Direct Thick Layer Rapid Prototyping From Medical Images

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Abstract

This paper discusses a technique for building medical prototypes directly from medical image data using ruled thick layers directly from medical image data. Medical image slices are currently much thicker than the layers used by most RP machines, but a direct slice to layer correspondence can be established with the use of thick layers. The proposed algorithm uses three image planes to interpolate a ruled edge cutter path using an adapted form of the marching squares algorithm. The algorithm has no problems with bifurcations or multiple loop contours and can create cutter paths from any high contrast image volume.

Introduction

Medical prototyping is an emerging and increasingly important form of rapid prototyping. Medical prototypes are created from scanned volume data such as CT and MRI scans. Prototypes are used for surgical planning, practicing surgical steps, diagnosis, and direct creation of implants. Wilford Hall Medical Center at Lackland Air Force Base has been using medical rapid prototyping for surgical planning and has used the technique with more than 70 different patients including a conjoined twin separation (US Air Force Press Release, 1997, 1998). A company called Anatomics in Australia provides medical rapid prototyping services. Customers send a CT or MRI file and Anatomics will return models of the desired tissues made with the SLA or FDM rapid prototyping processes. The company website gives more information, including case studies (http://www.qmi.asn.au/anatomics). In the future, direct prototyping of implants using implantable biocompatible materials will make medical prototyping more attractive. Researchers are currently developing bioceramics that are compatible with tradition SLS, FDM, and 3D Printing RP Systems (Bose, 1998, Steidle, 1998, Vail, 1998).

Medical prototyping is a three step process (see Figure 1). First, a medical image is made. Second, the image volume is processed to extract geometric surface information describing the tissue to be built. Third, the geometric surface data is used to construct a physical prototype using a rapid prototyping machine or NC machine. Most of the research related to medical rapid prototyping is in the areas of medical imaging scanners, image segmentation, and rapid prototyping materials development. Image segmentation is the focus

Volume Image Data   Polygonal Surface Model   Physical Model
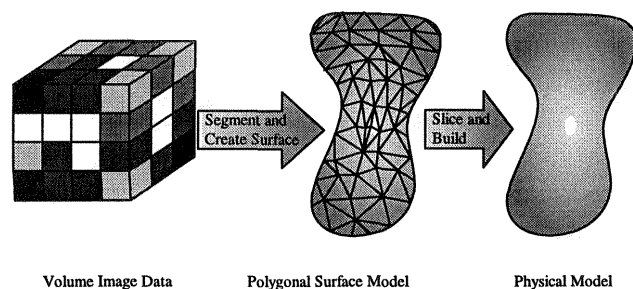
Figure 1
Generalized Medical Prototyping Process

of this paper.

All algorithms for medical image segmentation are based on the same principles and can be classified into two groups, contour segmentation or surface segmentation. In contour segmentation, each slice of the medical image is processed separately to produce a two-dimensional contour with one or more loops. The contour slices are then laced together to create a three dimensional surface. In surface segmentation, the entire volume is processed simultaneously to generate the three-dimensional surface directly. Both techniques are based on pixel or voxel intensity thresholding.

All segmentation algorithms are based intensity interpolation of a unit cell. In two dimensions the unit cell is the unit square, and in three dimensions the unit cell is the unit cube (Schroeder, 1997). The unit square is defined by the centers of four adjacent pixels in an image plane. The set of all unit squares for a plane forms a grid passing through the center of each pixel (see Figure 2 A). The unit cube is defined similarly with eight adjacent voxels from two image planes. Figure 2 B shows how to interpolate to find a line segment representing a given intensity value as it passes through the unit cell. The plus sign represents a pixel with an intensity higher than the desired value and the minus signs represent a pixels with an intensity with lower than the desired value. A simple linear interpolation of the intensities and coordinates of the points defining unit square produces the desired intensity line segment. Schroeder discusses all of the special cases for the unit cell and the unit square with a description of the marching squares and marching cubes algorithms.

