IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 46, NO. 4, AUGUST 1999

An Interactive Fly-Path Planning Using Potential Fields and Cell Decomposition for Virtual Endoscopy

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Abstract--Virtual colonoscopy has been developed as a non-invasive computerized medical procedure for examining the entire colon to detect polyps. Our group has successfully implemented an interactive navigation using a physically based camera control model and a hardware-assisted visibility algorithm. Unfortunately, the pre-processing (skeleton and potential field generations) consumes too much computing time to be acceptable in an interactive clinical environment. In this work, we focus on skeleton simplification by eliminating excessive inconsistent branches. The simplification is performed before skeleton generation. The idea is to utilize a hierarchical analysis to determine principal points for the skeleton. We also propose dynamic target navigation for virtual endoscopy. We combine potentials derived from the distance between source and target positions and from the distance between source and colon surface to guide path search processes. These potentials are utilized to assign priority in choosing the paths far away from colon wall and in the direction of target positions.

Index Terms: Path planning, skeletonization, virtual endoscopy.

I. INTRODUCTION

Colon and rectum cancer is the second leading cause of cancer deaths across the United States. Approximately 150,000 new cases of colorectal cancer are diagnosed every year. A cost-effective comfortable procedure with fewer complications and a shorter examination time is needed to diagnose the colorectal cancer at early stages. We have been developing an innovative technology [1, 2, 3], called virtual colonoscopy, for colon screening. This technology uses a computer system to navigate through the model of individual patient's colons based on reconstructed CT (computed tomography) or MRI (magnetic resonance imaging) data. It has been shown that this technology is effective in imaging colonic polyps as small as 3 mm in diameter by spiral CT data. (It is known that benign polyp of size greater than 5mm in diameter may progress and become malignant carcinomas).

Previous work of our group has focused primarily on interactive navigation system inside the colon model [4, 5]. This system consists of a camera control and an interactive rendering. The camera control essentially defines how the physician navigates inside the colon. It uses a physically based model of employing potential fields and rigid body dynamics. The camera control supplies a convenient and intuitive mechanism for examining the colonic surface while avoiding collisions. The interactive rendering of navigation system takes advantage of a hardware-assisted visibility algorithm by culling invisible regions based on their visibility through a chain of portals, thus providing interactive rendering speed (more than 15 frames per second by surface rendering).

The navigation system adopts the ideas developed in robotics for fly-path planning using potential fields. The robot in computer graphics is simplified to a point such as a camera model. The robot moves under the influence of the potential fields. Unfortunately, the pre-processing (the fly-path planning based on the potential fields) in our navigation system takes hours [4, 5] and the physician must wait until next day to navigate inside the patient's colon model. Speeding up the pre-processing is paramount for virtual colonoscopy to be acceptable as a routine real-time medical procedure. This is the goal of this work.

In according to Latombe's book [6], there are three basic approaches to path planning: (1) *roadmap*, (2) *cell decomposition*, and (3) *potential field.* Although this work is based on only cell decomposition and potential field approaches, we will review all of these three basic approaches for presentation purposes.

Roadmap: The path planning of a roadmap approach consists of building a network connection between the vertices of polygons. A searching procedure is utilized to find a path that connects the chosen start and end points of the network. This approach is more appropriate for polygon-based dataset, and has limitation in virtual colonoscopy.

Cell decomposition: The basic idea of cell decomposition is to utilize the divide-to-conquer policy to simplify the search problems. The technique consists of decomposition of the whole free (or interested) space into small regions, called cells, such that a connectivity analysis and search of these cells can easily generate a path in the free space. An approximate cell-decomposition method is often used to improve computational speed by searching a multiresolution dataset [6]. The define of connectivity constraint for the path is task dependent. This path planning also has limitation in virtual colonoscopy.

Potential field: The path planning of potential field approaches is based on the robot model, which is simplified to a point such as a camera model in computer graphics. The camera moves as a robot under the influence of a set of forces produced by attraction and repulsion potentials. The attraction potential pulls the robot toward the goal and the repulsion potential pushes it away from obstacles. The variation of potentials creates the attraction and repulsion forces. Although the potential field methods can be computationally efficient

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and are very useful for navigation through the colon model, they have a major drawback. The robot can get stuck in local minima. One way to solve this problem is to design potential fields without local minima. The other is to design powerful mechanisms to escape from local minima.

