LAYER BUILDING WITH SLOPING EDGES FOR RAPID PROTOTYPING OF LARGE OBJECTS

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ABSTRACT

An overview of current rapid prototyping techniques is presented. A need to produce rapid prototypes of large objects is identified. The current layer building techniques which use square edges on the layers are seen to be inadequate for creating large prototypes. A method to cut sections with sloping edges is introduced as a way to increase part accuracy when using thick layers. Two such systems are discussed, and an improved procedure for calculating the sloped surface path is presented. Some ways for improving accuracy are introduced, including using principle directions of minimum surface curvature, and using curved surfaces on the layer edges.

1 INTRODUCTION

Rapid prototyping and manufacturing techniques are very useful in product design and development. They enable designers to quickly obtain a real model that can be examined and tested. This allows a number of design and evaluation iterations to be performed quickly. Advances in the technology now allow functional metal prototypes to be produced without tooling. Soon production ready tooling will be able to be made faster and cheaper thanks to rapid prototyping. Current rapid prototyping systems are limited in the size of objects they can produce. It would not be practical to build a full scale model of a car or eighteen foot sailing skiff using machines presently available. However the advantages of rapid prototyping and manufacturing are not limited by part size. Thus there is a need to be able to produce prototypes for models larger than one cubic metre, quickly and accurately.

At the Queensland Manufacturing Institute, (QMI) there has recently been an investigation into new methods of rapidly producing large prototypes and tooling patterns (Tullberg, 1995). The methods they considered were, material removal, layer building, formative, and sculpturing. This paper will concentrate on layer building techniques, and how to increase their speed, and the surface accuracy of the models produced.

2 SYSTEMS CURRENTLY AVAILABLE

There are a wide variety of rapid prototyping machines, most of which have a build envelope of less than one cubic meter. Manufacturers often supply a number of models with different work volumes. Generally the larger the machine, the greater the price. For example the SLA-500 produced by 3D Systems has an operating envelope of 500 x 500 x 600 mm , and costs about twice as much as the SLA-250 with a work volume of 250 x 250 x 250 mm (Jacobs, 1992).

There are a number of systems that work on a similar principle to 3D Systems' StereoLithography Apparatus, and some have a larger build envelope than the SLA-500 (Kochan, 1993). Sony Corporation and Japan Synthetic Rubber have co-developed the Solid Creation System (SCS) with the largest system offering a work volume of 1000 x 800 x 500 mm. Mitsubishi Corporation developed the Solid Object Ultra-Violet Laser Plotting (SOUP) system. The largest machine they offer is the SOUP-850, with a work volume of 850 x 600 x 500 mm.

An alternative to having a large machine is to split the model into several smaller parts and build them separately. The smaller parts can then be joined to form the object. To build an object such as an eighteen foot skiff by this method, would take a long time using the current technology. The build time could be as much as 15 days, at a typical build rate of 15 mm / hour,. The time to assemble the pieces would also have to be added to this already excessive time.

A few systems are being developed that do not have a limited build envelope (Kochan, 1993). BPM Technology have developed a process they call Ballistic Particle Manufacturing (BPM). This system builds models using a three-axis robotic system with a piezoelectric ink-jet mechanism. The ink-jet mechanism directs streams of material at a target, producing multiple cross sections. The target can be a table, a floor, almost anything, giving the system no real size constraints. Incremental Fabrication Technologies is developing a system similar to BPM. Their focus is on using metal materials. They have built parts using tin, and have been reported to be working with aluminium. Another method for building metal parts is 3-D Welding, or Shape Melting. These methods use current technology, combining welding equipment to deposit metal and robotics equipment to control the positioning.

A system more suited to building large parts, called Cross-Sectional Prototyping (CSP), is offered by LaserCAMM. The CSP process takes 3-D CAD models and cuts out cross sections with a laser. To assist in part assembly the laser also cuts registration holes and engraves layer numbers. Once the parts are assembled, they are sanded and finished to produce relatively accurate prototypes. The process can use variable layer thickness, ranging from 0.125 to 37.5 mm. On detailed areas of a model, thin layers can be used to increase resolution, while on less detailed areas, the use of thicker layers can save cutting and assembly time.

