Fiducial-Free Registration Procedure for Navigated Bronchoscopy

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Abstract. Navigated bronchoscopy has been developed by various groups within the last decades. Systems based on CT data and electromagnetic tracking enable the visualization of the position and orientation of the bronchoscope, forceps, and biopsy tools within CT data. Therefore registration between the tracking space and the CT volume is required. Standard procedures are based on point-based registration methods that require selecting corresponding natural landmarks in both coordinate systems by the examiner. We developed a novel algorithm for a fully automatic registration procedure in navigated bronchoscopy based on the trajectory recorded during routine examination of the airways at the beginning of an intervention. The proposed system provides advantages in terms of an unchanged medical workflow and high accuracy. We compared the novel method with point-based and ICP-based registration. Experiments demonstrate that the novel method transforms up to 97% of tracking points inside the segmented airways, which was the best performance compared to the other methods.

1 Introduction

Lung cancer is among the most common forms of cancer and by far the deadliest of all types with a worldwide death toll of about one million annually [1]. In the United States about 15% of all cancers are diagnosed in the lung, accounting to 31% of all cancer deaths in males and 26% in females [2]. According to this, modern computer-guided bronchoscopy has become an indispensable tool due to its potential that enables doctors to examine and evaluate abnormalities for cancer in the inside airways of patients even at remote spots. Especially in pulmonary diagnostics, biopsy specimens taken from lung lesions followed by histopathologic, cytologic or microbiological assessments are a crucial procedure for the decision on an adequate therapy. The diagnostic success depends on various factors, among others, skill of the examiner, nodule size and location. Especially when it comes to accurately localizing peripheral solitary pulmonary nodules (SPN), traditional image-guided bronchoscopy based on fluoroscopic images reaches its limits. Inability or failure to reach designated targets and considering that many SPNs are not visible under fluoroscopy, often more invasive approaches, e.g.,

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CT-guided biopsy are facilitated, entailing an undesirable high exposure to radiation. Given the majority of SPNs situated in the lung periphery and the success rate using common techniques for biopsies typically between 18 and 62 percent, considerably depending on the lesion size and location [3], new procedures were facilitated. One possible solution to overcome the limits of traditional bronchoscopy is based on electromagnetic tracking (EMT) guided navigation as proposed by Hautmann et al. [4], Solomon et al. [5] as well as by Schwarz et al. [6], the latter using the commercial system by Superdimensions Inc.. All these studies showed good initial results. Their navigated bronchoscopy (NB) systems are based on tracking the tip of the bronchoscope by an electromagnetic (EM) sensor that is encapsulated in the tip of a flexible catheter pushed through the working channel of a bronchoscope or rigidly attached to its distal end. After a registration between tracking system and CT data, the sensor position can be visualized in the previously acquired CT images in real-time.

Recent attempts in registration and tracking for NB show considerable improvements. The approach of Wegner et al. [7,8] is to map the data from the EMT system to the closest point on a centerline of the segmented airways. Other approaches try to investigate more reliable and fully automatic registration procedures. Deguchi et al. [9] propose a method based on the iterative closest point (ICP) algorithm, to map the EM trajectory of the bronchoscope that is moved inside the airways to its segmented centerline from the CT data.

We propose a novel and fully automatic algorithm for the registration procedure in NB. Like the ICP approach we use the trajectory that is recorded during the routine examination of the airways at the beginning of the intervention. The algorithm is based on the assumption that the bronchoscope can be moved arbitrarily within the airways. In contrast to the ICP approach that enforces the trajectory to be close to the centerline, we try to create a more realistic model. We derived a new cost function for the registration that tests if a point, after applying the registration matrix, is inside or outside the segmented airways of the CT data. To make this approach fully automatic we developed an initialization procedure based on the main axes of both the segmented bronchial tree volume and the recorded trajectory. From experiments conducted on an airways phantom, we compared the results of different pneumologists using point-based, ICP-based and our newly developed registration method.

2 Method

Previously proposed and developed point and ICP-based registration techniques were integrated in our navigation system and compared with our fiducial-free approach.

2.1 Point-Based Registration

The simplest and most common method used to perform registration in NB is to find corresponding natural landmarks in the CT data and in the patient using the

EM sensor position data. Usually the anatomical landmarks inside the airways are chosen such that they are easy to recognize to avoid ambiguity and achieve better accuracy of the registration over external fiducials [5]. The localization procedure of the landmarks has to be performed meticulously since it directly affects the accuracy of the registration. Lacking accuracy and reproducibility, which are inherent to this method are among its main drawbacks.

