PROCEEDINGS OF THE 1984 INTERNATIONAL JOINT ALPINE SYMPOSIUM:

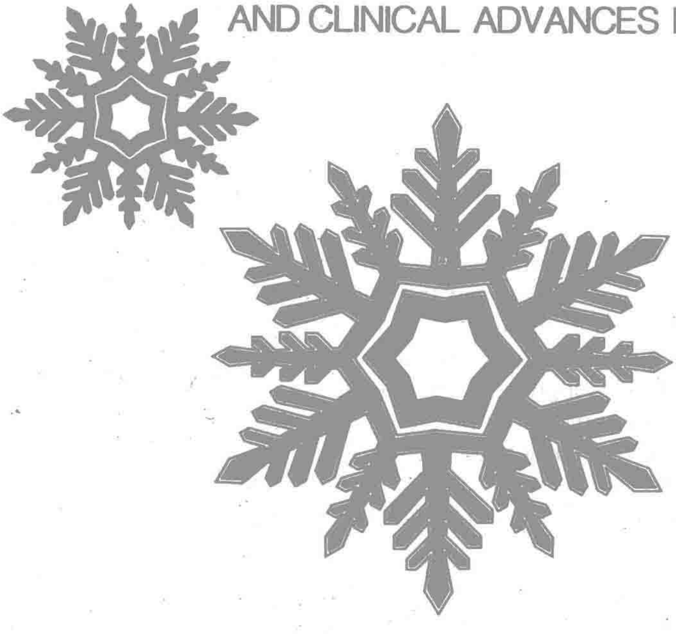
MEDICAL COMPUTER GRAPHICS AND IMAGE COMMUNICATIONS AND CLINICAL ADVANCES IN NEURO CT/NMR

COMPUTER SOCIETY PRESS

INNSBRUCK, AUSTRIA FEBRUARY 11–15, 1984

PROCEEDINGS
OF THE
1984 INTERNATIONAL JOINT ALPINE SYMPOSIUM:

MEDICAL COMPUTER, GRAPHICS AND IMAGE COMMUNICATIONS AND CLINICAL ADVANCES IN NEURO CT/NMR



ISBN 0-8186-0524-3
IEEE CATALOG NUMBER 84CH2006-5
IEEE COMPUTER SOCIETY ORDER NUMBER 524

1884 · 1984

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.

CO-SPONSORED BY:
FOUNDATION FOR ADVANCED MEDICAL DISPLAY TECHNOLOGY
A Nonprofit Educational and Research Foundation

IEEE COMPUTER SOCIETY

TECHNICAL COMMITTEE ON COMPUTATIONAL MEDICINE

Published by IEEE Computer Society Press
1109 Spring Street
Suite 300
Silver Spring, MD 20910

ISBN 0-8186-0524-3 (paper)
ISBN 0-8186-4524-5 (microfiche)
ISBN 0-8186-8524-7 (casebound)
IEEE Catalog Number 84CH2006-5
IEEE Computer Society Order Number 524

Order from: IEEE Computer Society
Post Office Box 80452
Worldway Postal Center
Los Angeles, CA 90080

IEEE Service Center
445 Hoes Lane
Piscataway, NJ 08854

1884 · 1984 The Institute of Electrical and Electronics Engineers, Inc.

The 1984 International Joint Alpine Symposium

INTRODUCTION

A meeting that joins two professional specialties requires a level of cooperation from both groups that is often rare and difficult to attain. That has not been the case for this 1984 International Joint Alpine Symposium. The participants for this intermingling of medical imaging clinicians, medical computer graphics scientists, engineers, and physicians have been exceptionally cooperative. Each has shown genuine interest in the success of the symposium. They recognize the growing need for dialogue between clinical medicine and the scientists who are now delivering new imaging devices and technology to medicine at an ever increasing pace.

Papers appearing in these proceedings document contributions from authors in the engineering sessions. They focus on issues in medical imaging that are central to this growing field. Papers from the session on medical computer graphics and techniques illustrate the increasing utilization in diagnostic medicine of computer systems and methodology that have their origins in the area of synthetic imaging and animation. Picture archiving and communication systems (PACS) contributions are also represented here. These topics reflect the interests in electronic image management for large hospitals and clinics. Papers in medical graphics applications demonstrate the clinical utility of graphics in routine surgical procedures. Several papers found here deal with fundamental issues of computer vision: methodology and techniques for image generation and enhancement. These, and papers submitted after the press deadline, are candidates for a special issue of the IEEE COMPUTER magazine dedicated to medical computer graphics and imaging to be published later this year.

I am particularly grateful to Professor Heinz Lemke and the entire Engineering Program Committee. They have worked hard to invite authors and to ensure a high quality of papers and presentations. Each has contributed to the success of the interdisciplinary nature of this symposium.

Dr. William V. Glenn assembled an internationally prestigious faculty for the clinical sessions. Presentations forming those sessions focus on precisely those topics in neurologic imaging that are emerging as the key issues in diagnostic medicine. The growing importance of spine imaging techniques using computerized tomography scanners and related techniques in magnetic resonance imaging is discussed by premiere radiologists and their colleagues from both sides of the Atlantic. Dr. Stephen L.G. Rothman was instrumental in organizing these clinical sessions by making certain that essential clinical issues were addressed and by carefully preparing the sequence of presentations.

Michael L. Rhodes
Multiplanar Diagnostic Imaging, Inc.
2730 Pacific Coast Highway
Torrance, California 90505
Symposium Co-chairman
1984 International Joint Alpine Symposium

Conference Committee

Co-Chairmen
William V. Glenn, Jr., M.D.
Michael L. Rhodes, Ph.D.