Although these systems have the potential to produce parts of almost any size, the time taken to build large parts can be excessive. All the current layer building systems use layers with edges square to the layer plane. This creates a step effect on the part. Very thin layers are used to maintain part accuracy. For example SLA systems use layers of between 0.1 and 0.5 mm thick. Using layers of this size to build something like a car body could take days or weeks. Systems such as LaserCAMM's CSP use thicker layers to reduce the build time. However the use of thicker layers reduces part accuracy and surface finish. To improve this the part can be sanded back, or filled and then sanded, but this adds more time and labour to the process. Figure 2.1 shows part of a 1:3 scale model sailing skiff, produced at QMI. The model was built from 10 mm thick square edge layers. The step effect can be quite easily seen in the picture. If this was a full size model being used to make tooling, or part of the final product, a lot of work would need to be done to bring the surface to a useable state. Thus a need has been identified for a way to produce large objects accurately, as well as quickly.

Figure 2.1 One third scale model of a skiff. The layers are 10 mm thick, and have square edges.

3 GENERATING LAYERS WITH SLOPING EDGES

A method to increase part accuracy, without affecting the cutting or assembly time, is to cut the layers with sloping edges that match the surface contour. The use of sloped edges could do away with, or at least greatly reduce any finishing procedures. The difficulties with using sloped edges stem from obtaining the data required to create the part from a CAD model. It is much easier to obtain the outline of a cross section then to obtain the edge surface information. Using sloped edges also means that a four or five axis controller is needed on the layer cutter, and this adds to the cost of the system.

Some work has been done at The University of Queensland using sloped edges (Stanford, 1994). An AutoLisp program was written to generate NC code from an AutoCad solid model. The program takes slices at a given thickness, and then generates NC code to cut the layers on a five axis waterjet cutter. Using this program a simple part was created to demonstrate the use of sloped edges in layer building objects.

Figure 3.1 A part cut with slopping layer edges.

The part produced was relatively simple, but it illustrated a number of important points. Firstly, use of sloped edges, as opposed to stepped edges, enables closer approximation to the actual part shape. Where the part has no intricate detail the use of sloped edges means considerably thicker layers can be used to build a part of comparable accuracy. The use of thicker layers will also mean faster build times for the part.

In the U.S.A, some rapid prototyping work has reported the use of layers with sloped edges. The Department of Mechanical Engineering at the University of Utah, is developing a system called the Shapemaker II (Smith-Moritz, 1995). Figure 2 illustrates the principle of the Shapemaker II. This system uses a hot wire to cut layers from sheets of 25 mm thick polystyrene foam. The hot wire is controlled by two plotter heads which simultaneously trace the top and bottom contours of a part slice. Once cut, each layer for a part is manually indexed and assembled.

Reports of the Shapemaker II system have only detailed a few parts. A four and a half metre long wind turbine aerofoil was made, and took approximately nine hours to cut and assemble. This indicates the time savings that can be made by using thick layers. The accuracy of the part compared to the CAD model is also claimed to be in the range of 0.08 to 0.6 percent. The largest inaccuracies for the Shapemaker II are in the build direction, and equate to about 30 mm for the four and a half metre long part. This is mainly due to inconsistencies in the thickness of the foam sheets, from which the layers are cut. This effect was also noted in the construction of the skiff model at QMI.

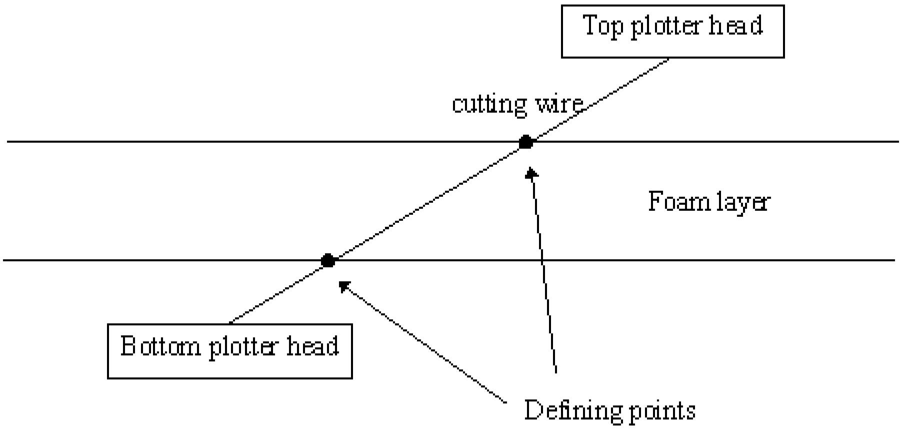

Figure 3.2 The cutting method of the Shapemaker II.

