A simple shading for computer displayed surfaces

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To the memory of Professor László Kalmár

Introduction

In order to achieve a visually realistic representation of the surface of a three-dimensional object on a cathode-ray tube, one has to solve the problems of removing the hidden parts of the surface and shading its visible parts. A commonly used approach which allows efficient solutions to both these problems is to approximate the surface so that it is composed of planar polygons [2]. Lack of continuity in the shading across polygonal boundaries causes undesirable artifacts which can be removed by continuous shading procedures such as the one suggested by Gouraud [2].

In this note we discuss an extremely simple and efficient alternative method for removing the artifact mentioned above. In the application area which is our main concern our method is not only two orders of magnitude faster than that of Gouraud's, but it also produces superior displays. In this application area the surface is approximated by a composition of squares, each one of which is parallel to one of three mutually perpendicular planes. In the next section we describe the nature of our application area.

Three-dimensional reconstruction from projections

The problem of reconstructing a three-dimensional object from a set of its two-dimensional projected images has arisen in fields ranging from electron microscopy to holographic interferometry. For example, in medicine we use an x-ray source to project the body onto the two-dimensional surface of a film. From a subset of all possible projections of a body, reconstruction algorithms [1] produce a three-dimensional array of numbers in which each number is an estimate of the average density of the body in one of a set of equal, non-overlapping cubes, called voxels (volume elements).

In order to see the shape of a particular organ, a three-dimensional boundary detection algorithm has been devised [3]. This detects the organ's boundary surface and generates the description of the surface in terms of the square faces of the voxels.

An example

For a demonstration of our ideas we use a plastic cast of an isolated canine left ventricle with some beads inserted on the surface. Figure 1 shows a television image of this cast, blurred so as to make the resolution similar to that obtained in the reconstruction process.

A variant of the Algebraic Reconstruction Technique [1] has produced from 34 x-ray projections of our cast a $64 \times 64 \times 28$ density array, with the edge of each voxel being $1.04 \times 1.04 \times 1.68$ mm. (Based on such a reconstruction variations in the surface smaller than a voxel could not possibly be displayed. For a fair evaluation of the efficacy of our display procedure its output should be compared to an image of the original which has been blurred as in Figure 1 to remove features

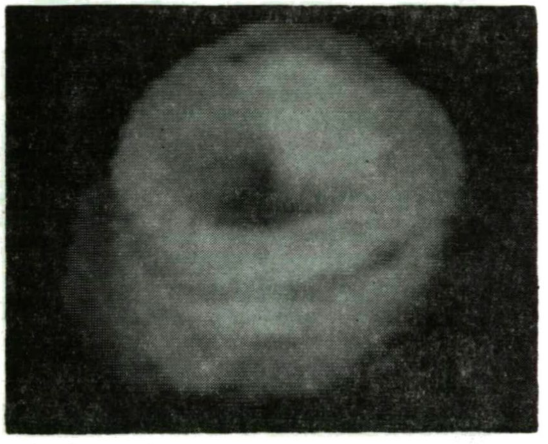

Fig. 1
A television image of the plastic cast of a canine left ventricle

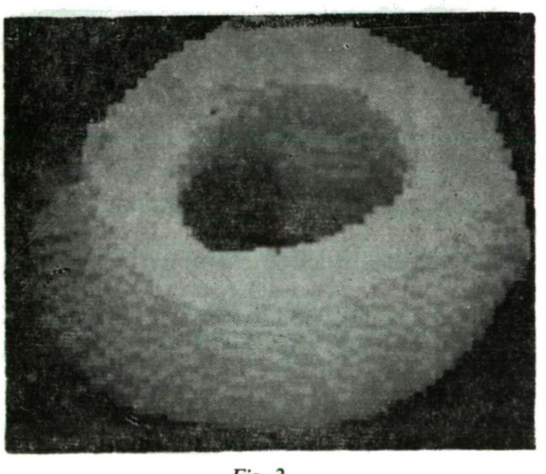

Fig. 2
Computer-generated display of the cast which was determined from 28 reconstructed cross-sectional levels of the cast