Clinical Program Chairman
Stephen L.G. Rothman, M.D.

Engineering Program Chairman
Prof. Dr. Hienz U. Lemke

Publications Chairman
J.M.S. Prewitt, Ph.D.

Treasurer and Operations Chairman
Larry W. Carter

Publicity Chairman
Samuel J. Dwyer, III, Ph.D.

Registration Chairman
H. Siegreif Stiehl, Ph.D.

Table of Contents

SYSTEMS FOR THREE-DIMENSIONAL DISPLAY OF MEDICAL IMAGES

Henry Fuchs[x] and Stephen M. Pizer[x+-]

Depts. of Computer Science[x] and Radiology[+], University of North Carolina
Chapel Hill, North Carolina, USA

Dept. of Medical and Physiological Physics[-], Rijksuniversiteit Utrecht
Utrecht, The Netherlands

Abstract

In our experience with the display of medical images provided as a set of slices the comprehension of global features of the configuration and relationship of 3D objects can be enhanced over 2D display alone with appropriate 3D displays. Real-time interaction and combining 2D and 3D display into a single system appear important.

The two major approaches to 3D display are reflection and projection. The relative strengths and requirements of these approaches are discussed. Advances in one major system in each category, shaded graphics and the varifocal mirror are presented. In particular, hardware and software that allow real-time or near real-time interaction with these two systems are set forth.

Introduction

Unlike the older, projective medical imaging modalities of radiography and scintigraphy, many of the newer modalities, such as transmission and emission computed tomography, ultrasound echography, and nuclear magnetic resonance imaging, provide information about one or more physical parameters as a function of three dimensions. The common method of displaying the data thus obtained is as a series of slices, but this is often inadequately three-dimensional to allow the observer easily to comprehend the 3D structure of the measured data. This paper will cover display methods and devices that can provide such immediate 3D comprehension.

To simplify the discussion let us temporarily assume that the object being imaged is made of a surface, i.e. it is a shell.

There are essentially two ways for a physical 3D surface to present itself: 1) by the reflection of light or 2) by being self-luminous. The two basic 3D display approaches simulate respectively each of these presentations.

1) Reflective display is provided by shaded graphics and its variants.

2a) Self-luminous display can be provided by methods based on calculating projections from appropriate viewing positions and displaying these using stereoscopy or the kinetic depth effect, or even possibly head-motion parallax (see later).

2b) Other approaches to self-luminous display actually place luminous points in 3-space and allow the visual system to generate the projections, as it does in natural situations.

In this paper we will discuss display systems and system improvements in each of these three areas. First, let us discuss the objectives of 3D display and the general requirements that these impose.

3D Display Objectives, Properties, and Requirements

For medical imaging one can distinguish two major objectives for 3D display. The first is to communicate to the therapist (e.g. surgeon or radiotherapist) the configuration of an object or objects that have already been identified so as to aid in the treatment planning or treatment. The second objective is that of the radiologist: exploration of an at least partially unknown 3D intensity distribution so as to come to understand its structure or perhaps make measurements of it.

Shaded graphics, dependent as it is on computing reflections from an object surface, can be effective for communicating known objects, but to date it has seemed unsuited to exploration.

In contrast to shaded graphics the projective (self-luminous) methods seem at least at first not to be restricted to the presentation of surfaces; in principle projection can occur for any 3D intensity distribution. As a result no object need be predefined, so projective methods have proved more effective for exploration. On the other hand, projection of a 3D distribution essentially treats the distribution as being translucent and thus has the inherent property that objects in front of or behind other objects obscure the object of interest, and even object interiors obscure their surfaces. Therefore, shaded graphics is often more effective for the presentation of known surfaces.

Shaded graphics is by no means limited to the presentation of opaque surfaces; transparent surfaces can be simulated with little difficulty (see figure 1 and (Whitted,1980)). However, with such transparency one loses some of the advantage over projective displays. On the other hand, without transparency objects within or behind other objects and back faces of objects are hidden from view. As a consequence interactive modification of the point of view and selection of spatial windows (clipping) is important in shaded graphics. Rotation, if done in real time, can also provide an important depth cue; it provides a more effective cue if the rotation is controlled by viewer hand or head movement (Lipscomb,1981).

Similarly, interaction is critical to projective display. Spatial windowing or object selection, intensity windowing, and rotation of point of view can limit the obscuration encountered in this display modality. Distinguishing selected objects by a display property such as blink can also be effective.

Interaction is also important to allow object measurement. One can point to positions in 3-space or sketch volumes to indicate regions whose volume or shape is to be measured or where the match between two objects (e.g. anatomy and radiation dose) is to be measured. Furthermore, since all 3D display inherently presents grey scale poorly or not at all, due to hiding or obscuration,it may be desirable to display selected, possibly oblique, slices on a normal 2D display to which the 3D display is joined. Interaction will then be necessary to translate the comprehension of the global 3D distribution provided by the 3D display into the selection of a slice.

For projective display, obscuration of object surfaces by their interiors can be lessened by displaying not the original image intensity but rather one related to the likelihood that a point is on the object surface (Pizer, Fuchs, et al, 1983). There is a real advantage of such surface identification over those needed by shaded graphics in that computation of surface likelihood can be an automatic, local calculation that does not require the surface to be recognized as such. We have had some success in displaying the magnitude of the gradient of the original intensity. However, with noisy or unsharp boundaries segmentation methods that calculate the probability of a boundary at each pixel would seem to be preferable (e.g. Feldman,1974; Burt,1981).

