Volume Rendering Based Interactive Navigation within the Human Colon

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Abstract

We present an interactive navigation system for virtual colonoscopy, which is based solely on high performance volume rendering. Previous colonic navigation systems have employed either a surface rendering or a Z-buffer-assisted volume rendering method that depends on the surface rendering results. Our method is a fast direct volume rendering technique that exploits distance information stored in the potential field of the camera control model, and is parallelized on a multiprocessor. Experiments have been conducted on both a simulated pipe and patients' data sets acquired with a CT scanner.

1 Introduction

Colon cancer is the second leading cause of cancer deaths in the United States. Unfortunately, it is most often discovered after the patient has developed symptoms. Therefore, the American Cancer Society has recommended a colon exam every 3 years after age 50 to detect colon polyps which may lead to cancer. Optical colonoscopy is the commonly used accurate diagnostic procedure which can biopsy detected polyps. However, most patients do not follow their physician's advice to undergo such a procedure because of the associated risk, discomfort, and high cost. Consequently, a new massive screening technique which is accurate, cost-effective, non-invasive, and comfortable would be extremely valuable. It would have the potential for a large population colon screening and could detect small colon polyps at their early stages. The detection and removal of these small polyps can completely cure the patient's condition.

Recently, considerable interest has arisen for developing a computer-based screening modality as an alternative to optical colonoscopy, by employing advanced computer graphics and visualization techniques [1, 2, 3, 4]. SUNY at Stony Brook is a pioneer and a leader in developing such a system, called *3D virtual colonoscopy* [3, 4]. The virtual colonoscopy system takes a spiral CT scan of the patient's abdomen after the entire colon is fully cleansed and distended with air. Several hundred high resolution CT images are rapidly acquired during a single breathhold of about 30 to 40 seconds, forming a volumetric abdomen data set. A model of the real colon is then segmented from the abdomen data set. It can be viewed either by automatic planned navigation [3] or interactive navigation[4].

Our previous systematic development was based mainly on surface rendering techniques [3, 4], although a fast Z-buffer-assisted direct volume rendering algorithm was employed as a supplementary tool for *electronic biopsy* [5]. However, such a surface rendering based system has shown several shortcomings in clinical applications as discussed in Section 2. Therefore, we have developed a direct volume rendering based virtual colonoscopy system as described in Section 3.

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2 Surface Rendering Based Navigation System

In previous work, we developed a surface rendering based virtual colonoscopy, where the colon surface was extracted from the colon volumetric data set using the Marching Cubes algorithm [6]. Since the number of triangles was enormous and could not be processed at interactive speed, a hardware-assisted visibility method was proposed by employing a center-line based colon surface subdivision. In addition, a physically-based camera control model was established by employing a *potential field* and kinematic rules to guide the interactive navigation inside the colonic interior, while avoiding collision with the colonic surface. During navigation, we rendered the isosurface triangles to generate colonic images on-the-fly. Interactive rendering rates were supported by graphics hardware accelerators and algorithmic designs.

Although such a surface rendering based navigation system was sufficient to give an overview of the interior surface of the colon at interactive rendering speeds, it suffered from some frustrating problems. For example, the virtual colonic surface image generated by surface rendering looked artificial, when compared with the real colon image obtained from the optical colonoscopy. Since the camera was immersed in the narrow colon tube, and was very close to the colon wall, we could clearly see the sharp edges and silhouettes of isosurface triangles in the image.

This surface rendering based system has also raised other problems, such as requiring accurate pre-segmentation and time-consuming iso-surface extraction and subsequent subdivision. For surface navigation, the volume data of the human colon must be pre-segmented to extract the colonic surface. However, at the time of a CT scan, some residual stool and colonic fluid are still retained in the colon after the flushing procedure. Their appearances are similar to the colon surface in the grey-level CT images, and presently there is no accurate automatic segmentation technique to distinguish them from the actual colon wall. Therefore, we can not guarantee that the surface extracted by the surface rendering based system is the actual colon surface. Moreover, the extraction and subdivision of colon surface are so time-consuming that it becomes a bottleneck of the preprocessing stage. We experimented with a real patient data set of size $512 \times 512 \times 411$. Surface extraction and subdivision took about three hours, which could delay the diagnosis and therapy of the patient, and is impractical for clinical use. It is our belief that the virtual colonoscopy should be as quick and as accurate as possible when compared to optical colonoscopy.