The principle of the Shapemaker II is to join two surface contours by a straight line. This method has a problem in determining what part of the top contour to connect to the bottom contour. Another drawback is that it only uses information about the surface in the plane of the contours. A more accurate way to cut a part is to take the mathematical definition of a surface, and make calculations at instantaneous points. With the definition of a surface, its slope and curvature can be found at any point. The advantage here is that no assumptions need to be made as to what part of the contours to join. The direction to cut in can be found from knowledge of the local surface slope.

4 PROPOSED SYSTEM

The system being proposed here takes the mathematical description of a surface, and generates NC code that will enable the layers to be cut. To ensure compatibility across CAD systems, it was decided to obtain the surface definition from an IGES file (U.S. Standard 1988). From the definition of a surface a contour can be traced at any desired level. At each point on the contour the instantaneous angle of the surface is calculated. The problem here is which angle to use. The direction square to the surface normal and square to the surface tangent gives a very good approximation to the model shape. However there are other directions that may give a more accurate surface, and these are dealt with later.

An illustration of the vectors involved is given in figure 4.1. In the case when the edge is square to the layer plane, the surface normal lies in the plane of the page and the cutting vector points directly into the page. Here the cutting vector is represented by the dot. When the surface is curved, or sloping, the normal vector will rotate about the surface tangent, pointing at an angle out of the plane of the paper. In this case the cutting vector points at an angle into the page. In the diagram the cutting vector is hidden by the surface normal.

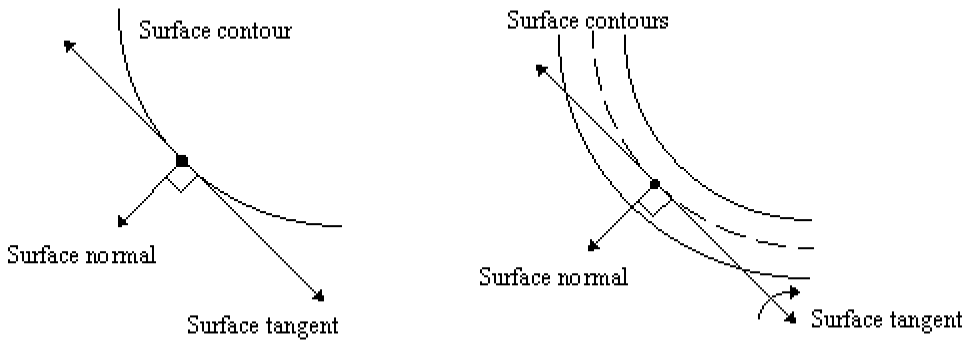

Figure 4.1 2D illustration of the method used to find the cutting vector.

Figure 4.2 represents one layer of a model. The solid contours represent the path that would be cut out by the cutting vector, while the dashed line is the contour calculated from the surface model. It can be seen that the calculated contour is at a height mid way between the top and bottom surfaces of each layer. This position was chosen to hopefully give the average slope over the layer.

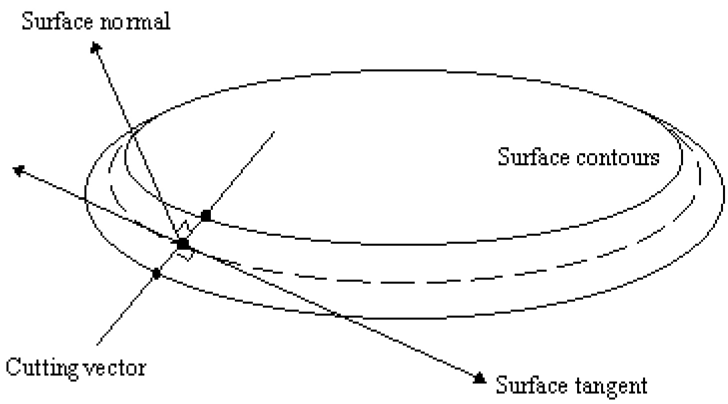

Figure 4.2 3D illustration of the method used to find the cutting vector.

At each point on the dashed contour, the surface normal and tangent are calculated. From these two vectors the cutting vector can be determined. If in figure 4.2, the model is a cone, then the cutting vector lies exactly on the surface. However if it is a hemisphere, only the calculated point lies on the surface, and the rest of the cutting vector is above the surface. Figure 4.3 illustrates the difference between the CAD model and the cut layers. For a convex surface extra material is left on the layer plane, while for a concave surface extra material is removed. In some cases the point from which the cutting vector is determined may be at, or near, an inflection. In such a case part of the cutting vector will be above the surface and part below. The error between where the cutting vector intersects the layer plane, and where the CAD model intersects the layer plane is dependent on three factors. Layer thickness, curvature of the surface, and the angle of the radius of curvature to the layer plane.

