Graduate School of Global Information and
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Abstract of Doctoral Dissertation

Research on Medical Image Processing Technologies for Fetal Surgical Navigation

胎児の手術ナビゲーションのための医用画像処理技術に関する研究

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Research on Image Processing □

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Congenital diaphragmatic hernia (CDH), which has a prevalence of 1 in 2,000-3,000 newborns and leads to approximately 8% of the known major congenital anomalies, is a severe birth defect of the diaphragm. In recent clinical practice, it has been reported that severe CDH could be treated in utero by a minimally invasive surgery (MIS) called fetoscopic tracheal occlusion (FETO), which places a detachable balloon into the fetal trachea to prevent pulmonary hypoplasia by increasing the pressure of the chest cavity. In order to perform an FETO surgery, the surgeon inserts a fiber endoscope having a diameter of 1.3 mm within a cannula (Karl Storz) having a diameter of 3.3 mm into the amniotic cavity through the abdominal and uterine walls, towards the fetal mouth and trachea, being navigated by 2D ultrasound (US) images and fetoscopic images. However, this operation is so difficult and risky that high-level surgical skills are required.

To facilitate the FETO surgery, a flexible wire-driven surgical tool, whose posture can be transformed to fit the internal structure between the fetal oral cavity and trachea, has recently been developed by Zhang et al., but the operation of this surgical tool is still difficult without an automatic navigation system. A prospective FETO surgical navigation system should be able not only to guide the surgical tool to the fetal trachea by analyzing medical images such as 3D US images and fetoscopic images, but also to provide the surgeon and control module with feedback information obtained by the medical image analyses. Among different technologies needed for achieving the prospective surgical navigation system, this thesis focuses on the following three main topics:

(1) 3D fetal face detection from 3D US images;

(2) Surgical tool location from 3D US images and fetal mouth tracking in real-time from fetoscopic images;

(3) Estimation of fetal trachea's position in 3D tracking space (the world coordinate system of 3D electromagnetic (EM) tracking system).

As described below, new methods for the three topics are proposed and explored. In addition, basic technologies (a) to (c), which are needed for the above-mentioned (1) to (3), are dealt with by this thesis as follows:

(a) Medical image segmentation, which is a pre-process for detecting the fetal face and head by (1), and is a pre-process for (b) also;

(b) Ellipse detection, which is needed for detecting the fetal head by (1) and fetal mouth by (2), and is needed for (c) also;

(c) 3D US calibration, which obtains transformation matrix between 3D US image coordinate system and the EM world coordinate system, and is needed for (1) to (3).

The contents of each chapter of this thesis are as follows.

Chapter 1 describes the background, related work, purpose, outline of the proposed approach and organization of this thesis. The background overviews image-guided procedures (IGP), congenital diaphragmatic hernia (CDH) and its treatments including fetoscopic tracheal occlusion (FETO). The related work reviews IGP systems, medical imaging and image process, and current navigation systems for the FETO surgery.

Chapter 2 overviews some existing IGP systems, which include tomographic image overlay systems, fluoroscopic X-ray systems, CT and MR based systems, and video based augmented reality systems. Related technologies on medical image processing are illustrated, where technologies on enhancement, segmentation, feature extraction, registration, visualization, and human computer interaction are included.

Chapter 3 elaborates on the prospective surgical navigation system and its related technologies, where one section explains the technologies needed for the navigation system, and the other section explains about three main topics (1) to (3).

Chapter 4 proposes new methods for (a) to (c) and studies their validities experimentally, as follows: (a) An improved Kernel-based fuzzy C-means algorithm is proposed for more accurate image segmentation than conventional methods. Experiments using synthetic gray-scale images, simulated brain MR images, and fetal 2D US images show that the proposed method has a strong robustness against image noise, and also achieves a better segmentation performance than the conventional methods. (b) An improved iterative randomized Hough transform algorithm is proposed for accurate ellipse detection despite occlusions and discontinuities. Experiments using clinical fetal US images demonstrate that the proposed method achieves more robust and accurate results, and has a better efficiency than conventional methods. (c) A novel 3D US calibration system using 24 fiducial points obtained by resin cones is proposed for more accurate calibration. Experimental results are comparable to those obtained by conventional methods using electromagnetic tracking.