smaller than the resolution of the reconstruction procedure.) A surface detection algorithm [3] has been applied to the reconstructed array and it produced an estimated surface of the cast consisting of a connected collection of faces of voxels. This collection is displayed in Figure 2 using a shading which is uniform within each face and whose value depends on the angle the face makes with an assumed direction of light and on the distance of the face from an assumed light source (Warnock's shading rule as given on page 624 of [2]). As can be seen, approximating the curved surfaces with small square surfaces generates an undesirable visual effect, caused mainly by having only three directions in which surface elements lie. Similar, though less disturbing artifacts are observable whenever a curved surface is displayed as a collection of planar polygons.

Gouraud's shading procedure

Gouraud [2] suggested a way to get rid of the artifact apparent in Figure 2. This approach is to modify the computation of the shading on each surface so that continuity exists across surface boundaries. This continuity can be achieved by assigning as normal at a vertex the average of the normals to each surface associated with this particular vertex. Each surface has a different shading for each of its vertices and the shading at any particular point inside the surface has to be computed as a continuous function of the shading at the vertices of the surface.

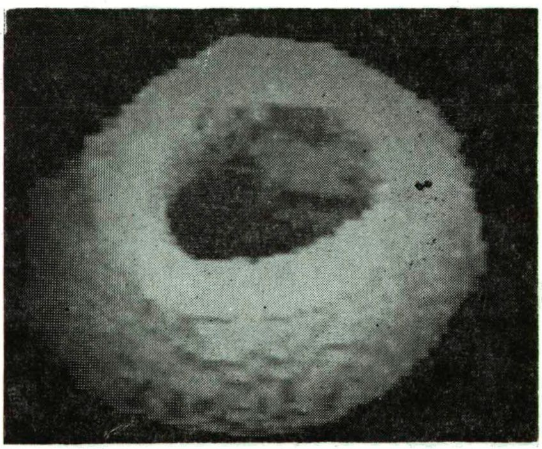

Fig. 3
Computer-generated display of the cast by use of Gouraud's shading procedure

Due to the large number of the surfaces in the objects we are interested in (typically 10,000), this approach is prohibitively time consuming. Also, the results are far from acceptable, because the surfaces are either parallel or perpendicular to each other. Figure 3 shows a display produced by Gouraud's method applied to the surface of the cast shown in Figure 2.

A simple smoothing procedure

In this section, we describe an alternative approach to this problem. Instead of smoothing the surfaces in object-space, we smooth the intensities in image-space.

Let $G_1, \ldots, G_9$ denote the shading intensities in a screen dot and its eight neighbors before smoothing, as indicated by the diagram below.

G_6	G_2	G_7
G_3	G_1	G_4
G_8	G_5	G_9

After smoothing, the new intensity of the center dot will be

$$G_1^{\text{new}} = \frac{G_1 + W * \sum_{i=2}^{5} f_i * G_i + W^2 * \sum_{i=6}^{9} f_i * G_i}{1 + W * \sum_{i=2}^{5} f_i + W^2 * \sum_{i=6}^{9} f_i}.$$

If the dot labelled by 1 is on an edge and does not have a neighbor labelled by i, then f_i is assumed to be zero, otherwise f_i equals one. W is a user adjustable weighting factor.

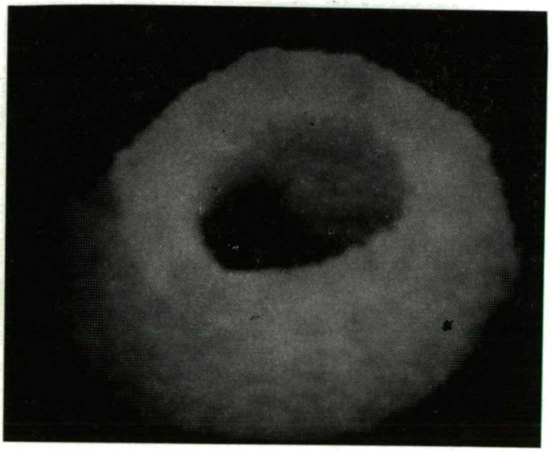

Fig. 4
Computer-generated display of the cast by the use of the proposed shading procedure

