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Path Planning for Virtual Bronchoscopy

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***Abstract*- We have developed an automated path planning method, which enables virtual-bronchoscopic 3D multidetector computed tomography (MDCT) image analysis and follow on image-guided bronchoscopy. The method fundamentals are novel combination of distance transformation and snake-based models. The computation time of our algorithm is faster than similar works and there were no missing or false branches in the final path of airways. The planned path is suitable for quantitative airway analysis and smooth virtual navigation.**

Keywords -- Path planning, Virtual Bronchoscopy

I. Introduction

Lung cancer is the leading cause of cancer related death for both men and women. More people die of lung cancer than of colon, breast, and prostate cancers combined [1]. Since most people with early lung cancer do not have any symptoms, only a small number of lung cancers are found at an early stage, then the subsequent treatment may dramatically increase the survival rate.

Modern multidetector computed tomography (MDCT) scanners provide large high-resolution three-dimensional (3D) images of the chest. MDCT scanning, when used in tandem with bronchoscopy, provides a state-of-the-art approach for lung-cancer assessment [2], [3]. Computed tomography (CT) Bronchoscopy (Virtual Bronchoscopy) is a promising new method for evaluation of thin tubular structures (e.g., airways), provide 3D position/shape information (e.g., for tumors/cancers), planning and guiding Bronchoscopic biopsies & probing and treatment planning. As a means for assessing large high-resolution 3D CT chest images [3]-[11], in most basic form, VB is a computer-based approach for navigating virtually through airways captured in a 3D MDCT image. When this basic navigation is supplemented with other viewing tools, such as multiplanar reformatted sections, projections, thin slabs, collision avoidance and stereoscopic display the physician gets a multi-faceted graphical view for assessing the chest anatomy [3], [5].

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Both for ease of use and quantitative assessment, virtual Bronchoscopic systems need airway paths for effective use. A major component of path planning system for VB is a method for computing the central airway paths from a 3D MDCT chest image. This paper describes and illustrates a method for building trajectories for VB inside 3D medical images automatically.

A suitable method must: 1) provide a detailed, smooth structure of the airway tree's central axes; 2) require little human interaction; 3) function over a wide range of conditions as observed in typical lung-cancer patients [3]; 4) allow faster processing toward the real-time applications; 5) be robust to noise and its dependency on pervious stages, 6) and be reproducible. We first point out that no existing method meets all of these requirements [3] and we propose an algorithm satisfying these requirements.

II. Related Works

The concept of medial axis extraction and path planning is a principal concept in machine vision and pattern recognition that has frequent applications in robotics, image compression, medical image processing and automated navigation. Each application takes advantage of some particular characteristics of the central path. The desired features of central path are listed below;

- Centeredness with respect to the object boundary,
- Less sensitivity to noise and local distortions (robustness),
- Preserving the structure of the original object (topology preserving),
- Connectivity preserving,
- Thin path, one voxel thick in all directions,
- Invariant under isometric transformations,
- Object reconstruction capability (the ability of reconstruct the original volume from the final path),
- Computational simplicity and memory usage efficiency,
- Time efficiency of algorithm for real-time procedures and automatic for easy use.

Path planning methods have mainly application in virtual endoscopy and robotics. Three general path planning approaches have been proposed [3]:

Branch following methods begin at the proximal end of the tree and trace their way through the structure to define a smooth set of the paths through the tree, these methods can fail to give many paths or give misleading results, when the structure exhibits an abrupt size change or asymmetry.

Unlike branch following, which progressively analyzes small local portions of data to build up a path or set of paths, *Skeleton-based* techniques first compute a

digital skeleton of the entire tree. Three general skeletonization approaches have been categorized:
The former approaches which is based on *distance transformation*, first introduced by Blum in 1967 [12]. The proposed method use the distance of object's voxels from the boundary of object for identify a set of points which are center of maximal discs which generalized to maximal spheres in 3D objects. It has been proven that every object can be presented in this way [13], [14]. Since the distance transform is a scalar field, vector field characterizations usually require computation of the gradient and eigenvalues, which are expensive. Due to discontinuity of extracted path then in this approach more post-processing is required. The method of Zhou and Toga [15], while specifically tailored to tree-like structures, gives inaccurate branch-point localization [16].
Topological thinning methods preserve the homotopy and work well for regular objects, but the end-point characterization needed for such methods is not easy in 3D. These methods are faster than the DT-based methods but the result is more sensitive to noisy surface features. As a result, the medial axis may contain spurious paths that do not provide a significant description of the overall geometry of the object [7], [8], [17], [18].
Voronoi methods are well suited for finding the medial axis/surface of polygonal models as opposed to volume models, however, computation of the 3D Voronoi diagram of arbitrary point sets is not easy [19].
Finally, *front-analysis* techniques analyze the properties of an evolving structure, which is created by region growing or other distance-based methods, to determine path sites and branch points.
These techniques typically produce only one path and they are not geared toward tree-like structures [7] and fail to provide visually smooth navigation paths. Rendering these paths is unsuitable for detailed navigation, these technique require excessive user input if many branches need to be defined.
In our proposed method, first we optimized the input-dataset for processing and define the start point. Then using DT-based methods we automatically detect the end points and initial primary path by steepest descend. Finally by snake model we center the path. Some of refinements that will be described have been performed to arrive at a final path. The resulting tree consists of a series of paths and branch structural data, suitable for the quantitative planning, navigation and live guidance of bronchoscopy.

