THREAD (Three-dimensional Reconstruction And Display) with biomedical applications in neuron ultrastructure and computerized tomography

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ABSTRACT

THREAD is a computer system capable of displaying three-dimensional images from serial two-dimensional sections. The serial two-dimensional input images can either be in the format of 35 mm films or in digital cross sectional pictures of live patients generated by the ACTA (Automatic Computerized Transverse Axial) Scanner. The hardware components of the system consists of FIDAC (Film Input to Digital Automatic Computer), MACDAC (Man Communication and Display to Automatic Computer), and the Display Subsystem of the ACTA-Scanner. The software includes such features as segmentation, rotation, hidden line removal, shading plane definition, shading and display. Two examples, one from serial electron micrographs of a neuron and the other from serial ACTA, live patient, scans are given to demonstrate the capability of the system.

INTRODUCTION & BACKGROUND

The study of tissues in the biomedical sciences is most often in the form of two-dimensional cross sections. This is especially true of microscopic data obtained from both the electron and light microscope. The recent advent of computerized tomography, whereby computer generated cross-sectional tomograms are produced anywhere in the whole living human body, provides a new additional source of two-dimensional serial images.

Three-dimensional reconstruction of this data has for the most part been avoided because of the difficult and time-consuming techniques involved. However, the added insights and the additional qualitative and quantitative data that can be obtained from three-dimensional studies, prompted investigators to undertake three-dimensional reconstructions using graphic art techniques. These reconstructions took the form of wax and plexiglass models as well as artists' drawings. Although these methods produced some elegant results, they were quite costly in terms of artists' fees, time-consuming and lacked simple means to obtain quantitative data such as volume, shape and surface area.

To obviate these disadvantages, computer graphic systems were employed to provide semi-automatic three-dimensional reconstructions of microscopic data. Most of these systems required some type of photographic manipulations of the input data in order to transform the information into digital format. These procedures included tracing photographic prints with light pens or cursors, the use of a camera lucida followed by tracing on a data tablet or manual tracking of cell outlines using the computer as a notebook for coordinate points. Output from these earlier systems was in three forms, purely quantitative data such as perimeters and surface area, schematic diagrams of reconstructed images or line drawings depicting the contours of the section outlines which in most cases served as a guide for artists who then drew shaded three-dimensional images of the structure. Most of these earlier systems provided the important advantage of image rotation so that any surface of the reconstructed object could be visualized.

In the field of computerized tomography, cross-sectional tomograms are taken allowing for the visualization of the internal anatomy of the living patient in the horizontal plane. Consecutive scans obtained at fixed intervals along the patient's longitudinal axis provide serial cross sections of the patient. Methods exist for the alignment of such data and the display of other (sagittal, coronal, or arbitrary) planes obtained from the original cross-sectional scans. Three-dimensional imaging of selected structures, however, allows a specific object (bone, organ, tumor, etc.) to be displayed as an isolated image which can be rotated to allow visualization of all surfaces. This display is analogous to the situation encountered with microscopic serial cross-section reconstruction and is the logical next step in computerized tomography data display.

The three-dimensional reconstruction and display of nonbiomedical data has been an active field in com-
puter graphics. The work of Roberts, Warnock, Sutherland and others demonstrates the excellent results that have been obtained in the three-dimensional reconstruction of geometric and architectural structures. However, the reconstruction and display of three-dimensional biomedical data of the type described above, differs from geometric data in two specific ways: (1) algorithms to reconstruct biomedical serial section data can take advantage of the initial condition that all two-dimensional sections are aligned with respect to their X and Y axes and that these sections follow each other sequentially along the Z axis prior to rotation, and (2) biomedical data reconstruction in three-dimensions is complicated by the lack of any geometric assumptions about individual section outlines, since they may assume any random shape and are often quite complex.

The THREAD system allows for the three-dimensional reconstruction of biomedical data in the form of serial cross sections, using existing hardware devices and methods analogous to earlier three-dimensional geometric or architectural reconstructions. The system locates objects of interest in each section automatically, thereby eliminating time-consuming manual outline tracing. THREAD can rotate objects to any viewing angle and the system generates both contour-grams (line drawings), as well as fully shaded, three-dimensional images in both color and black-and-white in a fast and highly automated fashion.

