Interactive navigation for PC-based virtual colonoscopy

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ABSTRACT

Virtual colonoscopy on powerful workstations has the distinct advantage of interactive navigation, as opposed to passive viewing of cine loops or pre-computed movies. Because of the prohibitive cost of hardware, only passive displays have been feasible for the wide-scale deployment required for mass screening. The purpose of our work is to compare low-cost commodity hardware as an effective tool for interactive colonographic navigation versus the expensive workstations.

Keywords: interactive navigation, guided navigation, virtual colonoscopy, virtual endoscopy, 3D medical imaging, exploration, mass screening

1. INTRODUCTION

Virtual endoscopy[1] is a technique that assembles a set a computed tomography or magnetic resonance (CT or MR) images into a 3D model and uses computer graphics and virtual reality to interactively fly through the interior of objects inspecting the interior of objects up close and from all directions. Hong et al.[2] demonstrated the first viable system for virtual colonoscopy. This system is significant because it allowed real-time interactive exploration inside of a volumetrically reconstructed colon lumen. Compared to all other systems at the time, it had the advantage of not being constrained to 2D slice inspection or only generating still 3D images from the volumetric reconstruction. While slice-by-slice inspection in these other systems has the capability of cross-sectional visibility, it is difficult to mentally reconstruct three dimensional information from a temporal sequence of cross-sections. Volumetric reconstruction solves this problem, but can obscure the information beyond the wall if not properly configured. A synchronized combination of these two techniques, as utilized by Hong et al., allows building on the advantages of each.

The early system permitted exploration within the colon lumen by simple forward/backward/turn controls much like an airplane. It was soon recognized that some form of assistance would be extremely helpful in relieving some of the tedium of navigation. A method to smoothly and automatically pull the viewpoint from cecum to rectum along a centerline was developed. This was integrated with interactive flying into a coherent, physically based navigation metaphor[3]. Navigation requires a set of pre-computed fields, which draw the viewpoint from end to end, and help to avoid collisions with the walls. These fields are sampled at each time-step and used to apply forces and torques to the viewpoint.

To accomplish its goals, this early virtual colonoscopy system utilized surface-based rendering. An isosurface was assumed at the mucosal surface and polygon extraction techniques were used to develop a polygon mesh representation[4]. This mesh was further broken into groups for more efficient rendering[5]. Even with grouping, only the very best available—and most expensive—graphics workstations were capable of rendering the mesh quickly enough to simulate reality at 30-60 frames per second. With the advent of high-performance graphics cards for personal computers, surface based rendering became more affordable; but the poor quality of surface based rendering made it insufficient for diagnostic purposes.

Volume rendering is demonstrably superior to surface-based methods because it permits visualization of *all* data (not just the presumed surface), permits interactive segmentation, delivers a higher quality image, and requires no pre-processing. Furthermore, volume rendering makes no simplifying assumptions about the data, whereas surface-based methods only extract a single isosurface from the data and ignore all other contextual information. Volume rendering continuously interpolates information among voxels, while surface based methods generate piecewise-linear approximations of the isosurface (see figure 1). An example of this in three dimensions is given in figure 2. The primary challenge with volume

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Medical Imaging 2001: Physiology and Function from Multidimensional Images, Chin-Tu Chen, Anne V. Clough, Editors, Proceedings of SPIE Vol. 4321 (2001) · 1605-7422/01/$15.00

rendering is making it fast, as it requires accessing massive amounts of data and processing. Various methods have been used to improve the rendering speed including algorithmic enhancements[6] and parallelization[7]. Algorithmic enhancements have been used along with parallelization to achieve multiple frames-per-second of volume rendering on high-end graphics multiprocessors such as the SGI Challenge costing several hundred thousand dollars, or with expensive graphics subsystems which still lack realistic shading[8].

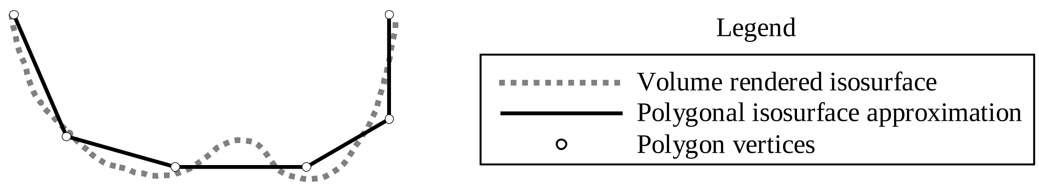

Figure 1: Polygonal isosurface approximation compared to volume rendered isosurface.

