DISTAL END OF FLEXIBLE BRONCHOSCOPE USING FIBER REINFORCED SOFT ACTUATOR

RINO FERDIAN SURAKUSUMAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Biomedical Engineering)

Faculty of Bioscience and Medical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2017

Specially dedicated to my beloved wive for her support and caring,
my family for their encouragement and blessings,
and my daugthers whom accompany me during my study

ACKNOWLEDGEMENT

I am grateful to Allah SWT, the most powerful and the most merciful on His blessings of giving me this opportunity to complete this master study successfully. I realize my effort was nothing compared to His provision. With this opportunity, I would like to express special gratitude and sincere appreciation to my supervisor, Prof. Dr. –Ing. Eko Supriyanto, Assoc. Prof. Ir. Dr. Ahmad 'Athif Mohd. Faudzi, and Dr. Dyah Ekashanti Octorina Dewi for the guidance, patience, and support throughout the study completion.

I am also thankful to Actuator and Automation Lab members for their advices, guidance, and experience sharing throughout the period of accomplishing the study.

I would like also to acknowledge Universiti Teknologi Malaysia (UTM) under UTM-RU Grant No. R.J130000.7909.4S091 and Ministry of Science, Technology and Innovation (MOSTI) Malaysia and AUN SEED under UTM-RU Grant No R.J130000.7909.4B197 for financial support of research.

More importantly a million of thanks to my wife, Mishbahul Jannah, my daughters, my *Murabbi,* Ust. Zainuddin Ma'ali, and all my friends who had persistently giving spiritual motivation and inspiration. With their concern and support during hard times, everything went smooth. May Almighty Allah bless and reward them for their generosity. Alhamdulillah.

ABSTRACT

Flexible bronchoscope (FOB) is a medical intervention instrument that provide distal end bending capability for inspecting respiratory airways. Although the use of the FOB is considered to be safe and easier, there are a major complication called pneumothorax which is a lesion on the surface of the respiratory airways that causes air leakage in the respiratory system due to the extreme movement of the distal end of the FOB. The bronchoscopist must also manually rotate the whole body of the flexible tube to do rotation movement. On the other side, research on fiber reinforced soft actuator (FRSA) becomes a prospective opportunity for development in medical devices and soft robotics. So, the objectives of this research are to develop a novel distal end of the FOB prototype that minimize the risk of pneumothorax by providing local rotation in the novel distal end of the FOB and apply soft actuator mechanism in the development of distal end of the FOB. The concept of the system is a distal end of the FOB that provide smooth motion bend, soft material, and local rotation by using FRSA mechanism. A simulation was conducted using finite element analysis software which compared by type of fiber angles, fiber amount, and material. Prototype fabrication was also conducted using Rapid Prototyping Software and Computed Numerical Control Machine. The In-Vitro Experimental Setup consist of deformation angle measurement, bending force measurement, and functional testing using respiratory airways phantom. The testing result showed the prototype is able to bend 90° to the right, 89° to the left and 166° to rotate. The simulation and experiment similarity was 75.7% for right, 82.5% for the left, and 85.7% for the rotation. The maximum force that produced from the bending movement was 0.2 N which able to minimize the occurrence of pneumothorax. By in-vitro test, the prototype also able to inspect and manuver inside the respiratory airways.