Several path planning have been reported recently for virtual colonoscopy, based on the well-established (skeleton) thinning approach [7]. Most of these efforts have been devoted to improve computational performance of the path planning, considering the complexity of the colon. For example: Paik et al. [8] utilize minimal path guide to maintain continuity consistency in order to improve the speed of the onion peeling approach [9], which is mainly based on the cell decomposition for the fly-path or skeleton. Due to the fact that the curve is on the surface, this method is very sensitive to an irregular surface. The frequent check of continuity can be a bottleneck for the approach. Zhou et al. [10] utilize an approximate minimum-distance (potential) field, based on the distance transform of Niblack at el. [11], for an improved speed on skeleton generation. The skeleton is expressed as a set of local maximum paths from the inner colon wall. Their search algorithm can not guarantee that the source and target points of each segment can be connected. The generated skeleton from the chosen start point to the chosen end point (by connecting all the segments) is not smooth.

In this work, we propose a hierarchical analysis on the attraction and repulsive potentials in the free space consisting of the cells in the colon lumen. The idea is to improve the quality and performance of skeleton generation and to escape from the local potential field minima. We also propose a dynamic target navigation for virtual endoscopy. We combine potentials derived from both distances between source and target positions and between source and colon surface to guide path search processes. These potentials are used to assign priority in choosing the paths far away from the colon wall and in the direction of target position.

II. METHODS

We are proposing a hybrid method for path planning by combining cell decomposition and potential field methods, based on the work of [10]. A flow chart is shown by Figure 1.

The CT dataset of abdominal images are acquired by an established protocol of 120 keV, 200 mA, 512x512 image array on field-of-view (FOV), and 5mm/1:1.5-2.0 pitch. The FOV size and pitch vary depending on patient size. The scanning time is in the range of 30 to 40 seconds (in a single breath holding). The images are reconstructed as 1mm thick slices. A typical dataset consists of 400 slices covering the entire colon. The images are segmented into free space (colon lumen) and obstacles (colon wall) using our developed algorithms [12, 13]. The distance transform of [11] is employed for the hierarchical analysis on the potential fields. One task of this interactive path planning is to generate the central fly-path efficiently with the capability of escaping from local potential field minima. Another one is to provide a dynamic target navigation for virtual endoscopy.

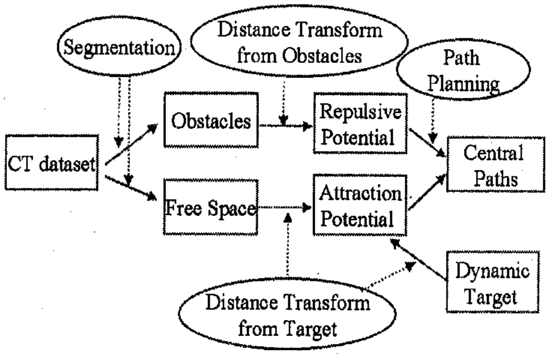


Figure 1: Flow chart of our interactive path planning.

[A] Hierarchical Analysis for Skeleton Simplification

The previous work for skeleton generation [10] followed a traditional pipeline. (1) Calculate DFSrf (distance from colon surface). (2) Detect attractors which are the points generated from the DFSrf distances located within the colon. (3) Search for a path between all attractors. (4) Calculate DFTrg (distance from target point). And (5) find centerline or skeleton between the chosen start and end points of the colon for an approximated minimum distance.

We propose an alternative architecture. (1) Calculate DFSrf and DFTrg. (2) Detect attractors. (3) Analyze attractors according to their contribution to principal attractors which are determined based on wave propagation of DFSrf and DFTrg. (4) Calculate distance from next consecutive principal attractor. And (5) find centerline between principal attractors. Our new approach has three advantages. (1) We eliminate "small" attractors during the hierarchical analysis. In other words, we are eliminating small, undesired branches. (2) We can guarantee connectivity between source and target points between the principal attractors. And (3) we search for paths between principal attractors and do not waste time in connecting those small attractors.

(a.1) Calculate distances from surface and target

We utilize the distance DFSrf from the colon surface as the weighting criterion, which reflects the importance of the attractors in their contribution to the principal attractors. For calculation of the distance, we attribute distance one to the surface points and store them in the queue. Then we remove all these points from the queue, find the non-visited neighborhood points, and add one to the distance and then add them into the queue. The process stops when the queue is empty. The procedure to calculate DFTrg is almost the same as the DFSrf algorithm. We only add the target point instead of all surface points to the queue.

(a.2) Detect attractors

We model DFSrf as waves, which propagate from the colon surface to the center of attraction force with progressing intensity. In other words, the center of attraction is a point with a maximum intensity. The waves become smaller and smaller from the surface to the attractor. Unfortunately in the discrete implementation of the distance transform [11], there are more than one attractor. These attractors are grouped in a set of attractors, called attractor cluster.

Moreover, the distance transform can produce local maxima in the positions where the waves met. Similarly, DFSrf transform produces paths with local maxima. These paths are narrow passages between attractors. They are also very important linkages. We call all the local maxima of a path as path cluster.