The major hardware subsystems of THREAD include: FIDAC (Film Input to Digital Automatic Computer) a flying spot scanner for 35 mm film, MACDAC (MAN Communication and Display to Automatic Computer) an interactive computer graphics terminal, and the video graphic display subsystem of the ACTA-Scanner. The software subsystems include: programs to digitize 35 mm film negatives, find boundaries of objects of interest in each section, align section outlines, erase hidden lines and programs to rotate and shade the completed three-dimensional object.

The THREAD system can accept input data in two forms, either 35 mm film negatives of serial sections photographed from any source or serial computerized tomograms generated by the ACTA-Scanner which are stored on magnetic tape. Figure 1 depicts the complete THREAD system.

In this paper we present a detailed discussion of the use of the THREAD system using two examples: reconstruction of images from electron micrographs recorded on film and macroscopic structures recorded in vivo from serial computerized tomograms obtained with the ACTA-Scanner.

HARDWARE DESCRIPTION OF THE THREAD SYSTEM

The hardware of the THREAD system was already in existence and consists of three major components, all of which convert digital information into graphic displays in an interactive manner. Input data can be digitized from 35 mm film negatives, as is the case with photomicrographs or if the input data is already in digital form as is the case with ACTA-Scanner output tapes, this information can be directly read by the computer from a magnetic tape unit. Data is processed by an IBM 360/44 computer equipped with disc storage for intermediate results.

**Film input**

Serial sections of structures can be recorded on 35 mm film and converted to digital form by the FIDAC device (Figure 2). Film is positioned in this device and a flying spot scan is generated whereby the image on the film is digitized into 16 grey-levels, the value of which is proportional to the relative translucency of the film at each particular spot. The scanner can sample some 450 rows of spots with 672 spots per row, converting a standard 35 mm film frame into a grid of 450 x 672 numerical values. This data is then transmitted on-line to the computer, the whole process requiring $\frac{1}{2}$ of a second.

The FIDAC device can also send the digital signals of its scan to the MACDAC display device (Figure 3) without storing them in the computer memory so the

![Figure 1—Block diagram of the complete THREAD system](From the collection of the Computer History Museum (www.computerhistory.org))
operator can see the image and make adjustments prior to computer data acquisition.

**MACDAC**

The MACDAC device is an interactive computer graphic system which provides for CRT display of digital information transmitted to it by the computer or FIDAC. In addition to display, the device has the capability of transmitting coordinates from its circuitry to the computer allowing the operator to interact with and modify the image on the CRT.

The operator may point out objects using MACDAC by positioning a light spot on the screen by means of a joystick controller and pressing a "Read" button on the device which sends the point's coordinates into the computer.

**Video display**

Output in the form of two 160 x 160 matrix pictures is generated by the THREAD system and stored on magnetic tape for viewing on the display processor of the ACTA-Scanner, Figure 4. The output portion of the ACTA-Scanner is usually employed in the display of computerized tomograms but also provides a flexible graphics display system for information which can be stored on magnetic tape as 160 x 160 or 320 x 320 matrices.

The components of the ACTA display system include: a magnetic tape unit (Figure 4-2), a pre-programmed video display processor called the RAMTEK (Figure 4-3,4), a 19-inch color TV monitor (Figure 4-5), two 12-inch black-and-white TV monitors (Figure 4-6), a mini-computer (Figure 4-7) and a teletypewriter console (Figure 4-1).

Two 160 x 160 matrix pictures (or a 320 x 320 matrix picture) are simultaneously displayed side-by-side on all three monitors. The display system has the
capacity of distinguishing 2048 discrete intensities which are viewed as sixteen grey-levels. For our purposes, the 2048 possible intensities are equally divided into the sixteen grey-levels, each with a range or width of 128 intensity values. These grey-levels may be assigned a continuous gradient of black to white or color codes may be selected for some or all of the individual grey-levels.

In the final display, a heading appears along with the two reconstructed images. The heading contains information describing the object and its orientation (Figure 13). A grey-level reference is also provided where the sixteen grey-levels are displayed as individual blocks along with the maximum and minimum intensity values represented by that particular grey-level.

The ACTA display system provides for automatic color coding, image enlargement and various photographic formats which the operator can request by means of selecting the appropriate code word on the teletypewriter.

SOFTWARE DESCRIPTION OF THE THREAD SYSTEM

All driver programs are written in either FORTRAN IV or Assembly and interact with the operator in everyday language via typewriter console.