ABSTRAK

Bronkoskopi fleksibel (FOB) adalah instrumen campur tangan perubatan yang menyediakan lenturan pada akhir distal untuk memeriksa saluran pernafasan. Walaupun penggunaan FOB itu dianggap selamat dan lebih mudah, terdapat komplikasi utama yang dipanggil pneumothorax iaitu luka pada permukaan saluran pernafasan yang menyebabkan kebocoran udara dalam sistem pernafasan disebabkan oleh pergerakan hujung distal FOB yang melampau. Bronchoscopist juga perlu secara manual memutar seluruh badan tiub fleksibel untuk melakukan pergerakan putaran. Di sisi lain, penyelidikan mengenai bertetulang gentian penggerak lembut (FRSA) menjadi satu peluang yang bakal untuk pembangunan dalam peranti perubatan dan robotik lembut. Jadi, objektif kajian ini adalah untuk membangunkan prototaip akhir distal FOB baru yang mengurangkan risiko pneumothorax dengan menyediakan putaran tempatan pada akhir distal FOB dan menggunakan mekanisme penggerak lembut dalam pembangunan akhir distal daripada FOB. Konsep sistem adalah akhir distal FOB yang menyediakan lancar bengkok gerakan, bahan lembut, dan putaran tempatan dengan menggunakan mekanisme FRSA. Simulasi telah dijalankan menggunakan perisian analisis unsur terhingga yang berbanding mengikut jenis sudut serat, jumlah serat, dan bahan. Fabrikasi prototaip juga telah dijalankan menggunakan Rapid Prototyping Perisian dan Machine Control Dikira Berangka. Eksperimen Persediaan In-Vitro terdiri daripada pengukuran sudut ubah bentuk, membongkok pengukuran daya, dan ujian fungsi menggunakan model saluran pernafasan. Hasil ujian menunjukkan prototaip mampu bengkok 90° ke kanan, 89° ke kiri dan berputar 166°. Persamaan simulasi dan eksperimen adalah 75.7% untuk betul, 82.5% untuk membela dan 85.7% untuk berputar. Daya maksimum yang dihasilkan daripada pergerakan lenturan adalah 0.2 N yang dapat mengurangkan berlakunya pneumothorax. Dengan ujian in-vitro, prototaip juga dapat memeriksa dan manuver dalam saluran udara pernafasan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

SCLC	-	Small cell lung carcinoma
NSCLC	-	non-small cell lung carcinoma
MRI	-	Magnetic Resonance Imaging
CT	-	Computed Tomography
TB	-	Tracheobronchial
BAL	-	Bronchoalveolar lavage
ET 1	-	Anterior Nasal Passages
ET 2	-	Posterior nasal passages, naso-oropharynx, and larynx
BB	-	bronchial region, including trachea and bronchi
bb	-	bronchiolar region consisting of bronchioles and terminal bronchioles
AI	-	alveolar-interstitial region, consisting of respiratory bronchioles, and alveolar ducts and sacs surrounded by alveoli.

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Flexible bronchoscopy or fiber optic bronchoscopy (FOB) is a medical intervention device that mostly be used for conducting inspection, biopsy, and interventional surgery in respiratory airways. This device consists of a flexible tube which has small diameter to fit enough to be inserted inside the respiratory airways. Inside the flexible tube, commonly there are three channels consisting of a light source, an image sensor, and a working channel to manipulate object in the respiratory airways environment. These channels are located along the way from distal-end of the FOB until video processing system, workstation, and the interface for the user or