A.
Unit Squares

B.
Intensity Threshold
Interpolating

Figure 2
Unit Square Definition and Intensity
Threshold Interpolation

Current segmentation techniques focus on obtaining a good surface representation of the tissue to be prototyped. That surface is then converted to an STL which can then be used to build a physical model by re-slicing it and running it through a rapid prototyping machine. The STL surface model must be generated from the medical image volume because the slice thickness of a rapid prototyping machine, ~0.1 mm, is much less than the slice thickness of medical image data, ~0.5 to 5 mm. The STL file is also the standard input to most RP machines, they will not accept medical image data. The creation of the STL surface also allows for surface smoothing to make the model look better, but the process can be slow and does not improve accuracy (Manichovich, 1994).

Ruled thick layer rapid prototyping techniques allow layer thicknesses ranging from 0.5 mm to several inches (Chamberlain, 1997). Thick layers could speed the prototyping process by eliminating the creation of a surface data set because
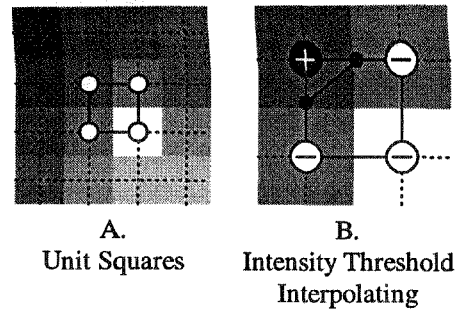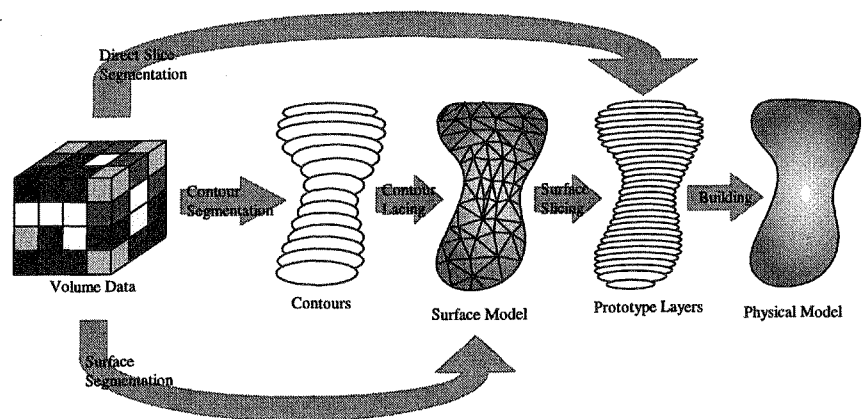

Figure 3
Ruled thick layer prototyping allows direct prototyping without the creation of an intermediate surface

layers with the same thickness as the image slices can be used. That means that it is possible to directly process the medical image data to create the layers for the RP machine (see Figure 3). The latest version of the thick layer ruled edge machine at the University of Utah is called ShapeMaker 2000. It is a four-axis waterjet cutter capable of building prototypes of 20 or more feet in size. It uses a semi-manual process that requires manual stacking and manual STL file splitting to remain within the machine's 3 ft x 5 ft cutting envelope. The wajerjet cutter operates at pressures up to 40,000 psi and can cut low density foams several inches thick or plastic sheet about 1 to 2 mm thick.
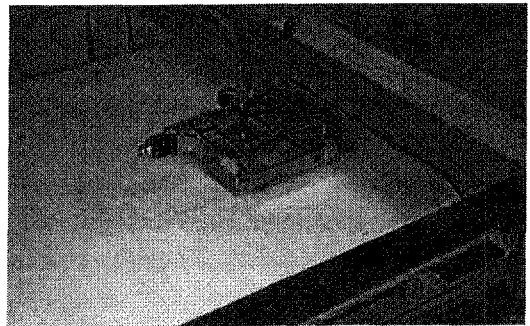

