学位報告

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主 論 文 の 要 旨

論文題目　New Approaches to Endoscopic Camera Motion Tracking for Bronchoscopy Navigation（気管支内視鏡ナビゲーションのための内視鏡カメラ追跡に関する研究）

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論 文 内 容 の 要 旨

Nowadays, navigated endoscopy is generally agreed to be the next generation of diagnostic or surgical endoscopy. It usually combines pre- and intra-operative imaging information to guide physicians during minimally invasive endoscopic interventions. However, endoscope motion tracking, which spatially and continuously synchronizes various imaging modality data, is still a general challenge for developing different endoscopic navigation systems.

This dissertation work proposes several promising approaches for endoscope motion tracking which is a vital core component of any endoscopic navigation systems to localize endoscopes (e.g., bronchoscope and colonoscope) and to estimate their motion. Generally, this dissertation is comprised of six chapters discussed as follows.

Chapter 1 presents a brief history and background, several certain roles, current status of minimally invasive diagnostic and therapeutic bronchoscopy and the advantages and challenges of navigated bronchoscopy for pulmonary diseases.

Chapter 2 describes the components of navigated bronchoscopy and formulates the certain problems to be tackled in this dissertation. Then it reviews current related work of localization and motion tracking methods and their disadvantages in the literature. Finally, the strategies/ideas and major contributions of this dissertation are discussed.

Chapter 3 focuses on addressing the limitations of image-based tracking approaches, particularly image registration techniques, which are commonly used in endoscope motion estimation. Image-based methods track the endoscope motion by finding the most similar virtual image (generated from CT slices using volume rendering techniques) to real images through an iterative optimization process. The major problem of such methods is that they usually get trapped in local minima during optimization. Such a problem was usually caused by the initial guess of the optimization process. Any good initial guesses (to be close to real position and orientation of the camera) result in not only reducing computational times but also accurately estimating the camera motion parameters during iterative optimization. On the other hand, the optimization function (image similarity measure between real and virtual

images is defined to be constrained on bronchial specific shapes; that is, the similarity is computed only in those specific shape regions, however, those specific shapes is not often observed on the real video images, resulting in incorrect similarity computation. The solution to the local minima problem in this study is to hybridize different computer vision techniques including scale invariant features, epipolar geometry analysis, Kalman filtering, and image registration to determine camera motion parameters. By utilizing scale invariant features and epipolar constraint, the relative camera motion between previous and current images can be recovered up to one scale factor (the magnitude of the motion) that is estimated by Kalman filtering. By the relative motion estimation, the initial guess of iterative optimization can be significantly improved. Note that such relative motion recovery is independent of any bronchial characteristic shapes and is on the basis of stable image texture information. From experimental results, this hybrid method was demonstrated to be more accurate and stable endoscope motion estimation, compared to any other image-based methods.