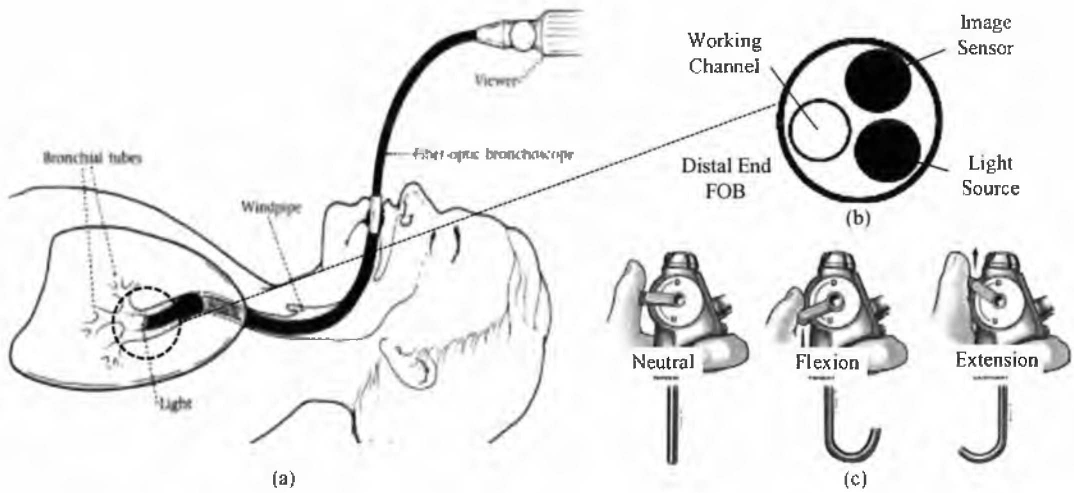

Figure 1.1: Current Flexible Bronchoscopy Device (Yoneda & Morrissey, 2008): (a) flexible bronchoscopy system, (b) Channels at the distal end, and (c) bending capability of distal end

known as bronchoscopist (D'Ippolito et al., 2007; Du Rand et al., 2013; Haas, Vachani, & Sterman, 2010; Ikeda, Yanai, & Ishikawa, 1968). To facilitate the bronchoscopist inserting and orientating the FOB to the target location inside the respiratory airways, the distal end is designed in such a way that it can bend with specific bending angle and controlled by the bronchoscopist using two thin wires as illustrated in Figure 1.1 (J. Toti, H. Wong, & Jay, 2001; Martin & Aimee Staggenborg, 2010).

However, altough the use of the FOB is considered to be safe and easier, there are still some drawbacks, such as discomfort feeling from pre-operative anaesthesia medication, hemorrhage, bronchospasm, aspiration, hypoxia, laryngeal edema, anesthetic accident, infection, dan Pneumothorax (Huang, Huang, Li, Browning, Parrish, Turner, Zarogoulidis, Kougioumtzi, Dryllis, Kioumis, Pitsiou, Papaiwannou, et al., 2014). Specifically in pneumothorax, it has become a major complication in the FOB due to the distal end injuries. In Video-Assisted Thoracopic Surgery (VATS), pneumothorax is appertain as in the highest three of complication and mortality rate (Luo et al., 2013) as describeb in Figure 1.2. In Transbronchial Lung Biopsy (TBBx), also known as Bronchoscopic Lung Biopsy (BLBx), pneumothorax is one of the two leading complications (Jain, Hadique, & Mehta, 2013).

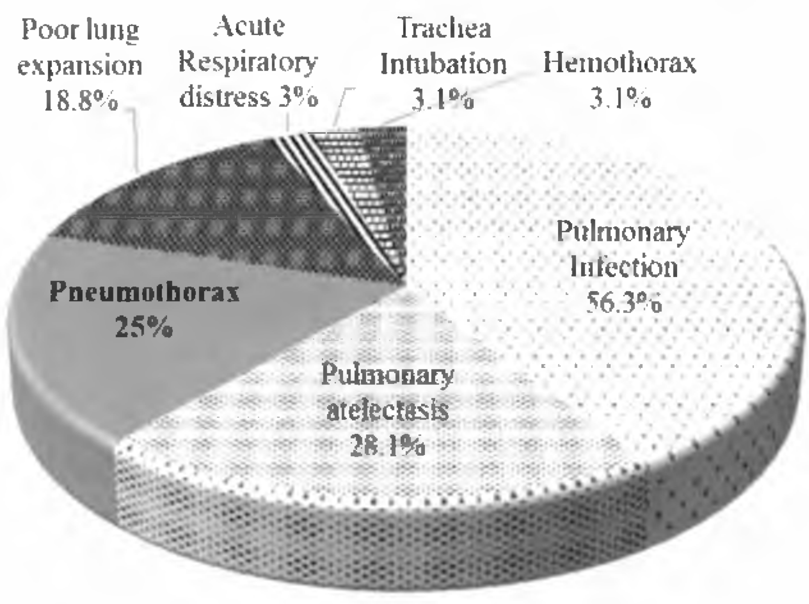

Figure 1.2: Post-Operative Complication and Mortality Rate After VATS (summarized from (Luo et al., 2013))