Figure 4
Photograph of ShapeMaker 2000 cutting head

Direct Slicing Algorithm

In order to create a direct slicing algorithm, one must first determine the image slice to prototype layer correspondence. One option would be to define layers with vertical edges based on the contours from a single image slice. This option has the disadvantage of thick stepped layers. A second option would be to use two adjacent image slice contours to create a general ruled edge. With this option it is difficult to connect rapidly changing contours or contours without the same number of loops. A third option would be to use three adjacent image slices to define a general ruled edge (see Figure 5). The prototype layer would be centered on the middle image slice, which would control the geometric topology of the layer (number of loops and general shape of contour). The top and bottom image slices would be used to define the cutter angle of the layer. This option has the disadvantage of being a tangent cut algorithm, meaning the layers form a model with jagged edges (Hope, 1997). This third layer definition provides the most robust algorithm because it does not break down with complex geometry, yet still provides a ruled edge result.
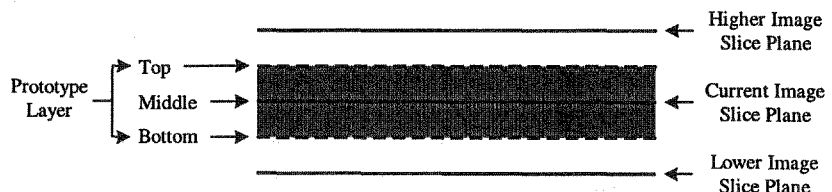

Figure 5
Prototype layer definition using three image slice planes

Implementation of the three plane layer definition required the creation of a new segmentation algorithm which will be referred to as the three plane marching squares algorithm. It is a modification of the basic marching squares algorithm as presented by Schroeder. The marching squares algorithm is a two loop search and sort algorithm. In the first loop, each unit cell in the image is intensity interpolated to determine if a contour segment crosses through it. If a segment does cross through it, that segment is added to an unordered segment list. In the second loop, the segments in the list are sorted to create the loops of the intensity contour. The three plane algorithm works with a similar search and sort method.

The searching step of the three plane marching squares algorithm is more complex than the searching step of marching squares algorithm. Figure 6 is a schematic of the steps involved

in the algorithm. The first noticeable difference is that the unit cell is defined by twelve voxels, three from each image plane, instead of four pixels. The first step of the algorithm (Fig. 6A) is identical to the marching squares algorithm. The four voxels on the mid-plane are used to define a unit square which returns a mid-plane contour segment. Each mid-layer segment endpoint then becomes the pivot point for a cutting angle at each end of the contour segment. The cutting angle at each end of the segment is determined independently in a multiple step process. Figure 6B is a schematic of the process for one end of the mid-plane contour. Two unit squares, one above and one below the mid-plane, are formed using the top, middle, and bottom image planes. A line is intensity interpolated in the top and bottom square independently, shown as the thick dotted lines terminated with small squares in Figure 6B. The average slope of the two interpolated lines is used to create a cutter angle line centered on the mid-plane contour and extending halfway to the top and bottom planes. The process is repeated for the other end of the intersection to produce a segment of the ruled edge cutter path, as shown in Figure 6C.

After the three plane marching squares algorithm is executed, the result is an unordered