To summarize, reflective 3D displays have advantages for presenting known surfaces, but projective displays have advantages for presenting 3D intensity distributions to be explored and intensity distributions not made of surfaces. Nevertheless, projective displays are more effective when object surfaces are emphasized. Interaction is important in both types of display. The systems should consist of both 2D and 3D display components. These should be integrated so that the result of interaction using one component shows its effect on both.

Reflective Displays

Fine shaded graphics presentations have previously been provided in medical imaging (e.g. Batnitzky,1981; Herman,1981). While good communication can be achieved with such displays, especially if one uses smooth shading algorithms based on multiple light sources (see figure 1), much of the information is lost without interaction. The challenge that we seek to meet is to provide good shaded graphics with real-time interactive rotation, spatial windowing and object selection, slice selection, etc., since slower interaction distinctly harms both perception and the control of manipulation. Furthermore, we wish to provide increased 3D comprehension using stereo and especially the strong depth cue of head-motion parallax. The real-time response necessary for head motion to aid in the perception of depth is a particularly great challenge.

Our approaches to fast recalculation of a shaded image based on new values of interactively determined parameters fall into three categories. First, noting that the anatomical and physical objects to be displayed do not themselves change during the display has led to the development of an approach whereby inter-tile relationships can be precalculated so as to be quickly usable in the hiding and shading calculations at display time. Second, the idea of successive refinement is being developed -- in this approach a coarse image is quickly calculated and displayed, with the image quality automatically and successively increasing when the interactive demands for new images lessen. Third, special-purpose hardware is being developed to accomplish the display calculations speedily.

Precalculating inter-tile relationships is achieved using a so-called binary space-partitioning (BSP) tree (Fuchs, Abram, Grant,1983). Each node corresponds to one planar polygonal surface tile, the two subtrees of which correspond to tiles that are respectively in front of and behind the plane of the tile at the root of the subtree, from some particular viewpoint. It can be shown that changing the viewpoint involves changing the order in which the tree is traversed, displaying tiles as they are encountered in the traversal. Furthermore, the order choice simply involves deciding at each tree node whether to display its left or right subtree first, with the decision dependent on the angle between the viewing direction and the tile at the node in question. Implementation of this algorithm on the processor of an Ikonas RDS-3000 display system allows clipping, lighting, and point of view to be dynamically modified, with new images calculated at the rate of approximately 1500 polygons/sec. This speed allows the user actually to examine the object interactively, but not with full naturalness, since smooth shading is not possible at this speed and medical images commonly require a few thousand tiles (see figure 2) and thus a new image can appear only every second or two.

Based on our experience, reported below, of the usefulness of successive refinement in projective 3D display, we believe that an approach of this type will also be useful in shaded graphics to overcome the above-mentioned limitations in display speed. Sampling of tiles and/or pixels would produce a coarse, fast display, followed by successive increase in these samples and finally smooth shading if interactive demands allow.

A considerable further speedup, allowing the avoidance of successive refinement approximations, can be achieved with a new design for display hardware. We have designed such a VLSI-based system, called pixel-planes, and built prototypes of it (Fuchs, Poulton, et al,1982). In pixel-planes a small amount of processor capability is added to each pixel in a frame buffer. Connecting the pixels together in a double binary tree structure according to the binary strings giving their x and y positions, respectively, allows a 1-bit adder at each pixel to compute an arbitrary linear function of x and y at all pixels almost simultaneously. This allows the pixel to calculate for itself its inclusion in each polygonal tile, its depth in that tile and thus the visibility of the tile there, and its shading. The result is that images will probably be able to be generated at the rate of 1000 tiles/display cycle (1/30 sec.) with a chip area on the order of only double that required by present frame buffers that have only memory functions.

Not only could pixel-planes be used to produce a highly interactive shaded graphics display to be viewed in the ordinary way, but it could also serve as the basis of a head-mounted display that would allow the user to walk around within a shaded graphics image (Sutherland,1968). This capability is achieved by having the position and orientation of the viewer's head determine the viewpoint in the image space. Such a display would provide both a strong increase in 3D comprehension using the cue of head-motion parallax, and a strong increase in the naturalness of interaction, since the user could point or gesture with his hand within the image. In addition to fast display, this scheme requires both an accurate head and hand tracker and a head mount arrangement for the screen. These are problems we are now addressing with some success (Bishop, Fuchs,1984), but space does not allow discussion of these solutions here.

Self-luminous Displays with Calculated Projections

We and others (e.g. Keyes,1982; Harris,1982) have successfully provided 3D comprehension by computing two or more projections of an image and then displaying the results as a rocking or rotating image (taking advantage of the kinetic depth effect), as a stereo pair, or both. Modern vector and raster display systems allow the computation of the projection of many thousand points or lines in a display cycle or the simultaneous storage of a small number of precomputed views among which one can cycle. Unfortunately, the number of points or lines computable in a display cycle is quite limited with systems doing on-line projection, and the pre-computation approach is unable to provide interactive control of viewpoint, spatial and intensity windowing, object selection, etc.

What appears to be needed is a very fast projection calculator. Such a device could allow natural presentation and interaction if a head-mounted display were used. It appears that an extension of the pixel-planes design might provide such a device, but our work is not far enough along to report here.

Displays Placing Luminous Points in 3-Space

Numerous 3D displays based on moving screens or mirrors have been developed. These operate by cyclically presenting transverse or radial planar slices of the 3D image in succession. Each plane is presented when the screen or mirror makes the image appear at the corresponding plane, and the successive images are presented with a speed high enough that they fuse into a 3D image. Many of these devices have significant mechanical drawbacks, high cost, or unrealistic time or space requirements for image data storage, interactive modification, or delivery. The most satisfactory in these respects appears to be that based on the vibrating varifocal mirror (Traub,1967; Baxter, 1982).