Pneumothorax is the lesion on the surface of the respiratory airways that causes air leakage in the respiratory system. This occurs due to the extreme movement of the distal end of the FOB during TBBx or VATS and the incapability of the patient to control the cough during the operation. (Boskovic et al., 2014; Huang, Huang, Li, Browning, Parrish, Turner, Zarogoulidis, Kougioumtzi, Dryllis, Kioumis, Pitsiou, Machairiotis, et al., 2014; Huang, Huang, Li, Browning, Parrish, Turner, Zarogoulidis, Kougioumtzi, Dryllis, Kioumis, Pitsiou, Papaiwannou, et al., 2014). Illustration of pneumothorax is describe in Figure 1.3.

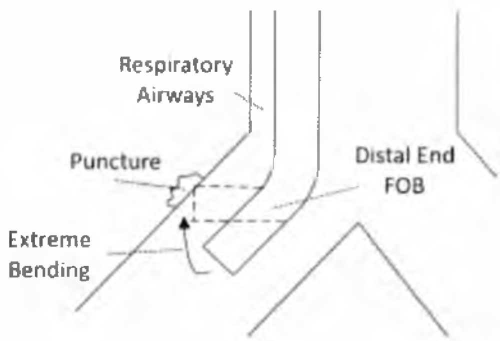

Figure 1.3: Pneumothorax due to the extreme bending of the distal end of the FOB

Besides, the anatomical structure of the respiratory airways has a complicated path with many intersections, extreme angles, and becomes smaller when it goes deeper (Hagberg, 2012; Hansen & Ampaya, 1975; Yeh & Schum, 1980). To help the bronchoscopist to point the FOB to the target location inside the bronchial tree, the FOB is capable of bending at the distal end of the FOB. Nevertheless, for rotation movement, the bronchoscopist must manually rotate the whole body of the flexible tube (global rotation). If the rotation capability is provided to the distal end of the FOB (local rotation), it may help the bronchoscopist to have manuverability and precision to point the FOB to target location (Kennedy, Morice, Jimenez, & Eapen, 2007),(Colt, 2011).

Research on soft actuator becomes popular nowadays to cover the needs of soft mechanism and soft material (Rusydi et al., 2014). Soft actuator is a new emerging technology, which provides soft mechanisms with smooth motion. It has has simple structure design, high compliance and high power to weight ratio (Faudzi & Razif, 2012). Recently, it has been used in many areas, including soft handling robots such as human-support robots, wearable power assist suits, robot hands for various works in size and shape such as fruit-harvesting end-effectors and medical application such as colonoscopy (Kure, Kanda, Suzumori, & Wakimoto, 2008; Noritsugu, 2005; Suzumori, Hama, & Kanda, 2006; Udupa, Sreedharan, Dinesh, & Kim, 2014). The mechanism of soft actuator that does not apply any metal wires or string making it safe to be used in endoscopy purposes. The application of soft actuator on bronchoscopy becomes a prospective opportunity for development in medical devices and soft robotics.Due to the small size of respiratory airways structures, this study is also possible to explore the fabrication of small sized soft actuator.