Chapter 5 proposes a new method for (1). Specifically, a novel boosting traversal scheme based on the spatial relations between each facial feature in 3D US images is presented for detecting the fetal face and locating five key facial features, which involve nose tip, two eyes' inner corners, nose upper bridge and upper lip. Experimental results indicate the proposed approach is efficient and robust for 3D fetal face detection and feature location. The accuracy of locating the key features is 100% as a result of testing 72 images of 6 subjects, and the location error 3.18±0.91 mm of the detected upper lip can be tolerated by the FETO surgery. It turns out that the system could complete the entire detection process within approximately 625 msec on a quad-core 2.60 GHz computer.

Chapter 6 proposes new methods for (2): locating the surgical tool and tracking the fetal mouth. Each of the 15 points on the surgical tool is located in 3D tracing space (the world coordinate system of 3D EM tracking system) based on a 3D skeleton extraction technology and the 3D US calibration system. Experimental results show that an average TRE (target registration error) of 1.99±0.49 mm and a maximum TRE of 2.61±0.49 mm are achieved, which satisfy 3.85 mm, the requirement of the FETO surgery. The fetal mouth is tracked from a fetoscopic video sequence via the AdaBoost algorithm, the Camshift algorithm, and the improved iterative randomized Hough transform algorithm. Experimental results demonstrate that the proposed approach can automatically and accurately detect and track the fetal face and mouth in real-time in the fetoscopic video sequence.

Chapter 7 proposes a method for (3): estimating the position of the fetal trachea. First, a 3D fetal model with oral cavity and airways is reconstructed. Second, the 3D fetal facial surface is extracted from 3D US images. Third, the reconstructed 3D fetal model is registered with the extracted 3D fetal facial surface using sparse and dense matching, and is localized in the 3D tracking space based on the 3D US calibration system. Finally, the position of the trachea is estimated in the 3D tracking space based on the geometric relationship between the internal organs and the 3D fetal facial surface in the 3D fetal model that can be known based on their design. In experiments, a mean TRE of 1.55±0.46 mm is achieved for the location accuracy of the 3D fetal facial surface extracted from 3D US images, and mean location errors of 2.51±0.47 mm and 3.04±0.59 mm are respectively achieved for the location accuracies of the pharynx and the trachea entrance, which satisfy the requirement of the FETO surgery.

Chapter 8 concludes this thesis and states future work.

List of academic achievements

Category	[Paper/Article] Author(s), "Paper Title", Conference/Journal Title, Issue number and page numbers, Presentation/Publication Date [Work] Author(s), Category, "Title", Role in creating the work (Competition/Art Festival Name, Place of Showing, Date of Award-winning/Publication, Award Type)
Articles in refereed journals	○***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Quasi Random Scheme Based Improved Iterative Randomized Hough Transform (IRHT) for Detection of Partial Ellipses in Medical Images", IIEEJ Transactions on Image Electronics and Visual Computing, vol. 1, no. 1, pp. 97-106, 2013. ○***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Locating Fetal Facial Surface, Oral Cavity and Airways by a 3D Ultrasound Calibration Using A Novel Cones' Phantom", IEICE Transactions on Information and Systems, vol.E97-D, no.5, pp.-, May, 2014.
Presentations at International conferences	○***Rong Xu*** and Jun Ohya, "An Improved Kernel-based Fuzzy C-means Algorithm with Spatial Information for Brain MR Image Segmentation", Proceedings of the 25th International Conference of Image and Vision Computing New Zealand (IVCNZ' 2010), Queenstown, No.173, pp.1-7, 2010. ○***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Automatic Fetal Head Detection on Ultrasound Images by An Improved Iterative Randomized Hough Transform", Proceedings of the 26th International Conference of Image and Vision Computing New Zealand (IVCNZ' 2011), Auckland, pp.288-292, ISBN: 978-0-473-20281-1, 2011. ○***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Flexible Surgical Tool Localization Using A 3D Ultrasound Calibration System for Fetoscopic Tracheal Occlusion (FETO)", Proceedings of MICCAI Workshop on Clinical Image-Based Procedures: From Planning to Intervention (CLIP 2012), Nice, France, Lecture Notes in Computer Science, vol.7761, pp.17-24, 2012. ○***Rong Xu***, Tianliang Xie, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Automatic real-time tracking of fetal mouth in fetoscopic video sequence for supporting fetal surgeries", Proceedings of SPIE Medical Imaging 2013: Image-Guided Procedures, Robotic Interventions, and Modeling, Orlando, FL, USA, vol.8671, 86710Z-86710Z-6, 2013. ○***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Automatic Fetal Face Detection By Locating Fetal Facial Features From 3D Ultrasound Images For Navigating Fetoscopic Tracheal Occlusion Surgeries", Proceedings of the 10th IEEE International Conference on Automatic Face and Gesture Recognition (FG 2013), Shanghai, China, pp.1-6, 2013.
Presentations at International conferences (co-author)	[1] Mengyao Duan, ***Rong Xu***, and Jun Ohya, "3D surface reconstruction based on image stitching from gastric endoscopic video sequence", Proceedings of SPIE Optics & Photonics 2013, Applications of Digital Image Processing XXXVI, San Diego, California, USA, vol.8856, pp.88561I-XII, 2013. [2] Ye Li, Jun Ohya, Toshio Chiba, ***Rong Xu***, and Hiromasa Yamashita, "Towards