3 Volume Rendering Based System

3.1 Motivation

A direct volume rendering based virtual colonoscopy has several advantages, when compared to a surface rendering based one:

– More realistic colonic image: Unlike isosurface rendering, volume rendering does not extract or display the object surfaces as a set of intermediate geometry primitives, but directly renders the colon images from the original 3D volume data. By using a transfer function to map different ranges of sample values of the original volume data to different colors and opacities, volume rendering can produce smoother and "softer" (fuzzier) interior colonic surface images that are closer to real colon images.

– No pre-segmentation: With volume rendering techniques, we provide a more powerful visualization and manipulation tool to distinguish residual stool and colonic fluid from the colon surface according to their different interior structures. Specifically, we first change the transfer function of the renderer to make the outer layers translucent, then render the interior structures by performing sampling, shading and compositing along each viewing ray. This method is more flexible and accurate than the pre-segmentation performed in the surface rendering based system.

– Fast preprocessing: Since surface polygon extraction and subdivision are not needed for volume rendering, the preprocessing can be greatly shortened, which makes our system fast enough for clinical practices.

– Electronic biopsy: In our previous surface rendering based system, electronic biopsy had to be separately implemented by volume rendering techniques as a supplementary tool with a pre-defined transfer function. However, this feature is directly supported by our current volume rendering based system without extra tools. It enables the examiner to inspect the internal 3D structures from different views and different transfer functions for confirmation and further analysis of suspected abnormalities.

– Hardware acceleration: A pioneering volume rendering accelerator, called VolumePro, is being produced by Mitsubishi Electric Research Laboratory [7] based on the Cube-4 architecture developed at SUNY Stony Brook [8]. It will support real-time volume rendering even on low cost PC platforms. Hence, a volume rendering based virtual colonoscopy system with real-time performance will be widely available to medical practitioners at low cost.

With the above considerations, we propose a novel interactive navigation system that is based completely on high performance volume rendering techniques. Our focus is on exploring and developing both fast and high quality volume rendering methods that are suitable for visualizing the human colon.

3.2 Volume Rendering Techniques

Many fast volume rendering techniques have been proposed, such as texture-mapping hardware-based volume rendering methods [9], the shear-warp technique [10], and image-based rendering approaches [11]. We would like to consider a more accurate volume rendering method – volume ray casting algorithm [12], since we strongly believe that image fidelity is paramount in the virtual colonoscopy application. We are especially interested in those acceleration strategies of ray casting which provide significant speedup without affecting image quality, such as the space-leaping techniques [13, 14, 15].

In our previous work, we proposed a fast ray casting algorithm primarily for electronic biopsy [5], where the rendering time was reduced by skipping over empty space between the camera and the colon wall. The distance from the camera to the closest colon wall along each ray was obtained from the Z-buffer generated by the corresponding surface rendering at the same view. The advantage of this method is that the computation overhead for space leaping is very small when volume rendering works along with surface rendering. However, for a pure volume rendering based navigation system, the establishment of the Z-buffer by surface rendering becomes a major overhead to our system. In this paper, we propose a new fast ray casting algorithm, called *potential-field-assisted* ray casting. It exploits both the specific features of the human colon and the available distance information stored in the potential field of the colon [4].

3.3 Potential-Field-Assisted Ray Casting

The potential field was originally generated in virtual colonoscopy for camera control [4]. It consists of two distance fields inside the colonic interior: distance $D_s(X)$ from the colonic surface and distance $D_t(X)$ from the target point of the current navigation, where X is the voxel (a grid vertex in the volumetric data set) position inside the colon. Distance $D_s(X)$ prevents the camera from getting too close to the surface and colliding or penetrating it, while distance $D_t(X)$ pushes the camera toward the target point. In our fast volume rendering method, we are more interested in $D_s(X)$, the distance from each voxel X to the nearest colonic surface. For each voxel inside the colon, this distance is calculated as an Euclidean distance map [16]. For the remaining voxels beyond or on the colon wall, the distance value is set to 0. The basic idea of our rendering method is described as follows.

