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# Virtual bronchoscopy method based on marching cubes and an efficient collision detection and resolution algorithm

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**Abstract**

A novel system for electromagnetic navigation in bronchoscopy (NaviCAD) to improve peripheral lesion targeting and diagnostic is currently under development. The virtual bronchoscopy module of this system, including the collision and resolution algorithm, together with some preliminary tests on a complex phantom are presented in this paper. The NaviCAD system consists of a planning and orientation software, a navigation forceps, and an electromagnetic tracking system connected to a computer running the NaviCAD software. NaviCAD can be used with any bronchoscopy system, it has a short set-up procedure time and learning curve. The system proves to be easy to use, accurate and useful for experienced users and novices, with precision in reaching targets in sub-segmental bronchi where a video-bronchoscope cannot reach.



*Keywords:* bronchoscopy; navigation; electromagnetic tracking; biopsy; lung diagnosis; virtual bronchoscopy.

## 1. Introduction

From the estimates of the International Agency for Research on Cancer regarding the worldwide incidence, mortality and prevalence of 26 types of cancer in the year 2012, it was shown that lung cancer was the most lethal one, causing 1.59 million deaths [1]. In order to diagnose lung cancer, medical doctors perform a trans-bronchial biopsy. First, this is planned by examining a number of Computed Tomography (CT) scan slices. Then, the procedure is performed by introducing a video bronchoscope into the bronchi as far as the diameter of the bronchoscope permits. With the bronchoscope, the doctor can see the larynx (voice box), trachea (windpipe), bronchi (large airways to the lungs), and bronchioles (smaller branches of the bronchi). Bronchoscopy can be combined with a procedure to collect pieces of lung tissue - the transbronchial lung biopsy. This procedure uses a flexible bronchoscope and biopsy forceps inserted through the bronchoscope working channel and is one of the easiest and safest methods in diagnosing such lesions. The success rate of the procedure is dependent on the size and location of the lesion and is lower in peripheral lesions and small lesions [2], compared with those of central and intermediate lesions. One of the reasons is that the forceps for transbronchial biopsy cannot reach small peripheral pulmonary lesions, due to the difficulty in maneuvering within the angles of the bronchi. Baaklini *et al.* [3] reported that lesions less than 2 cm in diameter had a diagnostic success of only 14% when located in the peripheral third, compared with 31% when located in the inner

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two thirds of the lung. When failure of the procedure occurs, pulmonologists must repeat the procedure or follow up with more invasive methods that have increased complication rates, such as CT-guided percutaneous (transthoracic) fine needle aspiration (FNA) or biopsy. Although the success rates of these techniques are very high, with 76-97% diagnostic accuracy [4], they have several shortcomings: they carry a risk of pneumothorax, or seeding the malignant cells along the biopsy path and into the pleural cavity. Shinagawa *et al.* used an ultrathin bronchoscope [2], but it has limited suction capability due to its extremely small working channel. Currently there are other technologies for guiding, like endobronchial ultrasound (EBUS) that is difficult to use for peripheral lesions due to dimension of the scope and x-ray fluoroscopy [2], [5] involving radiation for clinical personnel and patients.

More than 50% of lung targets are not accessible by conventional bronchoscopes due to the size of the constantly narrowing branches of the bronchial tree and due to orientation and maneuverability difficulties. Electromagnetic navigation bronchoscopy (ENB) is a guided bronchoscopic technique that allows accurate navigation to peripheral pulmonary lesions which cannot be reached by traditional bronchoscopy. The feasibility of electromagnetic navigation bronchoscopy (ENB) with a steerable instrument has been presented by Becker *et al.* [6] and Schwarz *et al.* [7].

A novel system called NaviCAD is currently being developed by the authors, for spatial guidance of a customized bronchoscopic forceps to reach peripheral targets within the bronchial tree, further than the diameter of the video bronchoscope permits. The technology uses preoperative CT images or other imaging techniques to create three-dimensional (3D) and virtual reconstructions of the region to be biopsied.

This paper describes the virtual bronchoscopy method from NaviCAD system, based on the Marching Cubes algorithm, used to calibrate and correct the path that the physician follows towards the lesions in the hard-to-reach periphery of the lung.

The preliminary tests of this procedure using a complex phantom prove that the system is easy to use and improves navigation through the bronchial tree. Further studies on phantom and large animals are planned to prove its efficacy for clinical and training usage.

