The Visual Computer

Reconstruction and semi-transparent display method for observing inner structure of an object consisting of multiple surfaces

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A system of techniques is proposed for reconstructing the original object from multi-layered cross-section data including open contour lines and for displaying the inner structure as well as the outside using a stereoscopic semi-transparent image and cut-away views. The procedure is divided into three steps: 1) selection/construction of contour lines for each cross-section, 2) reconstruction of the object based on the contour line information including cutting away part of the reconstructed object with a convex polyhedron, and 3) display of the reconstructed image. Control parameters are provided to allow easy and reliable observation of multi-layererd structures.

Key words: Semi-transparent display – Triangle method – Contour lines – Cut view – Stereoscopic display

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1 Introduction

A widely used method for describing complicated three-dimensional objects composed of various elements (characteristics of each element are not the same in general) and displaying them as sets of two-dimensional cross-sections. Usually, each cross-section is perpendicular to the center line of the object, and is composed of a number of contour lines. Direct comprehension of the original geometry based on this form of data is almost impossible. Therefore, the following two technologies are very important for understanding the complicated three-dimensional object in detail: i) reconstruction of the original object based on sets of two-dimensional cross-sections, and ii) display of the inner along with the outer appearance of the object in a form that may be easily understood. These technologies are desired especially in the study of development in the field of anatomy.

Traditionally, in the field of anatomy, a number of cross-section images were prepared, each section being a thin slice of an organism. The observer had to create the entire geometry in his/her mind based on the set of sections. The only solution to this situation was to simply obtain perspective drawings or 3-D models of the original object supplied by some researcher. This does not provide sufficient understanding if the interior geometry of the object is not simple.

This paper proposes a system of methods using computer graphics to solve this problem. The whole procedure is divided into three steps: 1) generation of contour lines based on each cross-section, 2) reconstruction of the object based on the contour line information, possibly cutting away a portion with a convex polyhedron, and 3) display of the reconstructed image.

In general, contour lines have been automatically generated by using a threshold value (Sumi, 1981). The elements of the two-dimensional data that exceed the value are selected, and then contour lines are generated using these elements.

Several modelling methods are available for reconstructing the original object from cross-sectional data. A surface model in which the objects represented as a set of surfaces is more appropriate than voxel modelling (Herman 1979), because the interior geometry of the object is easily understood when each surface is displayed as a semitransparent membrane. A widely used method of several surface modellings is to fill the area between two consecutive contour lines with a triangular mesh. A typical triangular mesh technique using graph theory was reported by Fuchs et al. (1977). However, this technique is not valid if elements branch off or join together between cross-sections. Christiansen et al. (1978) proposed a modified triangle method to handle this case. The algorithm is simple, and generates a good triangular mesh if there is no drastic change between two consecutive sections. However, they did not consider handling multi-surface cross-section data nor data in which open contour lines (such as a mouth) are allowed.

The reconstructed image could be displayed using a three-dimensional shading technique. However, to visualize the interior aspect more clearly, the surface of each element should be displayed as a semitransparent membrane (Sungunoff 1978; Sumi 1982). The semitransparent image is obtained by mixing the color of the background picture calculated by conventional methods and the color of the object to be displayed as a semi-transparent membrane (Newell 1972). However, direct application of the method is known to produce low apparent transparency. A remedy for this problem is to introduce a transparency parameter (Kay 1979). The transparency is high where the surface is perpendicular to the viewing direction, and it is low where the surface is parallel.

We have previously proposed a semi-transparent stereoscopic method (Nakamae 1985). In our new system, generation of contour lines is carried out by manual input of the contour lines using a digitizing tablet. This is because there exist features in cross-section data in our application shown in Fig. 1 where automatic contour line detection using the image processing technique is almost impossible.

For 3-D object reconstruction, two modifications have been made to Christiansen's method:

(i) Any number of contour lines may be included in each cross-section.

(ii) An appropriate triangular mesh is obtained even if drastica geometric change occurs between consecutive sections (Kaneda 1987).