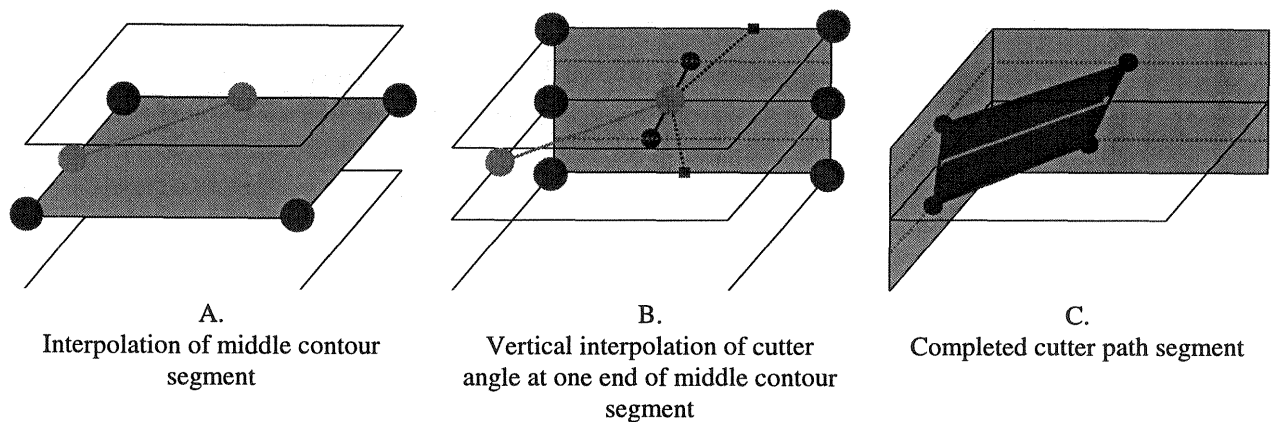| A.	B.	C.
Interpolation of middle contour segment	Vertical interpolation of cutter angle at one end of middle contour segment	Completed cutter path segment

Figure 6
Three plane square for the three plane marching squares algorithm

list of cutter path segments which are sorted using the mid-plane contour segments to produce the loops of the cutter path contours. The top and bottom contours, calculated from the cutter path angles, are added to the contour list along with the mid-plane contour. Several fixes are required to produce proper cutter paths that can be used by ShapeMaker 2000. First, angle limits are applied to bring the top and bottom contours closer together so that the angle of the cutting head is never more than the current 55 degree limit of the wajerjet(see Figure 7). Next, the cutter path must be examined for cutter path crossovers, which result in unnecessary motions that slow the cutting process and reduce the layer surface quality. Crossed cutter lines are fixed by swapping cutter lines, as shown in Figure 8. Cutter lines are always swapped on the side with the shortest cutter path segment. Cutter line crossovers are detected and fixed in a two dimension projection. Note that a cutter line represents a three dimensional line in space that the wajerjet will pass through as

$\alpha = atan(t/d)$

A.
Normal Side View

B.
Top View
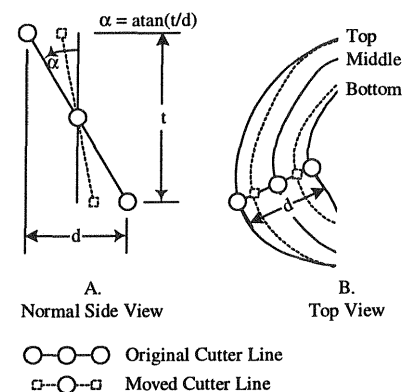
O—O—O Original Cutter Line
□--O--□ Moved Cutter Line

Figure 7
Setting cutter angle limits

it moves along the cutter path.

Three further modifications were added because of the small size of the bones to be prototyped. First, each layer was surrounded by a registration box which was cut into the material surrounding the layer. During stacking, the registration boxes can be aligned corner to corner to provide registration for gluing the layers together with high accuracy. Second, the waterjet tends to blow small pieces off from the cutting table after they have been cut. All of the smallest pieces of any layer were cut first, generally it does not matter if they blow off from the table because they are usually internal cavities that will be thrown out later. If the larger cuts that surrounded the internal cavity cuts blew off the table it would mean that the internal cavities would not be cut. Third, because ShapeMaker 2000's cutting table is several feet across, it was possible to cut a hundred or more layers one sheet of material by writing all of the layers into a single cutter file with an offset for each layer.
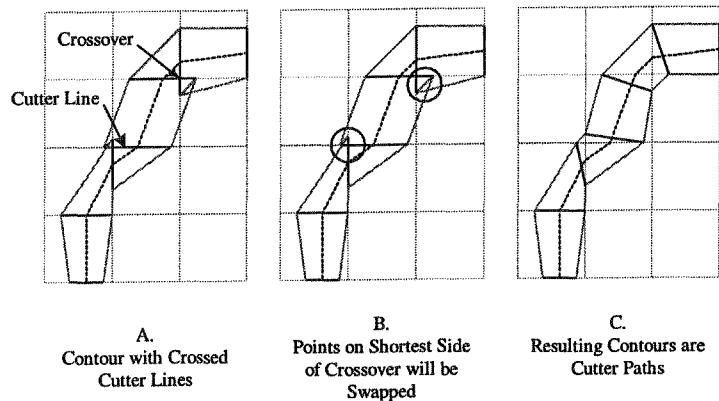

| A. Contour with Crossed Cutter Lines | B. Points on Shortest Side of Crossover will be Swapped | C. Resulting Contours are Cutter Paths |