After DFSrf calculation, the attractors can be detected by finding the local maxima. Unfortunately, there are some problems with this approach. We discuss them and propose a solution in the next section.

(a.3) Analyze hierarchical attractors

The attribution of local maxima to local attractors is convenient for computational performance. However, small irregularities on the colon surface can cause the creation of undesired attractors. As a result, a skeleton with peripheral (inconsistent) branches can be produced. These branches are not desirable under a navigation viewpoint. If we wish to connect the principal attractors to obtain the principal skeleton avoiding the branches, the question now becomes how can we find the principal attractors and how can we connect them?

Generally, powerful attractors (which have a high DFSrf value) are more important than weak ones (which have a low DFSrf value). In some cases where there are narrow regions, the low intensity attractor is essential for the links between large regions. Therefore, the principal attractors are those attractors with maximal power required to satisfy the connectivity criterion. We utilize an influence zone of the local maxima, DFSrf, and DFTrg as measures for our criterion for the skeleton simplification process. The influence zone is determined by the discrete potential field generated by propagation of wave from seed (source, target, and obstacle) points. Detailed description of the influence zone is beyond the scope of this paper.

We utilize DFSrf to build a hierarchy of attractors. A tree can represent this hierarchy. The attractors are stored from root to leaves according to their maximum and minimum DFSrf values. The major stem reflects the trend of the colon and the creation of branches is due to the irregular shape of the colon surface. The hierarchy of the tree gives us information about the importance of each node in accordance with its contribution to the principal skeleton. This tree also helps us to cut undesired branches.

We eliminate peripheral branches by searching for the influence zone. The idea is to take the most powerful attractor and scan its influence zone by 3D-distance region growing, where the attractor is the seed. The influence zone is defined as a region visited during the region growing procedure from center (the seed) to periphery. The growing stops when the influence of the attractor becomes zero. All located peripheral attractors are marked as *Secondary*. They are children of a principal attractor node. The process repeats for the next most powerful attractor until the start and end principal attractors of the colon are found.

It is very difficult for the user to find the principal attractors by interaction. Because of this deficiency, the source and target seed points of a segment can be at bad positions. To avoid this inconvenience, we search for the nearest principal attractors of these seeds by 3D region growing strategy.

(a.4) Search paths between principal attractors

Once the principal attractors are located, we need to connect them to obtain the principal skeleton or our central fly-path. In [10], Zhou et al. used maximum local paths (Mpaths) to connect a cluster (an attractor set with the same DFSrf). Unfortunately, there are some problems with this approach. The resulted skeleton is not smooth. Partial reason of the discontinuity problem may be due to the use of edge-neighbors (18-neighors) in their approach. Furthermore, the algorithm can not guarantee the connectivity between attractors. Our new navigation and subdivision visualization system utilizes face-neighbors (6-neighbors) in contrast with the edge-neighbors of Zhou's approach. We use an interpolation smoothing technique to find the face-neighbor's skeleton connecting the principal attractors.

We take the advantage of the distances from the target DFTrg and from the surface DFSrf to connect principal attractors. These distances are also required for the navigation system. We do not expend extra time on this computation for the navigation. We further apply our technique to dynamic target navigation for virtual endoscopy, as presented below.

[B] Dynamic Target Navigation for Virtual Endoscopy

According to the design concepts of camera control [4], there are four desirable properties. We are adding one more here. We enumerate them for clarity. (1) The camera automatically moves from the chosen start point towards the end point along the fly-path. (2) User can interactively modify the camera position and direction. (3) The camera stays away from the colon wall and experiences stronger repulsing force when moving towards the wall. (4) The camera should never collide with the wall, even it is incorrectly handled by the user. And (5) the physician can change the start and end positions.

Essentially, there are three groups of camera control techniques available in the literature: manual, planned and guided navigation. These techniques can not satisfy all the five proprieties above. However, our interactive camera control can satisfy all the requirements. The previously reported methods have limitation in handling organs such as the lung and brain with complex branch structure. Our interactive camera control has the potential to handle the complexity. This requires a rapid, interactive pre-processing and intelligent system for branch detection and representation in the navigation systems in order to achieve real-time virtual endoscopy.

In the following, we will focus on solving the above deficiencies and discuss problems introduced after the addition of property (5). First, the skeleton computation is too slow for an interactive environment. Second, the distance from the source (DFSrc), the distance from the target (DFTrg), the distance from the surface (DFSrf) and the distance from the skeleton (DFSkt) can not be processed in interactive time. Third, previously reported models do not allow dynamic generation of the path for navigation with dynamic source and target movements.