Data gathering phase

Film input data is received from the FIDAC device one frame at a time and the portion of the frame which contains the objects to be reconstructed is stored in sixteen grey-levels in the computer memory. Digital input from magnetic tape is handled in a similar fashion. Any single grey-level or composite of grey-levels may be displayed on the MACDAC monitor.

The operator is asked for information pertaining to each section including: its thickness and magnification. The operator is also instructed to point out, using the MACDAC light spot, the left-most boundary of an object of interest and three alignment points to be used later for orienting all sections in the series relative to one another. Automatic boundary location commences once the above information is obtained by the program.

Standard boundary detection methods are used: boundaries or section-object outlines which differ from their surroundings by one or more grey-level can be automatically located by the program. This process is initiated in the memory when the operator points out an object of interest and types the object's grey-level into the console. The coordinates of the light spot serve as a pointer or bug which moves to the right until contacting a grey-level which equals or exceeds the threshold set for this object. The program then moves the bug clockwise around the object boundary, recording the coordinates in a 4 x 1000 element array where the first two columns represent the boundary point's X and Y coordinates, the third column represents the Z coordinate (proportional to section thickness) and the fourth column is used for later coding of selected points. The boundary processing terminates when the starting point is again located by the bug. All points are plotted on the MACDAC monitor and the operator may choose to manually edit the result if the object outline was indistinct. Up to nine objects may be located and stored for each section.

The above procedure is repeated for each section in the series and once completed, all sections are aligned using the alignment markers previously obtained for each section. Alignment is obtained by a best-fit approximation. When all objects in the series are aligned, the lists of their boundary points may be stored on magnetic tape and a new series of sections can be processed.

Reconstruction phase

The reconstruction phase of the software package is divided into six distinct steps. These six steps are preceded by the acquisition of the object boundary point lists from magnetic tape and are followed by display of the completed image.

1. Segmentation: Each object outline in the series is subdivided into segments of equal length, the end points of which will later be connected between adjacent sections to facilitate shading. These segment end points are assigned consecutive code numbers termed segment marker numbers. As will be seen later, the higher the number of segments chosen, the greater will be the detail of the final image.

Segmenting begins by determining the section-object outline which contains the greatest number of boundary points. This number represents the greatest possible number of segment markers available for this object. The operator is then asked what percentage of this maximum should be used in the reconstruction. For example, if the maximum segment number equals 500 and the operator chooses to use 50% of these segments, a section through this object which contained 50 boundary points would have the fourth column of its 4 x 1000 boundary point array filled with consecutive numbers from 1 to 50. If the section outline had greater than 50 boundary points, zeroes would be inserted between segment marker numbers at regular intervals (e.g. 1,2,0,3,4,0, , 50) and if the object had less than 50 boundary points, segment marker numbers would be evenly deleted (e.g. 1,6,11,16, , 50).

2. Rotation: Section object outlines are rotated by selecting two rotational angles, one about the vertical Y axis and one about the horizontal X axis. These angles are substituted in a rotational transformation
matrix and the X, Y, and Z coordinates of all object boundary points are transformed by matrix multiplication. All rotated points must be checked to ensure that they are positive values and if negative values are encountered, the entire list of boundary points for the object must be shifted into the positive domain by addition of a constant to the appropriate coordinate set.

3. Hidden Line Removal: Hidden lines are defined as portions of section-object outlines which are overlapped by the addition of a new section on top of it. Other authors have used a variety of techniques to remove hidden lines during reconstruction, but solutions were directed at objects or groups of objects composed of plane polyhedra. These algorithms perform depth sorts along the Z axis at critical points and reject lines that would not be visible in the final image. However, input data for three-dimensional reconstruction from serial sections is already depth sorted, each section lying sequentially in front of the previous section. One merely examines the rotational angles to determine the forward-most section and the sequence will be known for all remaining sections. We define the forward-most section as the section last digitized unless the object is rotated greater than 90 degrees about either the horizontal or vertical axis in which case the first section to be digitized is defined as forward-most.

The procedure for hidden line removal amounts to stacking each section upon the previous section starting with the back-most and erasing any lines which fall within the area inside the forward-leaning section. The process begins by initializing a region of memory to zero. This region of memory is the same size as the completed picture (160 x 160) and is called the contour-gram matrix. Processing begins by "drawing" the back-most section on this matrix, this is accomplished by locating, on the contour-gram matrix, the X and Y coordinate of each boundary point for this section and inserting the value of that point's Z coordinate in the matrix. The Z coordinate is used later in processing and serves as a code for that particular point.