	Recognizing Surgeon's Action during Suture Surgery from the Video Sequence", Proceedings of the 9th Asian Conference on Computer Aided Surgery (ACCAS 2013), Tokyo, JS1-A2, 2013. [3] Ye Li, Jun Ohya, Toshio Chiba, ***Rong Xu***, and Hiromasa Yamashita, "Recognizing surgeon's actions during suture operations from video sequences", Proceedings of SPIE Medical Imaging 2014, San Diego, California, United States, Tracking No. MI14-MI102-188, Paper No. 9034-42, accepted, 2014.
Presentations at domestic conferences	[1] ***Rong Xu*** and Jun Ohya, "An Improved KFCM Algorithm in the Segmentation of Brain MRIs", Proceedings of the 9th Forum on Information Technology (FIT 2010), Kyushu University, Japan, G-017, vol.2, pp.563-564, Sep. 2010. [2] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Study of Segmenting Ultrasound Image Based on Bilateral Filtering and Fuzzy Clustering", Proceedings of IEICE General Conference 2011 (EiC 2011), Tokyo City University, Japan, D-16-2, vol.2, pp.205, Mar. 2011. [3] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Study of Automated Fetal Head Detection by Pre-processing Based On Ultrasound Image Gray Feature and Iterative Randomized Hough Transform", Proceedings of the 10th Forum on Information Technology (FIT 2011), Hakodate University, Japan, G-004, vol.2, pp.529-530, Sep. 2011. [4] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Improving Iterative Randomized Hough Transform for Automatic Detection of Fetal Head from Ultrasound Images", Proceedings of IEICE Technical Report 2011, Nogoya University, Japan, CS2011-76, IE2011-100, vol.111, no.349, pp.127-132, Dec. 2011. [5] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Study on 3D Fetal Model Construction with Oral Cavity and Airways", Proceedings of IEICE General Conference 2012 (EiC 2012), Okayama University, Japan, D-16-9, vol.2, pp.205, Mar. 2012. [6] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Cone Based Electromagnetic 3D Ultrasound Calibration", Proceedings of IEICE Technical Report 2012, Kobe University, Japan, vol.111, no.499, PRMU2011-281, pp.253-258, ISSN: 0913-5685, Mar. 2012. [7] ***Rong Xu***, Tomoki Hayashida, Jun Ohya, Harumi Kawamura, "Study of Estimating the Orientation of the Illumination from RGB and Depth Images", Proceedings of IIEEJ Media Computing Conference 2012, Waseda University, Japan, R7-4, pp.1-4, Jun. 2012. [8] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Registration Between 3D Ultrasound Images and 3D Fetal Model for Locating a Fetal Mouth in a Fetal Surgical Navigation System", Proceedings of the 11th Forum on Information Technology (FIT 2012), Hosei University, Japan, G-014, vol.2, pp.373-374, Sep. 2012. [9] ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Study of Automatic Fetal Face and Mouth Detection From 3D Ultrasound Images for Navigating FETO Surgeries", Proceedings of IEICE Technical Report: MI 2012,