Chapter 4 proposes an uncertainty-tracking model on the basis of sequential Monte Carlo methods that can deal with the state estimation for nonlinear/non-Gaussian dynamic systems in both image- and sensor-based approaches. Although the proposed method using scale invariant feature-based motion recovery can deal with the shortage of bronchial specific shapes and improve the initial guess of the iterative optimization, it has no ability to tackle uncertain measurements or problematic video images (images are mainly caused by the following problems: electronic noise, specular- or inter-reflections, bubbles, collision with bronchial walls, poor dark regions, motion blurring, artifacts caused by blood, and airway deformation; those images impede tracking procedures) and to recover any tracking failures automatically in image-based approaches. In addition, sensor-based methods, particularly electromagnetic trackers (EMT), are also suffered from uncertain measurements (positional sensor outputs), which are often caused by any patient movements (e.g., respiratory motion or cough) and magnetic field distortion. Furthermore, endoscope movements are somewhat unexpected due to physicians' occasional operations. Any motion tracking methods needs to take operational robustness into an important consideration. Hence, endoscope motion estimation is a multi-modal (uncertain images, ambiguous sensor outputs, and unexpected endoscope operations) tracking process and a dynamic procedure. As many problems need to estimate the state of dynamic systems using uncertain measurements in the system, sequential Bayesian nonlinear filtering is an efficient approach to deal with measurement uncertainties. Therefore, endoscope motion tracking can also be considered as a nonlinear filtering problem. This study discussed an uncertainty-tracking model based on sequential Monte Carlo (SMC) methods for tackling measurement uncertainties occurred in endoscope motion tracking to improve the accuracy and robustness of state-of-the-art approaches, such as image registration and EMT. Since the SMC-based tracking model generates a set of random particles described by camera motion parameters (position and orientation) and image similarity (particle weight) between virtual and real bronchoscopic images, it can accurately estimate the posterior probability of the current bronchoscope camera position and orientation under patient movements or image artifacts (problematic video images). The proposed SMC-based method was validated on patient and phantom data. From dynamic phantom validation, the SMC-based approaches improved the tracking performance of the successfully registered bronchoscopic video frames by 12.7% compared with our previous sensor-based approaches. In comparisons between tracking results and ground truth, the tracking accuracy was 1.51 mm (position error) and 5.44 degrees (orientation error). During patient assessment, the SMC-based method was more stable or robust than our previous image-based methods for bronchoscope motion estimation, showing 23.6% improvement of successfully tracked frames. Comparing the estimates of the SMC-based method to ground truth, the position and orientation errors are 3.72 mm and 10.2 degrees, while those of our previous image-based approaches were at least 7.77mm and 19.3 degrees.

Chapter 5 develops an external tracking prototype beyond current available techniques such as electromagnetic localizers or image-based approaches. Despite the fact that the proposed multi-modal tracking in accordance with SMC sampling was demonstrated to be a much accurate and robust camera motion estimation strategy. However, it still sometimes fails to track endoscope motion. In image-based methods with SMC sampling, such failures are caused by the shortage of global motion information (e.g., the insertion depth and the rotational angle and the bending angle of the endoscope); this also means the lack of global initial guess for generating particles with position and orientation information. In EMT-based tracking methods with SMC sampling, challenges to airway deformation and magnetic field distortion still remain. To tackle the lack of global motion information and avoid all limitations of EMT, an inexpensive, simple, and effective tracking prototype was initially constructed for endoscopic navigation in this dissertation, which provides a very promising means to track the endoscope motion and is expected to replace current external tracking techniques, such as optical tracking systems and EMT. The external tracking prototype is constructed on the basis of an optical mouse sensor and a mechanical encoder to directly measure endoscope movements. By using an optical mouse senor, the insertion depth and the rotational angle of the viewing direction of the endoscope can be directly measured. By attaching a mechanical encoder at the angle lever of the control head of the endoscope, the rotational angle of the lever can be automatically obtained, which was calibrated to determine the bending angle of the bendable tip of the endoscope. From the insertion depth and the rotational angle of the viewing direction and the bending angle of the bendable tip, endoscope motion parameters can always be roughly calculated. By combining the rough estimation of the tracking model with SMC sampling, the endoscope pose (position and orientation) can be determined. Since no patient data was obtained, the developed external tracking model was evaluated on phantom data. The experimental results demonstrated the accuracy and robustness of the tracking prototype by pose (position and orientation) errors of only 1.10 mm and 3.88 degrees, successfully registered a total of 7142 (86.0%) images, and increased the tracking performance by at least 23.4%, as the errors of image-based methods were 25.5 mm and 37.0 degrees and the errors of EMT-based approaches were 5.09 mm and 11.1 degrees.

Chapter 6 concludes this thesis work on medical tool localization and tracking for navigation. Several worthwhile aspects of the proposed techniques are summarized and highlighted. Furthermore, various promising research directions and some potential limitations of the proposed methods and open issues are discussed for the further developments of navigated bronchoscopy.