Image-Guided Medical Robotic Interventions

2011 IROS Workshop

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IROS 2011 Workshop: Image-Guided Medical Robotic Interventions

September 25, 2011, San Francisco, California - Full day workshop

Organizers

Sarthak Misra	**Jaydev P. Desai**
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Abstract

Medical robotic systems strive to make surgical interventions less invasive, less risky for both patients and clinicians, more efficient, less costly, and capable of achieving better patient outcomes. Increasing the targeting accuracy during robot-assisted minimally invasive surgical procedures requires the integration of pre-operative plans and intra-operative control. These planners require the development of models of the surgical instruments and their environment. While the controllers generally rely on image-guided feedback from a clinical imaging system, such as computed tomography (CT), magnetic resonance (MR), or ultrasound images. The focus of this workshop is to bring together researchers that use clinical imaging modalities to plan and control procedures for robot-assisted minimally invasive surgery. In addition, medical robotic systems used in conjunction with clinical imaging modalities will also be discussed.

List of Topics

Pre-operative tool-tissue interaction modeling and planning; Image-guided techniques to control the path of surgical instruments, Methods to integrate pre-operative plans and intra-operative control; MR-compatible systems.

List of Presenters with affiliations

- **Prof. Jaydev Desai**, University of Maryland
  Presentation Title: Challenges in MRI-guided interventions: From Macro-scale

to Meso-scale

Biography:
Dr. Jaydev P. Desai is currently an Associate Professor in the Department of Mechanical Engineering at University of Maryland, College Park (UMCP) and the Director of the Robotics, Automation, and Medical Systems (RAMS) Laboratory. He completed his undergraduate studies from the Indian Institute of Technology, Bombay, India, in 1993 with a B.Tech degree. He received his M.A. in Mathematics in 1997, M.S. and Ph.D. in Mechanical Engineering and Applied Mechanics in 1995 and 1998 respectively, all from the University of Pennsylvania. He is a recipient of the *NSF CAREER award* and the *Ralph R. Teetor Educational Award*. He was an invited speaker at the 2011 *National Academy of Sciences' Distinctive Voices @ The Beckman Center* and has also been invited to attend the *National Academy of Engineering's (NAE) 2011 U.S. Frontiers of Engineering Symposium*. His research interests include image-guided surgical robotics, haptics, reality-based soft-tissue modeling for surgical simulation, model-based teleoperation in robot-assisted surgery, and cellular manipulation. He is currently the member of the Haptics Symposium Committee, co-chair of the Surgical Robotics Technical Committee of IEEE Robotics and Automation Society, and a member of the Editorial board of IEEE Transactions on Biomedical Engineering and IEEE Transactions on Information Technology in Biomedicine. He is also a member of the ASME and IEEE.

- **Prof. Pierre Dupont**, Children's Hospital Boston/Harvard Medical School
  Presentation Title: Image-based Design of Procedure-specific Robots

Biography:
Pierre E. Dupont leads the newly established Pediatric Cardiac Bioengineering Program at Children's Hospital Boston and holds the Edward P. Marram Chair of Pediatric Cardiac Bioengineering. His academic appointments include Visiting Professor of Surgery at Harvard Medical School and Professor of Biomedical Engineering at Boston University. His research group develops robotic instrumentation and imaging technology for minimally invasive surgery. He received the B.S., M.S. and Ph.D. degrees in Mechanical Engineering from Rensselaer Polytechnic Institute, Troy, NY, USA. After graduation, he was a Postdoctoral Fellow in the School of Engineering and Applied Sciences at Harvard University, Cambridge, MA, USA. He subsequently moved to Boston University, Boston, MA, USA where, until recently, he was a Professor of Mechanical Engineering and Biomedical

Engineering. He is an IEEE Fellow and winner of the 2010 King-Sun Fu Best Paper Award of the IEEE Transactions on Robotics.

- **Prof. Paolo Fiorini**, University of Verona

Presentation Title: Multimodal 3D Data Fusion and Reconstruction for Needle Insertion Guidance in Cryoablation Procedures

Biography:
Paolo Fiorini, received the Laurea degree in Electronic Engineering from the University of Padova, (Italy), the MSEE from the University of California at Irvine (USA), and the Ph.D. in ME from UCLA (USA). From 1985 to 2000, he was with NASA Jet Propulsion Laboratory, California Institute of Technology, where he worked on telerobotic and teloperated systems for space exploration. From 2000 to 2010 he was an Associate Professor of Control Systems at the School of Science of the University of Verona (Italy) where he founded the ALTAIR robotics laboratory with his students. He is currently Full Professor of Computer Science at the University of Verona. His research focuses on teleoperation for surgery, service and exploration robotics and is funded by several European and Italian Projects. He is an IEEE Fellow (2009).

- **Prof. Gregory Fischer**, Worcester Polytechnic Institute

Presentation Title: A Modular Approach to Rapid Development of MRI Guided Surgical Systems

Biography:
Gregory Fischer is a faculty member at Worcester Polytechnic Institute (WPI) in Mechanical Engineering and Robotics Engineering with an appointment in Biomedical Engineering. He received his PhD from Johns Hopkins University in Mechanical Engineering in 2008 where he was part of the NSF Engineering Research Center for Computer Integrated Surgery (ERC-CISST). Dr. Fischer's primary research focus is on developing enabling technologies for MR-guided surgical interventions including fiber optic sensors, piezoelectric and pneumatic actuators, haptics and teleoperation, modular robot control systems and application testbeds. He is the director of the WPI Automation and Interventional Medicine (AIM) Robotics Research Laboratory (http://aimlab.wpi.edu/). The focus of the research in the AIM Lab is on medical robotics - the link that allows us to enable “closed loop medicine” by using real-time feedback to guide a surgical procedure. In order to take the most advantage of robots in surgery, we work towards integrating real-time medical imaging with the interventional procedure to provide as much information to a surgeon during a

procedure as possible and using that information in a way to produce better outcomes. We have developed a modular approach to MRI-compatible robotics including the software, control hardware and mechanical systems and have used this approach to develop robotic systems for image-guided diagnosis and therapy of prostate cancer and for stereotactic neurosurgery where we can perform surgical manipulation under live MR imaging.

- **Prof. Rao Gullapalli**, University of Maryland

Presentation Title:	Image Guided Interventions: Physics Clinical Challenges

Biography:
Dr. Gullapalli is an Associate Professor in the Department of Radiology and is the Director of the Core for Translational Research in Imaging @ Maryland (C-TRIM) and the Magnetic Resonance Research Center at the University of Maryland School of Medicine. He also holds a secondary appointment at the Fischell Department of Biongineering at the University of Maryland College Park facility. Dr. Gullapalli's research involves the development and application of advanced multi-parametric MRI/MRS techniques in the diagnosis of cancer, and studying pathophysiological changes following traumatic brain injury. Specifically, his interests are in developing multi-parametric techniques to minimize sampling errors by accurately assessing tissue and targeting biopsies through real-time image guided techniques using robotic assistance, and to provide optimal therapy to cancerous tissues using RF-ablative procedures aided by MR thermography under continuous imaging. More recently he has been very active in developing a centralized core for translation imaging that includes MRI, PET, CT and other imaging modalities. Prior to joining University of Maryland Baltimore, Dr. Gullapalli worked as a Senior Clinical Scientist at Picker International (currently Philips Medical Systems) where he was responsible for developing several rapid MR imaging techniques.