The human colon has a cavity structure with a bounding surface, and during navigation the camera is always located inside the empty colonic interior. Therefore, if we can skip over the empty space and only perform sampling in the neighborhood of the colon surface, much ray casting time can be saved. Based on such an observation, we propose a fast ray casting method by exploiting the distance information from each voxel inside the colon to the closest colon wall. Specifically, when we start ray traversal from the viewpoint, instead of performing regular sampling in the short equal-distance intervals, we first check the distance from the current sampling point to the nearest colon wall. If the distance is greater than the regular sampling interval, we directly jump to a new sampling point along the ray with this distance. Otherwise, it indicates that we are already very close to the colon wall and regular sampling is performed.

This method is illustrated in Figure 1, where point P_1 in the colonic interior is the current camera position. When ray R_1 is cast from the camera, instead of conducting regular sampling from P_1, we detect distance d_1 from P_1 to its closest colon surface, and then move to a new position P_2 along R_1 with distance d_1. We repeat this procedure from P_2, until we reach a new position P_n ($n > 1$), whose closest distance d_n is smaller than the regular sampling interval. Then, we switch to regular sampling from P_n, since we are already very close to the colon wall. Thus, most rays can be traversed quickly. However, there are some special cases as shown for ray R_2 in Figure 1. When R_2 approaches the colon wall, it does not go deeper into the colon wall, but grazes the colon surface and enters the empty colon interior again. This is possible during ray casting, because the voxels at the outer layers of the colon wall could be made translucent revealing unseen structures and for a smooth colonic appearance. When the ray grazes the colon wall and reenters the empty area, we can find that the distances from the sampling points to the closest colon wall increase and become greater than the regular sampling interval. In this case, we switch back from regular sampling to distance leaping, until this ray approaches the colon wall again. Obviously, the worst case of our method appears when the ray is almost "parallel" to the colon wall with a short distance that is, unfortunately, greater than the regular sampling distance. Therefore, each time we can jump only a small distance, and the traversal over the empty space slows down. Fortunately, this situation rarely happens in our study because the colon

shape is very twisted and its surface is not flat.

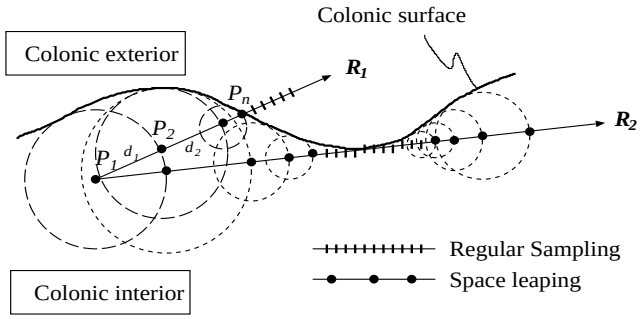

Figure 1: Fast ray traversal in the colonic interior.

Indeed, the idea of space leaping by exploiting the distance information is not new. It is very similar to existing distance-encoding methods [17]. Yet, to the best of our knowledge, no one has employed this in endoscopy simulations such as that of virtual colonoscopy systems. More importantly, our method is implemented very efficiently here, because no extra distance-coding procedure is needed in our system. The distance information of each voxel inside the colon is available from the potential field. During rendering, for a sampling point not coinciding with any voxel, trilinear interpolation is used to reconstruct the distance values from those of its eight neighboring voxels.