Display of the reconstructed object is specially designed to allow easy observation of the inner structure. This is because the most realistic semi-transparent representation of an object does not always offer the best information for observation. Two projected views are created, corresponding to positions of the left and right eye. The obtained stereoscopic effect enables three-dimensional observation of the object.

In our previous work, open contour lines were not allowed in a cross-section. However, open regions in the object, such as a mouth, are often important elements of the entire body. Thus, we have improved our previous reconstruction method to incorporate open regions in objects. We also have modified our system to allow cut-away views to be generated by cutting with a convex polyhedron. Using cut-away views, one can easily observe the inner structure and the shape of elements on arbitrary sections.

An example of application of the new proposal follows the detailed description. It demonstrates the usefulness of our techniques.

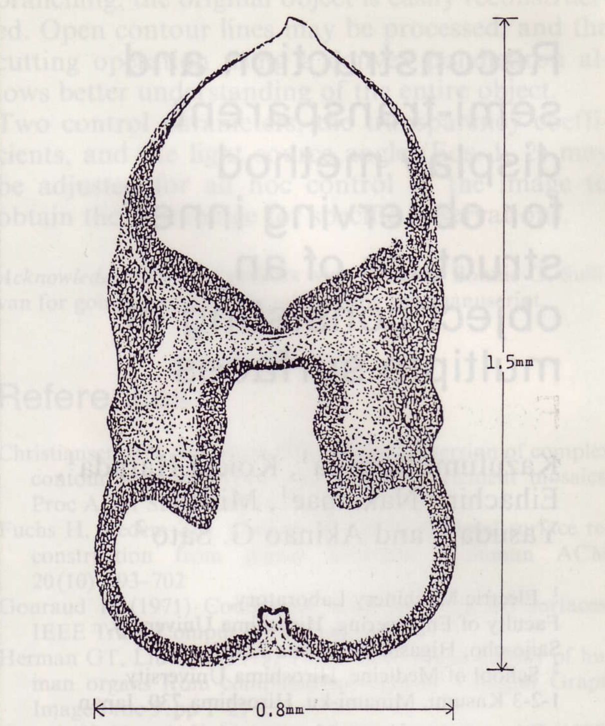


Fig. 1. Sectional photograph of mouse embryo. Interval between sections 7 μm

2 Reconstruction of the object from contour line data

2.1 *Data structure*

A hierarchical data structure is introduced in the new proposal to allow multiple contour lines that consist of object elements, subobjects, contour lines and contour points. Regions of different char-

