

Real-time motion compensation for EM bronchoscope tracking with smooth output – ex-vivo validation

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ABSTRACT

Navigated bronchoscopy provides benefits for endoscopists and patients, but accurate tracking information is needed. We present a novel real-time approach for bronchoscope tracking combining electromagnetic (EM) tracking, airway segmentation, and a continuous model of output. We augment a previously published approach by including segmentation information in the tracking optimization instead of image similarity. Thus, the new approach is feasible in real-time. Since the true bronchoscope trajectory is continuous, the output is modeled using splines and the control points are optimized with respect to displacement from EM tracking measurements and spatial relation to segmented airways. Accuracy of the proposed method and its components is evaluated on a ventilated porcine ex-vivo lung with respect to ground truth data acquired from a human expert. We demonstrate the robustness of the output of the proposed method against added artificial noise in the input data. Smoothness in terms of inter-frame distance is shown to remain below 2 mm, even when up to 5 mm of Gaussian noise are added to the input. The approach is shown to be easily extensible to include other measures like image similarity.

Keywords: Localization and Tracking Technologies, Endoscopic Procedures, Intraoperative Imaging

1. INTRODUCTION

Transbronchial interventions are widely employed in clinical routine for diagnosis and treatment of pulmonary diseases – in particular of lung cancer, which is the most common cause of cancer-related death in men and women worldwide. The use of navigation and visualization systems provides benefits for endoscopists and patients, in terms of increased confidence, patient safety, and better outcomes.

Since bronchoscopy is an inherently monitor-based procedure, intraoperative imaging can easily be augmented with information from planning. While endoscopists are well aware of the endoscope’s current position and orientation most of the time, visual indications of otherwise invisible targets will enable a more precise guidance. Thus, lymph nodes can be more reliably targeted and important anatomical structures like blood vessel might be more reliably avoided. However, an accurate determination of the bronchoscope position and orientation is necessary in any case.

Bronchoscope tracking by electromagnetic (EM) tracking systems has been known for more than a decade,¹ recent advances include hybrid EM and image-based tracking,² filtering using particle filters,³ novel sensors,⁴ and in-vivo validation of hybrid systems.⁵

There has been work on the correction of static EM tracking errors due to distortions of the EM field.⁶ An ongoing challenge is compensation of dynamic tracking errors, which can be due to patient movement, breathing motion, or cardiac motion, as well as errors from EM tracking artifacts due to quick movements of sensors. However, with hybrid EM and image-based tracking methods small changes in the EM measurements can lead to large jumps between local minima after image-based registration. Such jumps in the tracked endoscope position and orientation in turn affect where augmented reality overlays are placed, leading to a shaky visualisation. A new approach to this problem is modeling the true trajectory as continuous. This will yield a more consistent and physically plausible tracking result.

2. NEW OR BREAKTHROUGH WORK TO BE PRESENTED

Our contribution is three-fold: First, we augment our previously published approach⁷ by including segmentation information in the tracking optimization instead of image similarity. Thus, the new approach is feasible in real-time and complements the previous approach. Second, we present an evaluation on a ventilated porcine ex-vivo lung, thus extending our previous evaluation on an artificial dynamic phantom. Third, we present a quantitative analysis of the robustness of our proposed approach against artificial noise in the input data.

3. METHODS

Since the real bronchoscope trajectory, as well as respiratory motion and heartbeat, is smooth, it is desirable to have a continuous description of bronchoscope position and orientation. Thus, we model the output of our method as a spline curve. For interpolation of positions we use Catmull-Rom splines,⁸ a special class of cubic Hermite splines where each control point is included in the resulting curve and tangents are continuous over multiple segments. For interpolation of orientation we use spherical linear interpolation (SLERP),⁹ which provides “smooth and natural” motion.