Compared with our previously implemented Z-buffer-assisted ray casting technique, our new potential-field-assisted ray casting has both advantages and disadvantages. Typically, several jumps are needed in our new algorithm to skip the empty space before approaching the nearest colon wall, while in the Z-buffer method we obtained the distance value from the Z-buffer and reached the colon surface directly. As a result, ray casting time in our new algorithm tends to be longer. From our experiment on a patient data set (as shown in Figure 2 — see color plates), the average traversal distance along each ray before hitting the colon wall is about 11.3 voxels, and takes an average of 2.1 jumps. On the other hand, since the colon surface in volume rendering is somewhat transparent, some rays may graze the colon surface and reenter the colon cavity. For these rays, Z-buffer could only provide an estimate of the distance to the closest colon wall along each ray, with no more information beyond that. In our new method, after a ray reenters the empty colon interior, it can be accelerated again by space leaping, as shown for ray R_2 in Figure 1. The significance of our new method is that no surface rendering is needed for acceleration. Thus, it saves on both surface rendering time and memory space for millions of triangles extracted from a colon volume.

Our method has also been parallelized on a multiprocessor for further speedup. We have employed the same image-based partition strategy as we proposed in our previous work for the Z-buffer-assisted ray casting [5]. Specifically, each image is divided into equal sized rectangular blocks, for example, four by four for 16 processors. Each pixel of the block is allocated to one processor for ray casting using our potential-field-assisted acceleration. A good load balance has been achieved during our experimentation.

3.4 Interactive Electronic Biopsy

In our new system, we provide an interactive electronic biopsy with a user-friendly interface to modify the transfer function. Thus, when a suspicious abnormality is detected, the physician can interactively change the transfer function to observe the interior structures inside the abnormalities or beyond the colon wall for a more accurate diagnosis and measurement. Since camera parameters are often fixed during the electronic biopsy procedure, the distance from the camera to the visible colon wall is also fixed. Hence, when we display a polyp at a fixed view with different transfer functions, we do not need to use the potential-field-assisted method to skip the empty space step by step along each ray. Instead, we directly skip over the entire empty space using the intersection information secured in the previous volume rendering frame.

4 Experimental Results

Our volume rendering based virtual colonoscopy system has been implemented on a Silicon Graphics Power Challenge equipped with 16 processors in a bus-based symmetric shared-memory configuration. We have conducted experiments on a simulated data set and more than twenty patients' colon data sets.

Figure 3b (see color plates) shows a volume rendering image of a phantom pipe data set, rendered by our potential-field-assisted ray casting method. This simulation is based upon a CT scan of a plastic pipe of 20mm radius forming a volume of $512 \times 512 \times 107$. To simulate colonic polyps, we attached three small rounded rubber objects to the inner surface of the pipe, which have been clearly depicted in the rendering. In Figure 3a, we provided the corresponding surface rendering image at the same view, generated by our previous surface rendering based system. We can see that the volume rendering image provides a smoother view. In the surface rendering image, sharp triangle edges appear at the boundary of the closest polyp and other sites on the interior pipe surface.

Table 1: *Volume rendering times (in seconds) for the pipe data set. (NP: Number of processors; VR: volume rendering techniques)*

Image:	512×512			256×256		
NP\VR	Pure	Z-buffer	New	Pure	Z-buffer	New
1	8.70	4.85	5.96	2.10	1.22	1.45
4	2.22	1.22	1.50	0.52	0.30	0.36
9	0.99	0.55	0.67	0.23	0.13	0.17
16	0.59	0.32	0.40	0.15	0.08	0.10

Table 1 presents the average rendering times of the pipe data set with a different number of processors and image sizes, using different acceleration methods for volume rendering. These results show that the rendering time of the our new method (New) is slightly longer than that of the Z-buffer-assisted ray casting method (Z-buffer); both are shorter than that of the standard ray casting method (Pure) without space leaping. Similar results were shown for the patient's data sets. It is worth pointing out that the rendering time of the Z-buffer method in Table 1 neither included the related surface rendering time to generate the Z-buffer nor the Z-buffer loading time. The average surface rendering rate was about 18 Hz, or close to 0.05 seconds per frame. The loading time on our SGI Challenge was about 0.02 seconds. Accordingly, the total overhead time for each Z-buffer-assisted ray casting image would be about 0.07 seconds. If this overhead were counted, the time difference between these two accelerated ray casting methods would be insignificant. When more processors are used, our new method would be even faster than the Z-buffer method, since the time overhead of the Z-buffer method is constant.