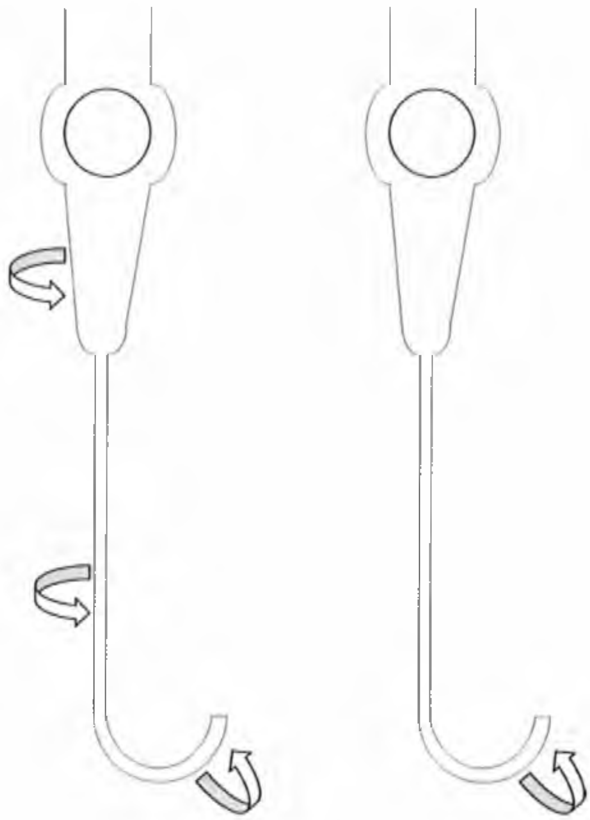

Figure 1.4: Rotation mechanism on the FOB, Global Rotation vs Local Rotation

1.2 Problem Statements

A dedicated research on the development of a novel safer FOB is needed to offer a new solution in the prevention of pneumothorax. Problem statement in our study consists of:

(1) The extreme movement of the distal end of the FOB during TBBx and VATS may cause pneumothorax. Therefore, there is a need of a distal end of the FOB to have a soft movement to minimize the risk of pneumothorax.
(2) Global rotation in the FOB may be difficult to perform during the bronchoscopy procedure. Hence, there is a need of local rotation feature in the distal end of the FOB to ease the movement control.
(3) Soft actuator with its smooth motion is potential for medical application. However, according to our knowledge, it is not yet applied in the FOB.

Our hypothesis is that soft actuator mechanism is possible to be implemented for a safer FOB which can minimize the risk of pneumothorax by providing small size, soft motion bending, and local rotation.

1.3 Research Objectives

The objectives of this research are:
(1) To develop a novel distal end of the FOB prototype that minimize the risk of pneumothorax;
(2) To provide local rotation in the novel distal end of the FOB to solve global rotation problem;
(3) To apply soft actuator mechanism in the development of distal end of the FOB by fabricating small size and soft motion bending for the FOB.

1.4 Scope of Works

The scope of this research consists of:
(1) Design
   a. Bending and Rotation Capabilities
      A measurement of a respiratory airways model is conducted to obtain the minimum bending angle. Bending feature consists of two directions which are flexion and extension. Rotation feature is

designed in such a way that the distal end of the FOB is capable to have half sphere viewing region.

b. Structure and Diameter

To obtain bending and rotation capabilities, a braided angle soft actuator (BASA) mechanism is applied and two chambers bending soft actuator structure and one chamber rotation soft actuator structure are combined. However, due to the limitation of the fabrication equipment, the prototype of distal end of the FOB is targeted until seconday bronchi. Thus, the diameter of the distal end of the FOB is designed in such a way that it possible to manuver in secondary bronchi. The prototype also does not include the working channel.

c. Fibers Pattern and Angle

Fibers are needed in the BASA mechanism. They are knitted on the surface of the soft actuator. Selection of them determine the produced bending and rotation angle. A simulation using finite element analysis (FEA) software (MARC MENTAT) is conducted to select the optimum fibers pattern and angle.

d. Material Selection

Materials are compared by simulation using FEA software to determine the optimum produce bending and rotation angle.

e. Endoscope Camera

A product benchmark is conducted to choose the endoscope camera that suit to the design of distal end of FOB.

(2) Simulation

Simulation is conducted using FEA software by develop 8 models of fiber reinforced soft actuator.

(3) Fabrication

Molds for forming the soft actuator are designed using a solid modeling computer-aided design (CAD) software (SOLIDWORKS) and fabricated using Computer Numerical Control (CNC) machine. The material pouring and mixing is applied into the mold to fabricate the prototype of distal end of the FOB.