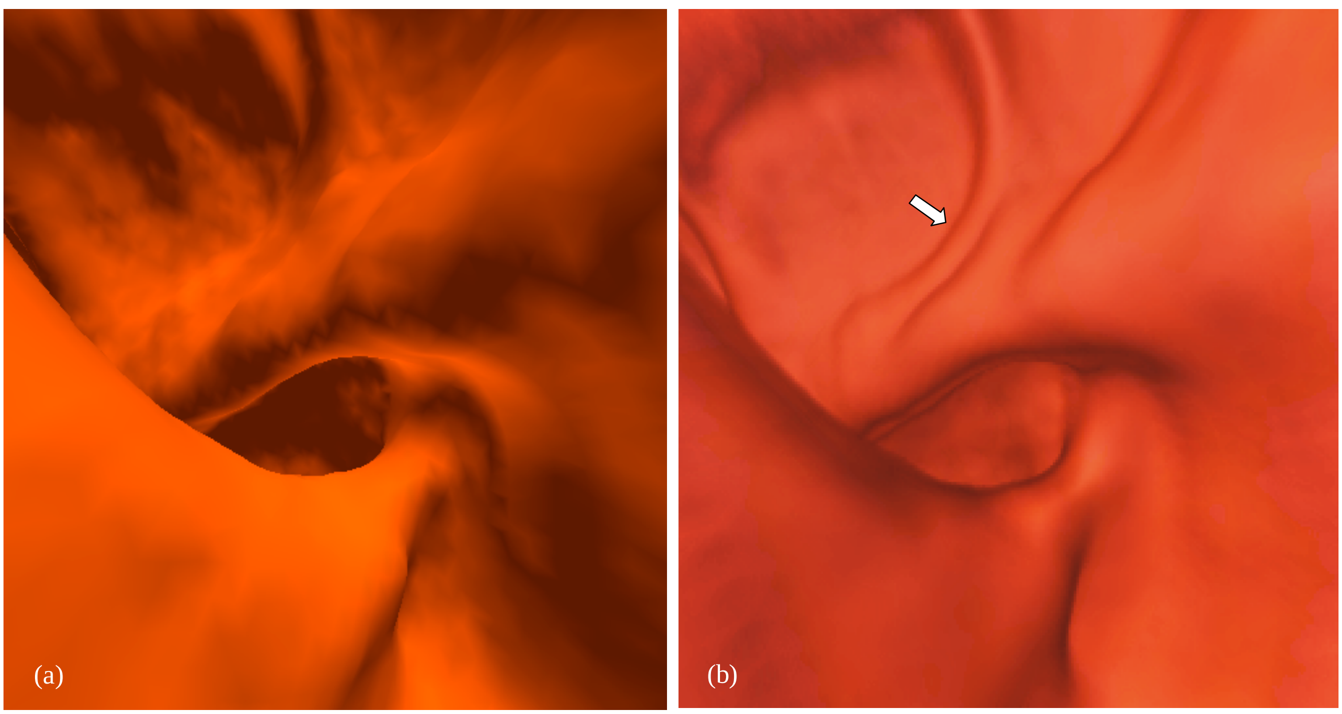

Figure 2: Qualitative comparison of (a) polygonal isosurface approximation and (b) volume rendering. Note the haustral fold indicated by the arrow which is present in volume rendering, but missing in the polygonal isosurface.

Such heavy-handed, expensive processing power can be avoided if the volume rendering is performed off-line and stored in a cine-loop for subsequent review[9]. This is often the only feasible solution for clinical use, where cost causes limitations in usable hardware. A cine-loop with proper volumetric shading provides 3D context for understanding the physiology of the colon wall. However, simply moving along a single path provides insufficient visibility of the entire colon wall due to the irregular nature of the colon, e.g., behind haustral folds, around sharp bends, etc. Simply examining single still frames from a pre-computed cine-loop reveals no additional information. The only way to glean additional information is to freely navigate within the lumen, moving closer to suspected anomalies and rotating the viewpoint around them. Thus, a viable virtual colonoscopy system must be fully interactive with at least multiple frames-per-second created by volume rendering to create image quality this is of diagnostic utility.

To meet these needs and to make the system affordable for widespread general practice, Kreeger et al. implemented “virtual colonoscopy” with real volume rendering on a standard personal computer (PC), with the aid of a hardware volume rendering accelerator[7,10]. Previously we examined the method of rendering and the quality of the images. In this paper, we investigate the resulting efficacy of the navigation.

2. METHODOLOGY

15 CT virtual colonoscopy datasets from patients who had optical colonoscopy on the same day or college-aged volunteers who had two virtual colonoscopy studies separated by one week were evaluated. We applied an automatic segmentation method that extracted the interior air regions, computed the distances from the cecum and rectum, and calculated the distances from the colon wall. We did not include the pre-processing times in our study because it is independent of the actual time to review and navigate through the data set.