This simple smoothing method gives surprisingly good results. Figure 4 shows the display shown in Figure 2 after our smoothing procedure with $w = 0.8$. The time required for this smoothing procedure is under eight seconds (CDC 3500) while our implementation of Gouraud's method needed 985 seconds to produce the smoothing shown in Figure 3. (Note that the time required by our procedure is dependent only on the number of picture elements in the display, while the time required by Gouraud's method depends on the number of polygons from which the surface is made up.) Also, in our opinion, the true image (Figure 1) is better approximated by the display produced by our method (Figure 4) then it is by the display produced by Gouraud's method (Figure 3).

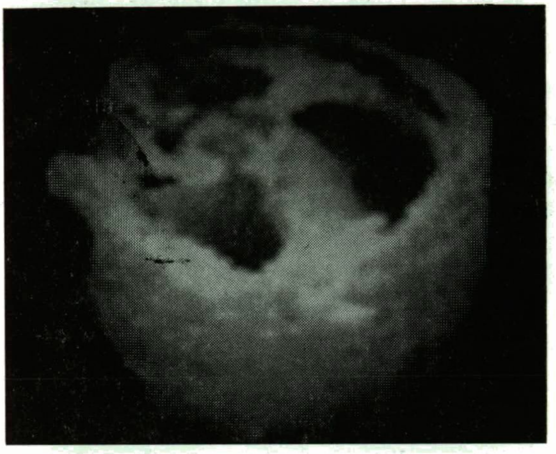

Fig. 5
Computer-generated display of a canine heart which was determined from 30 reconstructed cross-sectional levels of the heart

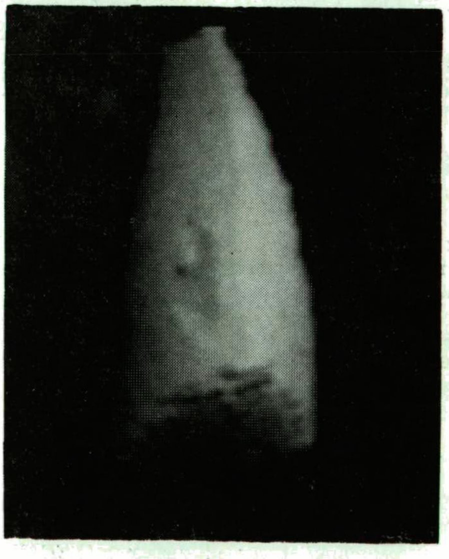

Fig. 6
Computer-generated display of a part of a canine left lung which was determined from 64 reconstructed cross-sectional levels of the intact thorax of a dead dog

Further examples

We demonstrate our display method on reconstructions of two further biological objects.

In Figure 5, we display the surface of an isolated canine heart whose $64 \times 64 \times 30$ reconstruction has been produced from 50 x-ray projections.

In Figure 6, we display the surface of a part of the left lung of a dog. Thirty-five x-ray projections of an intact dead dog have been taken and the thorax and contents of the dog were reconstructed as a $64 \times 64 \times 64$ array. The input to the surface detection algorithm was a $28 \times 64 \times 64$ subarray containing most but not the whole of the left lung. The surface detection algorithm [3] was applied to detect the surface of the lung in the thorax and the result is displayed in Figure 6. The imprints in the lung of the heart and of the major airway above it are clearly visible.

Conclusion

We have proposed a display smoothing algorithm which is very efficient if the surface to be displayed consists of many polygonal surface elements. Efficiency is due to the smoothing being done on the image and not on the surface. In the display of organ surfaces obtained by three-dimensional reconstruction, our algorithm produces results visually superior to Gouraud's smoothing procedure in a small fraction of the time required by that procedure.

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Abstract

This note proposeses a simple way of removing the artifact caused by approximating curved surfaces with polygons in computer-generated three-dimensional display. The method is compared with Gouraud's continuous shading method.

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