(4) Experiment

Experimental setup for test the prototype of distal end of the FOB consist of Bending angle measurement, rotation angle measurement, force measurement, and phantom test.

1.5 Organization of the Project Report

This project report consists of 5 chapters. First chapter introduce the reseach background, determined the problem statement, objective of the research, and research scope. Second chapter present about literature review in scientific analysis, patent analysis, and product analysis. Third chapter present about methodology. This chapter explain about overal system design, how to design the specification of the system, fabrication procedure, and experimental setup. Fourth chapter present the result of the methodology and discuss about all simulation and prototype movement result, the comparative study, and technical analysis conducting in the research. Fifth chapter is about conclusion and future recommendation.

REFERENCES

Benjamin Warren Purow, M. P. C. (2003, May 27). Sheath device with dressing for prevention of pneumothorax. Retrieved from https://www.google.com/patents/US6569121

Boskovic, T., Stanic, J., Pena-Karan, S., Zarogoulidis, P., Drevelegas, K., Katsikogiannis, N., … Zarogoulidis, K. (2014). Pneumothorax after transthoracic needle biopsy of lung lesions under CT guidance. *Journal of Thoracic Disease*, *6*(SUPPL1). http://doi.org/10.3978/j.issn.2072-1439.2013.12.08

Bronchoscopes Product Comparison System. (2003). Pennsylvania.

Colt, H. (2011). *The Essential Flexible Bronchoscopist* (1st ed.). USA: Bronchoscopy International, Laguna Beach, CA 92651.

D'Ippolito, R., Foresi, A., Castagnetti, C., Gesualdi, S., Castagnaro, A., Marangio, E., & Olivieri, D. (2007). Indications for flexible fiberoptic bronchoscopy and its safety in the very elderly. *Monaldi Archives for Chest Disease = Archivio Monaldi per Le Malattie Del Torace / Fondazione Clinica Del Lavoro, IRCCS [and] Istituto Di Clinica Tisiologica E Malattie Apparato Respiratorio, Università Di Napoli, Secondo Ateneo*, *67*(1), 23–9. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/17564281

Douglas, J. M., & Spaniol, S. (2002). Prevention of postoperative pneumothorax in patients undergoing cardiac surgery. *The American Journal of Surgery*, *183*(5), 551–553. http://doi.org/10.1016/S0002-9610(02)00839-5

Du Rand, I. A., Blaikley, J., Booton, R., Chaudhuri, N., Gupta, V., Khalid, S., … Munavvar, M. (2013). British Thoracic Society guideline for diagnostic flexible bronchoscopy in adults: accredited by NICE. *Thorax*, *68 Suppl 1*, i1–i44. http://doi.org/10.1136/thoraxjnl-2013-203618

Faudzi, A., & Razif, M. (2012). Development of bending soft actuator with different braided angles. *… (AIM), 2012 IEEE/ …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6266037

Graham, M. W., Gibbs, J. D., Cornish, D. C., & Higgins, W. E. (2010). Robust 3-D airway tree segmentation for image-guided peripheral bronchoscopy. *IEEE Transactions on Medical Imaging*, *29*(4), 982–997. http://doi.org/10.1109/TMI.2009.2035813

Haas, A. R., Vachani, A., & Sterman, D. H. (2010). Advances in diagnostic bronchoscopy. *American Journal of Respiratory and Critical Care Medicine*, *182*(5), 589–97. http://doi.org/10.1164/rccm.201002-0186CI

Hagberg, C. A. (2012). *Benumof and Hagberg's Airway Management: Third Edition*. *Benumof and Hagberg's Airway Management: Third Edition*. http://doi.org/10.1016/B978-1-4377-2764-7.00057-9

Hansen, J. E., & Ampaya, E. P. (1975). Human air space shapes, sizes, areas, and volumes. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *38*(6), 990–995.