Table 2: *Volume rendering times (in seconds) for a patient data set. (NP: Number of processors; VR: volume rendering techniques)*

Image:	512×512			256×256		
NP\VR	Pure	Z-buffer	New	Pure	Z-buffer	New
1	6.80	2.40	4.20	1.75	0.59	1.00
4	1.72	0.64	1.12	0.53	0.17	0.33
9	0.89	0.27	0.55	0.24	0.08	0.15
16	0.54	0.17	0.36	0.15	0.05	0.09

In the second experiment, we used a real colon data set obtained from a patient at Stony Brook University Hospital. 411 slices of high-resolution (512×512) abdomen images were produced by a GE HighSpeed CT in the helical mode. The measured rendering times are presented in Table 2 for different methods with a different number of processors and image sizes. Figure 2 shows a pair of volume rendering and surface rendering images at the same view inside the patient's colon. Clear aliasing (the edges of triangles) appeared on the ridge in the center of the surface rendering image. When we analyzed the rendering times in Table 1 and 2, we saw a strange phenomenon. Although the patient data set was much larger than the pipe data set, the rendering time of the former was faster. The reason for this is that the colon tube was much more twisted than the plastic pipe, so that shorter rays are traversed for each frame.

Additional experiments have been conducted on other patients' data sets obtained from the University Hospital of SUNY at Stony Brook. Figure 4 (see color plates) shows a close view of a detected polyp during the interactive electronic biopsy procedure.

5 Conclusions

In order to solve the problems of our previous surface rendering based virtual colonoscopy system, we have developed a novel interactive navigation system based completely on volume rendering techniques. We developed a fast ray casting algorithm by exploiting the distance information stored in the potential field to achieve interactive volume rendering rates during navigation. Our new system provides more realistic colonic images, flexible electronic biopsy, and less preprocessing time. It has been in clinical testing in the Radiology Department of the Stony Brook University Hospital. The radiologists have already studied over 20 patients, and are planning to further test our system with several hundred volunteers. In addition to advancing our new techniques to become a large-population screening procedure, a full clinical trial is necessary to validate its accuracy, investigate its sensitivity and specificity to visualize polyps, when directly compared to optical colonoscopy. Physicians have confirmed that our ray casting images of the human colon are very close to what they observed in optical colonoscopy. Furthermore, we have already confirmed with our techniques that we can visualize polyps as small as 3 mm, and polyps that have been detected during optical colonoscopy have also been identified with our virtual colonoscopy.