The error associated with this matter is called Fiducial Localisation Error (FLE) [10]. However, for the evaluation of the registration accuracy the Target Registration Error (TRE) that is induced by FLE at a given target, is a more realistic error criteria. To determine the FLE an experiment was conducted. Experienced pneumologists were asked to identify five corresponding anatomical landmark sets: main carina, (RUL) right upper lobe carina, (ML) middle lobe carina, (LUL) left upper lobe carina, S6 carina. This procedure was carried out five times for each physician and the FLE determined subsequently. The results are listed in table 1. To visualize the TRE associated with point-based registration, error ellipsoids corresponding to SPN positions were computed in a Monte Carlo simulation based on the FLE determined in the experiment (see figure 1).

Table 1. Standard deviation for a selection of anatomical landmarks in CT and tracking space. In the CT half the element spacing $[0.47, 0.47, 2.0]$ was added.

	STD Anatomical Landmarks CT Space (in mm)					
	Main C.	*RUL C.*	*ML C.*	*LUL C.*	*S6 C.*	*All*
$\begin{pmatrix} x \\ y \\ z \end{pmatrix}$	$\begin{pmatrix} 0.924 \\ 0.987 \\ 1.720 \end{pmatrix}$	$\begin{pmatrix} 0.978 \\ 1.241 \\ 1.791 \end{pmatrix}$	$\begin{pmatrix} 1.033 \\ 5.465 \\ 8.235 \end{pmatrix}$	$\begin{pmatrix} 1.072 \\ 0.697 \\ 1.559 \end{pmatrix}$	$\begin{pmatrix} 0.777 \\ 0.812 \\ 1.562 \end{pmatrix}$	$\begin{pmatrix} 0.964 \\ 2.664 \\ 4.290 \end{pmatrix}$
	STD Anatomical Landmarks Tracking Space (in mm)					
$\begin{pmatrix} x \\ y \\ z \end{pmatrix}$	$\begin{pmatrix} 2.647 \\ 0.792 \\ 1.364 \end{pmatrix}$	$\begin{pmatrix} 0.741 \\ 0.499 \\ 0.737 \end{pmatrix}$	$\begin{pmatrix} 0.522 \\ 0.635 \\ 0.622 \end{pmatrix}$	$\begin{pmatrix} 0.355 \\ 0.399 \\ 0.354 \end{pmatrix}$	$\begin{pmatrix} 1.044 \\ 0.988 \\ 0.364 \end{pmatrix}$	$\begin{pmatrix} 1.345 \\ 0.695 \\ 0.781 \end{pmatrix}$

2.2 ICP-Based Registration

ICP was originally developed by Besl and McKay [11] to match two point clouds by iteratively minimizing the distances between point correspondences. The algorithm proceeds iteratively in two steps until convergence. At first establishing correspondences between spatial entities, in this specific case triangulated airways surface data or extracted centerlines from a CT and the trajectory, followed by estimation of a rigid transformation based on the correspondences that best maps one entity on the other. Subsequently, the transformation is applied to the trajectory points, aligning the respective entities closer. The underlying model for the approach assumes that the trajectory runs closely along the centerline or surface, respectively. However, this is not a realistic constraint, since the bronchoscope can move arbitrarily within the airways.

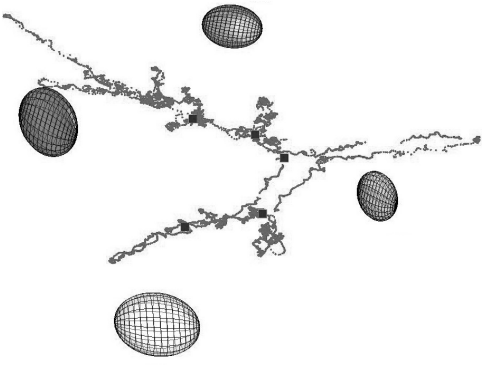

Fig. 1. TRE ellipsoids for exemplary SPNs. Squares indicate fiducial locations used

2.3 In-Volume Maximization Algorithm

During a pulmonary intervention the primary airways are initially examined using a bronchoscope. The covered path of the bronchoscope is tracked by an EMT system, which forms a three-dimensional trajectory. After the acquisition of the trajectory the in-volume maximization (IVM) algorithm optimally fits the trajectory into the segmented airways of the CT volume. Compared to the common approaches, IVM takes the most advantage of the current medical workflow and in contrast to ICP imposes no further constraints. The procedure consists of three steps: initialization, optimization and registration.

Initialization. Prior to optimization using non-linear techniques, the trajectory has to be roughly aligned with the CT data set. Therefore, we determine the approximate main carina location and spatial orientation of each entity (trajectory and CT). Given the natural constraint that the examination starts and ends within the trachea, its location can be recovered easily. Having estimated the trachea position, we approximate its direction by PCA regression. The main carina location coincides with one of the two ends of the trachea. A similar procedure is applied to the segmented CT data using PCA or the extracted centerline for recovering the orientation of trachea and the position of both main carina and RUL. The latter is identified by the anatomical property of the right main bronchus being wider, shorter and more vertical than the left one.