Helferty, J. P., Sherbondy, A. J., Kiraly, A. P., & Higgins, W. E. (2007). Computer-based system for the virtual-endoscopic guidance of bronchoscopy. *Computer Vision and Image Understanding*, *108*(1-2), 171–187. http://doi.org/10.1016/j.cviu.2006.10.010

Higgins, W. E., Helferty, J. P., Lu, K., Merritt, S. A., Rai, L., & Yu, K. C. (2008). 3D CT-Video Fusion for Image-Guided Bronchoscopy. *Computerized Medical Imaging and Graphics*, *32*(3), 159–173. http://doi.org/10.1016/j.compmedimag.2007.11.001

Huang, Y., Huang, H., Li, Q., Browning, R. F., Parrish, S., Turner, J. F., … Zarogoulidis, P. (2014). Approach of the treatment for pneumothorax. *Journal of Thoracic Disease*, *6*(Suppl 4), S416–20. http://doi.org/10.3978/j.issn.2072-1439.2014.08.24

Huang, Y., Huang, H., Li, Q., Browning, R. F., Parrish, S., Turner, J. F., … Zarogoulidis, P. (2014). Transbronchial lung biopsy and pneumothorax. *Journal of Thoracic Disease*, *6*(Suppl 4), S443–7. http://doi.org/10.3978/j.issn.2072-1439.2014.08.48

Ikeda, S., Yanai, N., & Ishikawa, S. (1968). Flexible bronchofiberscope. *The Keio Journal of Medicine*, *17*(1), 1–16. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/5674435

J. Toti, A., H. Wong, M., & Jay, K. (2001). Endotracheal Tube With Distal end of the

FOB Directional Control Position Preserving Mechanism.

Jain, P., Hadique, S., & Mehta, A. C. (2013). *Transbronchial Lung Biopsy*. http://doi.org/10.1007/978-1-62703-395-4

Kennedy, M. P., Morice, R. C., Jimenez, C. A., & Eapen, G. A. (2007). Treatment of bronchial airway obstruction using a rotation distal end of the FOB microdebrider: a case report. *Journal Cardiothorac Surgery*, *2*, 16. http://doi.org/10.1186/1749-8090-2-16

Kotora, J. G., Henao, J., Littlejohn, L. F., & Kircher, S. (2013). Vented chest seals for prevention of tension pneumothorax in a communicating pneumothorax. *The Journal of Emergency Medicine*, *45*(5), 686–94. http://doi.org/10.1016/j.jemermed.2013.05.011

Kure, K., Kanda, T., Suzumori, K., & Wakimoto, S. (2008). Flexible displacement sensor using injected conductive paste. *Sensors and Actuators, A: Physical*, *143*, 272–278. http://doi.org/10.1016/j.sna.2007.11.031

Lee, P., Yap, W. S., Pek, W. Y., & Keong Ng, A. W. (2004). An Audit of Medical Thoracoscopy and Talc Poudrage for Pneumothorax Prevention in Advanced COPD. *Chest*, *125*(4), 1315–1320. http://doi.org/10.1378/chest.125.4.1315

Leong, S., Shaipanich, T., Lam, S., & Yasufuku, K. (2013). Diagnostic bronchoscopy--current and future perspectives. *Journal of Thoracic Disease*. http://doi.org/10.3978/j.issn.2072-1439.2013.09.08

Light, R. W. (1990). Intrapleural Tetracycline for the Prevention of Recurrent Spontaneous Pneumothorax. *JAMA*, *264*(17), 2224. http://doi.org/10.1001/jama.1990.03450170072025

Luo, Q., Han, Q., Chen, X., Xie, J., Wu, L., & Chen, R. (2013). The diagnosis efficacy and safety of video-assisted thoracoscopy surgery (VATS) in undefined interstitial lung diseases : a retrospective study. *Journal of Thoracic Disease*, *5*(3), 283–288. http://doi.org/10.3978/j.issn.2072-1439.2013.04.12

Marc 2014 Release Overview. (2014).

Martin, K. T., & Aimee Staggenborg. (2010). *Fiberoptic Bronchoscopy*. RC Educational Consulting Services, Inc.