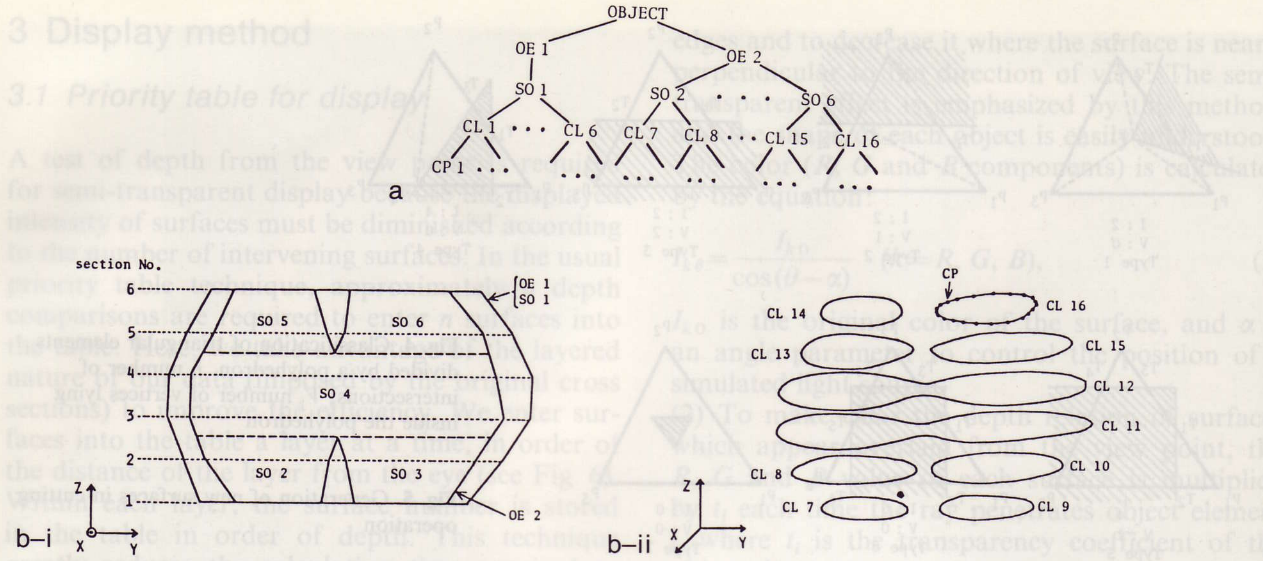


Fig. 2. a Hierarchical data structure. **b–i** Object elements and sub-objects. **b–ii** Contour lines. *OE*, object element; *SO*, sub-object; *CL*, contour line; *CP*, contour point

acteristics are assigned to different object elements. Therefore, each object element is a region sharing the same characteristics. An object element is divided into several sub-objects in general if it branches out or comes together between cross-sections. Each contour line defined on a cross-section corresponds to one object element. Furthermore, a contour line is defined by a set of contour points. Figure 2 illustrates an example of the hierarchy. The sub-object information in our data structure eliminates the need for special processing to determine which pairs of contour lines on consecutive cross-sections should be connected. The user simply associates the name of the sub-object with its contour line on each cross section when digitizing the data. Thus, contour lines may contain other contour lines, and objects may exhibit branching structures.

2.2 Open contour lines

If cross-sections include open regions such as a mouth there exist open contour lines. Two combinations of consecutive cross-sections are possible as shown in Fig. 3. For (a), both cross-sections are open, and the triangular mesh generation is initiated with one terminal point from each section (P_1 and Q_1) and the process ends at the other terminal point (P_n and Q_m). For (b), one cross-section

