APPLICATIONS OF THREE-DIMENSIONAL CELLULAR AUTOMATA TO THREE-DIMENSIONAL IMAGE DISPLAY AND ANALYSIS

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Abstract: A software system, called Triakis, has been developed for the Macintosh® computer that emulates a 3D cellular automaton of up to 16M processing elements. Initially this system was used to demonstrate missile track detection for SDI. More recently it has been applied to medical image display and analysis in radiology, for quantitation of thin bones in 3D CT, and in pathology, for serial-section reconstruction in breast tumor visualization.

Keywords: cellular automata, missile detection, computed tomography, serial-section reconstruction.

1. Introduction

This paper starts with a description of Kensal Consulting's work for SDIO (Strategic Defense Initiative Organization) on the use of 3D cellular automata for missile track detection. TV commentary on the recent war with Iraq has mentioned the US Government satellites in orbit carrying IR (infrared) television cameras for the purpose of observing the surface of the earth to detect missile liftoffs. The world is vast and the resolution and total picture elements of these IR cameras are limited. Therefore, when a missile lifts off, its image appears as a single "dot," i.e., an image that falls on a single IR detector. In other words the image of a missile is a subpixel event. Also, unlike objects imaged in biomedicine, missiles are uncooperative targets. The enemy does its best to shield the heat-emitting portions of each missile and to limit the extent of the plume. In a worst case the SDIO estimates that the image signal-to-noise ratio in the plane of the IR detector array on liftoff is 12dB. Although 12dB appears to be a comfortable signal-to-noise ratio, consider that at 12dB there will be 3% false alarms. In other words there are "dots" everywhere in the IR image even when there are no liftoffs at all.

Figure 1 illustrates this situation. This figure is recorded directly from the Apple Macintosh screen showing the user interface for Kensal Consulting's Triakis software for 3D image analysis. In the background of Figure 1 there are a multiplicity of 64x64 squares, each containing more than 100 "dots." Each square represents one frame of a typical thresholded IR television image in 12dB noise. In the case illustrated in Figure 1, four of the "dots" in each frame are missiles. The problem to be solved is to locate the missiles in the noise background in a reliable manner. This can only be done by multiframe processing [1].

Shown in the upper left of Figure 1 is a three-dimensional rendering of 64 frames for the 64x64 IR detector array. No missile tracks are evident. The noise obscures everything. In order to process these data Triakis considers the 256K voxels in the 64x64x64 display as a 3D cellular automaton consisting of an array of 256K computers in the FCC (Face Centered Cubic) tessellation. The three-dimensional kernel of this tessellation is illustrated in Figure 2. It is the well-known tetradakahedron of classical geometry [2]. Its central voxel is surrounded by 12 equispaced neighboring voxels.

The first step in missile detection is to conduct two iterations of a binary rank 2 transform on the 64x64x64 data array. Any "dot" whose 3D neighborhood contains two or more "dots" is preserved while all other "dots" are eliminated. The results of two such iterations are shown in the center of Figure 1. Even after the first iteration the missile tracks become evident. But, after the second iteration, there are still false alarms. These false alarms are eliminated by means of two final iterations where a "dot" is preserved only if its two neighboring "dots" are in separate frames. This is called "crossing number processing" in that the two adjoining dots in separate frames cause the
“dot” being examined to have a neighborhood with a crossing number of four. Kensal’s Triakis supports crossing number analysis both for “dots” that are present and “dots” that are absent. As can be seen in the lower right of Figure 1, two final iterations using crossing number processing yield no false alarms whatsoever. There are some dropouts along the missile tracks that have been found, but these in no way prevent the missiles from being detected.

2. Applications To 3D Medical Imaging

What can the Triakis software, originally developed for SDIO, bring to medical imaging? Triakis offers three useful features. First, it offers 3D shaded-graphics imaging of binary volumes. Second, it offers 3D analysis of this volumetric data. Thirdly, it offers the user an exceptionally low cost workstation, the Apple Macintosh II, on which to perform 3D display and analysis.

Figure 3 shows an example of the application of Triakis to pathology. Serial sections of an intraductal breast tumor showing an invasive process into the surrounding tissue were obtained from Dr. Richard Siderits, Shadyside Hospital, Pittsburgh, Pennsylvania. These are shown in the upper left portion of Figure 3. These serial sections are taken from tissue slices microtomed at a separation of 10 micrometers. The voxel-to-voxel spacing within a section is two micrometers. Therefore there are four empty planes between each pair of serial sections as shown in Figure 3.

Triakis is able to interpolate between these serial sections as follows. First, three iterations of a binary ranking transform of rank 3 are executed. This propagates information from each serial section into the neighboring empty planes and merges this information with the information contained in adjacent planes [3]. This is followed by four iterations of rank 7 for the purpose of smoothing. Rank 7 in the twelve-element neighborhood of the FCC tessellation is equal to a median plus one half (the even number 12 has no integer median.) The result of this interpolation is shown in the lower left of Figure 3. Each voxel is now 2x2x2 micrometers. The intraductal tumor itself is ap-

Figure 1: Detection of four missile tracks in 64 frames of simulated IR TV images for a S/N=12dB.
approximately 100 micrometers in diameter and the invasive process can be seen extending to the upper right.