III. Method

Fig. 1 depicts a block diagram of the propose method. Our algorithm can be categorized as a path planning method, which the dataset is optimized, the start point and the end points are automatically defined, and then the paths are initialized and centralized. Our algorithm consists of the following steps:

1. Preparing and optimizing the data-set
2. Automatic Start point detection
3. Distance transform mapping
4. Automatic end points detection
5. Paths initialization
6. Paths Centering
7. Refinements

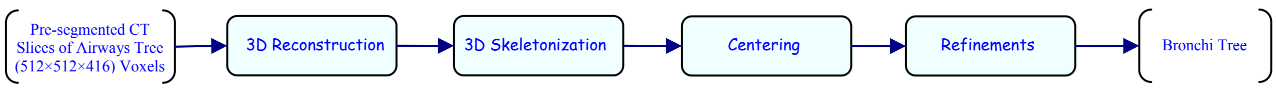


Fig 1. Block diagram of proposed path-planning method.

A pre-segmented 3D meta-image-format from whole airways is used as input. It has been filled and refined. The segmented airways occupy less than 1% of the data-set's space. More space of 3-D data-set consist of the other organs which was removed in segmentation process as it was carried the position information. We apply an optimization procedure for elimination of redundant voxels in order to reduce the volume of objective data-set.

Detection of start point (SP) which plays the role of reference and starting seed of the final path is a fundamental stage of algorithm that guarantees the accuracy of next steps and final result.
Due to fix and standard direction of taking the CT slices in supine position, we select the SP automatically so that it lies approximately on the central axis of the trachea.

We have applied the distance transformation (DT) two times in this algorithm. The first one is explained here. This step gives each voxel's distance from the selected SP site with computation of chamfer DT with <3,4,5> metrics. The DT map is computed by assigning the SP voxel a distance of zero and iteratively assigning neighbor voxels using weighted metrics: 3 for face, 4 for edge and 5 for vertex neighbors

$$
\begin{aligned}
&\mathrm{Distance}_{cha<A,B,C>}(p,q) = \\
&\quad A \cdot \max\{\,|p_x - q_x|, |p_y - q_y|, |p_z - q_z|\,\} + \\
&\quad (B-A) \cdot \max\{\,\min\{\,|p_x - q_x|, |p_y - q_y|\,\}, \\
&\qquad\qquad \min\{\,|p_x - q_x|, |p_z - q_z|\,\}, \qquad (1) \\
&\qquad\qquad \min\{\,|p_y - q_y|, |p_z - q_z|\,\}\,\} + \\
&\quad (C-B-A) \cdot \min\{\,|p_x - q_x|, |p_y - q_y|, |p_z - q_z|\,\}
\end{aligned}
$$

The reasons for using this metric over the other well-known DTs are: 1) Assigns the more to voxels with region growing in comparison to exact Euclidean metric, 2) More accurate approximation of true

Euclidean distance metric in comparison to other chamfer distances, 3) Allocating integer values to voxels, which speeds up the next computations.

The voxels of the object which have been coded as local maximas are labeled as an end point. Each voxel is compared to its neighbor voxels to define if it has the maximum distance or not. In order to avoid spurious end points, we define a neighboring window in which the selected end point must have the local maximum DT value.

Having the end points and the start point, the initial paths can be generated starting from each end point moving toward the start point. For constructing the primary paths, we used the steepest decent method, which has more shortening behavior. Therefore from each of the end points have been found minimum code of DT in its neighbors and labeled as a point of path and iteratively be done this procedure for next point of path to reach the start point. The first or longest path is constructed by connecting the end point which has the max DT value to SP, and for the rest of end points paths are constructed starting from each end point and terminating when a voxel on the pervious paths has reached. Path has formed from 26-connected voxels. This makes more relax path and preserves the original topology and geometry of the object.

The initial paths are a good approximation of the shortest path between the each of end points and starting point that have considered as a parameterized curve (snake), which evolves in order to minimize energy of the image. The image force is defined as follows

$$F(v) = G(v) - \frac{(v.G(v)).v}{|v|^2} \qquad (2)$$

with G (v) = -Gradient (-D(v)) (3)

where D is Euclidean distance transformation inside the object from the boundary. Middle axis has minimum of gradient(G) so F(v) is a decreasing function which forcing the snake to move towards the middle axis of object.

The planned path need to some of refinements to be suitable for camera navigation;

a) Length-based Elimination: This step eliminates relatively short terminal branches that are most likely due to insufficient data resolution so the branches that are junior in length are detected and eliminated to reach the optimum path for our virtual bronchoscopy application.

b) Continuity: because of centering's discrete nature, we encounter discontinuous paths that need to be continuous. We do this by inserting sufficient voxels between the discontinuities of the paths.