- **Prof. Gregory D. Hager**, Johns Hopkins University

Presentation Title:	Video Guidance for Human-Machine Collaborative Intervention

Biography:
Gregory D. Hager is a Professor and Chair of Computer Science at Johns Hopkins University and the Deputy Director of the NSF Engineering Research Center for Computer

Integrated Surgical Systems and Technology. His research interests include time-series analysis of image data, image-guided robotics, medical applications of image analysis and robotics, and human-computer interaction. He is the author of more than 220 peer-reviewed research articles and books in the area of robotics and computer vision. In 2006, he was elected a fellow of the IEEE for his contributions in Vision-Based Robotics.

- **Prof. Robert Howe**, Harvard University

Presentation Title:	Cathbots: Ultrasound-Guided Beating Heart Surgery

Biography:
Robert D. Howe is Abbott and James Lawrence Professor of Engineering, Area Dean for Bioengineering, and Associate Dean for Academic Programs in the Harvard School of Engineering and Applied Sciences. Dr. Howe founded the Harvard BioRobotics Laboratory in 1990, which investigates the roles of sensing and mechanical design in motor control, in both humans and robots. His research interests focus on manipulation, the sense of touch, and human-machine interfaces. Biomedical applications of this work include the development of robotic and image-guided approaches to minimally invasive surgical procedures. Dr. Howe earned a bachelors degree in physics from Reed College, then worked as a design engineer in the electronics industry in Silicon Valley. He received a doctoral degree in mechanical engineering from Stanford University in 1990, and then joined the faculty at Harvard. Among his honors are the National Science Foundation Young Investigator, as well as Best Paper awards at mechanical engineering, robotics, and surgery conferences.

- **Dr. Rainer Konietschke**, German Aerospace Center - DLR
  Presentation Title: Minimally Invasive Surgical Procedures with the DLR MiroSurge Robotic System

Biography:
Rainer Konietschke received his Dipl.-Ing. degree in mechanical engineering from the Technical University of Munich in 2002 and at the same time his master's degree from the Ecole Centrale Paris. Since then, he has been

working at the Institute of Robotics and Mechatronics, DLR, in the field of medical robotics, kinematics, optimization, and optimal surgery planning. He received his Ph.D. degree in electrical engineering from the Technical University of Munich in 2007. He coordinated the efforts of DLR in the EC-funded projects AccuRobAs and SAFROS. Currently he is vice coordinator of the medical group at DLR.

- **Prof. Ken Masamune**, University of Tokyo
  Presentation Title: Needle Guidance Robot and Augmented Reality System for On-site MRI Guided Surgery

Biography:
Ken Masamune received the Ph.D. degree in precision machinery engineering from the University of Tokyo, Japan, in 1999. From 1995 to 1999, he was a Research Associate in the Department of Precision Machinery Engineering, the University of Tokyo. From 2000 to 2004, he was an Assistant Professor in the Department of Biotechnology, Tokyo Denki University, Tokyo. Since 2005, he has been an Associate Professor in the Department of Mechanoinformatics, Graduate School of Information Science and Technology, the University of Tokyo. His current research interests include computer-aided surgery, especially medical robotics and visualization devices and systems for surgery.

- **Prof. Sarthak Misra**, University of Twente
  Presentation Title: Predicting Target Motions for Planning of Medical Interventions

Biography:
Sarthak Misra joined the University of Twente as an Assistant Professor in August 2009. He is a member of the Control Engineering Group and MIRA - Institute for Biomedical Technology and Technical Medicine. Sarthak obtained his doctoral degree in the Department of Mechanical Engineering at the Johns Hopkins University, Baltimore, USA. Prior to commencing his studies at Johns Hopkins, he worked for three years as a dynamics and controls analyst at MacDonald Dettwiler and Associates on the International Space Station Program. Sarthak received his Master of Engineering degree in Mechanical Engineering from McGill University, Montreal, Canada. He is the recipient of the Netherlands Organization for Scientific Research (NWO) VENI award, Link Foundation

fellowship, McGill Major fellowship, and NASA Space Flight Awareness award. Sarthak's broad research interests are primarily in the area of applied mechanics at both macro and micro scales. He is interested in the modeling and control of electro-mechanical systems with applications to medical robotics.

- **Prof. Philippe Poignet**, University of Montpellier 2 - LIRMM
  Presentation Title: Robust 3D motion tracking for robotic-assisted beating heart surgery

Biography:
Philippe Poignet received the M.E and Ph.D. degrees in control engineering from the University of Nantes, France, in 1992 and 1995, respectively. He is currently Full Professor at the University of Montpellier 2 doing his research at the LIRMM laboratory. He leads the DEXTER team working on design and control of robots for manipulation and more particularly the Medical Robotics group. His research interests include robot identification, nonlinear control and the applications to surgical robotics and rehabilitation. He has been or is involved in several national and European projects focusing on medical robotics and has co-authored over 60 peer reviewed publications. He is also co-organizer of the European Summer Schools in Surgical Robotics.

Tentative Workshop Schedule

9:00 - 9:10:	Sarthak Misra and Jaydev P. Desai - Introduction to the workshop
9:10 - 9:40:	Robert Howe - Cathbots: Ultrasound-Guided Beating Heart Surgery
9:40 - 10:10:	Sarthak Misra - Predicting Target Motions for Planning of Medical Interventions
10:10 - 10:40:	Gregory D. Hager - Video Guidance for Human-Machine Collaborative Intervention
10:40 - 10:55:	Poster Teaser Session - I

- Brian C. Becker, Robert A. MacLachlan, Louis A. Lobes, Jr., and Cameron N. Riviere - *Micron: An Image-Guided Intelligent Handheld Tool for Accurate Vitreoretinal Surgery*
- Tamás Haidegger, Balazs Benyó and Peter Kazanzides - *Challenges with Controlling Patient Motion in Image-Guided Robotic Surgery*
- Elif Ayvali, Chia-Pin Liang, Yu Chen, Jaydev P. Desai - *A Discretely Actuated Steerable Cannula with Integrated Optical Coherence Tomography (OCT) Imaging*
- Rob Reilink, Stefano Stramigioli, Astrid M.L. Kappers and Sarthak

Misra - *Steering Flexible Endoscopes for NOTES using Haptic Guidance*

- Phillip J. Swaney, Jessica Burgner, Diana Cardona, Hao Su, Thomas Pheiffer, D. Caleb Rucker, Ray A. Lathrop, Hunter B. Gilbert, Gregory S. Fischer, Michael I. Miga, and Robert J. Webster III - *Image-Guided Targeting of Concentric Tube Robots: Experiments using Ultrasound, Computed Tomography, and Magnetic Resonance Imaging*
- Luis G. Torres and Ron Alterovitz - *Image-Guided Motion Planning for Concentric Tube Robots for Skull Base Surgery*
- Dimitris P. Tsakiris, Michael Sfakiotakis, Xenophon Zabulis, and Nikolaos Pateromichelakis - *Visual Servoing for Robotic Endoscopic Capsules*

10:55 - 11:05:	Coffee Break
11:05 - 11:35	Poster session - I (Discussion between Poster presenters and Workshop attendees)
11:35 - 12:05:	Gregory Fischer - A Modular Approach to Rapid Development of MRI Guided Surgical Systems
12:05 - 12:35:	Jaydev P. Desai - Challenges in MRI-guided interventions: From Macro-scale to Meso-scale
12:35 - 13:05:	Ken Masamune - Needle Guidance Robot and Augmented Reality System for On-site MRI Guided Surgery
13:05 - 14:00:	Lunch
14:00 - 14:30:	Philippe Poignet - Robust 3D motion tracking for robotic-assisted beating heart surgery
14:30 - 15:00:	Rao Gullapalli
15:00 - 15:15:	Poster Teaser session - II