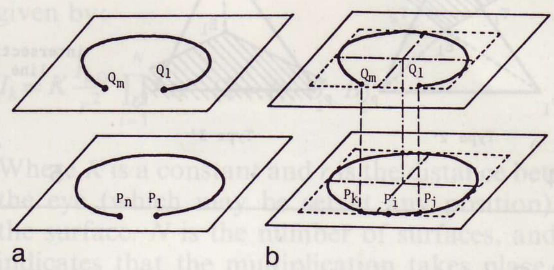


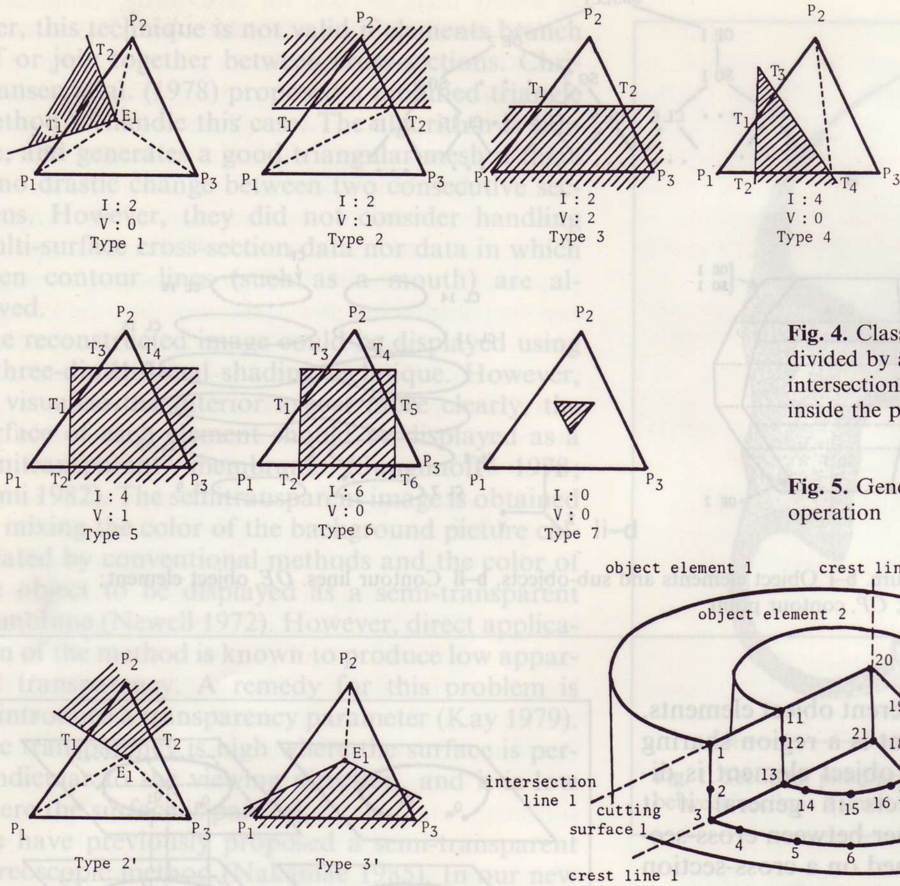
Fig. 3 a, b. Two combinations of contour lines on consecutive cross-sections. **a** Same type of contour lines. **b** Different type of contour lines

is open and one closed. This case is treated by first locating the point P_i where the bifurcation occurs. Then the pair P_i and Q_1 are used as the initial point for triangular mesh generation, and the process ends at the pair P_i and Q_m. Bifurcation points are located as follows (see Fig. 3):

(1) The cross-sections are translated so that their centers line up.

(2) P_j, the contour point nearest to Q_1, and P_k, the contour point nearest to Q_m, are located.

(3) The point P_i ($k \leqq i \leqq j$), which satisfies $\overline{P_{i-1}Q_m} < \overline{P_{i-1}Q_1}$ and $\overline{P_iQ_m} > \overline{P_iQ_1}$ is taken to be the bifurcation point.



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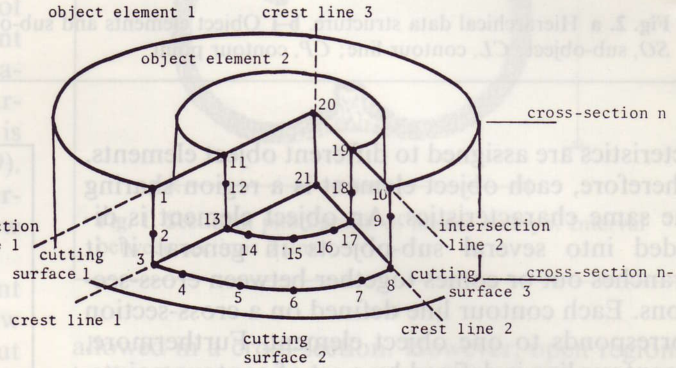

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Fig. 4. Classification of triangular elements divided by a polyhedron. *I*, number of intersections; *V*, number of vertices lying inside the polyhedron

Fig. 5. Generation of new surfaces in cutting operation

2.4 Cut view

Appropriate cut-away views often facilitate better and easier observation. This operation provides new information on the inner structure and interrelations of different surfaces. We allow the entire object, as described by a number of triangles, to be cut by a convex polyhedron, and new surfaces are generated to show the cutting surfaces.