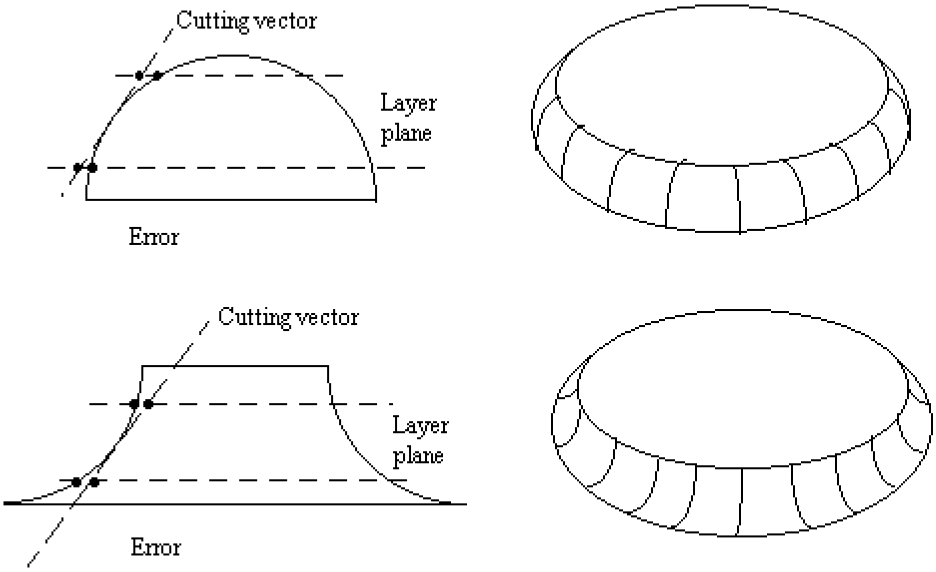

Figure 4.3 The error between the CAD model, the cut layers.

The graph in figure 4.4 shows the error when the angle of the radius of curvature to the layer plane is zero. The diagonal lines represent when the radius of the surface curvature is equal to, twice, and three times the layer thickness.

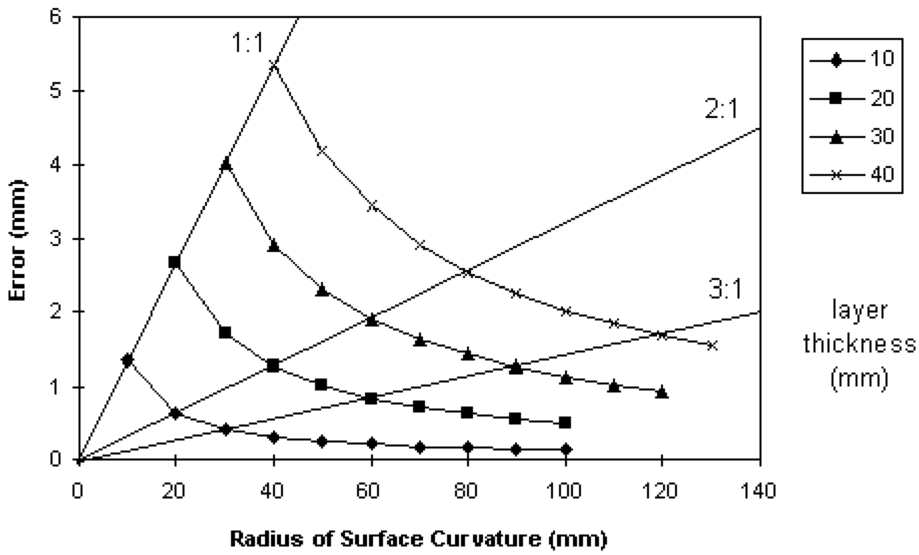

Figure 4.4 Graph representing errors for various layer thicknesses.

At first these errors may appear excessive. However on large objects with thick layers, they are very good. Especially when it is realised that a stepped edge layer with a surface angle of 45° has an error equal to the layer thickness. The graph shows that the errors rapidly become larger as the radius of curvature approaches the layer thickness. The errors are quite reasonable when the radius of curvature is twice the layer thickness, and even better at three times. In models of considerable size the radius of curvature is likely to be much greater than the layer thickness used. However there may be sections of a model that contain significantly more detail than the rest of the model. To allow for this it is possible to include an error checking algorithm in the layering software. Such an algorithm would allow the user to select an acceptable error tolerance, and then check each layer. If the error on any particular layer is unacceptable, the program could introduce sections with thinner layers to bring the error within the given tolerance.