- Madusudanan Sathianarayanan, Seung-Kook Jun, Xiaobo Zhou, Sudha Garimella, Wayne Waz, Frank Mendel, and Venkat Krovi - *Quantitative Performance Assessment within an Image-Assisted Patient-Specific Haptic SIMulator for Needle Biopsies (SIMBiopsies)*
- Ann Majewicz, Steven P. Marra, Mark van Vledder, Ming D. Lin, Michael A. Choti, Danny Y. Song, Allison M. Okamura - *Robotic Needle Steering in ex Vivo and in Vivo Tissue*
- Jasper D. Keuning, Jeroen de Vries, Leon Abelmann, and Sarthak Misra - *Image-Based Control of Microparticles*
- D. Caleb Rucker, Hunter B. Gilbert, Jessica Burgner, Philip J. Swaney, and Robert J. Webster III - *Jacobian-Based Control of Concentric-Tube Robots*
- Hao Su, Xiaoan Yan, and Gregory S. Fischer - *A 4-DOF Parallel*

Robotic Platform for MR Image-Guided Percutaneous Prostate Interventions

- Thomas R. Wedlick, Steven P. Marra, and Allison M. Okamura - *Evaluating Deflection Models for Straight and Curved Steerable Needles*

15:15 - 15:25:	Coffee Break
15:25 - 15:55:	Poster session - II (Discussion between Poster presenters and Workshop attendees)
15:55 - 16:25:	Pierre Dupont - Image-based Design of Procedure-specific Robots
16:25 - 16:55:	Paolo Fiorini - Multimodal 3D Data Fusion and Reconstruction for Needle Insertion Guidance in Cryoablation Procedures
16:55 - 17:25:	Rainer Konietschke - Minimally Invasive Surgical Procedures with the DLR MiroSurge Robotic System
17:25 - 18:00:	Discussion

Poster Abstracts - I

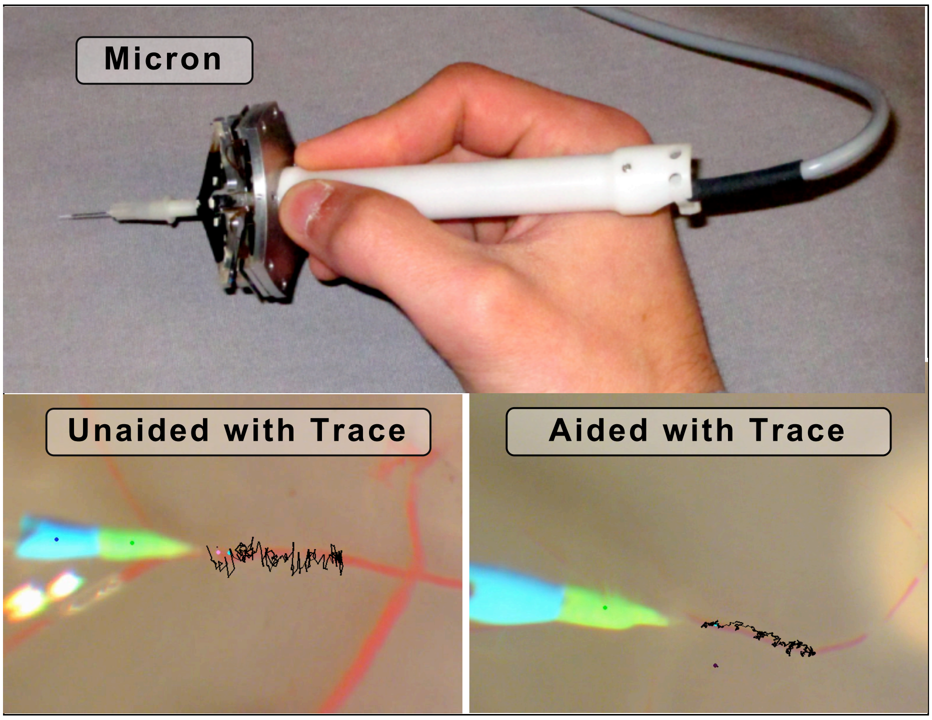
MORNING SESSION

Micron: An Image-Guided Intelligent Handheld Tool for Accurate Vitreoretinal Surgery

Brian C. Becker*, Robert A. MacLachlan*, Louis A. Lobes, Jr.**, and Cameron N. Riviere*

* *Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, USA*

***University of Pittsburgh Medical Center, Pittsburgh, PA, USA*



Abstract:
Medical robotic systems for retinal surgery are often large and bulky, increasing costs, requiring valuable OR space, and necessitating burdensome adaptations to the surgical workflow. Micron is a handheld micromanipulator tool designed for use in delicate operations, such as vitrectomy procedures. It is a fully handheld tool that is lightweight, easy-to-use, and inexpensive. By leveraging familiarity with handheld instruments, Micron is intuitive for surgeons and provides a number of intelligent behaviors. Tremor suppression reduces involuntary and debilitating hand motion during the procedure. Motion scaling provides extra precision as all movements, including tremor, are scaled down. Cameras mounted to the microscope see the same workspace as the operator, allowing smart behaviors such as “snap-to" or “avoid area” relative to the target tissue. Using image-guidance, we derive control techniques for position-based virtual fixtures, where the fixtures are generated in real-time from microscope video. Additionally, we develop motion scaling behavior centered on virtual fixtures as a simple and direct extension to our formulation. We demonstrate that hard and soft (motion-scaled) virtual fixtures outperform state-of-the-art tremor cancellation performance on a set of artificial but medically relevant tasks: holding, move-and-hold, trajectory following, and vein tracing. In an example application of microinjections into tracked vessels of *ex vivo* porcine retina, an experienced vitreoretinal surgeon was able to inject 2/7 vessels without Micron and 5/8 with Micron’s image-guidance, showing increased performance with micromanipulator aid. Furthermore, reduced overall tremor lessens trauma to the surrounding tissue.

Challenges with Controlling Patient Motion in Image-Guided Robotic Surgery

Tamás Haidegger*, Balazs Benyó* and Peter Kazanzides**
** Budapest University of Technology and Economics (BME–IIT), Budapest, Hungary*
*** Johns Hopkins University, CISST ERC/LCSR, Baltimore, MD, USA*
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Abstract:

In robotic surgery, it is crucial to provide clear benefits to the physician and the patient. Intra-operative image guidance can allow for the precise handling of tissue motion, however, advanced materials and technology comes with a significant cost [1]. Despite the high inherent accuracy of the tracking and actuating devices, the overall application accuracy of robot-integrated image-guided (IG) systems is still relatively low, due to several factors [2].

Our research has been focusing on the identification of major sources of errors in the particular case of a CT/MR-guided, co-operatively controlled skull-base surgery robot—developed at the Johns Hopkins University. It incorporates a NeuroMate (Renishaw plc.) equipped with a 6 DOF force/torque sensor and a bone drill, while a StealthStation (Medtronic Inc.) is used for guidance. The initial cadaver and phantom trials showed approximately 1 mm application accuracy. However, the necessary registration and calibration procedures introduce further errors. The patent is registered through a classical fiducial based method to the robot, which fails to guarantee absolute precision. One of the major concerns is the occurrence of post-registration drifts and shifts in the setup. This may be a result of large forces applied by the surgeon, loose setup or equipment failure. Our experiments showed that the compliance of the cranial frame and the robot arm can result in 0.85 mm and 1.55 mm RMS errors, respectively, therefore reducing the effectiveness of the IG treatment [3].