Two virtual colonoscopy systems were used for analysis. The first used a 16-processor SGI workstation with Infinite Reality graphics costing several hundred thousand dollars, and a version of our colonoscopy software parallelized to take advantage of 12 processors for volume rendering, and the rest for control of navigation and the user interface. The other system was a dual processor PC with a VolumePro board and nearly identical software. The software was first ported from Unix to Windows so it would run natively on the PC. Next we supplanted the parallelized volume rendering with a commercially available graphics hardware accelerator. The PC system performs volume rendering at approximately the same rate and quality as the parallelized code on the multi-processor[10] (see figure 3). The navigation portion of the software was optimized for speed and compactness, and compacted into the primary application thread on the PC, but the method remained substantially the same as on the multi-processor.

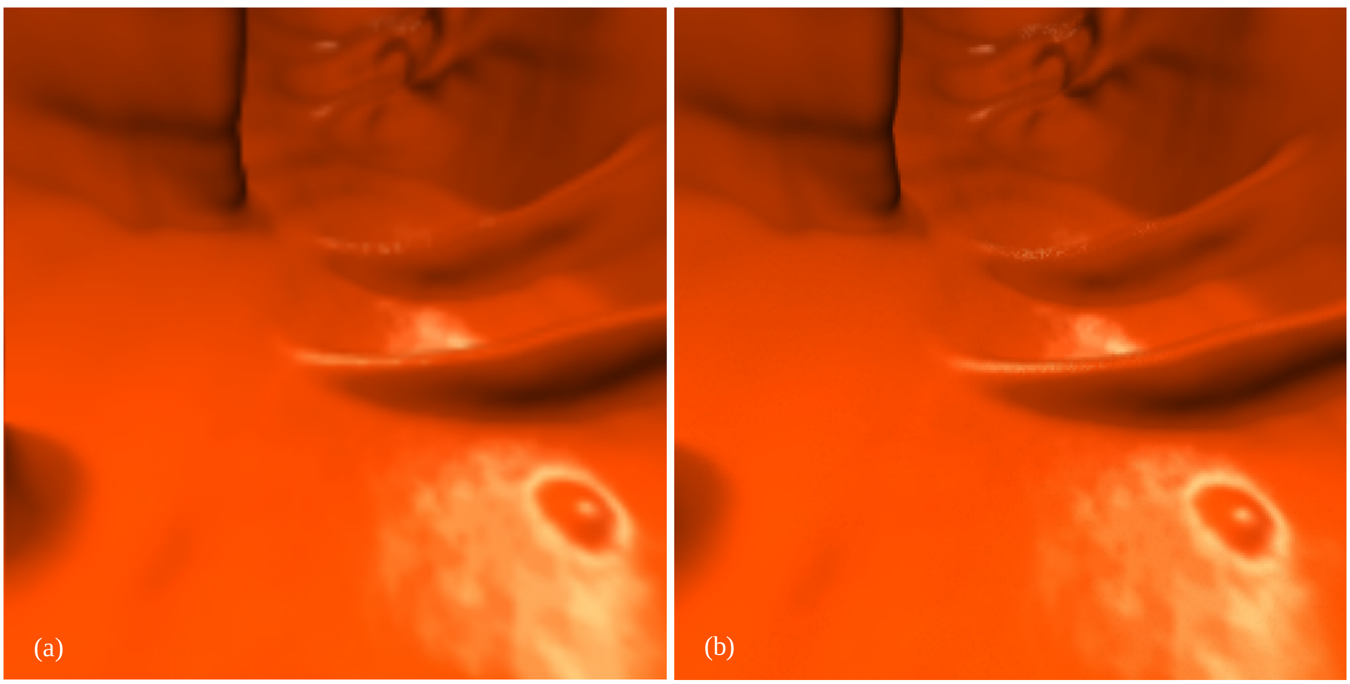

Figure 3: A comparison of image quality between (a) the PC system and the (b) SGI workstation

The navigation interface is designed as a physically based simulation of a small inertial mass inside a flowing, viscous fluid in the colon lumen (see figure 4). The flow can be started, stopped, and oriented to flow in either the forward or reverse direction, aiding navigation from end-to-end and back. The walls of the colon are modeled as hard surfaces that do not allow penetration and also repel the viewer. This tends to keep the viewer centered within the lumen. As described previously, this setup only allows the user to travel back and forth along the centerline of the colon. However, to support user-directed interactive navigation, the user is able to click anywhere in the image to fly toward that point. Repeated clicks provide complete six degrees-of-freedom control over the viewpoint, allowing complete examination of any region.