Previously reported work on the skeleton generation required pre-defined seeds, start and end points. Because of this requirement, it can not handle organs with complex branches such as the bronchus and artery. Therefore, we must improve the pre-processing performance to achieve real time interactive navigation. We also need to design an intelligent system for branch detection and graph-guided navigation. The techniques described in Section A can achieve real-time interactive navigation and rapid detection of branches. Detailed implementation for the dynamic target navigation on complex branches will be reported in another paper.

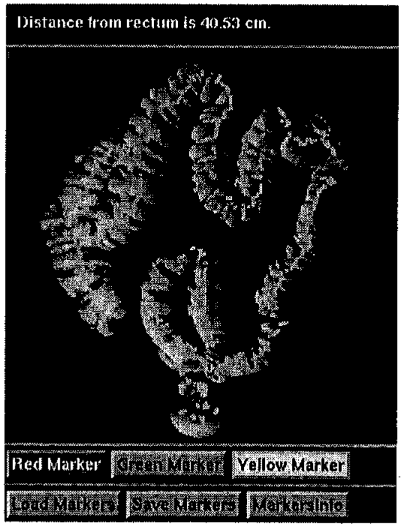
III. RESULTS

All our experiments utilized a patient CT dataset. The acquisition protocol for the CT dataset was described in Method Section. A SGI/Challenge graphics system with 3 Gigabytes memory was used to measure the performance of the algorithms. The requirements for interactive path planning using potential fields are: (1) efficient calculation of the distances DFTrg, DFSrf, DFSrc, and DFSkt and (2) improvement of the central fly-path generation. Our implementation for DFSrf, for example, took 60 seconds in contrast with our previous version (10 minutes). Our implementation of 3D region growing to accumulate distance from target is acceptable for interactive environment (5 seconds) without spending time for memory allocation and initialization that are done one time when the program starts.

The challenge is to improve computational performance for central fly-path generation. The global attractor detection for irregular surface such as colon wall can not be processed in real time. Our solution is to find the principal attractor for each wave propagated from each target point. Then, we store these points in a tree. In this way we eliminate the small attractors. Dynamic modification of target positions does not require the processing of the DFSrf and the attractor detection (low performance). It just needs to connect the adjacent attractors. This connection can be done quickly by minimal path generation or spline interpolation.

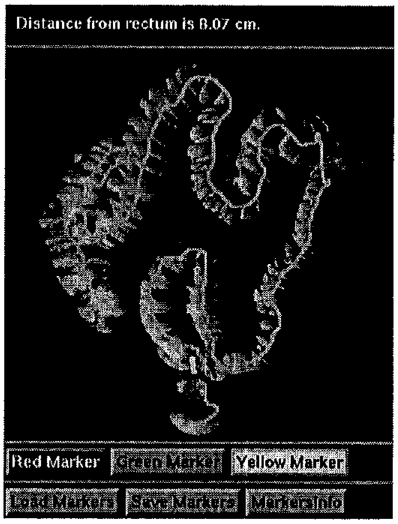
The smoothing procedure based on the spline interpolation can be used to eliminate lengthy and jerky behavior of the center path. Our results fulfill the time criterion for interactive processing (less than 10 seconds), this is because of the significant reduction of the search space.

The total time for the distance computation and central path generation was in the order of a few minutes. The detected principal attractors are shown in Figure 2. Most of the attractors are located in the central area of the colon model. These points reflect the trend of the colon wall configuration in three dimensions. After the interpolation/connection of all the principal attractors, the generated fly-path is shown by Figure 3. The smoothness and positioning of the skeleton inside the colon wall are very similar to the result of our previous version (see Figure 5 of reference [4]).



Distance from rectum is 40.53 cm.

Figure 2: The colon wall is reconstructed by mesh generation. The points (or principal attractors) are determined by attractor detection and simplification.



Distance from rectum is 8.07 cm.

Figure 3: The detected points (or principal attractors) are connected by interpolation smooth techniques.

The generated skeleton is excellent and the interactive path planning is computationally efficient. With this improved pre-processing, the physician can navigate inside the patient's colon model in less than an hour after the CT scan.

IV. CONCLUSION

Real time performance of potential field calculations and efficient skeleton generation are required for dynamic target navigation for virtual endoscopy. Our approach improved the computing time significantly from several hours to a few minutes for application in virtual colonoscopy. This is because of our hierarchical analysis for detection of the principal attractors before the skeleton generation. Our approach is suitable for branch detection and path search and has potential to handle complex branches for virtual endoscopy. Further investigation is needed using more patient data sets.

V. ACKNOWLEDGMENTS

We are very thankful for the valuable comments of the reviewers. The corrections of English grammar marked by the reviewers facilitate greatly this revision. This work was supported by NIH Grant CA79180, Grant HL51466, and ITG fund of Biotechnology Center of New York State and E-Z-EM Inc.

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