The aim was to improve surgical robot navigation through identification of Surgical Cases in the Operating Room. A generic approach is proposed for integrated IGS systems, using the intra-operative navigation device's internal coordinate base frame to better estimate the possible changes in the environment. Understanding the procedure and technology of brain and spine surgery will help to develop systems that better suit the surgeons' need.

References

[1] N. Nathoo, M. C. Cavusoglu, M. A. Vogelbaum and G. H. Barnett, "In Touch with Robotics: Neurosurgery for the Future," Neurosurgery, vol. 56, no. 3, pp. 421–433, 2005.

[2] P. Kazanzides, G. Fichtinger, G. D. Hager, A. M. Okamura, L. L. Whitcomb and R. H. Taylor, "Surgical and Interventional Robotics: part I," IEEE Robotics and Automation Magazine (RAM), vol. 15, no. 2, pp. 122–130, 2008

[3] T. Haidegger, P. Kazanzides, J. Sandor and Z. Benyo, "Technological challenges of image-guided robotic surgery—abrupt changes in the operating room," in Proc. of the 4th Scientific Meeting of the Japan-Hungary Surgical Society (JHSS), Yokohama.

A Discretely Actuated Steerable Cannula with Integrated Optical Coherence Tomography (OCT) Imaging

Elif Ayvali*, Chia-Pin Liang**, Yu Chen**, Jaydev P. Desai*
** Robotics, Automation, and Medical Systems (RAMS) Laboratory*
**Maryland Robotics Center, Institute for Systems Research*
**Department of Mechanical Engineering*
***The Fischell Department of Bioengineering*
University of Maryland, College Park, USA

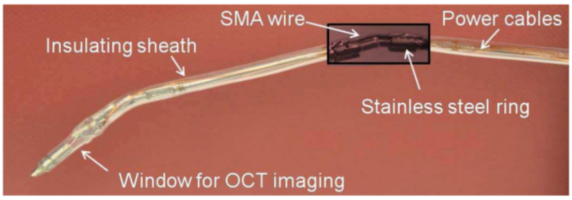


Fig.1. 2-DOF cannula prototype

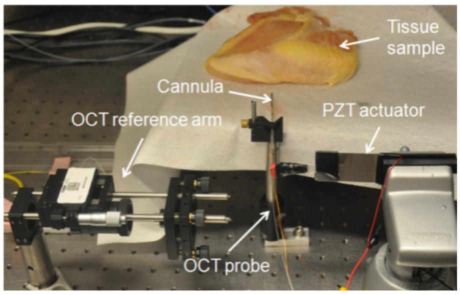


Fig.2. Experimental setup for OCT system

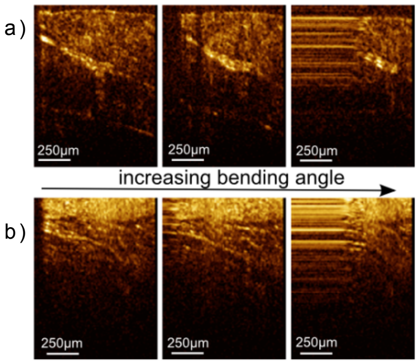


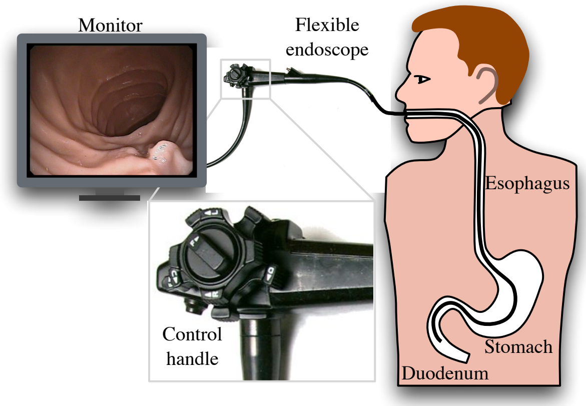
Fig.3. Microstructures of (a) porcine tissue, (b) chicken breast

Abstract:

We have designed, developed, and evaluated the performance of a discretely actuated steerable cannula with shape memory alloy (SMA) actuators and integrated optical coherence tomography (OCT) imaging capability. This will enable us to deliver diagnostic as well as therapeutic devices to the target location through hollow inner core of the cannula. We propose use of SMA to generate bending forces due to its small size and high power density. SMA wires were shape-setted through a customized training process to an arc shape and mounted on the outer surface of the cannula to generate local bending action upon thermal actuation. Pulse width modulation (PWM) -based control scheme was implemented via use of a switching circuit to control all SMA actuators simultaneously to enable multiple joint motion. Proposed controller was validated through an experiment inside gelatin to mimic the motion of the cannula inside a medium which requires significant amount of force for moving the various joints of the cannula. To demonstrate the delivery of a diagnostic tool through our cannula, we showed that we can pass an OCT probe through the cannula and perform micro-scale imaging. Through several *ex-vivo* experiments, we demonstrated the versatility of our discretely actuated cannula by imaging different tissue types as well as imaging at various joint angles.

Steering flexible endoscopes for NOTES using haptic guidance

Rob Reilink*, Stefano Stramigioli*, Astrid M.L. Kappers** and Sarthak Misra*
*University of Twente, Enschede, The Netherlands
**Utrecht University, The Netherlands



Abstract:
A flexible endoscope enables a physician to examine the internal body cavities of the patient in a minimally invasive way. The control of the endoscope is not intuitive, since steering in the up/down and left/right directions is operated by two concentric wheels. This makes steering difficult, especially for less experienced physicians. Recently, advanced endoscopes have been developed that allow physicians to also perform surgical procedures (NOTES-Natural Orifice Transluminal Endoscopic Surgery). These advanced endoscopes have many more degrees of freedom, making the control even more difficult.

In order to aid the physician in steering the endoscope through an endoluminal path, we have developed a computer vision algorithm that finds the direction of the lumen using endoscopic images. An experimental setup was designed, in which this algorithm was used to robotically steer an endoscope through an endoluminal path from the mouth up to the duodenum in an anatomical model.

Subsequently, a shared control approach was studied, in which the physician uses a multi-degree-of-freedom haptic device to steer the endoscope in an intuitive way. The aforementioned computer vision algorithm was used to generate the haptic guidance. The haptic device was used to display a force that guides the physician to the motion that is required to get the lumen centered in the endoscopic image.

This shared control approach was evaluated using a human subject experiment in which 6 experienced physicians and 12 students participated. They were given the task to insert a colonoscope up to the end of the colon in a colonoscopy simulator. The results suggest that the addition of haptic guidance will reduce the patient discomfort.