IV. Results

A. Method Performance

We applied our algorithm to 2-D objects and then generalize it to 3-D objects. We designed some phantoms same as real data-set and then performed a series of test on real human images. Our data-set was provided by technical university of Munchen (TUM). These images were acquired from either a Siemens MDCT scanners. The scans consisted of 512×512 voxels in the transverse plane. The anisotropic voxels in these images had in-plane resolution of $\Delta x = \Delta y =$ 0.59 mm, and Δz resolution (slice-to-slice spacing) 0.50 mm. We point out that our test image contains over 40 branches, providing more than sufficient variety of test situations. Fig 2 illustrates a typical data-set, which has been processed. A PC with 2.8 GHz Intel Celeron Pentium-IV processor, 1.5 GB of RAM, and Windows XP, was used to perform these tests.

Our method is a combination of pervious proposed methods with some novelties applied to improve the performance of the algorithm. In most of the pervious works [3], [7] we have encountered with miss branches and false branches that affected on the accuracy of algorithm, but we have not any miss branches or false branches in our results, all of branches were detected. Our algorithm has less sensitivity to noise that make the algorithm more compatible with various protocol and hardware. The computation time of algorithm is presented in table I, which is less than pervious works [3], [7] by factor of 2 in best quality mode so the proposed method can be used for real-time and intra-operative procedures.

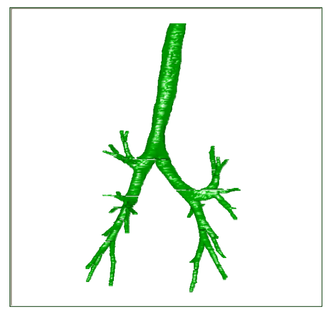
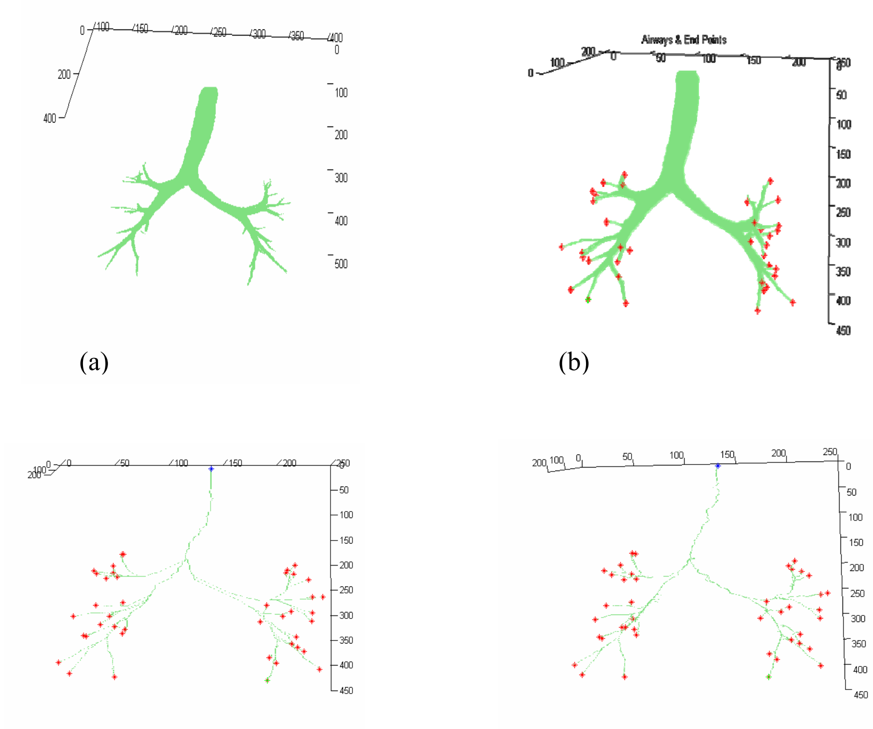


Fig 2. 3-D Segmented Airways Tree

Table I: Timing Performance Breakdown of Proposed Method

Stage/Step	Computation Time(sec)	% of Total Time
Data-set Optimization	14.7	20.6
Start Point Detection	0.02	0.03
Distance Transformation	7.9	11.1
End Point Detection	11.9	16.7
Path Initialization	1.4	1.9
Centering	35.3	49.6
Total Time	71.2	



(a) (b) (c) (d)

Fig 3. Path planning of airways. (a) Segmented airways tree, (b) Endpoints of branches, (c) Initial path, (4) Centered path.

B. Experimental Results

Fig 3 illustrates procedure and results of the proposed techniques for a real data-set.

V. Conclusion

In this paper, we have presented an efficient algorithm for path planning in virtual bronchoscopy. The final result can be used in quantitative airway analysis and automated virtual bronchoscopy. We have applied the method successfully to 3D synthetic and rubber phantom and 3D CT images of human airways scan. While our extended interest has been to apply the method to the planning and guidance of bronchoscopic surgery and combine with robotic surgery approach, we have also tried to use of suitable approach to lead the instruments and get the strong feedback from the performance of the method.

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