Let $R_{CT}, R_{trajectory} \in \mathbb{R}^{3x3}$ denote the matrices containing the orthogonal direction vectors in CT and recorded trajectory data, respectively. Further, let $t_{CT}, t_{trajectory} \in \mathbb{R}^3$ be the main carina position in the two data sets. We compute the initial transformation $T = \begin{pmatrix} R & t \\ \mathbf{0} & 1 \end{pmatrix} \in \mathbb{R}^{4x4}$ that maps the trajectory to the corresponding position in the CT, where $R = R_{CT} R^t_{trajectory}$ and $t = t_{CT} - R \cdot t_{trajectory}$.

Optimization. The IVM algorithm estimates the transformation that maximizes the number of trajectory points lying within the segmented airways volume

after applying the transformation matrix. The accuracy of the EM sensor position measurements is influenced by many factors, among others, magnetic field distortion, sensor velocity and acceleration. Thus the permanent quality fluctuation should be accounted for in the cost function. Assuming that we can measure the degree of uncertainty at which a trajectory point is acquired, we weight each point within the cost function such that the target is biased favoring points fitted into the volume with low uncertainty.

Let $\mathcal{X} = \{x_i\}, x_i \in \mathbb{R}^3$ be the trajectory and x be an arbitrary point with measurement uncertainty ϵ_i, then we define a weight function $g : \mathbb{R}^3 \mapsto \mathbb{R}$ with $g(x_i) = {\epsilon_i}^{-1}$.

We determine the transformation T that maximizes the number of trajectory points located within the segmented airways volume. For measuring the quality of a registration step, we define a ratio-based cost function, penalizing trajectory points moving out of the airways of the registered CT data. This is, however, an assumption, which is valid only in the absence of noise and organ deformation.

Furthermore, let $M(\mathcal{X})_{in}$ denote the set of trajectory points after applying the transformation that are tested to be inside the airways. $M(\mathcal{X})_{out}$ are respectively the points tested to be outside the segmented volume. Additionally, let S be the ratio of trajectory points inside the segmented airways volume given the EM trajectory $\mathcal{X}$ and a transformation matrix T. Then the cost function $S(T, \mathcal{X}) : \mathbb{R}^{4\times4} \times \{\mathbb{R}^3\} \mapsto [0, 1]$ is defined as,

$$S(T, \mathcal{X}) = \frac{\sum_{x \in M(\mathcal{X})_{in}} g(x)}{\sum_{x \in M(\mathcal{X})_{in}} g(x) + \sum_{x \in M(\mathcal{X})_{out}} g(x)} \tag{1}$$

Let T^* be the transformation, which maximizes the number of trajectory points lying within the airways:

$$T^* = \max_{T} S(T, \mathcal{X}) \tag{2}$$

T^* is determined iteratively using an optimizer. Here we have a six-dimensional search space (3DOF translation, 3DOF rotation) and generally numerous local minima. To avoid convergence at a local minimum, a robust optimization algorithm is needed. Our first choice was the Simulated Annealing Simplex (SAS) algorithm, which is a modified version of the standard simplex in combination with simulated annealing. It is initiated with a virtual temperature of 10^6 that is lowered by 20% every two iterations. Occasionally the annealing procedure is restarted.

3 Navigation System Setup

For tracking of the bronchoscope (BF-1T180, Olympus) within the airways an EMT system was used (3D Guidance; Ascension Technology Corporation; Burlington, VT, USA). The setup contained a metal immune flat panel field generator and two minimized receiver sensors (diameter, 1.3 mm; length, 6.7 mm). Within the defined tracking volume of 400 x 400 x 460 mm, the 6DOF pose of each sensor is measured. One sensor is encapsulated in the tip of the

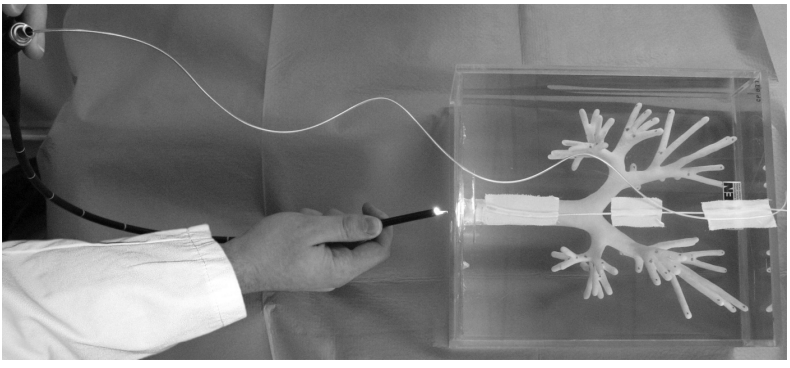

Fig. 2. The system setup for the bronchoscope navigation system. The flat panel field generator of the tracking system is positioned under the phantom. An EMT sensor is mounted on the tip of the bronchoscope.

bronchoscope. A second sensor is attached onto the surface of the phantom, approximately above the sternum. It is used as reference coordinate system. Thus, spontaneous transmitter and phantom patient motion can be compensated. We used a rubber lung dummy molded in silicone for our experiments.