The basic idea of the cut-away operation is that the volume of the object intersected by the cutting polyhedron is to be removed. Each triangular patch of the object can be classified as lying totally inside, totally outside, or intersecting the cutting polyhedron. Those lying outside are displayed unchanged, those lying inside are discarded, and those intersecting must be further processed. Intersected triangular patches are classified as one of 7 types based on the number of intersections with the polyhedron and the number of vertices of the triangle contained within the polyhedron (see Fig. 4). Classifications Type 2′ and 3′ are also used for triangles which intersect two edges of the polyhedron. The classification is carried out whether the crest line of the cutting polyhedron penetrates the triangular patch or not.

As shown in Fig. 4, for each class of triangle, the shaded area is removed (except for Type 7, where the area is considered negligibly small), and the remaining area of the triangle is divided into new triangles, as shown by the dotted lines. This helps simplify further processing.

An efficient priority table technique, explained in Sect. 3, is used for display. The efficiency of this application of the priority table derives from the fact that the data is already partitioned (because of the cross-sections) into parallel layers. We must be careful to generate the new cut surfaces in the same way. Fig. 5 illustrates the generation of new surface elements for a pair of concentric cylinders with an angular wedge cut away.

3 Display method

3.1 Priority table for display

A test of depth from the view point is required for semi-transparent display because the displayed intensity of surfaces must be diminished according to the number of intervening surfaces. In the usual priority table technique, approximately n depth comparisons are required to enter n surfaces into the table. Here, we take advantage of the layered nature of our data (imposed by the original cross sections) to improve the efficiency. We enter surfaces into the table a layer at a time, in order of the distance of the layer from the eye (see Fig. 6). Within each layer, the surface number is stored in the table in order of depth. This technique greatly reduces the calculation time required to build the priority table.

3.2 Semi-transparent display method

We have researched a number of algorithms for semi-transparent display and have determined that the following leads to easy and reliable observation:

(1) The function $1/\cos\theta$ (where θ is the angle between the surface normal and the eye direction) is used to increase the color of the surface near edges and to decrease it where the surface is nearly perpendicular to the direction of view. The semi-transparent effect is emphasized by this method, and the shape of each object is easily understood. The color (R, G and B components) is calculated by the equation:

$$I_{k\theta}=\frac{I_{k0}}{\cos(\theta-\alpha)} \quad (k=R, G, B), \tag{1}$$

I_{k0} is the original color of the surface, and α is an angle parameter to control the position of a simulated light source.

(2) To make clear the depth relation of surfaces which appear overlaid from the view point, the R, G and B value of each surface is multiplied by t_i each time the ray penetrates object element i, where t_i is the transparency coefficient of the object element i.

(3) The depth relations of surfaces are even more emphasized by reducing the color of each surface proportional to the squared length of travel of the ray in the surrounding material of the object. The final equation for the color of each surface is then given by:

$$I_k=K\frac{I_{k0}}{r^2}\prod_{i=1}^{N}{}^{*}\, t_i \quad (k=R, G, B). \tag{2}$$

Where K is a constant and r is the distance between the eye (which may be set at any position) and the surface. N is the number of surfaces, and $\prod^*$ indicates that the multiplication takes place only if the surface is penetrated by the ray.

(4) Gouraud's smooth shading technique (1971) is applied in displaying the image. It smoothes over edges caused by the triangular mesh. Thus, the observation becomes easier.

The proposed equations are evaluated by application to a simple set of objects, namely, a set of concentric cylinders. A pair of views has been produced to allow stereoscopic observation. The result demonstrates the semi-transparent effect, and the three-dimensional geometry is easily perceived (see Fig. 7).