With a varifocal mirror display a mirror plate or membrane is made to vibrate sinusoidally at about 30Hz, normally by placing a loudspeaker behind it. The viewer looks at a CRT reflected in the mirror (figure 3). The apparent depth of the CRT varies over 20cm or more as the mirror center moves only a few millimeters. Therefore, a sequence of points written on the CRT screen during the vibration cycle will appear at successively greater depths for the first half of the cycle, and then at successively closer depths. It appears that with present single-beam CRT's one is limited to a few hundred thousand points in a cycle, but display technologies that are more parallel could increase this number.

As described in detail in (Fuchs, Pizer, et al,1982a;1982b), we have shown how an ordinary color raster graphics display system with at least 17 bits/pixel can be used to display at least ½-million points in a 1/30 sec. display cycle in synchrony with the mirror vibration. Simply stated, the red, green, and blue systems are used to provide x, y, and intensity values for each point, and the location of the point in the frame buffer determines the time and thus the depth of the point.

This approach to varifocal mirror display not only provides an inexpensive means of 3D display to those with a color raster graphics system, but it also provides interactive capabilities and 2D/3D combination possibilities (see Pizer, Fuchs, et al,1983; Fuchs, Pizer, et al,1982b for details) that, we have suggested, are invaluable. The look-up tables and registers of the raster graphics system can be used to achieve spatial and intensity windowing. The internal processor of the system can be used to provide translation (and thus cursor movement), rotation, scaling, object selection, object blinking, and cinematic display. This is accomplished with software using the standard graphics approach of having object descriptions transformed to refresh buffers based on the value of interactive parameters. Such a system can also provide oblique slice selection, interpolation of the slice from the object description, and display of the resulting slice on a 2D display using a separate scan generator on the same frame buffer memory.

All but the 2D, 3D display combination have already been implemented on the Ikonas RDS-3000/VAX-780 system at UNC. This system is capable of displaying about 120,000 points at present, and ultimately about double this. These points must be approximately uniformly distributed in depth, but each is specified with 9 bits in each of the transverse dimensions. The flexibility of this design for varifocal mirror display has recently been demonstrated by its implementation on a Gould/DeAnza 8500 raster graphics system at Rijksuniversiteit Utrecht.

Image preprocessing to achieve contrast

enhancement and transformation of intensities to surface likelihood by methods such as those discussed in (Pizer, Fuchs, et al,1983) are frequently important for varifocal mirror display. Note that the desire not to fill the 3-space densely with intensity implies that a 3D raster representation of the 3D data is inferior to the point list in our system (Pizer, Fuchs, et al,1983). However, the density and continuity of points on the object surfaces needs to be high. In our experience increasing the number of points from 30,000 to 100,000 strongly increases the physician's ability to comprehend clinically important features in single organs. An object description area holding many of these objects is desirable, as selection of a small number of these objects at a time permits a good appreciation of the object relationships without obscuration. Methods for defining object-enclosing regions (not necessarily the exact object surfaces) are therefore of importance.

Interaction is of considerable importance in varifocal mirror display in our experience with clinical applications. Of course, good human engineering to make the interactive control easy is quite important. This implies attention to methods for the selection of objects and associated transformations as well as to devices for controlling continuous parameters of translation, rotation, contrast, etc. Fast feedback is necessary to make control of the latter transformation natural. This fast feedback is provided by successive refinement. It operates in this case by randomizing the order of points in each object and then displaying the number of points that can be transformed in 1 frame time, with further points being transformed if no further image modification is interactively indicated. Only objects being modified need be retransformed, as a special portion of the refresh buffer is allocated to these presently dynamic objects.

Our experience with clinical application of the varifocal mirror and shaded graphics systems described above covers CT scans of the brain, abdomen, pelvis, chest, and blood vessels in the neck, as well as a small number of NMR and ECT images. We frequently hear from physician users looking at one of these 3D displays, "I didn't realize that the 3D configuration was like that when I looked at the array of slices." The experience of numerous groups is that 3D display is useful for guiding therapists with regard to known objects. We suggest that the addition of appropriate interaction strengthens this result in reflective displays. Furthermore, our experience leads us to believe that with an appropriately integrated 2D display, an increased number of points, improved interactive devices, and improved methods for object surface enhancement and object-enclosing region definition, projective 3D displays such as the varifocal mirror will be clinically important in exploratory applications for comprehending and measuring global 3D structures or relationships from 3D medical images.

Acknowledgements

The work reported above was partially supported by NIH Grant NS/HL 16759-01 and partially by funds provided by Technicare, Inc. and Atari, Inc. We gratefully acknowledge the important contribution of our radiological colleagues, Dr. Edward Staab, Dr. Julian Rosenman, Dr. Ralph Heinz, and Dr. Edward Chaney, and of our research assistants, Gregory Abram, John Austin, Sandra Bloomberg, Bradley Hemminger, Peter Mills, and Dorothy Strickland. We thank Dr. J. Turner Whitted for useful suggestions and Bo Strain and Karen Curran for photographic assistance.

References

Batnitzky, S., H.I. Price, P.N. Cook, S.J. Dwyer (1981), "Three-Dimensional Computer Reconstruction in the Study of Brain Lesions", Automedica, 4(1): 37-50.

Baxter, B., L.E. Hitchner, R.E. Anderson (1982), "Application of a Three-Dimensional Display in Diagnostic Imaging", J. Comp. Ass. Tomo., 6(5): 1000-1005.

Bishop, G., H. Fuchs (1984) "The Self-Tracker", in Proc. MIT VLSI Conf., Artech House, Dedham, MA.