Noritsugu, T. (2005). Pneumatic soft actuator for human assist technology.

International Symposium on Fluid Power, 11–20. Retrieved from http://jfps.jp/proceedings/tukuba2005/pdf/s2.pdf

Ogura, K., Wakimoto, S., Suzumori, K., & Nishioka, Y. (2009). Micro pneumatic curling actuator - Nematode actuator -. *2008 IEEE International Conference on Robotics and Biomimetics*, 462–467. http://doi.org/10.1109/ROBIO.2009.4913047

Rossel, J., Perez, A., Cabras, P., & Rosell, A. . (2012). Motion Planning for the Virtual Bronchoscopy. *International Conference on Robotics and Automation*, *31*(7), 872–885. http://doi.org/10.1177/0278364912441954

Rusydi, M., Razif, M., Athif, A., Faudzi, M., Bavandi, M., Najaa, I., … Yaakob, O. (2014). Two Chambers Soft Actuator Realizing Robotic Gymnotiform Swimmers Fin.

Shinagawa, N., Yamazaki, K., Onodera, Y., Miyasaka, K., Kikuchi, E., Dosaka-Akita, H., & Nishimura, M. (2004). CT-guided transbronchial biopsy using an ultrathin bronchoscope with virtual bronchoscopic navigation. *Chest*, *125*(3), 1138–1143. http://doi.org/10.1378/chest.125.3.1138

Suzumori, K., Endo, S., Kanda, T., Kato, N., & Suzuki, H. (2007). A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. *Proceedings - IEEE International Conference on Robotics and Automation*, (April), 4975–4980. http://doi.org/10.1109/ROBOT.2007.364246

Suzumori, K., Hama, T., & Kanda, T. (2006). New pneumatic rubber actuators to assist colonoscope insertion. *Proceedings - IEEE International Conference on Robotics and Automation*, *2006*(May), 1824–1829. http://doi.org/10.1109/ROBOT.2006.1641971

Suzumori, K., Maeda, T., Watanabe, H., & Hisada, T. (1997). Fiberless flexible microactuator designed by finite-element method. *IEEE/ASME Transactions on Mechatronics*, *2*(4), 281–286. http://doi.org/10.1109/3516.653052

Udupa, G., Sreedharan, P., Dinesh, P. S., & Kim, D. (2014). Asymmetric bellow flexible pneumatic actuator for miniature robotic soft gripper. *Journal of Robotics*. Retrieved from http://www.hindawi.com/journals/jr/2014/902625/abs/

Wakimoto, S., Kumagai, I., & Suzumori, K. (2009). Development of large intestine endoscope changing its stiffness. *2009 IEEE International Conference on Robotics and Biomimetics, ROBIO 2009*, 2320–2325. http://doi.org/10.1109/ROBIO.2009.5420727

Wakimoto, S., Ogura, K., Suzumori, K., & Nishioka, Y. (2009). Miniature soft hand with curling rubber pneumatic actuators. *Proceedings - IEEE International Conference on Robotics and Automation*, 556–561. http://doi.org/10.1109/ROBOT.2009.5152259

Xu, D., Xu, S., Herzka, D. A., Yung, R. C., Bergtholdt, M., Gutiérrez, L. F., & McVeigh, E. R. (2010). Single-view 2D/3D registation for X-ray guided bronchoscopy. In *2010 7th IEEE International Symposium on Biomedical Imaging: From Nano to Macro, ISBI 2010 - Proceedings* (pp. 233–236). http://doi.org/10.1109/ISBI.2010.5490370

Yeh, H. C., & Schum, G. M. (1980). Models of human lung airways and their application to inhaled particle deposition. *Bulletin of Mathematical Biology*, *42*(3), 461–480. http://doi.org/10.1016/S0092-8240(80)80060-7

Yoneda, B. K. Y., & Morrissey, B. M. (2008). The technique of adult flexible bronchoscopy : Part 1, (Table 1), 1–7.