SYSTEMS FOR THREE-DIMENSIONAL DISPLAY OF MEDICAL IMAGES

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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 effec-

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tive 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 $\frac{1}{4}$-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.

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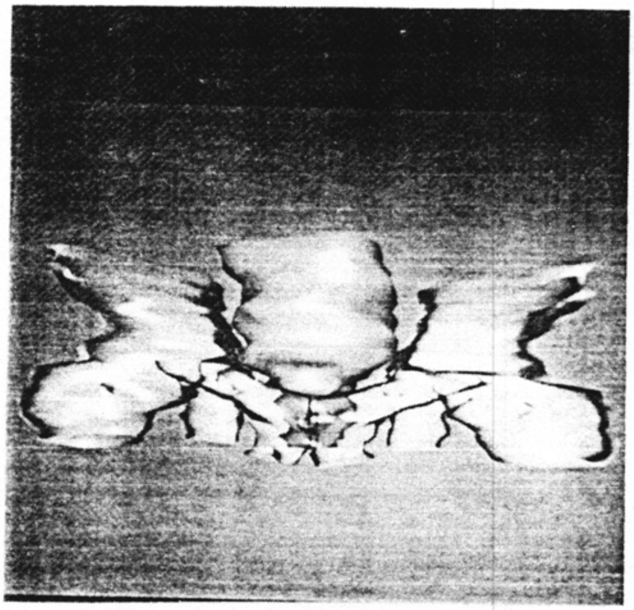

FIGURE 1: Smooth-shaded display with multiple light sources and transparent object of male pelvis from CT scans.

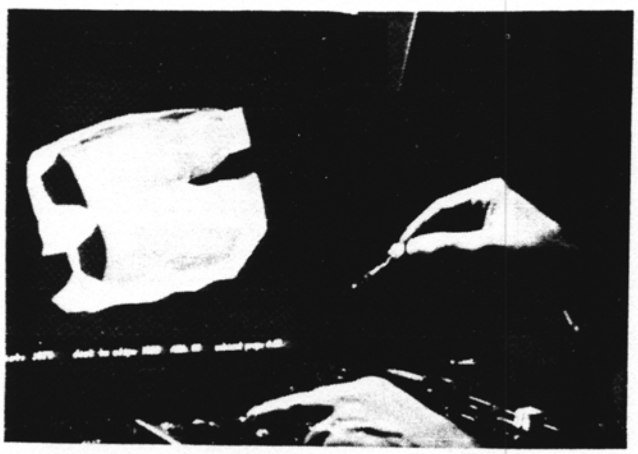

FIGURE 2: Coarse display allowing one second interactive modification of carotid artery (partially being clipped away) from CT scans.

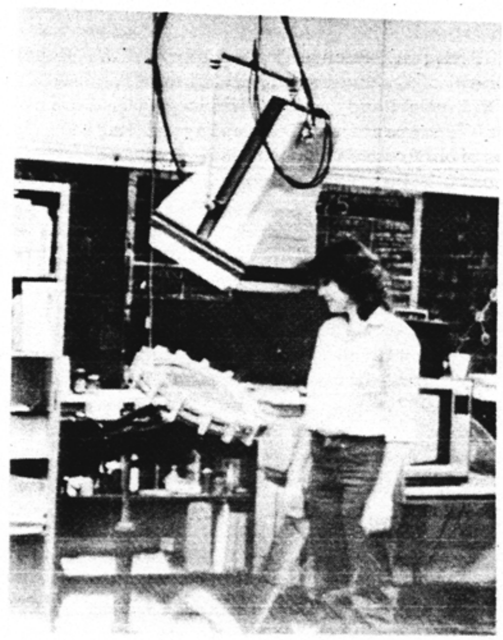

FIGURE 3: Varifocal mirror viewing arrangement.