Burt, P.J., T.-H. Hong, A. Rosenfeld (1981), "Segmentation and Estimation of Image Region Properties through Co-operative Hierarchical Computation", IEEE Trans. Sys., Man, & Cyb., SMC-11(12): 802-805.

Feldman, J.A., Y. Yakimovsky (1974), "Decision Theory and Artificial Intelligence: I. A Semantics-Based Region Analyzer", Artif. Intell., 5(4): 349-371.

Fuchs, H., G.D. Abram, E. Grant (1983), "Near Real Time Shaded Disp.", Comp. Graph., 17(3).

Fuchs, H., J.W. Poulton, A. Paeth, A. Bell (1982), "Developing Pixel-Planes", Proc. Conf. on Adv. Res. on VLSI, MIT, Artech House, Dedham, MA.

Fuchs, H., S.M. Pizer, L.-C. Tsai, S.H. Bloomberg, E.R. Heinz (1982a), "Adding a True 3-D Display to a Raster Graphics System", IEEE Comp. Graph. and Appl., 2(7):73-78.

H. Fuchs, S.M. Pizer, E.R. Heinz, S.H. Bloomberg, L.-C. Tsai, D.C. Strickland, "Design of and Image Editing with a Space-Filling 3D Display Based on a Standard Raster Graphics System", Proc. on Proces. and Disp. of Three-Dim. Data, 367, ed. J.J. Pearson, SPIE, Bellingham, WA:117-127 (1982b).

Harris, L.D. (1982), "Display and Analysis of Medical Volume Images", Nuclear Medicine and Biology, Pergamon Press, Vol. II:2181-2184.

Herman, G.T., J.K. Udupa (1981), "Display of Discrete Surfaces", Proc. SPIE, 283:90-97.

Keyes, J.W. (1982),
in Nuclear Medicine and Biology, Pergamon Press, Vol. II:~2175.

Lipscomb, J. (1981),
Ph. D. Dissertation, Dept. of Comp. Sci., Univ. of

North Carolina.

Pizer, S.M., H. Fuchs, E.R. Heinz, E.V. Staab, E. L. Chaney, J.G. Rosenman, J.D. Austin, S.H. Bloomberg, E.T. MacHardy, P.H. Mills, D.C. Strickland (1983), "Interactive 3D Display of Medical Images", Information Processing in Med. Imaging (Proc. 8th IPMI Conf.), Nuc. Med. Dept., Akademisch Ziekenhuis VUB, Brussels.

Sutherland, I.E. (1968), "A Head-Mounted Three Dimensional Display", Proc. Fall Joint Comp. Conf.: 757, Thompson Books, Washington.

Traub, A.C. (1967), "Stereoscopic Display Using Rapid Varifocal Mirror Oscillations", App. Optics, 6(6):1085-1087.

Whitted, J.T. (1980),
in Comm. ACM.

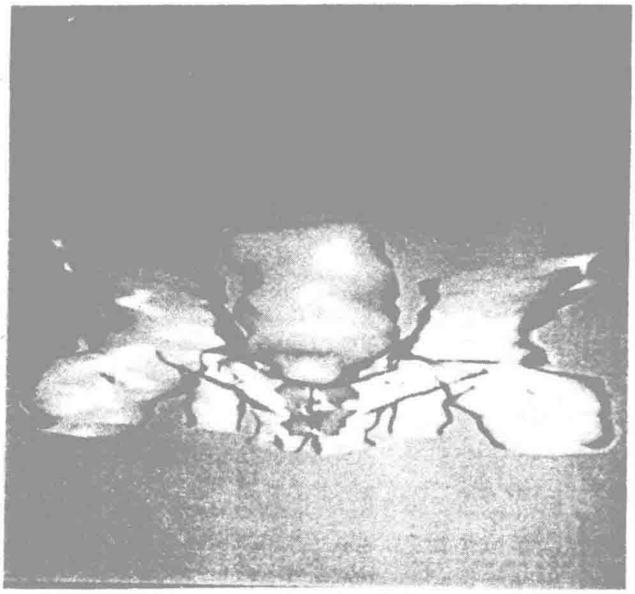


FIGURE 1: Smooth-shaded display with multiple light sources and transparent object of male pelvis from CT scans.

FIGURE 3: Varifocal mirror viewing arrangement.

FIGURE 2: Coarse display allowing one second interactive modification of carotid artery (partially being clipped away) from CT scans.

THREE-DIMENSIONAL RECONSTRUCTION AND DISPLAY OF COMPLEX ANATOMICAL OBJECTS

Harald Scharnweber, Klaus D. Tönnies

Technische Universität Berlin
Institut für Technische Informatik
Franklinstr. 28/29, D-1000 Berlin 10, West-Germany

ABSTRACT

An experimental software system has been developed for processing and three-dimensional display of X-ray computed tomograms. The software system is composed of a set of independent modules in a processing line with accurately defined interfaces between its modules. The main goal in the experimental environment is to develop methods to aid clinicians in their diagnosis and in the visualization of complex anatomical objects. The components of the processing line for 3-D reconstruction and display are described in more detail and results for vector graphic and raster graphic displays are presented.

INTRODUCTION

Medical diagnostics are characterized by a rapidly expanding use of digital imaging techniques such as ultrasound scanners, nuclear medicine systems, computed tomography scanners, digital radiology, and lately nuclear magnetic resonance scanners. These techniques have resulted in the development of new methods for the processing, analysis and visualization of digital images in order to provide the clinicians with optimal support in their diagnosis and therapy.