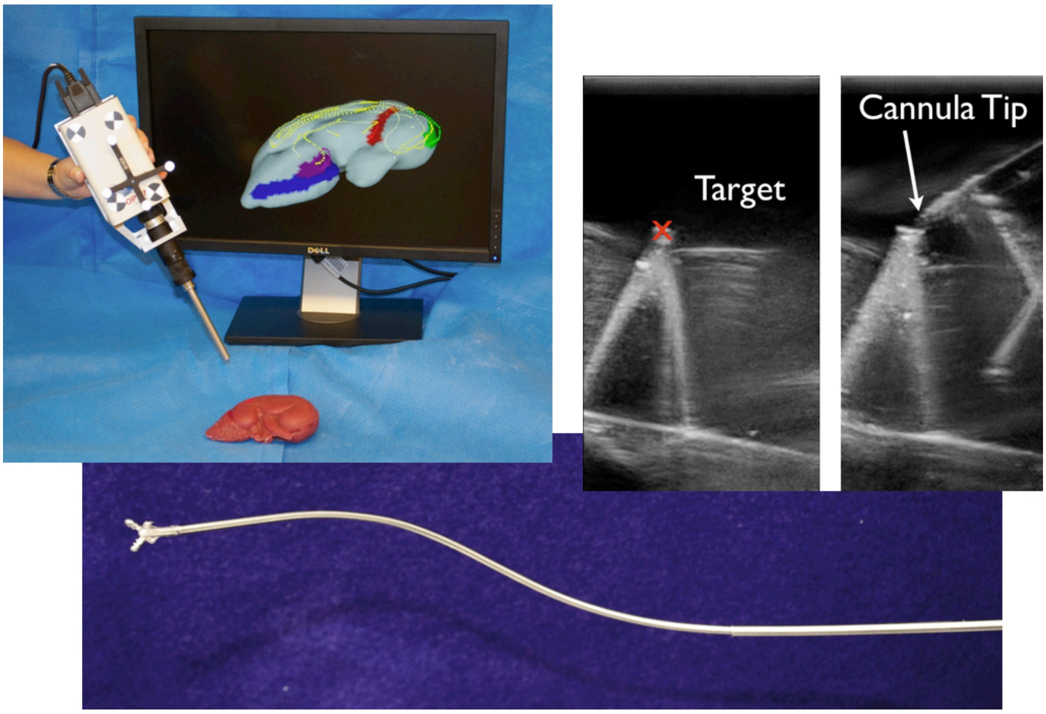
References

[1] R. Reilink *et al.*, *Image-based flexible endoscope steering*. In Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems, Taipei, Taiwan, 2010; pp 2339 – 2344
[2] R. Reilink, *et al.*, *Evaluation of flexible endoscope steering using haptic guidance*. In The International Journal of Medical Robotics and Computer Assisted Surgery, 2011; vol.7, no. 2, pp 178-186

Image-Guided Targeting of Concentric Tube Robots: Experiments using Ultrasound, Computed Tomography, and Magnetic Resonance Imaging

Phillip J. Swaney*, Jessica Burgner*, Diana Cardona*, Hao Su***, Thomas Pheiffer**, D. Caleb Rucker*, Ray A. Lathrop*, Hunter B. Gilbert*, Gregory S. Fischer***, Michael I. Miga**, and Robert J. Webster III*

*Vanderbilt University, Department of Mechanical Engineering, Medical & Electromechanical Design Laboratory
**Vanderbilt University, Department of Biomedical Engineering, Biomedical Modeling Laboratory
***Worcester Polytechnic Institute, Department of Mechanical Engineering, Automation and Interventional Medicine Laboratory



Abstract:
We will present experimental results in image guidance of concentric tube robots using several different imaging modalities. These needle-diameter robots can function as either miniature tentacle-like manipulators (the subject of a paper we will present later at IROS), or as steerable needles. In this poster, we will present recent experimental results for targeting locations within soft tissues under (1) ultrasound, (2) CT, and (3) MRI guidance. The primary clinical goal of these experiments is to access multiple target locations through a single needle entry point for thermal ablation of tumors and other structures. However, our systems, models, and guidance algorithms are applicable to a wide variety of needle-based procedures, including brachytherapy, injections, biopsy, etc.

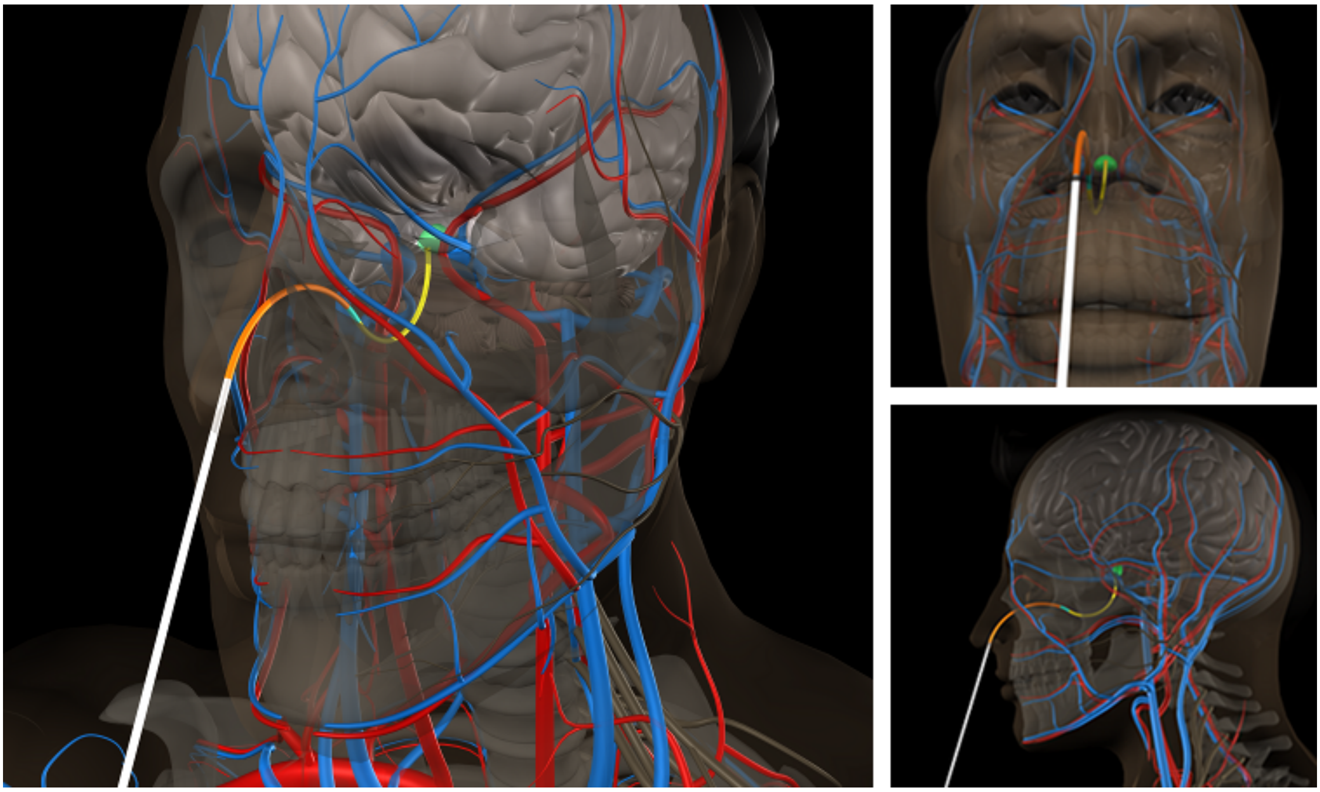
References

[1] R. A. Lathrop, D. C. Rucker, and R. J. Webster III. Guidance of a Steerable Cannula Robot in Soft Tissue Using Preoperative Imaging and Conoscopic Surface Contour Sensing. IEEE International Conference on Robotics and Automation, 5601-5606, 2010.

[2] E. M. Boctor, P. Stolka, C. Clarke, D. C. Rucker, J. M. Croom, E. C. Burdette, and R. J. Webster III. Precisely Shaped Acoustic Ablation of Tumors Utilizing Steerable Needle and 3D Ultrasound Image Guidance. Proceedings of SPIE Medical Imaging, 2010.