## 2. General description of the system

NaviCAD is an image-guided navigation system including an electromagnetic tracking system (ETS) Aurora (NDI Inc., Canada) for spatial positioning and orientation tracking. Aurora is an electromagnetic spatial measurement system, which determines the location and orientation of objects that are embedded with sensor coils. When the object is placed inside a controlled, varying magnetic field, voltages are induced in the sensor coils. These induced voltages are used by the measurement system to calculate the position and orientation of the object. The magnetic fields are of a low field strength and can safely pass through human tissue [8].

The system is connected to a computer that runs a specific software application. It features also single-use navigation forceps for biopsy with electromagnetic sensor to determine its spatial position and orientation in the magnetic field. The NaviCAD software uses multiple technologies for anatomy 3D reconstruction, registration, manual calibration and navigation, with two main screens for user interface.

The system can compute the instantaneous position of biopsy forceps tip related to the patient and CT space. When the bronchoscope diameter is too big to advance in the sub-segmental bronchi, the user extends only the navigation forceps further to the peripheral target. The navigation is performed using the virtual bronchoscopy visualization in the NaviCAD system and the instantaneous position of the forceps tip overlaid on the 3D model. The biopsy using the forceps can be performed when the target is reached. Improved diagnosis is accomplished via enhanced navigation and targeting.

## 3. The virtual bronchoscopy procedure

In virtual bronchoscopy (VB), a computer simulation of the video bronchoscope image from the bronchoscope camera [9] is created from the 3D CT volume, with the same view angle and zoom setting. More precisely, the VB is the descriptive term given to an indirect or artificial (virtual) visualization of the bronchi and surrounding structures created from spatial information derived from imaging sources other than the bronchoscope itself (usually from CT) [9]. VB is valuable for procedure planning and during bronchoscopy; when the video display is not available due to e.g. reduction of eyesight by blocked camera from mucus or blood, reduced view by swelled tissue [10], or when navigation of tracked tools are outside the visual range of the bronchoscope. It is also used in image alignment procedures.

The Marching Cubes (MC) [11] is an algorithm that extracts surfaces from volumetric scalar data. It is used extensively in visualization and analysis of medical data from modalities like CT and MR, usually after a 3D segmentation of the structures of interest have been performed [12].

The Marching cubes works by creating a polygonal meshed surface from an implicit 3D function by iterating ("marching") over a uniform grid of cubes superimposed over a region of the function. If a cube intersects the function, polygons and vertices are generated at the intersection. After "marching" over all cubes, polygons for each cube are added and the final mesh is the union of all these polygons. The smaller the cubes, the smaller the mesh polygons will be, making the approximation more closely match the target function [13].

In our implementation, the Marching Cubes algorithm is applied for the 3D reconstruction of lungs. For this, only the cubes from the CT scan regions within a certain intensity range, e.g. Hounsfield scale corresponding to the lung tissue, are taken into account.

The virtual bronchoscopy method implemented in the NaviCAD system was developed based on the implementation of the Marching Cubes algorithm for extracting surfaces from volumes using OpenCL and OpenGL [12].

This algorithm has four stages:

1. Data transfer. The dataset is stored as a 3D texture.
2. Reconstruction of the surface of the lung tissue using the Marching Cubes algorithm.
3. Render the surface extracted in the previous step.
4. Navigation using collision detection and resolution.

## 4. Collision detection and resolution in virtual bronchoscopy

Virtual bronchoscopy and Image Guided Therapy (IGT) electromagnetic tracking are performed inside the surface obtained, applying the "Marching cubes" algorithm over data obtained from CT scans.

In virtual bronchoscopy, the user "navigates" through the CT volume and the virtual navigation "camera" should always remain inside the airways surface. But, due to various errors, the tool may seem to be placed outside the airways if no corrective measure is implemented. There are several important error sources: i. The Marching Cubes algorithm only approximates the lungs tissue isosurface, so one does not obtain an exact surface that covers the airways; ii. Volumes registration operations – the alignment between CT volume and the real tracking volume is not perfect and: iii. Electromagnetic tracking measurements.

Due to tracking errors mentioned above, there are moments when the tool is represented on the virtual bronchoscopy outside the surface representing the lung airways. To avoid this wrong representation, which could confuse the user, we use an algorithm of collision detection and resolution that will keep always the representation of the tracking tool inside the airways.

