the default value of 0.005 inch (half of laser beam diameter), 0.004, 0.003, 0,002, 0.001 inches and zero. For each value, the area of the resulting offset is compared to the original area of the cross-section. The difference between the two areas is considered to be the build error. The offsetting value with the smallest error is picked and displayed by the code.

5. METHOD EXAMPLE
How a part cross-section could be displayed before it is built using our method is shown in this section. A part with a cross-section that contains a concave and a convex feature was chosen. The progression of a sample cross-section is shown in Figure 10 below.

(a) Plot cross-section   (b) Spool on SL grid   (c) Highlight erroneous points
of cross section by dots

(d) Offset to the inside   (e) Offset to the outside and obtain final shape
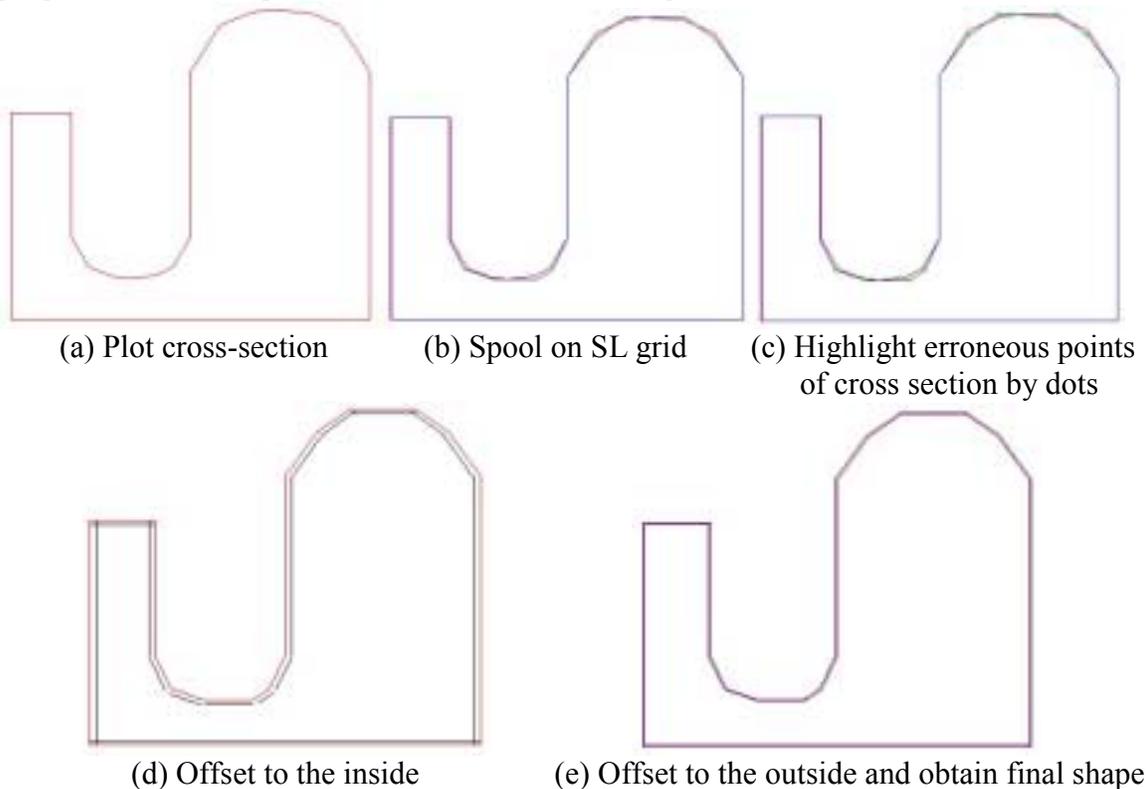Figure 10. Offsetting method steps

In Figure 10 above, the original cross-section is shown with the red color whereas the offsets are shown with blue. When the part is sliced, the cross-section is spooled onto a SL grid in Figure 10 (b) that has certain spacing. Then, points that are spooled away from the original cross-section are highlighted in Figure 10 (c). Afterwards, the part cross-section is offset to the inside of the cross-section as shown in Figure 10 (d). As the last step, cross-section is offset to the outside in order to get the final as-built shape, in Figure 10 (e).

Since there are a number of offsetting values that are evaluated during a build, it is important to select the best one for a particular cross-section. This is done by calculating the surface area difference between the desired shape and the as-built shape for different offsetting values, and then selecting the offsetting value that gives the least error. In this example, 0.001-inch offsetting value had the lowest error; therefore, this offsetting value would give the best possible as-built cross-section.

6. CONCLUSIONS AND FUTURE WORK

Build parameters affect build resolution differently. Using linewidth compensation may change the thickness of thin cross-sections, while sweeping and build orientation affect the overall accuracy of the part. Smooth circular surfaces can be built using StereoLithography technology if the deviation value is optimized for a given radius of curvature.

The ability to view cross-sections before they are built by applying offsetting has been demonstrated. This allows the user to foresee potential build problems due to resolution limitations. Future work that will help improve process resolution includes increasing SL grid capability, designing a laser optic system with a smaller laser beam diameter, and reducing layer thickness of StereoLithography process.

ACKNOWLEDGEMENTS

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