Image-Guided Motion Planning for Concentric Tube Robots for Skull Base Surgery

Luis G. Torres and Ron Alterovitz
University of North Carolina at Chapel Hill, USA



Virtual simulation of a concentric tube robot executing a motion plan for neurosurgery at the skull base. The robot is inserted through the nostril and guided toward the pituitary gland (highlighted in green) in the skull base while avoiding skin, bone, blood vessels, and healthy brain tissue.

Abstract:
Concentric tube robots have the potential to enable new, safer neurosurgery procedures by maneuvering through the nasal cavity to reach difficult-to-reach sites at the skull base. Planning motions for concentric tube robots is challenging due to their complex kinematics; these devices are composed of thin, pre-curved, telescoping tubes and can achieve a variety of shapes via extension and rotation of each of their constituent tubes. We introduce a new image-guided motion planner to maneuver these devices to clinical targets in the highly-constrained workspace of the nasal cavity and the skull base. The planner uses segmented pre-operative medical images (e.g. CT scans or MRI) to define the robot's feasible workspace. Unlike prior planners for these devices, we more accurately model device shape using mechanics-based models that consider torsional interaction between the tubes. We integrate these models with a sampling-based approach based on the Rapidly-Exploring Roadmap to guarantee finding optimal plans as computation time is allowed to increase. These plans minimize the estimated probability of colliding with sensitive structures (e.g. vessels, tissue) under motion uncertainty. We demonstrate our planner using both synthetic environments and an anatomy-based neurosurgery case that requires maneuvering to a difficult-to-reach pituitary gland tumor at the skull base.

Visual Servoing for Robotic Endoscopic Capsules

Dimitris P. Tsakiris*, Michael Sfakiotakis*, Xenophon Zabulis*
and Nikolaos Pateromichelakis*
* *Institute of Computer Science - FORTH, Heraklion, Greece*

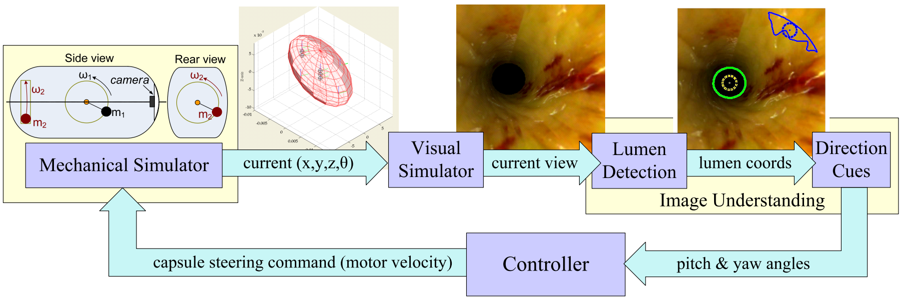


FIGURE – Simulation framework of the visual servoing scheme.

Abstract:
The clinical practice in capsule endoscopy is based on passive capsule propulsion inside the gastrointestinal tract (GIT) by peristalsis. Current research aims at endowing these devices with means of active locomotion, transforming them to full-fledged robotic systems, with locomotion, sensing, powering, control and data transmission capabilities. However, this necessitates the involvement of the medical personnel, performing the examination, also in the navigation of the capsule through the GIT. It becomes, therefore, desirable that certain, potentially cumbersome, aspects of this task, such as traversing long segments of the GIT, be automated, at least to some extent.
To this end, our group has been investigating the use of visual information, obtained by the real-time analysis of the images acquired from the capsule's on-board camera, for implementing capsule steering by appropriate visual servoing techniques [1-2]. Such image-based control strategies, for navigating the capsule by aligning its line-of-sight with the GIT, based on the detection of the intestinal lumen in the acquired images, have been developed and adapted to active locomotion of the capsule, either by on-board vibratory actuation or by external magnetic fields. Extensive modeling and simulation studies have been performed, focusing on the interaction of our devices with the GIT, the image acquisition and analysis process and the controller design [3]. The overall simulation framework is illustrated in the above Figure. The use of such strategies for robotic capsule devices is currently being investigated, also based on the findings of ex-vivo and in-vivo tests of related experimental prototypes [4-6].

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Poster Abstracts - II

AFTERNOON SESSION

Quantitative Performance Assessment within an Image-Assisted Patient-Specific Haptic SIMulator for Needle Biopsies (SIMBiopsies)

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Sudha Garimella *MD*, Wayne Waz *MD*, Frank Mendel and Venkat Krovi
State University of New York at Buffalo

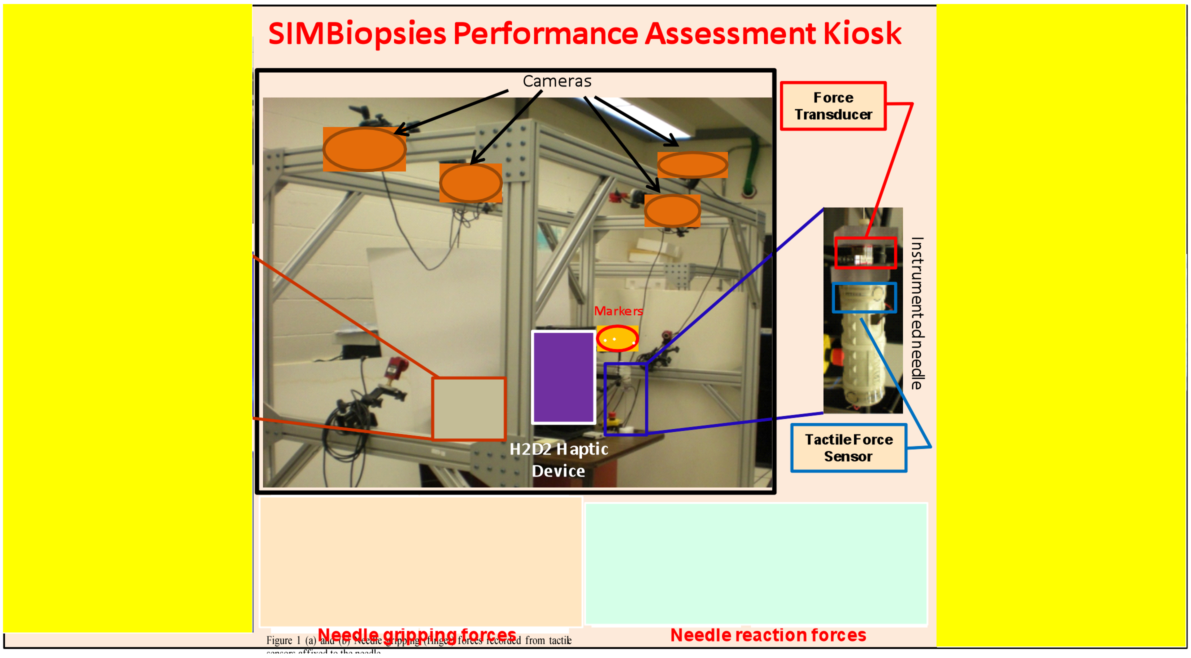

FIGURE – Quantitative Performance Assessment of Trainees under Virtual and Physical Simulation Mode Operation using SIMBiopsy Framework with MR/ Ultrasound Image-Guidance

Abstract:

Needle biopsy is an important and common procedure for lesion detection or tissue extraction within the human body. Physicians conducting such procedures rely primarily on the sense of "touch" (kinesthetic feedback from needle) to estimate the current needle position and organs within its vicinity. This skill takes time to acquire and mature, often by biopsies on live patients. Medical residents and fellow trainees thus have limited opportunities both in terms of real life scenarios as well as testing platforms to develop and validate their skills.