The virtual airways surface is formed by more than 200.000 polygons. In order to reduce the computations that could slow down the application, the polygons are stored in an efficient manner. The intersections line-polygons are tested only on the polygons found in the vicinity of the line segment. This means that the surface is covered with "boxes", each box stores the polygons that intersect it, and the tests are calculated only on the polygons stored in the boxes intersected by the line segment.

In the proposed algorithm, we suppose initially, before starting the collisions detection, that the tool representation is inside the airways surface. A timer will give the position of the tool at discrete-time values. Also, the virtual representation of the airways surface is formed by "small" polygons. The steps of the collision detection and resolution are as follows:

1. Given two positions $P_t$, $P_{t+1}$ at two successive moments in time, t and (t + 1), we evaluate the intersection of the segment $P_tP_{t+1}$ with the polygons from the airways surface. Only the polygons in the "neighbourhood" of the segment are taken into account. If no intersection is detected, then the position $P_{t+1}$ is still inside the surface.
2. If the segment $P_tP_{t+1}$ intersects a polygon (noted by Tr in Fig. 1, $P_{tr}$ being the intersection point), then $P_{t+1}$ is added back on the same side of Tr as $P_t$ through a "shortest" path ($P_{t+1} \rightarrow P'_{t+1}$), as follows:

(a) A line perpendicular to the Tr plane is drawn from the position $P_{t+1}$. The intersection is denoted by $P'_{Tr}$ and, if the tracking time step is small enough, it should be inside the polygon Tr. If not, additional corrections are required as follows:

(b) A parallel to the Tr plane is drawn starting from $P_t$, in the plane ($P_tP_{t+1}P'_{Tr}$).

(c) The intersection of the line $P_{t+1}P'_{tr}$ with the parallel to the Tr plane represents the corrected position $P'_{t+1}$ of the tool.

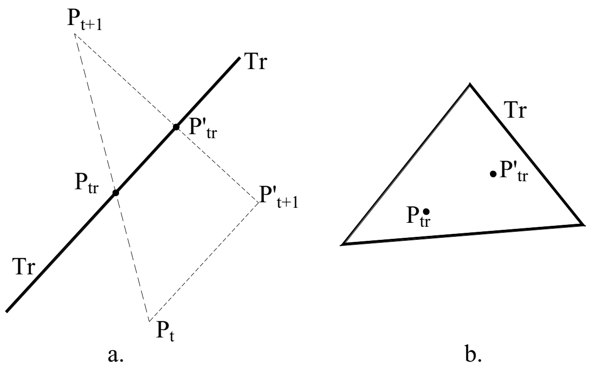


Fig. 1. Polygon collision detection and resolution if the point is projected inside the polygon.

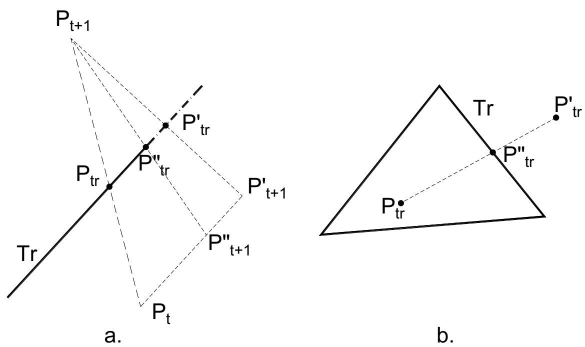


Fig. 2. Polygon collision detection and resolution if the point is projected outside the polygon.

In the case when the projection of the position $P_{t+1}$ on the plane Tr is actually outside the polygon Tr (see Fig. 2), then the line formed by the two points $P_{tr}$ and $P'_{tr}$ is intersected with the polygon perimeter in the point denoted $P''_{Tr}$. The intersection of the lines $(P_tP'_{t+1})$ and $(P_{t+1}P''_{tr})$ represents the corrected position $P''_{t+1}$ of the tool.

An artificial structure generated "mathematically" was used to test the collisions algorithms. Virtual bronchoscopy and IGT tracking were performed first on this structure. In Fig. 3, the boxes covering the mathematically generated structure is shown.

## 5. Results for a complex phantom

In this preliminary phase of NaviCAD development, a complex shape phantom of lung airways is used for experimental tests of the virtual bronchoscopy navigation method. A 3D CAD model was designed by segmentation and surface reconstruction using a patient CT scan (Fig. 4a) and the phantom was created on a precision 3D printer (Fig. 4b). Several tumour models from ceramic powder, with diameters between 10-25 mm were fixed in various locations on bronchial branches after phantom construction.