6 Acknowledgements

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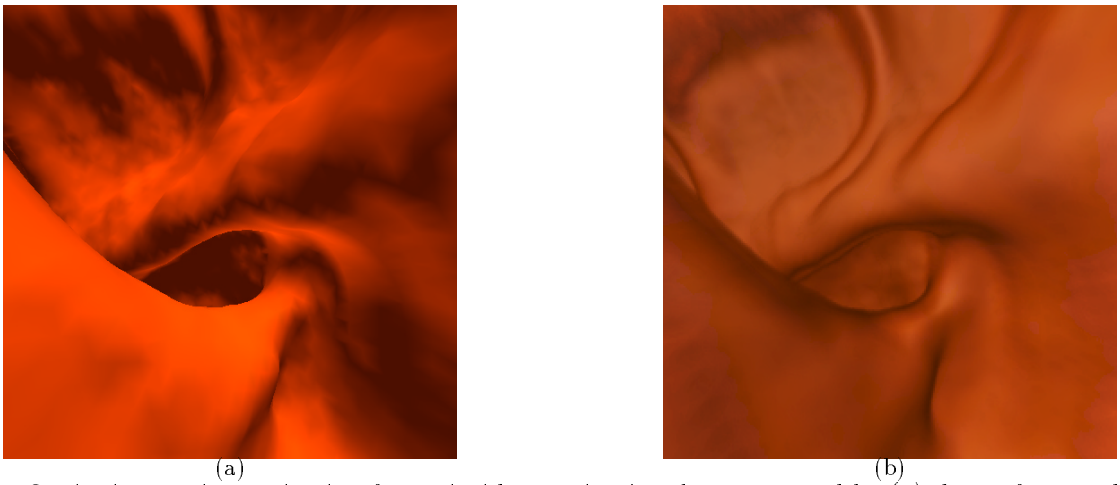
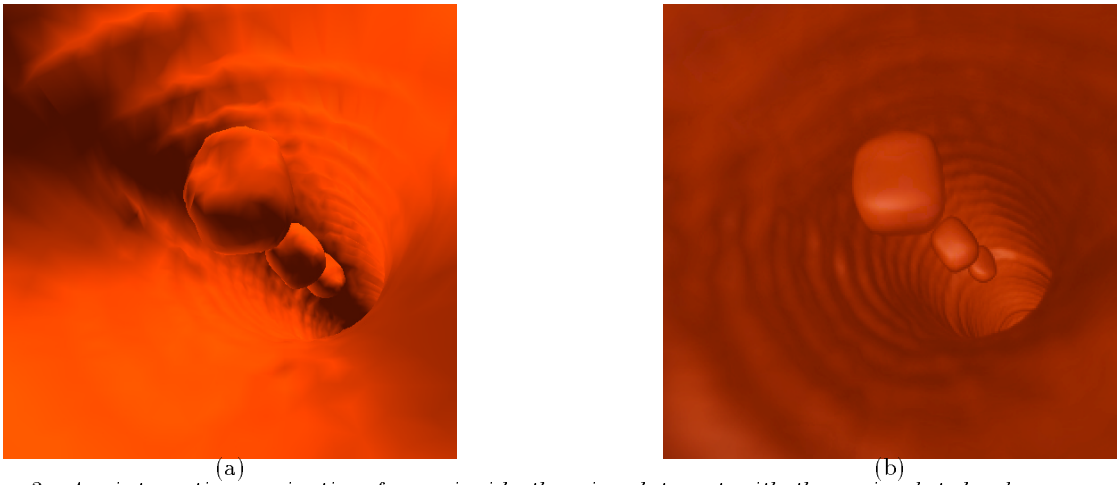


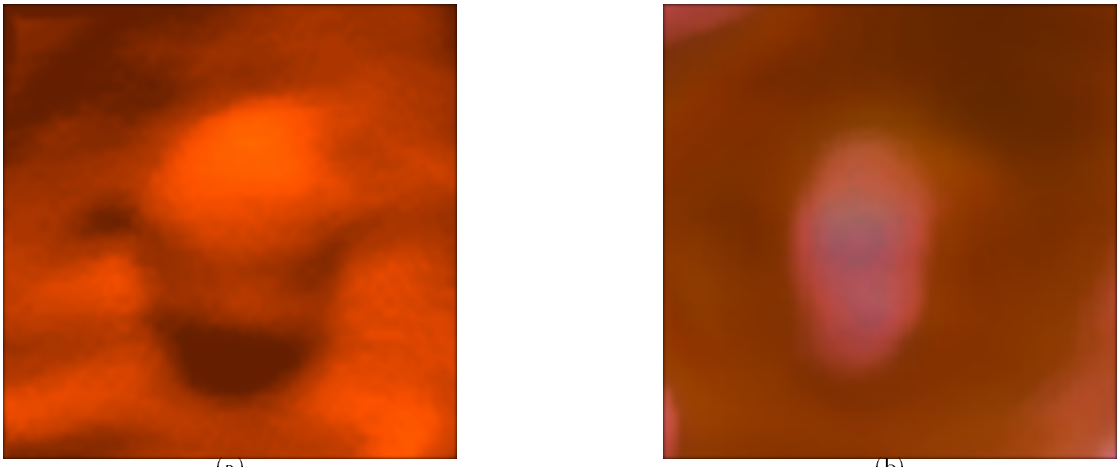
(a) (b)

Figure 2: *An interactive navigation frame inside a patient's colon, generated by (a) the surface rendering based system, and (b) our volume rendering based system.*



(a) (b)

Figure 3: *An interactive navigation frame inside the pipe data set with three simulated polyps, generated by (a) the surface rendering based system, and (b) our volume rendering based system.*



(a) (b)

Figure 4: *A close view of a 4mm polyp using the interactive electronic biopsy: (a) a mostly opaque rendering, and (b) a translucent virtual biopsy.*