4 Experiments and Results

In order to compare the registration performance of different algorithms we conducted a series of experiments. We acquired high resolution CT data of our phantom and segmented the airways up to the fourth bifurcation using a standard graph cuts algorithm. Subsequently, a centerline graph of the bronchial tree was extracted from the segmented airways. In the examination room experienced pneumologists performed a point-based registration (see section 2.1) selecting corresponding natural landmarks in the CT dataset and within the tracking space guided by the video of the bronchoscope. Furthermore, they performed a regular examination with the video bronchoscope throughout the entire visible bronchial tree with an attached EM sensor. The trajectory during this examination was recorded. In course of the experiments, we performed the initialization (see section 2.3), the ICP to the surface of the segmented model and its centerline (see section 2.2), and finally the IVM approach (see section 2.3).

The criterion to measure the quality of the registration is the percentage of recorded trajectory points inside the segmented bronchial tree after applying the transformation matrix. The point-based registration yields between 17 - 64%. With the initialization we achieve between 13 - 75%. The optimization using surface ICP achieves between 28 - 64%, using centerline ICP between 72 - 93%, and finally our IVM achieves between 75 - 97%. Table 2 shows the results of each trial of the experiments in detail. The computational time for both IVM and ICP registration took 2 to 5 minutes on a Intel Pentium M 1.73 GHz machine with 1 GByte of RAM.

Table 2. Registration performance for different registration algorithms. Indicated is the percentage of trajectory points inside the segmented airways volume after applying the various estimated registration transformations.

Experiment No.	*Registration Method*				
	Point-based	*Initial*	*Surface ICP*	*Centerline ICP*	*In-Volume Max*
1.	27	30	40	83	93
2.	64	20	52	72	75
3.	28	50	28	93	96
4.	18	59	62	88	97
5.	17	13	64	92	95
6.	31	30	58	85	86
7.	49	75	61	92	94
8.	37	28	64	89	96
9.	29	25	54	82	91
10.	31	35	55	86	92

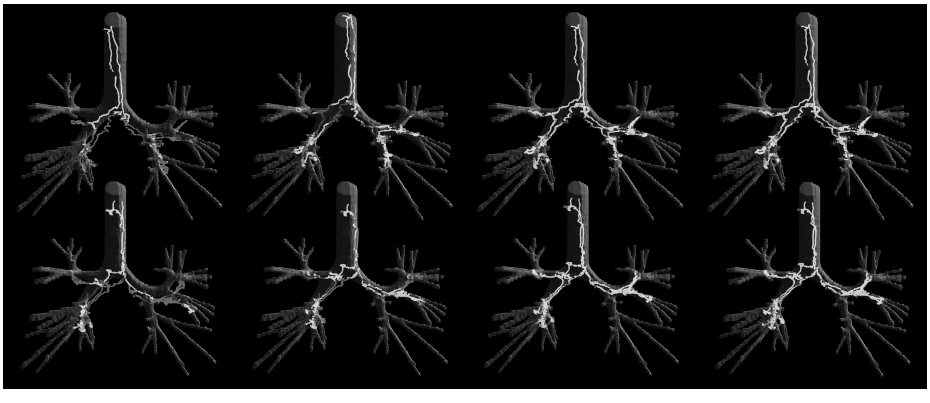

Fig. 3. Trajectories 4. and 8. from table 2 after registration. From left to right: point-based, surface ICP, centerline ICP and IVM. Bright spots are located inside the airways volume, gray ones outside.

5 Conclusion and Discussion

The low diagnostic success rate for SPNs without the support of navigation systems, especially crucial for peripheral SPNs with a diameter below $2cm$, facilitates the development of new methods. Various systems were proposed for navigation of a transbronchial biopsy needle within the previously acquired CT data by means of EMT. Standard procedures mainly employ point-based registration, which is often error prone and thus failing to provide the necessary accuracy. We showed in our experiments that registration can be based on the usage of an acquired EM trajectory data recorded during routine examination. Our developed IVM method smoothly integrates into the clinical workflow and

improves the overall estimated accuracy. For the upcoming in-vivo tests, breathing and deformation will be an issue. A third sensor that is capable of tracking the respiratory state will allow to perform gated registration. The registration using the entire trajectory information is one further step towards a robust and non-rigid system for NB.

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