Interactive Path Planning for Virtual Endoscopy [1]

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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 environment. In this work, we focus on skeleton simplification to eliminate excessive ramification. We perform the simplification before the skeleton generation. The idea is to utilize a hierarchical analysis of attractors to determine principal attractors. We also propose a dynamic target navigation for virtual endoscopy. We combine potentials derived from the distance between source and target positions and from the distance to the colon surface to guide path search processes. These potentials are essential to obtain priority in choosing the paths far away from colon wall and in the direction of target positions.

I. INTRODUCTION

Colon and rectum cancer has been 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 patient-confortable procedure with fewer complications and a shorter examination time is needed to diagnose the disease at an earlier stage. We have been developing an innovative technology [1, 2, 3], called 3D virtual colonoscopy, for massive colon screening. This technology uses a computer system to navigate through the model of patient colons reconstructed from computed tomography (CT) data. It has been shown that this technology is effective in imaging colonic polyps as small as 3mm in diameter. (It is known that polyps of size greater than 5mm in diameter will progress toward malignant carcinoma).

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 a potential field 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.

The navigation system adopts the ideas developed in robotic field for path planning. An adequate and efficient path planning is necessary for the navigation inside the colon model. The Latombe's book [6] is a good reference. The path planning consists of three approaches: (1) *roadmap*, (2) *cell decomposition*, and (3) *potential field*.

Roadmap The path planning of roadmap approach consists of building a network connection between the vertices of polygons. A searching procedure is utilized to find a path that connect source and target points. 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 space into small regions, called cells, such that a connectivity analysis and search of these cells can easily generate a path. An approximate cell-decomposition method is often used to improve computational speed by searching for multiresolution dataset [6]. This path planning also has limitation in virtual colonoscopy.

Potential field The robot of potential field approaches is simplified to a point such as a camera model in computer graphics. The camera moves under the influence of a set of potentials produced by the attraction and repulsion potentials. The attraction potential pulls robot toward the goal and the repulsion potential pushes it away from the obstacles. The variation of potentials create the attraction and repulsion forces. Although the potential field methods can be computationally efficient, this approach has a major drawback; the robot can get stuck in local minima. One way to solve this problem is to design potential without local minima. The other is to design powerful mechanisms to escape from local minima.

Unfortunately, the pre-processing (using the path planning based on potential field) for virtual colonoscopy in our previous work takes many hours [1, 2] and physician must wait until the 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 procedure in the medical community. Many efforts have been devoted to improve the computational performance. For example: Paik at el.[7] utilize minimal

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path guide to maintain a continuity consistency of the onion peeling approach [8]. Due to the fact that the curve is on the surface, this method is very sensitive to an irregular surface. The constant check of continuity can be a bottleneck for the approach. Zhou at el. [9] utilizes the approximate minimum distance field based on the ideas of Niblack at el. [10]. The skeleton is expressed as a set of local maximum paths from the inner colon wall. Their search algorithm can not waranty that the target and source points can be connected.

In this work, we propose a hierarchical analysis of attractors by discrete transform from obstacles and by distance from targets. The idea is to improve the quality and performance of the skeleton generation and to scape from the local minima of pontential fields.

We also propose dynamic target navigation for virtual endoscopy. We combine potentials derived from both the distance between source and target positions, and from the colon surface to guide path search processes. These potentials are essential to obtain priority in choosing the paths far away from the colon wall and in the direction of target position.

II. Methods

A. Attractor Analysis for Skeleton Simplification

The previous work for skeleton generation [9] follows a traditional pipeline. (1) Calculate DFSrf (distance from colon surface), (2) detect attractor, (3) search path between all attractors, (4) calculate DFTrg (distance from target point), and (5) find centerline between start and target points.

We are proposing an alternative architecture. (1) Calculate DFSrf and DFTrg, (2) detect attractors, (3) analyze attractors according to their contribution to principal skeleton, based on the 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 attractor analysis; in other words, we are eliminating small-undesired branches. (2) We can warrant connectivity between start and target points. (3) We search paths just between principal attractors and do not waste time in connecting the small attractors.

1) *Calculate Distance from Surface and Target, (DFSfc and DFTrg)*

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

2) *Detect Attractors*

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

Moreover, distance transform can produce local maxima in the positions where the waves met. Similarly, DFSfc transform produces paths of 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 DFSfc 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.

3) *Analyze Hierarchical Attractors*

The attribution of local maxima to local attractors is convenient for computational performance. However, small irregularities on the surface can cause the creation of small attractors. As a result, a skeleton with peripheral ramifications can be produced. These ramifications are not desirable under a navigation view point. If we wish to connect the principal attractors to obtain the principal skeleton avoiding the ramifications, our questions now are: How do we find the principal attractors? And how to connect them?

Generally, powerful attractors are more important than weak ones. 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 the minimal attractors with maximal power required to satisfy the connectivity criterion. We utilize influence zone, DFSfc and DFTrg as measures for our criterion for simplification process.