Figure 8
Swapping cutter line crossovers

Results

The software was tested with data sets obtained from the website of the Laboratory of Human Anatomy and Embryology, University of Brussels (ULB), Belgium. Two windowed high contrast data sets were used, a C1 vertebrae from the top of a human neck and a human humerus shaft. The C1 vertebrae data set is 24 MB in size. The voxels are stored in a 16 bit format with 512x512x47 voxels, 0.5x0.5x0.5 mm in size. The humerus data set is 200 MB in size. The voxels are stored in a 16 bit format with 512x512x298 voxels, 0.5x0.5x1.0 mm in size. Figure 9 shows a rendering of part of the processed C1 dataset displayed as a series of stacked layers with a 47.5 degree angle limit. A physical model of the part was built at 2.54 times actual size because at the proper scale the layers were too small to glue manually. The total build time for the C1 model was 16 hours, about 4 hours of cutting and 12 hours of manual stacking. The physical model was build from Sintra sheet, a high density PVC foam, and assembled with clear PVC adhesive. Figure 10 shows a scanned image of the built humerus shaft. This was also built using Sintra sheet and purple PVC adhesive primer was used to accentuate the layers. The total build time for the humerus model with 8 hours, about 1.5 hours of cutting and 6.5 hours of manual stacking.

Conclusions