Hence our focus is on developing and validating a biopsy-training simulator-kiosk using cadaveric specimens to allow for both realism as well as diversity. We mapped the Hounsfield density of MR images of cadavers to virtual-haptic models facilitating creation of "patient-specific" models. Cross validation is now possible by material-testing (force/displacement) experiments on the cadaveric specimen by an instrumented 6-DOF robot needle driver. Trainees interact with a biopsy-needle and ultrasound probe (attached to instrumented high-fidelity haptic-devices) with either hand within our simulator-trainer kiosk instrumented with real-time motion-capture cameras. Quantitative and transparent capture of raw biopsy performance data (motion-force haptigrams) is now possible on both virtual- and physical-cadaveric specimens and forms the basis of extraction of quantitative performance assessment metrics.

Robotic Needle Steering in *ex Vivo* and *in Vivo* Tissue

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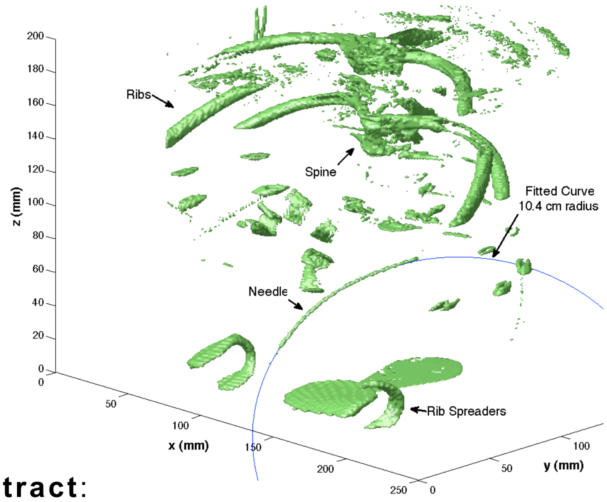
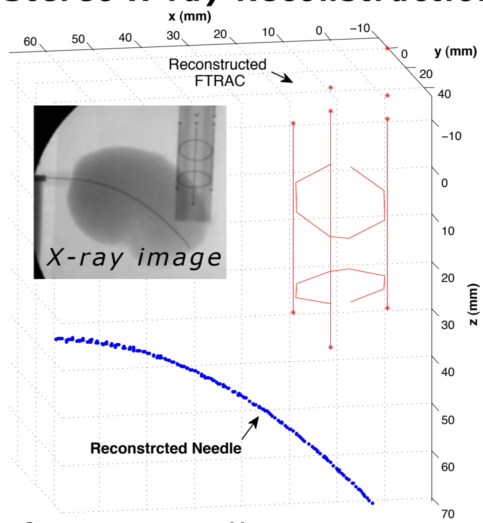
CT Reconstruction



Stereo X-ray Reconstruction



Abstract:
Needle-based procedures are popular for minimally invasive medical diagnosis and interventions, including neoadjuvant therapy, biopsy, ablation, and brachytherapy. In many procedures, image-guided control and accurate tip placement are critical. Robotic needle steering is a promising technique that allows for accurate needle guidance by enabling the clinician to redirect the needle in tissue and avoid anatomical obstacles.

In this work, we explore the capabilities, challenges, and clinical relevance of asymmetric-tip needle steering through experiments in *ex vivo* and *in vivo* tissue. We measure needle curvature from stereo x-ray reconstructions and CT data in prostate, kidney, and liver, using a fluoroscope tracking fiducial (FTRAC). We also measure steering forces using a 6-axis force-torque sensor. We compare steerable needles to conventional stainless-steel needles and generate a dataset for needle steering in *ex vivo* tissue to facilitate statistical analysis of the effects of various parameters on needle steering. In *in vivo* experiments, we examine the effects of blood perfusion on needle steering and assess the operative trauma of needle steering through post-operative blood work and histology.

We found that blood perfusion affects needle curvature and force, particularly in liver, with minimum radius of curvature of pre-bent needles in *ex vivo* tissue of 5.23 cm and in *in vivo* tissue of 10.4 cm. This discrepancy could be due to increased stiffness and the effect of inhomogeneity due to perfused blood vessels. Through histological analysis of *in vivo* tissue, we found that steerable needles do not damage tissue more than conventional stainless steel needles. Finally, steerable needles do not exhibit enough curvature to be clinically relevant in prostate, which indicates the need to improve needle steering design for those applications.

Image-Based Control of Microparticles

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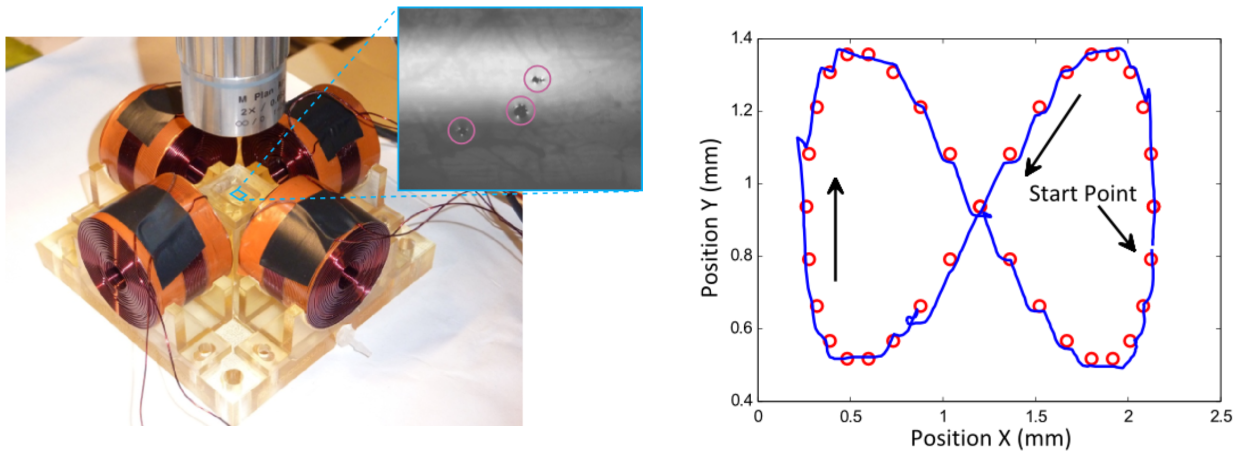

Left: An image of the setup with an image captured by the camera. Right: The microparticle following a figure-eight path. The red circles are the setpoints. The blue line is the measured path of the microparticle.

Abstract:
Microrobotic systems can be inserted into the body and use natural pathways, such as arteries and veins or the gastrointestinal tract, to reach their target for drug delivery or diagnosis. This can greatly reduce the trauma to the patient when compared to reaching this target using conventional minimally invasive surgical procedures. Reducing the size of these robots will further increase their potential penetration depth inside the body. The smaller size means they will be able to travel through smaller pathways to reach their target.