We utilize DFSfc to build a hierarchy of attractors. This hierarchy can be represented by a tree. The attractors are stored from root to leaves according to their maximum and minimum DFSfc values. 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. The influence zone is defined as a region visited during the region growing procedure from center 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 powerfull attractor until the source target principal attractors 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 can be in a bad position. For solving this inconvenience, we search for the nearest principal attractors of these seeds by 3D region growing.

4) Search Paths between Principal Attractors

Once the principal attractors are searched we need to connect them to obtain the principal skeleton. In Zhou at el. [9], they used Maximum Local Paths (Mpaths) to connect a cluster (an attractor set with the same DFSfc). Unfortunately, there are some problems with this approach. The produced skeleton is neither smooth nor warranted the connectivity between attractors. Specifically, our new navigation and subdivision systems utilize face-neighbors(6-neighbors) in contrast with edge-neighbors(18-neighors) of Zhou's approach. The edge-neighbors can cause discontinuity problems. We are working to find the face-neighbor's skeleton.

Our plan is to take the advantage of the distance from the targets and from the surface to the connected principal attractors. These distances are also required for the navigation system. We do not expend extra time on this computation for the navigation.

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 source point towards the target point. (2) User can interactively modify the camera position and direction. (3) The camera stays away from the surface. (4) The camera should never penetrate through the surface, even when incorrectly handled by the user. (5) The physician can change source and target positions.

Essentially, there are three groups of camera control techniques: manual, planned and guided navigation. These techniques can not satisfy all the five proprieties. The previous methods can not handle organs such as the lung and brain with complex ramification structure. Only our camera control can satisfy all requirements. An short, interactive pre-processing and intelligent system for branch detection and representation is primordial for navigation systems of virtual endoscopy.

This paper focuses on solving these deficiencies and discusses 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, previous models do not allow dynamic generation of the path for navigation with dynamic source and target moviments.

Previous work on the skeleton generation requires pre-defined seeds, source and target points. Because of this rigid pipeline, it can not handle complex ramification organs such as the bronchus and artery. Therefore, we must improve the pre-processing performance to achieve interactive time. We also need to design an intelligent system for branch detection and graph-guided navigation. We achive these goals by the techiques described in Section A.

III. Results

All our experiments utilize a patient CT dataset. A Silicon Graphics challenge with 3 Gigabytes memory was used for performace measure of the algorithms. There are requirements for interactive path planning based on potential fields. One is the speed up of the DFTrg calculation and the other is the improvement of the centerpath generation. Our implementation for DFSrf took 60 seconds in contrast with previous version (10 minutes). Our implementation of 3D region growing to accumulate distance from target is acceptable for interactive enviroment (5 seconds) without time for memory allocation and initialization that are done one time.

The challenge is to improve computational performance for centerpath generation. The global attractor detection for irregular surface such as colon wall can not be processed in interactive time. Our solution is to find the global attractor for each wave propagated from each target point. Then, we store this points in a tree. This way we easily eliminate the small attractors. The 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 miminal path generation or spline interpolation. The smoothing procedure can be used to eliminate lengthy and jerky behavior of center path. Our results fulfill the time criterion for interactive processing (less than 10 seconds), because we reduce the search space significately. See figures 1 and 2.

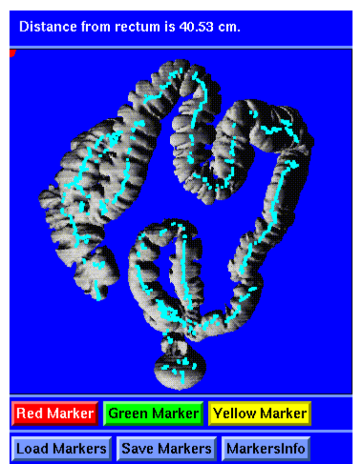

Figure 1: The colon wall is reconstructed by mesh generation. The center points are calculated by attractor detection and simplification.

IV. Conclusion

The interactive performance of potential field calculations and an efficient skeleton generation algorithm are primordial for dynamic target navigation for virtual endoscopy. Our approach evaluates attractors to detect principal attractors

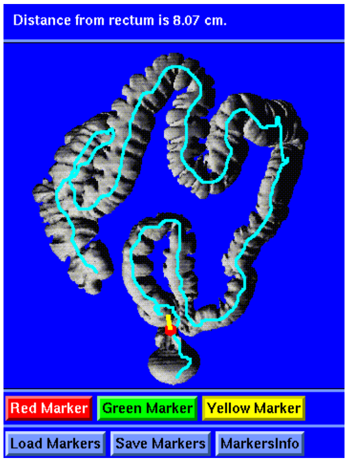

Figure 2: The center points are conneted by interpolation smooth techniques.

before the skeleton generation and is suitable for branch detection and path search algorithms. The speed-up is significant (from several hours to a few seconds), because we only check principal attractors.

V. References

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