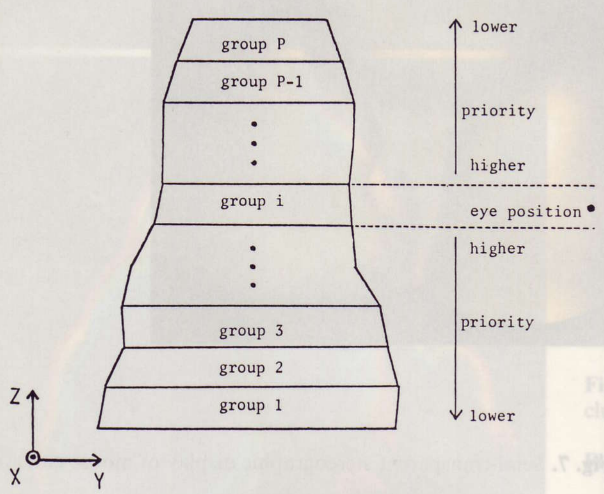
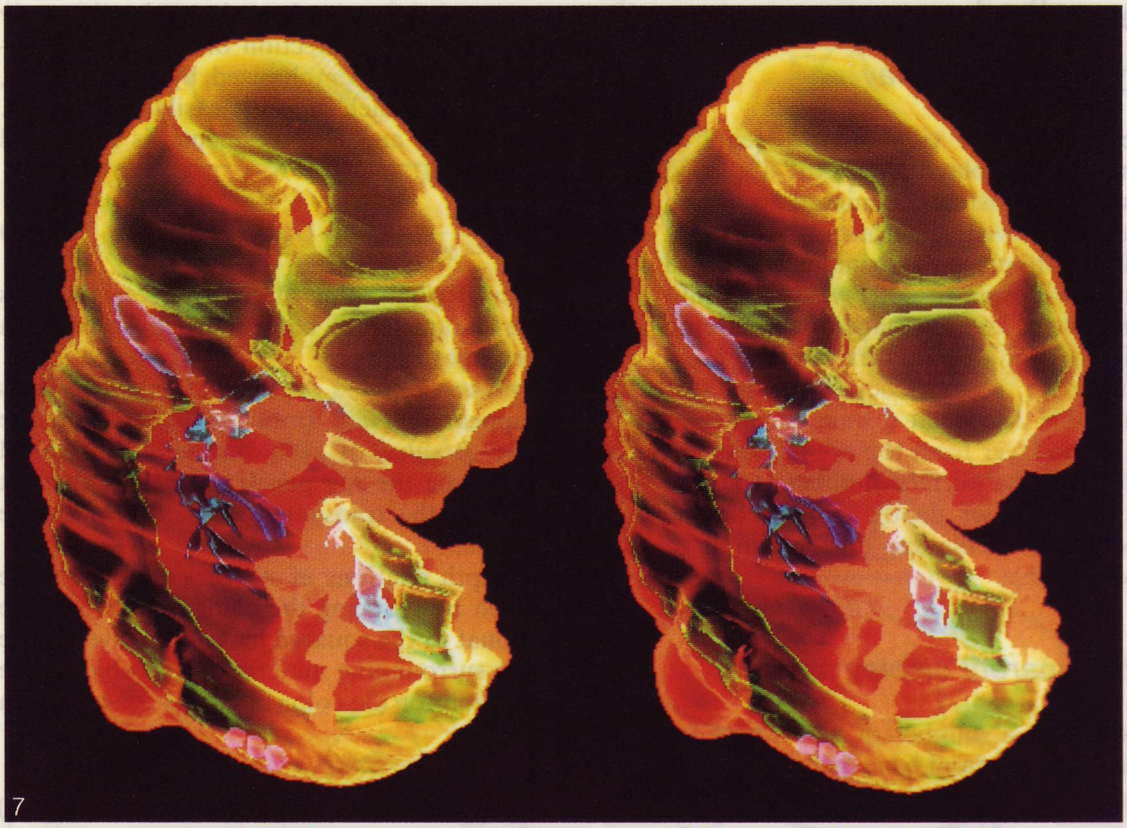


Fig. 6. Priority test based on sectional partition

3.3 Examples

The proposed system is applied to data from a mouse embryo. The data are composed of 69 cross-sections, and there are 8 object elements. Fig. 7 shows a stereoscopic representation of the entire