The application of advanced Computer Vision and Computer Graphics techniques as far as biomedical image processing is concerned in a dramatic increase in the 1970ies[1]. Methods of 3-D reconstruction and 3-D display for diagnostic interpretation have been developed especially in the area of Computed Tomography and their number is increasing.

An experimental software system has been developed for processing and 3-D display of X-ray computed tomograms at the Institut für Technische Informatik at the Technical University of Berlin in the COMPACT project (COmputerized Management, Processing and AnaLysis of Computed Tomograms). The main goal in the environment is to develop methods to aid clinicians in their diagnosis and in the visualization of complex anatomical structures. The system renders possible interactive processing and analysis of cranial and cardial Computed Tomograms. So far automated analysis of cranial CT's has been demonstrated at the ventricles of the brain and at the skull.

The software components of the experimental system are divided into three parts according to their functions:

- Computer Vision components for image enhancement, image segmentation, and image analysis
- 3-D reconstruction for generation a 3-D representation of object surfaces from analysed serial CT's
- Computer Graphics components for 3-D display of complex anatomical objects

3-D reconstruction from serial CT's and appropriate display of 3-D anatomical objects offers a useful information source in the process of medical diagnosis and therapy. This 3-D representation of organs of interest and pathological processes can provide a suitable base for deriving valuable stereometric data like distance measures between arbitrary points of objects in space, volume and surface area estimates and other quantitative data[2].

3-D computer graphics techniques provide various visualization modes to generate displays from these representations. Such 3-D displays give the clinician better insight into 3-D shape, location and related structures than 2-D sections of arbitrary orientation can do. These techniques may be a valuable aid in surgical planning[3], radiation treatment planning[2], and other fields of therapy planning.

COMPONENTS OF COMPACT PROCESSING LINE

The experimental Processing Line of the COMPACT project consists of independent modular software components communicating through datainterface links. Fig. 1 shows a schematic view of the subdivision of the Processing Line into data files, processing components for computer vision, 3-D reconstruction and computer graphics as well as user interaction facilities. Interactive input devices for users are keyboard and digitizer, whereas visualization is realized through vector graphic and color raster graphic display systems and plotter output. Input data for the Processing Line consist of serial CT's from head and body scanners, the slice thickness of which is usually 8 - 10 millimeters.

CH2006-5/84/0000/0007$01.00 © 1984 IEEE

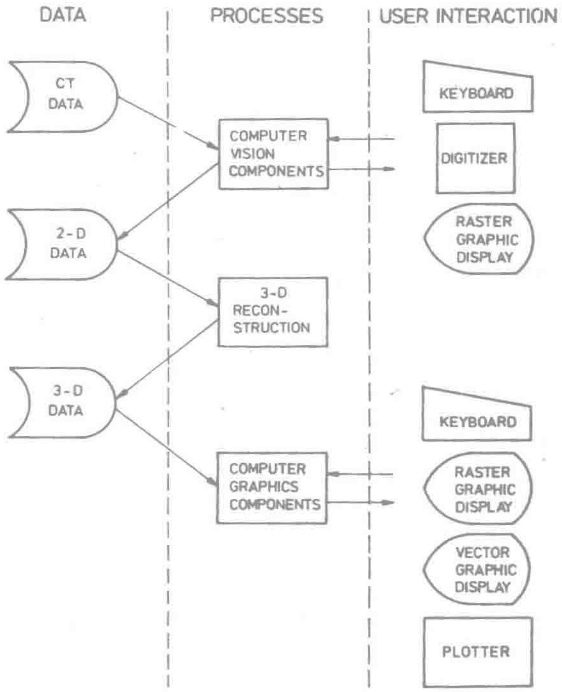


Fig. 1. COMPACT Processing Line

Computer Vision Components

Computer vision components of the Processing Line comprise methods for

- image processing (noise smoothing and contrast enhancement)
- interactive and semiautomatic segmentation with contour following methods
- automated segmentation of cerebrospinal fluid (CSF) filled cavities and skull bones
- automated recognition and analysis of ventricles of the brain and skull bones

All methods of the experimental system for image preprocessing serve for examination and development of

- improved visualization of structural image content for clinicians
- methods of enhancement for special image classes, e.g. cranial CT's
- optimal support of the succeeding segmentation process

Following the image preprocessing, interactive segmentation of CT's can supported by edge detection operators. Interactive contour tracing by means of a digitizer or semiautomatic contour following by interactive input of several starting points on the edge of the object of interest is possible.

The automated processing of cranial CT's was demonstrated by experimental components for segmentation, recognition and analysis of CSF filled cavities and skull bones. A detailed description of the developed experimental system for model guided analysis can be found in [4] and [5]. The aim of this approach is the partial-volume corrected computation of the ventricles volume as well as the 3-D reconstruction of the complex morphology of the ventricles because this anatomical structure is of special importance to the diagnostician: the ventricles shape, size, position, symmetry and volume are significant features of neurological diagnosis and therapy and are also indicators of pathological disorders of the brain[4].

The result of the model guided analysis is a structural image description of the ventricles and of the skull from a series of processed cranial CT's. Part of the description defines the boundary contours of the ventricles and the skull for the succeeding 3-D reconstruction. A heuristic algorithm has been developed for the boundary detection process taking the partial-volume-relation of the regions of ventricles as a basis which can calculate up to 7 subslices for one CT slice of 10 millimeters thickness[4]. Thus covering the morphology of the ventricles much more exactly. Fig. 5 shows the result of this algorithm by means of the ventricles of the brain analysed from 5 serial CT's and for which 7 subslices have been calculated for each single slice.