Following this step, the same procedure is carried out for the next forward-leaning section. This is followed by erasure of overlapped boundary points lying inside the newly added section. Erasure is accomplished by a line-by-line examination of the matrix points lying within the confines of the forward-leaning section. Each point lying within these confines, regardless of its value, is replaced by a negative number, the magnitude of which is equal to the section's number in the serial set (e.g., the area inside the outline of section number 5 is coded with -5's). The use of a special negative number serves two purposes: (1) it defines areas of the matrix as within the confines of a specific section outline (a code used later in processing), and (2) it allows for simplified display of the complete contour-gram by lighting only those points on the MACDAC monitor which have positive values (i.e. the unerased Z coordinates). All sections are processed in sequence from back to front in this way.

4. Plane Definition: Planes are defined as rectangular areas lying between visible portions of adjacent sections and are formed by connecting corresponding segment markers. Starting with the forward-most section, a search is made of the boundary point list for the lowest segment-marker number. Once found, a similar search is made for the same number in the boundary point list of the section immediately behind the first. If either marker is missing, the program moves to the next marker number and the search is repeated.

If both segment markers are found in the arrays, the contour-gram matrix is examined to determine if these points (represented by their Z coordinates) appear in the picture or if they have been erased during hidden line removal. Three possible outcomes exist: (1) if both points are located, they are connected by a line and the program moves to the next marker number; (2) if neither point is located, the line is ignored and the program moves on; (3) if one of the two points is missing, it is dealt with as a special case.

In the special case of a missing point in the forward-leaning section (Figure 5a), a line is drawn connecting the located back segment point and the expected position of the missing forward marker point. Points along this line are tested from back to front and the line is terminated when it encounters a positive number. The case is similar for a missing back segment marker except that the points along the connecting line are tested from front to back (Figure 5b).

Finally, a case exists where both segment marker

![Figure 5](https://www.computerhistory.org)

Figure 5—Special cases in "plane" determination described in text, (a) arrow shows partial line drawn in case of missing segment marker point in the forward-leaning section, occurring with two large sections straddling a smaller section, (b) arrow shows partial line drawn in case of missing segment marker in back-leaning section, (c) arrows show potential erroneous lines with both segment marker points visible in contour-gram (dotted lines indicate hidden lines not seen in final image)
coordinates can be located in the contour-gram but the connection of these points would be erroneous (Figure 5c). To eliminate this possibility all connecting lines are always tested to insure that their points never enter an area coded with the negative value of the forward-most section. When this occurs, the line is discarded.

After all segment markers in each section pair have been processed, adjacent connecting lines are grouped in pairs resulting in planes lying between the two sections. The program examines all sections in the series, defining planes between them and generates a list of the vertices of all planes.

5. Shading Values: Shading values or the light intensity assigned to each plane are derived using the methods described by Bouknight. The light source and the viewer are defined as being in the center of the viewing screen and at an arbitrary distance from it. Since the graphic display system can distinguish 2048 intensities, this defines the range of shading values available. Each plane is assigned a shading value proportional to the angle it makes relative to a normal to the viewing screen. Those planes lying perpendicular to the normal are brightest and those parallel to it are darkest.

6. Shading: Using its respective vertices, each plane including the surface of the forward-most section is essentially "colored-in" with its assigned shading value on the 160 x 160 contour-gram matrix. The completed image and the image of the contour-gram generated for this object at the selected angles are then stored on magnetic tape for display.

RESULTS

Microscopic structures

Three-dimensional reconstruction on an ultrastructural level is demonstrated for a nucleolus obtained from cross sections through a neuron of the cat brain (Figure 7). This cell was serially sectional and photographed in the electron microscope at a uniform magnification. Six equally spaced sections through the cell’s nucleolus were used as input data for the reconstruction process. The physical time required to position the film in the FIDAC device, digitize the picture and locate the nucleolar outline was approximately two minutes.

As was previously described, varying the number of segment markers alters the degree of detail in the final image. This can be seen in Figure 8 where the contour-gram of two sections through the nucleolus is seen with varying numbers of segment markers connected. Image 8a was produced using only 10 percent of the available segment markers. Image 8b uses 50 percent, while Image 8c uses 90 percent of the markers. The number of planes produced in the image as well as the processing time required to generate these planes increases as the number of segment markers increase. The difference in processing time is significant and is demonstrated by the fact that Image 8c required approximately two minutes of processing time while Image 8a required only 15 seconds.