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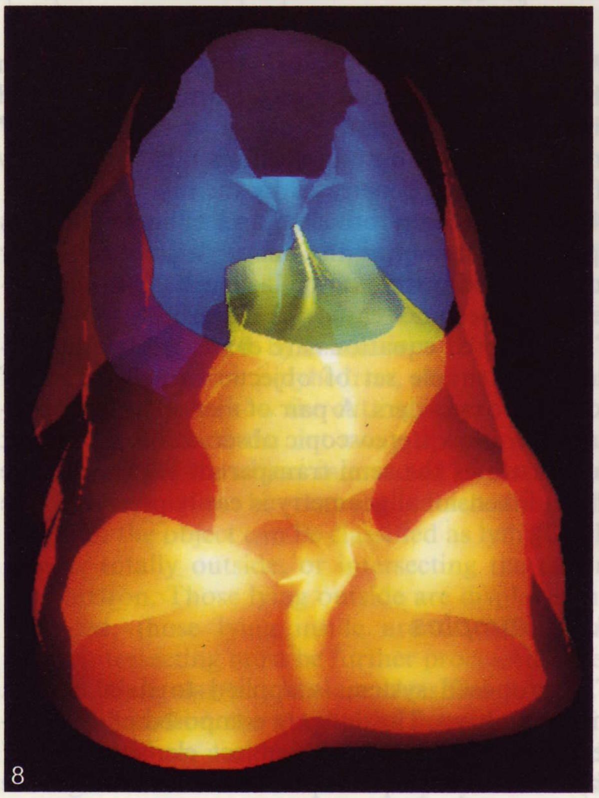

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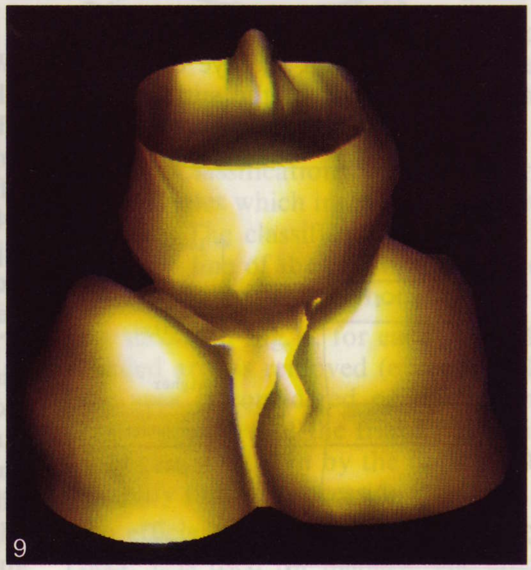

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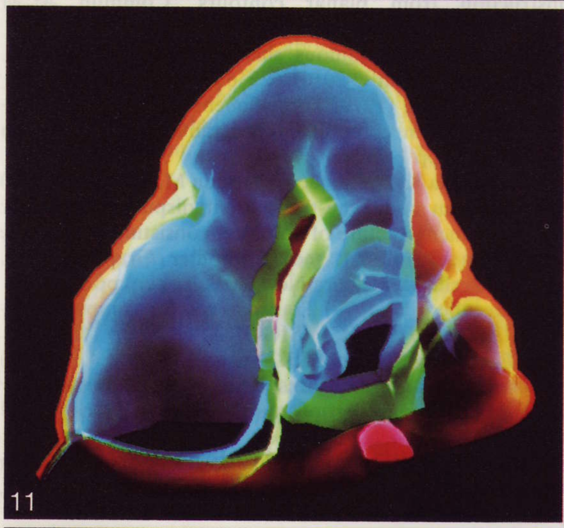
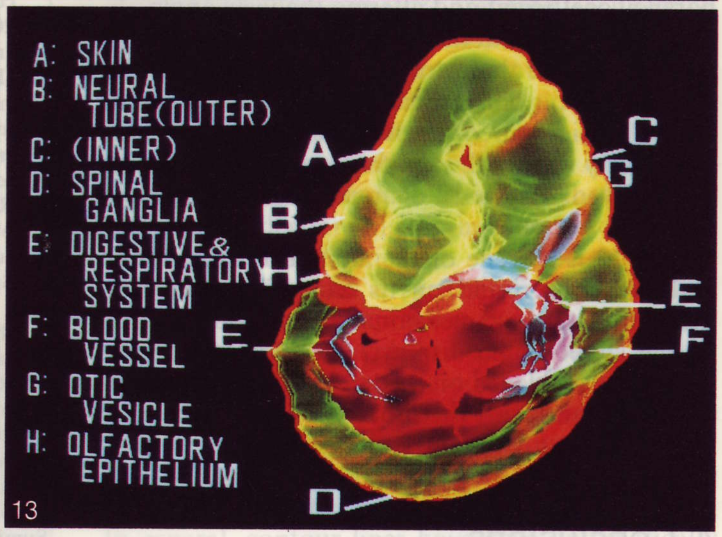
Fig. 7. Semi-transparent stereographic display of mouse embryo