3-D Reconstruction

A further calculation of diagnostic data and a 3-D display nessessitate a 3-D reconstruction of the 2-D regions or contours of the analysed objects. There are two main approaches for 3-D reconstruction of objects from serial sequences:

Volume Oriented Approach: Here, the complete object volume is represented by a set of simple geometric polyeder, e.g. cubes. Using the Cuberille representation developed by Herman and Udupa[3] objects are being represented by a set of cubes (voxel) of equal size of CT's pixel size. A graph-theoretical boundary detector traces the surfaces out of the 3-D scene which is then displayed by computer graphics methods.

Surface Oriented Approach: In this case the object is solely represented by its surface. The basis for this approach are the contours extracted from serial sections of the object to be reconstructed. These contours are simple closed curves, i.e. no contour crosses itself. Between the contours of adjacent slices surface elements are constructed according to different methods. The most frequently used surface element is the triangle and there are heuristic and graph-theoretical approaches to triangulation of contours[2,6].

3-D Reconstruction in COMPACT

The algorithm developed in the COMPACT project is a further development of the algorithm by Fuchs et al[7]. The algorithm by Fuchs et al approximates the surface by minimizing the surface area of the triangles. The further development of this algorithm by Tönnies[8] under the COMPACT project allows the automatic processing of complex contours which can differ considerably in shape, position and size and

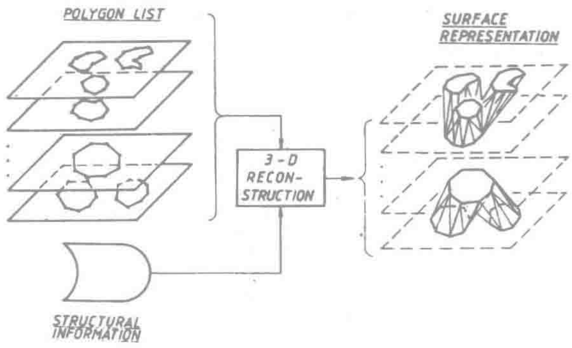


Fig. 2. Triangulation of object contours

may show arbitrary branching. Branchirg means a merging or splitting of contours from one slice to the next slice. Fig. 2 shows in an schematic view the process of triangulation of contours.

The decisive criterion for determination of the most minimal object surface leads to sharp edges on the surface in the case of highly complex contours, i.e. plane normals of adjacent triangles can differ considerably. By extending the rules of decision smoother surfaces are reconstructed in the COMPACT algorithm and reconstruction errors of the graph-theoretical approach can be avoided.

Input data for the 3-D reconstruction module consist of complete contours of the analysed object which were generated from the 2-D regions by the analysing module and of a list of structural information for spatial links of contours in order to solve the problem of interconnection of contours from successive slices. For interactively or semi-automatically generated contours this structural information has to be fed interactively with the help of a graphic terminal and has as well to supplied as an input file for the 3-D reconstruction module. The result is a fully described surface of the reconstructed object. Fig. 6 shows the triangulation of automatically analysed and reconstructed ventricles of the brain, which had been analysed from five CT's of 10 millimeters slice thickness.

The time needed for processing the 3-D reconstruction depends on the complexity of the reconstructed structures. For objects of a similar complexity of those shown in Fig. 6 with 1000 to 1300 contour points 1 to 2 minutes computation time is required.

Advantages of 3-D Reconstruction for Medical Use

The afore mentioned methods for reconstruction of surfaces approximate quite well the complete 3-D geometric information of an object. These data are the prerequisite for realistic visualization of anatomical objects and pathological processes and form the basis for the calculation of further diagnostical quantitative data. Cook et al[2] estimate for example the volume and object surface area from its surface representation. The measurement of spacing or spatial relationship between various objects is possible through this representation or, as Dwyer III et al[9] suggest, shape analysis on the basis of polyeder of e.g. reconstructed ventricles may be used to predict location of a lesion.

Interactive Computer Graphics Components

The visualization of reconstructed 3-D structures from serial CT's is the last task in the Processing Line. Interactive computer graphics components support this task for 3-D display on vector graphic and color raster graphic displays.

The visualization of 3-D structures necessitates on one hand the possibility to view the object from any vantage point and on the other hand the use of depth cues to aid the human visual system in depth perception since display of 3-D objects is performed on a 2-D screen or as a 2-D plott. Depth cues are perspective, stereoscopic views, removal of hidden lines/surfaces, shading, transparency and motion.

In order to select the desired view of the object the user has at his disposal various types of view transformation which are applied to object coordinates: translation, rotation, reflexion and perspective. After using view transformations the most simple and fastest display mode are wireframes. Fig. 3 shows such display, produced on a plotter. A stereoscopic view has been used as depth cue in this 3-D display of human thorax. The spatial interpretation is only possible with a stereoscope. The complexity of stereoscopic views is restricted to a certain size to avoid confusion of the human viewer. Motion is needed to overcome this restriction, but so far this has been possible only with expensive vector graphic display systems. With such display system we examine this combination of depth cues to find best methods for visualization and for measurements of 3-D structures.

More realistic displays can be generated by applying a hidden line removal. Fig. 5 and 6 show results on a raster graphic display. The algorithm has been implemented in the COMPACT project in line with the method by Petty and Mach[10].

Under a feasibility study all mentioned visualization techniques are being examined to establish to what extent they are suitable to visualize the human thorax and heart structure and whether or not they are apt to serve for measurements to fit an artificial heart in the patients thorax[11]. For example the thorax shown in Fig. 3 was manually digitized from 22 cardial CT's. To enhance the outlines of the vessel system a bolus of 50 ml contrast medium was injected. Fig. 4 shows a shaded display of the heart and spinal cord only.