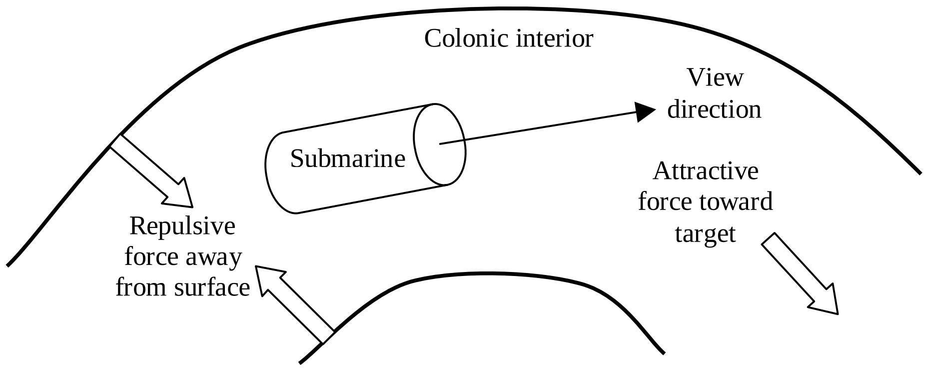

Figure 4: Physically based interactive navigation setup.

The system provides many features to augment the endoscopic view. First, the system provides non-oblique, multi-planar formatted (MPR) slice images synchronized to the current view. This allows not only an examination of the visible shape of the surface, but also the underlying structure beneath the surface. Furthermore, a translucent “virtual biopsy” mode allows the user to analyze the internal structure of the shape by applying a colored X-ray view in the endoscopic mode. Through a combination of these techniques the user is able to differentiate simple shapes from structurally significant anomalies.

We performed virtual flythroughs of the 15 datasets, keeping track of the total examination using wall clock time. This included automated flythrough from end to end and interactive inspection of suspected anomalies. Generally, the bi-directional flight consumed about half of the total exam time, and the closer inspection consumed the remainder.

3. RESULTS AND DISCUSSION

The datasets varied in length due to factors such as collapsed regions, quality of distension, and actual length. The automatically segmented colon lumens were up to about 150 cm in length. To account for the variation in the lengths, the times were normalized to 150 cm, to assume the worst case for our tests. To complete the described examination required an average of 9.2 minutes on the workstation and 9.4 minutes on the PC (see Table 1). The examinations averaged only 2% longer on the PC, which is not statistically significant. A pooled variance t-test (two-sided p-value = 0.769) revealed no significant difference.

Table 1: Statistics for the examinations

Statistic	*SGI Workstation*	*Personal Computer (PC)*
Minimum	7.0	7.0
Mean	9.2	9.4
Maximum	13.3	12.9
Median	8.5	9.0
Standard Deviation	2.2	2.1

We also analyzed the subjective “feel” of the examinations. Since the frame rate of both systems was similar, as well as the rendering quality, both systems were able to deliver the same quality of visual imagery. Focusing on the quality of the interactive navigation, the physical simulation that permits six degrees-of-freedom navigation within a flowing, viscous fluid was able to process just as quickly on the PC as on the workstation. This led to a snappy, interactive feel that encouraged free exploration of the dataset via simple mouse clicks. This immediate interaction afforded a better comprehension of spatial relationships compared to using only the standard cine-loop or hands-free guided navigation.

Furthermore, the diagnostic confidence increased during interactive navigation because closer looks and different angles revealed additional information. Similar to examining a physical object by twisting it around in your hands and holding it closer to your eye, interactive navigation within the colon affords better viewing and increased understanding of the data. In our evaluation a single flight in one direction was able to visualize 70% of the colon surface; a bi-directional flight achieved up to 95% coverage; but only with interactive navigation were we easily able to visualize more than 99% of the surface.

4. CONCLUSIONS

We have shown that a practical system for virtual colonoscopy reading can be implemented using a small, affordable personal computer in place of a large, expensive multi-processor workstation. Both deliver high-quality visual imagery, interactive navigation, and practical examination times. Both are able to process the physically based motion of an object within a flowing, viscous fluid—in real time—in response to user interaction. Advances in computer technology and algorithms have enabled newer PCs to supercede conventional movie-based cine-loop readings with an interactive, guided navigation.

The new availability of compact, inexpensive virtual colonoscopy readings makes possible mass screening and flexible viewing configurations. The readings can take place in the comfort of the radiologist office, in shared reading rooms, in the gastro-enterology suite, or even in the referring physicians office.

ACKNOWLEDGMENTS

This work was supported by NIH grant CA82402, ONR grant N000140110034, and Viatronix, Inc. The authors wish to thank Ingmar Bitter, Bin Zhang, Mark Kontak, Carolann Collins, Gail Akeson, and Rob Strauss for administrative and technical help at critical times.

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