3.1 Objective Function

Control points are assigned to frames in regular time intervals and initialized with the original EM tracking measurements. Then, each for each control point its position p and orientation q are optimized with respect to a cost function $E(\cdot)$. In the proposed approach, we choose

$$E(p, q) = \underbrace{\lambda_1 \cdot R_T(p)}_{\text{tension}} + \underbrace{\lambda_2 \cdot R_S(p)}_{\text{structure}}, \quad (1)$$

where λ_1 and λ_2 are weighting parameters, and $R_T(\cdot)$ and $R_S(\cdot)$ are regularizers incorporating prior knowledge about EM tracking measurements and segmentation of anatomical structures, respectively. $R_T(\cdot)$ is modeled as spring forces depending on displacement of each position p_k from its corresponding original EM tracking measurements $p_{k,0}$:

$$R_T(p, q) = \sum_k \|p_k - p_{k,0}\| \quad (2)$$

$R_S(\cdot)$ is the Euclidean distance from each position p to the nearest airway voxel. Segmentation of airways was performed using an iterative region growing approach,³ and for computational efficiency a distance map was computed. All voxels inside the airways have a distance of zero.

Since the bronchoscope does not necessarily move close to the bronchus centerlines, the effect of $R_S(\cdot)$ is similar to a maximization of the number of measurements which are inside the airways.¹⁰ Since the continuous-by-definition trajectory is an even stronger consistency condition than e.g. a particle filter, we do not need to match the measurements to the nearest bronchus. Such a projection could match the position into the wrong bronchus. Instead, jumping between neighboring bronchi is prevented by the uniqueness of the spline curve.

3.2 Optimization

We employed our existing gradient descent framework,⁷ where for generality the gradient is approximated via finite differences. Thus, similar to inclusion of a distance map, the framework is easily extensible to include other measures, e.g. image similarity measures^{2,7} (cf. Table 1), where a closed form description of the gradient might not be available.

In this particular implementation, only frames up to the current time are considered. This makes our approach suitable for real-time applications, where no future data is available. In contrast, for offline applications all data is available, so the optimization might “look ahead” for additional motion compensation.

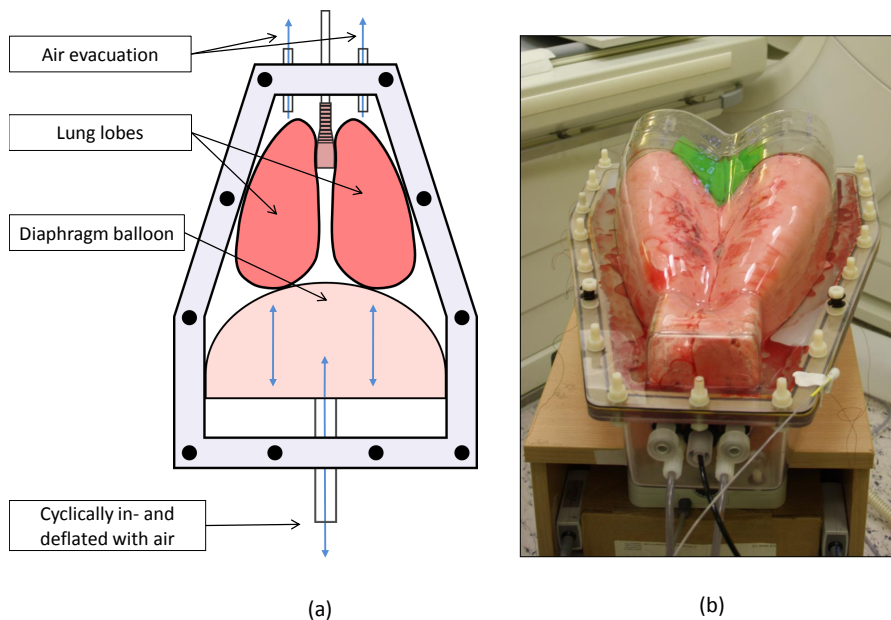


Figure 1. ArtiChest thorax phantom: a) schematic of design and operation, and b) setup with inflated lung and bronchoscope inserted through trachea.