Triakis is also capable of sectioning and rotating the tumor as shown in the central two frames of Figure 3. Rotation without sectioning is also shown. These operations are useful in visualization of the tumor.

Operations over large numbers of voxels are relatively time consuming with Triakis. For example, the operation shown in Figure 3 emulates a 3D automaton consisting of approximately 2M computers. About three minutes are required for serial section interpolation. To generate each 3D shaded graphics image requires approximately 30 seconds. Considerable improvement in speed can be obtained by extracting a 64x64x64 cube from the 2M volume as shown in Figure 4. In the background this figure shows the 64 serial sections. In the foreground are shown five shaded graphics renderings including the previous illustration of serial section interpolation. In this smaller data volume serial section interpolation takes less than one minute and each surface rendering takes approximately 10 seconds.

Another illustration of the ability of Triakis to transfer from a large data volume to a 64x64x64 cube is illustrated in Figure 5. This figure uses data furnished by Dr. Jay Udupa of the Department of Radiology, University of Pennsylvania. The data is obtained from CT scans of a dry skull interpolated to a voxel size of 2x2x2 millimeters. The entire skull is shown in the upper right of Figure 5. The central portion of Figure 5 shows the basilar process extracted from the skull and displayed as a 64x64x64 cube. The serial sections of this cube are shown in the background as well as a single section (256x256 voxels) of the entire skull (upper left). One item of interest to the radiologist is to find “thin bones,” i.e., bone which is no thicker than two voxels. This may be done readily for the basilar process by Triakis using crossing-number processing. Voxels which are contained in bone one-voxel thick have a crossing number for absent voxels of four and may be extracted in a single iteration. Voxels which are part of boney structures two-voxels thick may be extracted by finding “surfaces of surfaces.” This requires two iterations. The results of these three

![Figure 2: The kernel of the FCC tessellation.](image)
iterations are then summed to produce the final result which is shown in the lower left frame of Figure 5. In this particular case the original basilar process contained approximately forty-five thousand voxels while the voxels contained in “thin bone” amounted to four thousand voxels. Thus “thin bone” composed 10% of the basilar process of the skull under examination.

3. Hardware Implementation

A computing structure has been invented and patented for executing all of the operations illustrated above by implementing them on a single silicon chip [4]. This chip would utilize approximately 700,000 transistors in an architecture as shown in Figure 6. In this figure incoming 3D voxel data is entered in a multi-ported replicate memory and flows through pipelines that feed multiple LUTs (Lookup Tables). LUT processing is feasible in the FCC tessellation since the 12 element neighborhood of any voxel is represented by a 12-bit word. The architecture shown in Figure 6 permits, in one clock cycle, 12-bit neighborhoods from 16 voxels to simultaneously address 16 LUTs. This produces 16 results which are then stored in the data space reserved for the transformed binary information. It is estimated that such a computing structure with a 20 MHz clock will operate at 200 megavoxels per second. Such a chip may be embedded in an accelerator board for the Macintosh II. Such a board would give the Macintosh the power of approximately 10 supercomputers! The estimated price of such a board would be of the order of $1000.

An emulation of this board has been carried out by Kensal Consulting in May of 1991. This permits real-time 3D movies to be shown on the screen and recorded with a VCR. (A representative example was shown at the Symposium.)

4. Conclusions

In this paper we have illustrated how technology originally devised for subpixel target detection for SDIO has been transferred to the medical community for 3D display and analysis. A software package called Triakis has been created to emulate our patented computer architecture on the Macintosh II. Even in software this is an exceptionally fast program permitting shaded

Figure 3: Serial-section reconstruction of an intraductal breast tumor having an invasive process.
graphics rendering of 64x64x64 cubes in approximately 10 seconds. If the hardware accelerator for this same workstation is produced, then real-time 3D movies may be shown on the Macintosh screen and real-time 3D data analysis executed. The chip currently being proposed to both SDIO and other funding agencies would furnish the power of ten supercomputers in a workstation costing approximately $5000. This would truly be an exciting achievement. It abundantly demonstrates that research originally initiated by SDIO can have significant applications in the civilian sector.

5. Acknowledgements

The work reported here was supported in part by Naval Ocean Systems Center contract 85-D-0203 and National Institutes of Health grant GM44424.

6. References


Figure 4: Serial-section reconstruction, 3D imaging, and 3D sectioning using a 64x64x64 automaton.
Figure 5: Analysis of thin bones in the basilar process of the human skull.

Figure 6: Computer architecture for executing 3D cellular transforms.