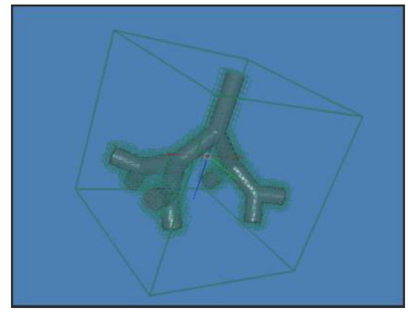

Fig. 3. View of the boxes covering the mathematically generated test.

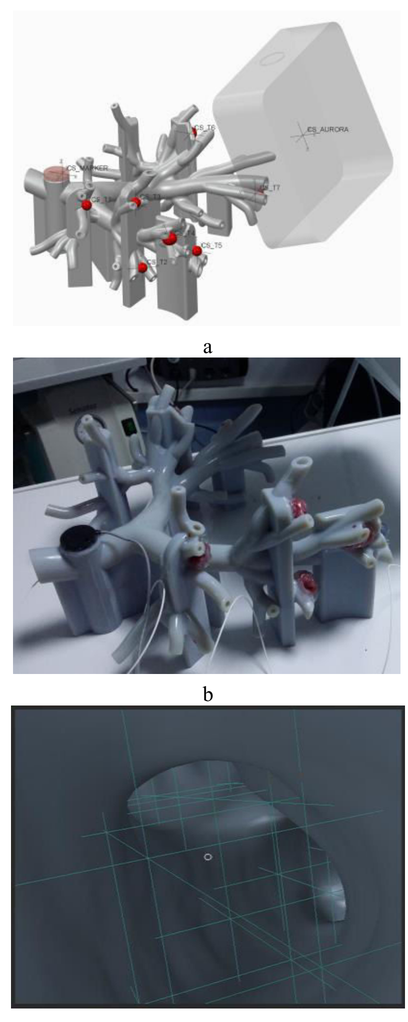


Fig. 4. a) The CAD model, b) 3D printed phantom, c) view inside the phantom "airways".

The phantom was scanned using a Siemens Somatom Sensation 4 slices CT system, (Siemens Medical Systems, Erlangen, Germany) and stack was loaded in NaviCAD system.
In Fig. 4c, a view inside the airways during the virtual navigation is presented using virtual bronchoscopy module from NaviCAD.

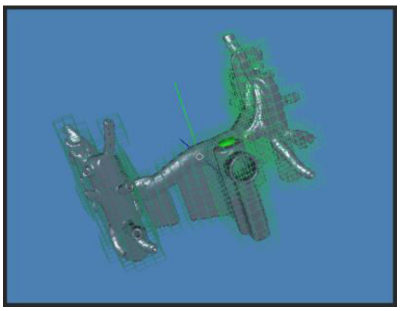

Fig. 5. View of the boxes covering the surface extracted from the phantom.

The surface model from the CT stack, created using the Marching Cubes method was used to test the utility and accuracy of the virtual bronchoscopy module, by navigating in airways, up to the tumour closest proximity. There were seven “tumour” targets that users had to reach at different depths inside the airway tract. Tests proved that virtual bronchoscopy module created an accurate surface from the CT stack, with low number of errors (holes). Furthermore, the navigation time decreased significantly due to our collision algorithm that keeps the camera inside the airways and close to the median line, avoiding penetration through the airways walls.

## 6. Conclusions

The paper describes a new virtual bronchoscopy method based on the Marching Cubes algorithm, used to calibrate and correct the path that the physician follows towards the lesions in the hard-to-reach periphery of the lung. Preliminary tests were performed on this system for ease of use and improvement of navigation time on a phantom, which simulates the bronchial tree. The preliminary tests using a complex phantom proved the system is easy to use and improves navigation through the bronchial tree in both inexperienced and experienced operators. The collision detection algorithm proved to be useful, decreasing the procedure time, eliminating the necessity to return in a previous position with the biopsy tool when airways wall was virtually penetrated and increases the success rate. The virtual bronchoscopy planning phase helps doctors to locate targets, to determine the optimal paths and to get familiarized (through the virtual navigation) with the trajectory that the bronchoscope should follow in the real procedure. Nevertheless, repeated corrections by the collision algorithm are not desired because it will increase the navigation error. Therefore, an additional registration correction is recommended when anatomical landmarks, like branch intersections, are encountered.

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