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Presentations at domestic conferences (co-author)	[1] Naotomo Tatematsu, ***Rong Xu***, Jun Ohya, Harumi Kawamura, and Shunichi Yonemura, "A Fundamental Study of Estimating Lighting Source's Position from A Single Image by Detecting Spherical Regions", Proceedings of the 10th Forum on Information Technology (FIT 2011), Hakodate University, Japan, H-049, vol.3, pp.215-216, Sep. 2012. [2] Tianliang Xie, ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "A Study of the Detection of Fetal Mouth for An Automatic FETO Surgery", Proceedings of IEICE General Conference 2012 (EiC 2012), Okayama University, Japan, D-12-14, vol.2, pp.108, Mar. 2012. [3] Tianliang Xie, ***Rong Xu***, Jun Ohya, Bo Zhang, Yoshinobu Sato, and Masakatsu G. Fujie, "Research on Tracking Fetus' Mouth in Endoscope Video Sequence for Supporting Fetal Surgeries", Proceedings of IEICE Technical Report 2012, Kobe University, Japan, vol.111, no.499, PRMU2011-278, pp.235-240, ISSN: 0913-5685, Mar. 2012. [4] Mengyao Duan, ***Rong Xu***, and Jun Ohya, "A Study on 3D Point Cloud Stitching for SFM Reconstruction" , Proceedings of IEICE General Conference 2013 (EiC 2013), Gifu University, Japan, D-11-78, vol.2, pp.78, Mar. 2013. [5] Mengyao Duan, ***Rong Xu***, and Jun Ohya, "Endoscope based gastric 3D reconstruction and surface mosaic", Proceedings of the 12th Forum on Information Technology (FIT 2013), Tottori University, Japan, H-047, vol.3, pp.197-198, Sep. 2013. [6] Mengyao Duan, ***Rong Xu***, and Jun Ohya, "Study of Structure-from-motion Based 3D Reconstruction and Surface Mosaic", Proceedings of IEICE Technical Report 2013, Tottori University, Japan, vol.113, no.196, PRMU2013-44, pp.113-118, Sep. 2013. [7] Ye Li, Jun Ohya, Toshio Chiba, ***Rong Xu***, and Hiromasa Yamashita, "Fundamental Study of Recognizing the Surgeon's Action during Suture Surgery from the Video Sequence", Proceedings of the 12th Forum on Information Technology (FIT 2013), Tottori University, Japan, H-038, vol.3, pp.179-180, Sep. 2013.
Published Books	***Rong Xu***, Limin Luo and Jun Ohya (2012). Segmentation of Brain MRI, Advances in Brain Imaging, Dr. Vikas Chaudhary (Ed.), ISBN: 978-953-307-955-4, InTech, DOI: 10.5772/27596. Available from: http://www.intechopen.com/books/advances-in-brain-imaging/segmentation-of-brain-mri.

Curriculum Vitae

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Educational Background

Jiangyan High School in Jiangsu province, Sep. 1996 – July, 1999

Bachelor of Engineering, Southeast University, China, Sep. 1999 – June, 2003
School of Information Science and Engineering (Major in Telecommunication and Information Engineering)

Master of Engineering, Southeast University, China, Sep. 2006 – June, 2009
School of Computer Science and Engineering (Major in Image Science and Technology)

Doctorate program in Waseda University, Sep. 2009 – Sep. 2012
withdrew from the doctorate program in Graduate School of Global Information and Telecommunication Studies

Research Experience

Visiting Researcher, Global Information and Telecommunication Institute, Waseda University, Sep. 2012 – Present

Working Experience

Aug., 2003 – Aug., 2006
Software Engineer, Nanjing Fujitsu Computer Products Co., LTD., Nanjing, China

Feb., 2013 – Present
Project Manager, Japan Tsinghua TongFang Software, Tokyo, Japan

Awards and Punishment

Third Honor in third National Postgraduates Mathematical Contest in Modeling, China, 2006
Alumni Scholarship, Southeast University, 2007
Postgraduate Outstanding Scholarship, Southeast University, 2008
Scholarship for the Ph.D project by the China Scholarship Council (CSC), 2009-2012

Academic Society and Social activities

IEICE Society, from 2012
IEEE Society, from 2012
SPIE Society, from 2013