3.3 Registration Refinement

For each control point, the original EM tracking measurements and a corrected position are available. Thus, after a trajectory has been processed once, it is possible to compute the optimal Euclidean transform between both point sets, i.e. between original and corrected positions. E.g. a visual inspection of all accessible branches is commonly recommended prior to a bronchoscopic procedure,¹¹ so the refined and approved registration can be used for subsequent navigation and visualization, well integrated into the clinical workflow.

4. EVALUATION AND RESULTS

For a realistic evaluation we used the ArtiChest thorax phantom (PROdesign, Heiligkreuzsteinach, Germany), cf. Figure 1. A porcine heart lung explant is placed in the phantom, and cyclic motion is induced by inflation and deflation of an artificial diaphragm. A CT scan of the lung was obtained with 0.8 mm spacing.

We used an Aurora EM tracking system (Northern Digital, Radolfzell, Germany) and a model 7268 bronchoscope (Richard Wolf, Knittlingen, Germany) with one 5D EM tracking sensor permanently integrated into the bronchoscope tip. Additional sensors were placed next to the artificial diaphragm of the ArtiChest phantom, in order to capture the motion range.

Video images and EM tracking data were synchronized, and point-based registration between landmarks in the CT image and corresponding EM tracking measurements was performed for initial registration, as clinically established. Residual error after point-based registration was 10.6 mm. Camera intrinsics and distortion were determined as proposed by Wengert et al.,¹² and all endoscopic video images were undistorted before further processing.

4.1 Expert Ground Truth Data

As for previous evaluations,⁷ we recorded ground truth data in multiple sessions with a human expert. Virtual bronchoscopy images were aligned manually with the real bronchoscope images (cf. Figure 2), until visual inspection showed optimal similarity. This approach has the advantage that the general ability of image-based

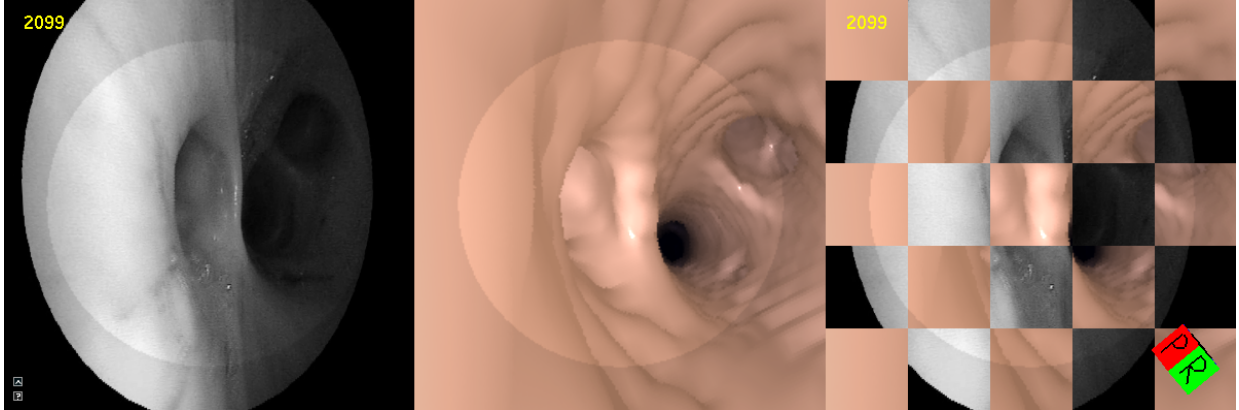


Figure 2. Screen shot of user interface with real endoscopic image (left), virtual image rendered at current position and orientation (right), which can be changed by the user, and checkerboard overlay for locating differences (right).

Method	Accuracy
Uncorrected	10.82 mm
Corrected using EMT only	10.79 mm
Corrected using above + refined registration	10.70 mm
Corrected using above + segmentation	9.57 mm
Corrected using above + image similarity	9.52 mm
Expert agreement	2.32 mm

Table 1. Accuracy comparison of uncorrected data and data corrected with different approaches.

approaches and the ambiguity of the tracking data can be estimated from expert agreement. Further, we are interested in position relative to anatomy, thus we need to compare to intraoperative imaging. In our case, intra-expert agreement (mean standard deviation) was 2.32 ± 1.76 mm and $5.34 \pm 2.71^\circ$. Given that this data was recorded in a real porcine lung explant instead of an artificial phantom, this is comparable to earlier determined variation within and between experts, i.e. up to 1.66 mm and 5.80° .⁷

In order to quantify the effect of the components of our method, their accuracy, in terms of mean deviation from ground truth, was evaluated separately. A comparison is given in Table 1. The refined registration was acquired using a second dataset, which was not used for evaluation.