For processes where a model is to be sanded back, after assembly, it would be desirable for each layer to have extra material left on. To achieve this, concave areas of the surface need to be identified, and adjustments made to the position of the cutting vector. This can be done by estimating the surface curvature from layer to layer, and then calculating the positional error of the cutting vector. Thus allowing reasonably accurate adjustments to be made.

5 FUTURE WORK

5.1 DEVELOP SYSTEM

The next step in this project is to cut some parts with a waterjet cutter, to test the speed and accuracy of the proposed method, and aid development. It is likely that a sloped edge model of a skiff will be made from the same CAD data that was used to make the square edge one. This will be useful in clearly illustrating the advantages of using sloped edges in layer building.

The method discussed for cutting layers with sloped edges can operate on currently available NC equipment, such as the five axis waterjet cutter at QMI. It only requires new software development to produce the NC code. However the use of a five axis waterjet cutter for a commercial system would be inappropriate due to its cost. Therefore the development of a cheaper special purpose machine to perform the layer cutting is something that needs to be considered.

5.2 USE OF PRINCIPAL CUTTING DIRECTIONS

It was mentioned earlier that there were cutting directions that may produce a more accurate surface. At any point on a surface there are two directions in which the normal curvatures take extremum values (Hosaka, 1992). These directions are called the principal directions, and the curvatures are called the principal curvatures. If at least one of the principal curvatures is zero, the line of curvature on the surface is straight, the surface is developable. These surfaces can be cut by a straight wire without any error. Traditionally developable surfaces were important for yachts.

Even if a surface is not developable, one of the principal directions will give the direction of minimum surface curvature. If this direction is followed by the cutting wire, the minimum error is achieved. Thus using the direction of minimum curvature is more accurate than the direction square to the surface normal and square to the surface tangent.

In some cases these two directions are the same. For example on a cone, which is a developable surface, the direction square to the surface normal and square to the surface tangent, is the direction of minimum curvature.

5.3 USE OF CURVED CUTTING EDGES

Another method to increase the accuracy of the model further still, is to use curved surfaces on the layer edges. Thus the layer edge would not only be sloped to match the surface slope, but curved to match the surface curvature. To achieve this a hot wire or thin laminate could be used to cut the layers. One method to curve the cutting medium is to move the controlling heads closer together, and cause it to bend. The amount of bending would depend on how far the heads are moved. However it may be difficult to control the direction the cutting medium bends in. Alternatively the controlling heads could rotate the tips of the cutting medium to cause it to bend in the required direction. A more accurate method is to use three points for the cutting medium. Figure 5.1 illustrates the points used.

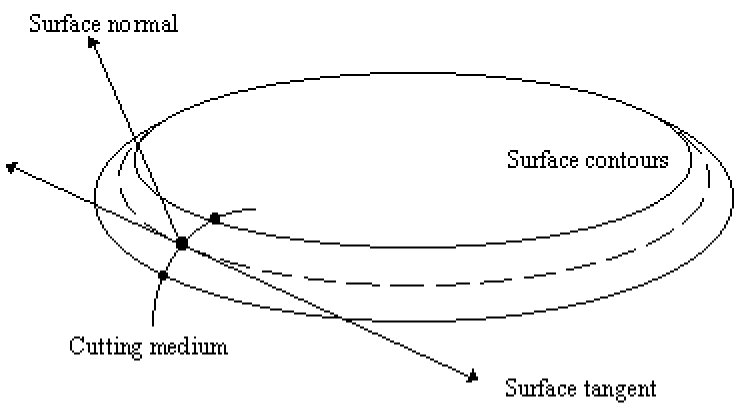

Figure 5.1 Using three points to cut a curved surface edge on layers.

As shown, three points on the surface are used for each layer, and each one is traced simultaneously to cut the layer.

The main difficulty in using three point cutting is that it may require the development of specialty apparatus, and that more axis of control are needed. However the benefits in terms of surface accuracy are very significant.

6 CONCLUSION

The inadequacies of current layering rapid prototyping techniques in relation to model size need to be remedied. They can be overcome by either increasing build rate or more accurately producing layer edges to allow for thicker layers. This paper has summarised the current situation and proposed a new system to improve the edge definition of layers. It is hoped that the work discussed in section 5 will allow a breakthrough to enable large objects to be prototyped with the same benefits currently available for small ones.

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