Contour-grams of this nucleolus at four different rotational angles can be seen in Figure 9. Contour-grams such as these can be displayed along with the shaded three-dimensional image at the end of processing or can be visualized during processing on the MACDAC monitor.

Figure 6—Block diagram of THREAD software (Reconstruction phase)
Figure 7—Electron micrograph of neuron from the cat brainstem. The dark round area in the center is the nucleolus.

Figure 10 shows the final shaded image of the neuron nucleolus at two rotational angles varied with respect to the vertical axis. The structure is tapered at one pole and is slightly constricted at the center. Processing time for this image was slightly under five minutes. Image quality was consistent throughout a wide range of rotational angles.

Computerized tomography

A patient with a biopsy-proven brain tumor was referred for computerized tomography of the head. A serial set of ten ACTA scans was obtained at 1 cm intervals beginning at the level of the external auditory canal. Contrast material was used since it enhances tumor visualization in the brain. The tumor was present in five of the ten scans (Figure 11).

Figure 8—Contour-gram of sections through a neuron nucleolus showing the effects of varying the percentages of segment marker points used in the reconstruction, (A) 10 percent, (B) 50 percent, (C) 90 percent.

Figure 9—Contour-grams of the nucleolus seen in Figure 7 at four rotational angles.

The five sections showing the tumor were recorded on magnetic tape and served as the input data to the THREAD system. Processing resulted in the shaded three-dimensional views of the isolated tumor mass seen in Figure 12. Since no tumor was seen above or below the 5 input sections, the resultant image is truncated at both poles. Thinner input sections would provide a more detailed view of these regions. Each individual picture point on the viewing monitor represents 1.5 square millimeters for surfaces parallel to the viewing screen.

Figure 13 shows the standard display format of the THREAD system including: date, object orientation and composition in coded form and the grey-level block display with reference numbers described earlier. Usually, a contour-gram and a shaded image or two shaded images at different rotational angles are viewed side-by-side on the screen. Figure 13 shows the automatic enlargement feature of the system with which the operator can type a code word into the console and have either the left or right image enlarged on the opposite side of the screen. Color formats are also available as is the capability for Polaroid photography from the monitors.

SUMMARY AND FUTURE BIOMEDICAL PROSPECTS

The THREAD system represents an effective and highly automated method for three-dimensional reconstruction and display of biomedical data from many...
Figure 10—Shaded three-dimensional image of a neuron nucle­
olus generated at two rotational angles by the THREAD sys­
tem: (A) right lateral view, (B) left lateral view. The program
assumes viewer and light source are directly in front of monitor
and assigns the brightest shades to planes lying parallel to the
viewing screen.

Figure 11—Two adjacent computerized tomograms produced by
the ACTA scanner from a patient with uptake of contrast
material by a brain tumor in one cerebral hemisphere. Skull
defects are the result of previous surgery.

Figure 12—Three-dimensional reconstruction of brain tumor by
the THREAD system, (A) Contour-gram of inferior and medial
surfaces of tumor mass, (B) Shaded image of A, (C) Greater
rotation of same tumor about the horizontal axis, showing more
of the inferior surface.

The shaded image might be further enhanced by a
number of techniques to reinforce the three-dimen­
sional illusion created by the shaded image. Smoothing
of the shading planes by performing successive linear
interpolations in both the X and Y direction will result
in a more continuous shading gradient. Stereo pairs
can be generated, side-by-side, on the viewing screen
with each image symmetrically rotated with respect to
its vertical axis and by adjusting the relative X-axis
spacing of the two images to accommodate for differ­
ing interocular distances in the viewer. In addition,
movies could be made of the object at consecutively
varying rotational angles thereby allowing for rapid
viewing of all object surfaces.

Finally, quantitative data such as volume, shape, and

Figure 13—THREAD display format with headings, display
level shading block and reconstructed brain tumor. The image
on the right has been automatically enlarged four times and
displayed on the left side of the viewing screen.
surface area may be readily calculated for individual objects. Comparison of this type of data are important in the study of changing cell morphology during experimental manipulations. Similarly, quantitative data obtained from reconstructed computerized tomograms can be used to study normal anatomy in vivo and to examine the effects of various treatment modalities on the size and morphologic characteristics of tumors and other pathological entities.

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