4.2 Robustness against Noise

In order to evaluate the robustness of our method against noise, we added Gaussian noise with standard deviations of between 1 and 5 mm to the input EM tracking data and repeated the measurements. Such noise can be caused by e.g. conductive materials within the EM field or by electric equipment in the vicinity, and thus robustness was evaluated.

Quantitative results for those measurements are given in Figure 3. While maintaining better accuracy than the uncorrected data across all noise levels, the smoothness of the output data, in terms of inter-frame distance, is only marginally affected by noise.

5. DISCUSSION

At the time of construction of our prototype EM tracked bronchoscope, only 5D sensors were small enough to be integrated into the bronchoscope tip. Thus, rotation around (approximately) the bronchoscope main axis is undefined.

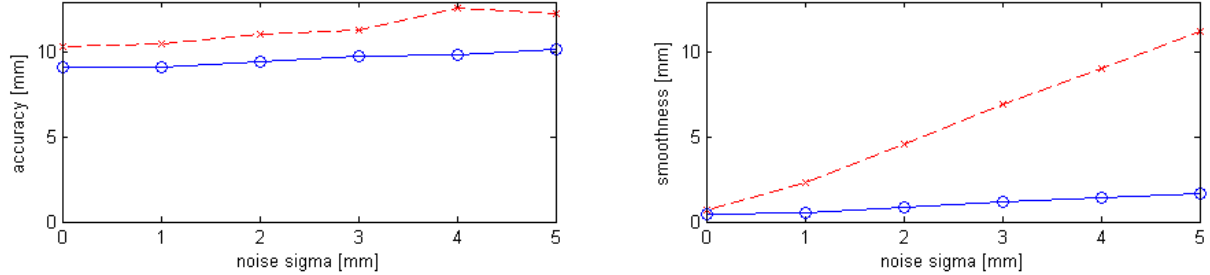


Figure 3. While maintaining better accuracy (left), the smoothness (right) of the proposed method (circles, solid line), in terms of inter-frame distance, is only marginally affected by additional noise in the input data, in contrast to the uncorrected data (crosses, dashed line).

After inclusion of image similarity, runtime per frame increases to 0.54 seconds, which is representative of the current trade-off between image-based approaches and real-time applications. Improvement by inclusion of image similarity was limited, since only a 5D tracking sensor was used and the arbitrary rotation around the bronchoscope axis is hard to correct within a limited number of optimizer steps. However, sensors have been further minimized since and we are going to include a 6D sensor in the next prototype, and the definition of R_T (cf. equation 2) or other cost measurements can easily be extended to include orientation differences as well.

The residual error after point-based registration is quite large, but CT landmarks correspond to full inflation, while the EM tracking measurements were acquired during cyclic motion. Range of diaphragm motion, as determined by additional sensors, was up to 29.8 mm.

For the evaluation up to now only data from a single observer was recorded. Work is in progress to again record data from additional observers, in order to confirm that also the inter-observer agreement agrees with previously published results. However, time is a precious resource in clinical routine and when working diligently, the acquisition process is very time-consuming.

6. CONCLUSION

We presented a novel real-time approach for bronchoscope tracking combining EM tracking, airway segmentation, and a continuous model of output. A detailed, quantitative evaluation on a ventilated porcine ex-vivo lung model with respect to human expert ground truth data was performed. While maintaining better accuracy than the uncorrected data across all noise levels, the smoothness of the output data, in terms of inter-frame distance, is only marginally affected by noise.

7. ACKNOWLEDGMENTS

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