Fig. 8. Effect of brightness phase

Fig. 9. Selection of an object-element





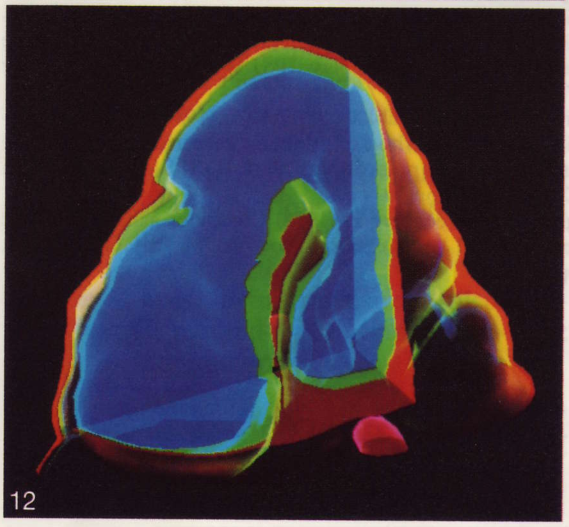


Fig. 10. Semi-transparent stereographic display of mouth, which includes open contours

Fig. 11. Cut-away view

Fig. 12. Cut-away view with semi-transparent cut surfaces

Fig. 13. One scene of an animation

object. $\alpha=0$, and each transparency coefficient t_i is set to 0.6. In Fig. 8, the yellow object element is emphasized by setting α to 90 degrees and deleting an object element outer neural tube, which are not needed for observation. These examples demonstrate the effect of the simulated light source angle.

Transparency coefficients may be used to emphasize some particular object elements among others. Figure 9 shows the result when the transparency coefficient of an object element is set to zero and the angle parameter is 90 degrees. With this parameter choice, the representation of the specified object element is the same as that of conventional (non-semi-transparent) methods.

Treatment of open contour lines is shown in Figure 10. The mouth object element colored pink is emphasized in this example by lowering its transparency coefficient and altering the view angle.

The cutting operation was used to obtain the image in Fig. 11. The data are of the head of a mouse embryo with a portion cut-away by a rectangular solid. If it is desired to view the cutting surfaces, a cut-away view with semi-transparent cut surfaces is displayed. Figure 12 demonstrates this application.

Figure 13 is a scene of the animation; the mouse embryo turns round on its axis. The animation also offers three dimensional observation as well as the stereoscopic display. The object elements' names are displayed on the left side and the arrows turning round with the mouse embryo point each object element out.

4 Conclusions

A system of techniques has been proposed for reconstructing the original object from multi-layered cross-section data and for displaying it as a stereoscopic semi-transparent image.

At the reconstruction step, the new sub-object oriented data structure enables the handling of objects with multiple surfaces. Even if subobjects exhibit branching, the original object is easily reconstructed. Open contour lines may be processed, and the cutting operation using a convex polyhedron allows better understanding of the entire object.

Two control parameters, the transparency coefficients, and the light source angle (Eqs. 1, 2) may be adjusted for ad hoc control of the image to obtain the best image for specific observations.

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