Wireframes are suitable for use in a diagnostic system as fast controlling display for the estimation of the selected object view. However, they are not suitable for a realistic display of 3-D structures.

The best realistic impression can be achieved through shaded pictures on color raster graphic displays. Further components needed in the viewing process are a hidden surface removal algorithm and an illumination model. In order to solve the hidden surface removal problem an algorithm by Eastman[12] has been implemented requiring polygons of the object surface as input data and producing scan line oriented spans of the visible polygons. An illumination model by Blinn[13] subsequently defines for all spans of a polygon an intensity value. This value is being computed through diffuse and specular reflections of the light and the object color determined by the position of a simulated illumination source to both the object polygon and the viewer.

It is possible to calculate shades by arbitrarily positioning the illumination source horizontally next to the viewer. Fig. 4, 7, 8 show examples for shaded displays with shade casting produced with these algorithms. Different coloring for partial structures (e.g. in Fig. 4 for the heart, aorta and spinal cord may improve visual interpretation of the objects for the viewer. In the display of anatomical objects for diagnostic use shades are not realistic, but shade casting considerably improves the visualization of spatial relationship. Therefore, this artificial effect cán be of great advantage to something applications.

CONCLUSION AND AIMS

The presented software components of the experimental Processing Line allow the interactive or automated processing of serial 2-D digital images like computed tomograms. The multivarious software modules, all implemented in FORTRAN IV on PDP 11/60 or ITEL AS/5 computers, are suitable to develope additional application oriented methods for diagnostic and therapeutic evaluation of CT's and other digital image modalities. The mentioned applications of automated analysis, 3-D reconstruction and display of the ventricles of the brain and interactive processing of cardial CT's for 3-D reconstruction of the thorax and heart has shown the advantage of 3-D display for interpretation of complex anatomical objects. The 3-D surface representation is suitable for generation of 3-D display and for calculation of few diagnostic data. Further research must be done to develope a 3-D geometric model of patient specific data to allow not only viewing of 3-D shape, but quantitative analysis of spatial relationship, extraction of stereometric data and, most complex of all, interactive modeling[14]. In the medical field, where 3-D data are very important for diagnosis and therapy, e.g. in general surgical planning, stereotactic surgery and radiation treatment planning, such 3-D model would be a reasonable base to assist application programs for valuable medical image functions.

ACKNOWLEDGEMENTS

The authors wishes to thank Dr. H.S. Stiehl for the advise given on his work on computer vision components and S. Bednorz, P. Lönz and P. Kocitsch for specifying and implementing most of the computer graphics components and Claudia Stüve for her help in preparing the manuscript.

1 H.K. HUANG, Biomedical Image Processing. CRC Critical Reviews in Bioengineering, Vol.5, Issue 3, 1981, pp.185-271.

2 L.T. COOK et al, A Three-Dimensional Display System for Diagnostic Image Applications. IEEE Computer Graphics & Appl., Vol.3, No.5, 1983, pp.13-19.

3 G.T. HERMAN, J.K. UDUPA, Display of 3-D Digital Images: Computational Foundations and Medical Applications. IEEE Computer Graphics & Appl., Vol.3, No.5, 1983, pp.39-46.

4 H.S. STIEHL, Automatische Verarbeitung und Analyse von kranialen Computer Tomogrammen. Diss. at Technische Universität of Berlin, 1980.

5 H. NEUMANN, H.S. STIEHL, Modellgestützte Analyse der Liquorräume in kranialen Computer-Tomogrammen. DFG-Kolloquium im Schwerpunktprogramm "Modelle und Strukturanalyse bei der Auswertung von Bild und Sprachsignalen", Karlsruhe, West Germany, April 1983.

6 E. KEPPEL, Approximating Complex Surfaces by Triangulation of Contour Lines. IBM J. Research and Development, Vol.19, 1975, pp.2-11.

7 H. FUCHS, Z.M. KEDEM, S.P. USELTON, Optimal Surface Reconstruction from Planar Contours. Comm. ACM, Vol.20, No.10, 1977, pp.693-702.

8 K.D. TÖNNIES, D. JACKEL, Automatische dreidimensionale Oberflächenrekonstruktion aus Konturlinien zur Visualisierung von komplexen anatomischen Objekten. Medizinische Informatik und Statistik, Bd.40, Springer-Verlag, 1983, pp.323-329.

9 S.J. DWYER III et al, Medical Image Processing in Diagnostic Radiology. IEEE Transactions on Nuclear Science, Vol. NS-27, No.3, 1980, pp.1047-1055.

10 J.S. PETTY, K.D. MACH, Contouring and Hidden Line Removal Algorithms for Vector Graphic Displays. TR AFAPL-TR-77-3, Air Force Aero Propulsion Laboratory, Wright Patterson Air Force Base, Ohio, 1977.

11 K. AFFELD, H. SCHARNWEBER, C. CLAUSSEN, The Use of Computer Graphics to Find an Optimal Fit for a Human Total Artificial Heart. 29. ASAIO, Am. Soc. Artif. Internal Organs, Toronto, April 1983.

12 J.F. EASTMAN, An Efficient Scan Conversion and Hidden Surface Removal Algorithm. Computer and Graphics, Vol.1, 1975, pp.215-220.

13 J. F. BLINN, Models of Light Reflection for Computer Synthesized Pictures. ACM Computer Graphics, Vol.11, No.2, 1977, pp.192-198.

14 H.U. LEMKE, Using Computer Graphics to Enhance Medical Imaging. Proc. 2nd Intern. Symp. on Body Computed Tomography and New Imaging, Barcelona, May 1983.