The three plane marching squares algorithm is robust and easy to use. This was proven by the C1 vertebrae data set which had anywhere from one to 30 loops on a layer and multiple birfucations on most layers. It would be difficult to extract a surface from the dataset and it would be even more difficult to construct a set of ruled edge cutter paths from the resulting STL
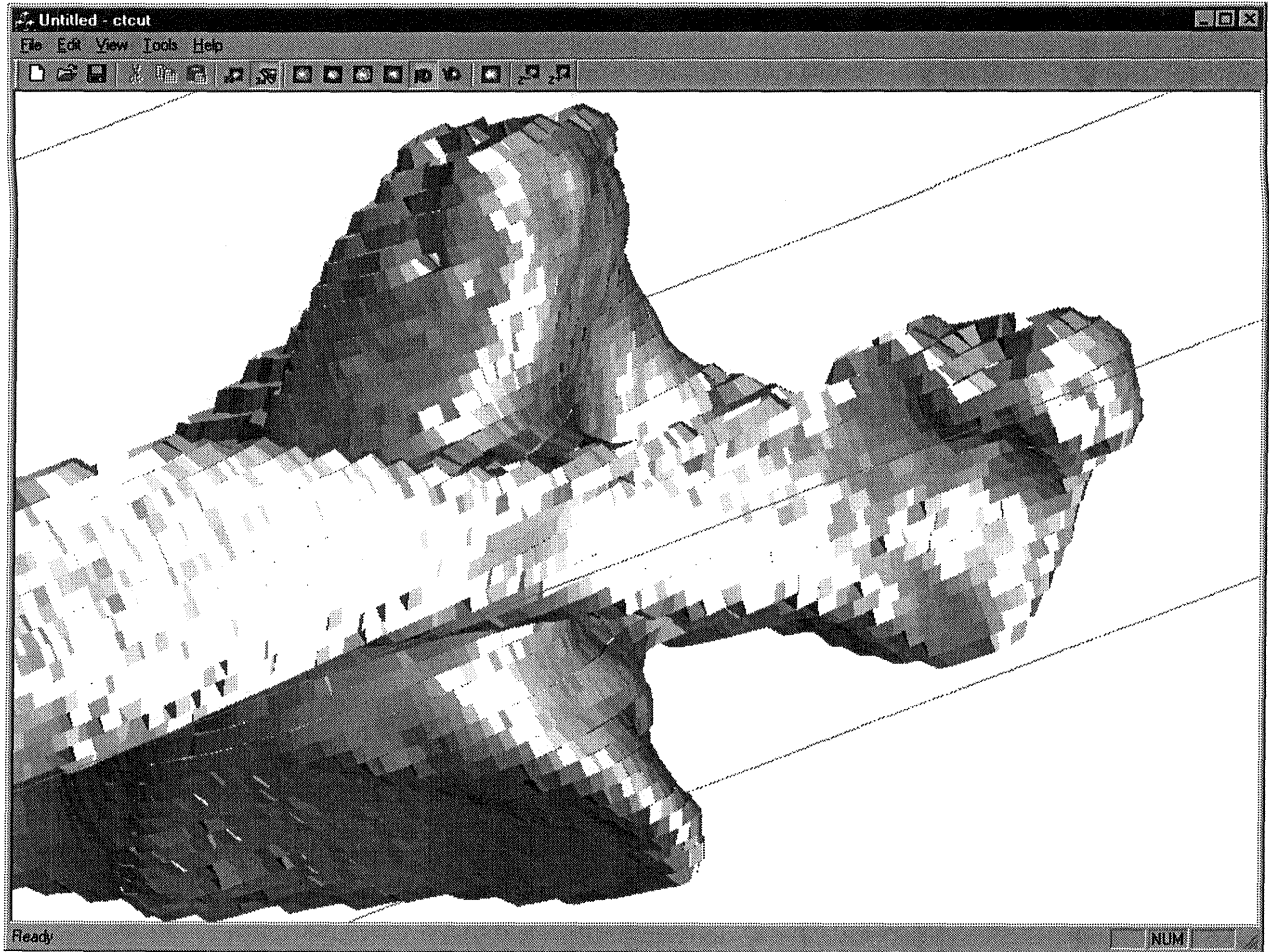
Figure 9
Screen capture of human C1 vertebrae rendered in OpenGL as stacked ruled edge layers with an angle limit of 47.5 degrees

file. The humerus prototype showed particularly good results. The near vertical edges cut and stacked accurately, giving a model with great surface quality. This shows the potential of a ruled edge RP machine to improve surface quality when it is working within its angle limits.

The current research immplementation of ShapeMaker 2000 is not suitable for building models of human bones or organs because the machine is designed for objects an order of magnitude larger. A smaller version of ShapeMaker with automatic stacking might make this particular prototyping process practical.

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Anatomics web site: http://www.qmi.asn.au/anatomics

The image datasets used in this experiment were from the Laboratory of Human Anatomy and Embryology, University of Brussels (ULB), Belgium
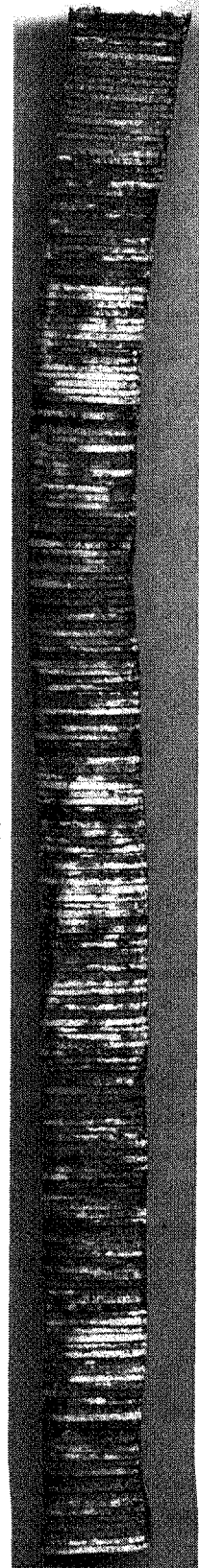

Figure 10
Human humerus