Robust bronchoscope motion tracking using sequential Monte Carlo methods in navigated bronchoscopy: dynamic phantom and patient validation

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Abstract
Purpose Accurate and robust estimates of camera position and orientation in a bronchoscope are required for navigation. Fusion of pre-interventional information (e.g., CT, MRI, or US) and intra-interventional information (e.g., bronchoscopic video) were incorporated into a navigation system to provide physicians with an augmented reality environment for bronchoscopic interventions.

Methods Two approaches were used to predict bronchoscope movements by incorporating sequential Monte Carlo (SMC) simulation including (1) image-based tracking techniques and (2) electromagnetic tracking (EMT) methods. SMC simulation was introduced to model ambiguities or uncertainties that occurred in image- and EMT-based bronchoscope tracking. Scale invariant feature transform (SIFT) features were employed to overcome the limitations of image-based motion tracking methods. Validation was performed on five phantom and ten human case datasets acquired in the supine position.

Results For dynamic phantom validation, the EMT–SMC simulation method improved the tracking performance of the successfully registered bronchoscopic video frames by 12.7% compared with a hybrid-based method. In comparisons between tracking results and ground truth, the accuracy of the EMT–SMC simulation method was 1.51 mm (positional error) and 5.44° (orientation error). During patient assessment, the SIFT–SMC simulation scheme was more stable or robust than a previous image-based approach for bronchoscope motion estimation, showing 23.6% improvement of successfully tracked frames. Comparing the estimates of our method to ground truth, the position and orientation errors are 3.72 mm and 10.2°, while those of our previous image-based method were at least 7.77 mm and 19.3°. The computational times of our EMT– and SIFT–SMC simulation methods were 0.9 and 1.2 s per frame, respectively.

Conclusion The SMC simulation method was developed to model ambiguities that occur in bronchoscope tracking. This method more stably and accurately predicts the bronchoscope camera position and orientation parameters, reducing uncertainties due to problematic bronchoscopic video frames and airway deformation during intra-bronchoscopy navigation.

Keywords Sequential Monte Carlo methods · Bronchoscope motion tracking · Virtual bronchoscopy · Navigated bronchoscopy

Introduction

With an estimated 222,520 new cases and 157,300 deaths in 2010, respectively, accounting for about 15% of all cancer diagnoses and about 28% of all cancer deaths, lung and bronchus cancer are the leading cause of cancer deaths in the United States [1]. To reduce the incidence rates or the
mortality of lung and bronchus cancer patients, early diagnosis is greatly needed to allow for more effective treatments in the preliminary stages of cancer. For early detection and treatment of such cancers, physicians usually acquire such pre-interventional information of the patient chest as a noninvasive three-dimensional (3D) computed tomography (CT) scan and perform such invasive bronchoscopic procedures as the transbronchial lung biopsy (TBLB). Such conventional bronchoscopy only provides two-dimensional (2D) information (bronchoscopic video images) and only displays the visible bronchial wall surfaces through the natural orifices of patients and miss anatomical structures under the bronchial surfaces. Because a TBLB procedure must be performed inside the very complex bronchial tree structure, it remains challenging to accurately localize the biopsy needle in the region of interest (ROI) to sample tissue inside the airway tree. To address such disadvantages, current popular processes first use pre-interventional information (e.g., 3D CT datasets) to build virtual bronchoscopic images and combine intra-interventional information (live bronchoscopic videos) to construct bronchoscopy navigation systems. They usually provide various guidance information, e.g., the positions of abnormalities, a TBLB-guidance map of the suspicious regions, automatical displays of the anatomical names of the currently observed bronchial branches, and particularly visualizing the anatomical organs beyond the bronchial walls (see Fig. 1).

To develop such a navigation system, the most challenging task is to explore a method that precisely and powerfully tracks the bronchoscope camera motion inside the complex airway tree structure. Various techniques have been proposed. Image-based tracking methods usually estimate the bronchoscope camera motion parameters on the basis of image registration techniques that usually compute the similarities between live bronchoscopic video frames and CT-based virtual bronchoscopy images [2–4] and combine intra-interventional information (live bronchoscopic videos) to construct bronchoscopy navigation systems. They usually provide various guidance information, e.g., the positions of abnormalities, a TBLB-guidance map of the suspicious regions, automatical displays of the anatomical names of the currently observed bronchial branches, and particularly visualizing the anatomical organs beyond the bronchial walls (see Fig. 1).

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This study introduces sequential Monte Carlo (SMC) sampling to address the above limitations (a), (b), and (c) that occur in image-based and hybrid-based bronchoscope motion tracking approaches during navigated bronchoscopy. Since we use sequential Monte Carlo methods to generate a set of random samples including the camera motion parameters and the similarity between augmenting the virtual bronchoscopic and patient-specific real bronchoscopic images, our proposed SMC-based methods can accurately approximate the posterior probability distribution of the current bronchoscope camera pose with patient movement or image artifacts (uninformative images). Our experimental results demonstrate that using SMC methods powerfully deals with the restrictions of image-based methods and the disadvantages of EMT systems. Preliminary work of this method was presented at the ACCV (Asian Conference on Computer Vision) conference [18].

Methods

Bronchoscope motion tracking aligns a virtual camera pose with a real bronchoscope camera pose in a live or a real bronchoscopy. The virtual camera pose is generated by placing a virtual camera inside a 3D CT-derived virtual bronchoscopy environment. The motion tracking alignment seeks a transformation relationship between the bronchoscope camera and the CT coordinate systems (see Fig. 3). During the proposed image- and hybrid-based guidance bronchoscopy, our strategy first uses SMC samplers to produce random samples in terms of the current bronchoscope camera pose and the current similarity information. Next, these samples are deterministically drifted and stochastically diffused to generate a series of new samples to approximate the distribution space of the current bronchoscope camera pose. Finally,