In this work, we describe the design of compact a system for controlling the position of spherical paramagnetic microparticles that have an average diameter of 100 μm. The focus of this study lies in designing and implementing a system that uses microscopic images and electromagnets. Preliminary experiments have been done to verify the feasibility of the system to track and control the position of these microparticles. The system was used to position microparticles within 8.4 μm of a setpoint, achieving speeds of up to 235 μm/s. We also demonstrated that the microparticle could follow a circular and a figure-eight path. Currently we are focusing on improving the tracking performance of the microparticle by implementing a model-based controller. Also the microparticles will be replaced by self-propelled microrobots that take energy from their direct surroundings for propulsion. At the moment catalytic reactions between platinum and hydrogen peroxide are being investigated. Here, the propulsion will come from oxygen bubbles formed on the platinum surface or self-electrophoresis. With these robots the magnetic fields will be utilized to steer the microparticle in the right direction.

Jacobian-Based Control of Concentric-Tube Robots

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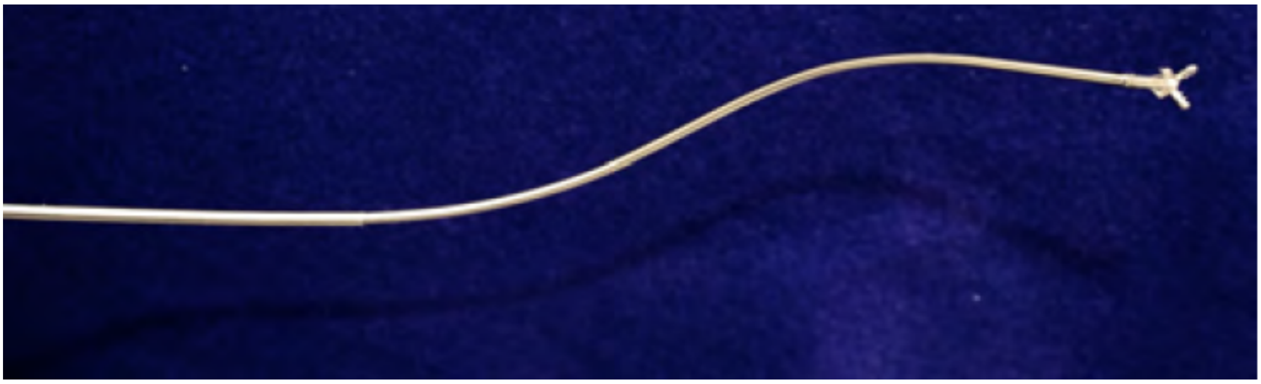

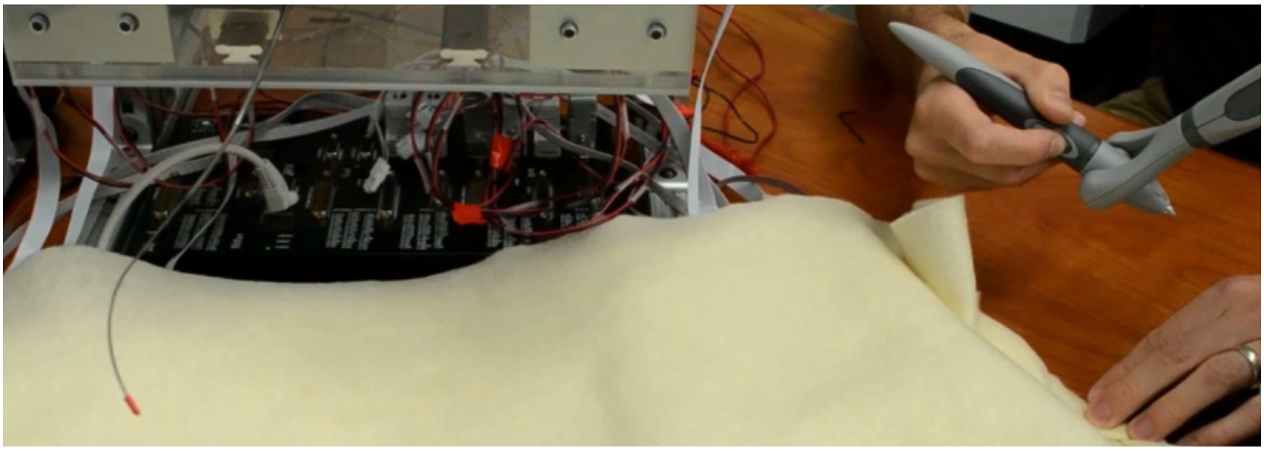

Abstract:
We present a Jacobian-based method to enable real-time control of concentric tube robots. This method is useful for image-guided or sensor-based visual servoing, and for teleoperation. It involves real-time (>1000 Hz) computation of the mechanics-based model differential equations that define the robot's kinematics and Jacobian. These equations also account for external loads applied to the robot by tissue. We present a resolved rates algorithm, which tracks a desired trajectory that can be specified by a physician using medical images, or with a master input device. The robot also simultaneously accomplishes secondary goals such as avoiding joint limits and undesirable configurations. This method enables concentric tube robots to be guided to or away from specific medical targets or obstacles using image or sensor feedback.

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A 4-DOF Parallel Robotic Platform for MR Image-guided Percutaneous Prostate Interventions

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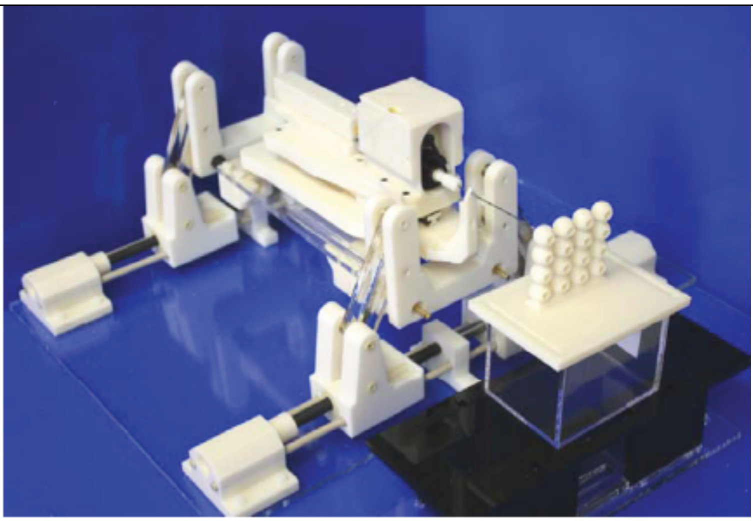

MRI compatible 4-DOF manipulator prototype integrated with a 3-DOF piezoelectrically actuated needle driver module to provide needle manipulation motion for prostate interventions.

Abstract

As part of our effort to develop modular software, robot controller hardware and robotic mechanisms for use under magnetic resonance imaging (MRI) guidance, this paper describes a modular design approach for a robotic surgical manipulator. The challenges come from electromagnetic compatibility within the high-field (1.5 Tesla or greater) MRI environment and mechanical constraints due to the confined close-bore space. Moreover, needle based interventions incur physical interaction between needle and organs, thus the needle is susceptible of deflection and surgical targets could migrate.

By leveraging a novel mechanism, the proposed manipulator provides 2 degree of freedom (DOF) Cartesian motion and 2-DOF pitch and yaw motion, this allowing Cartesian position and angulation of a needle. Primarily built of dielectric materials, it utilizes a parallel mechanism and is compact in size to fit into the limited space of close-bore MRI scanner. The platform is designed to serve a modular base for needle-based surgical procedures which usually require positioning and orientation control for accurate imaging plane alignment. In the primary application, this modular manipulator is coupled with a 2-DOF needle driver module (insertion and rotation) for prostate interventional applications. In addition, this robotic system provides software programmed remote center of motion and is capable of more dexterous prostate intervention.

References

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Evaluating Deflection Models for Straight and Curved Steerable Needles

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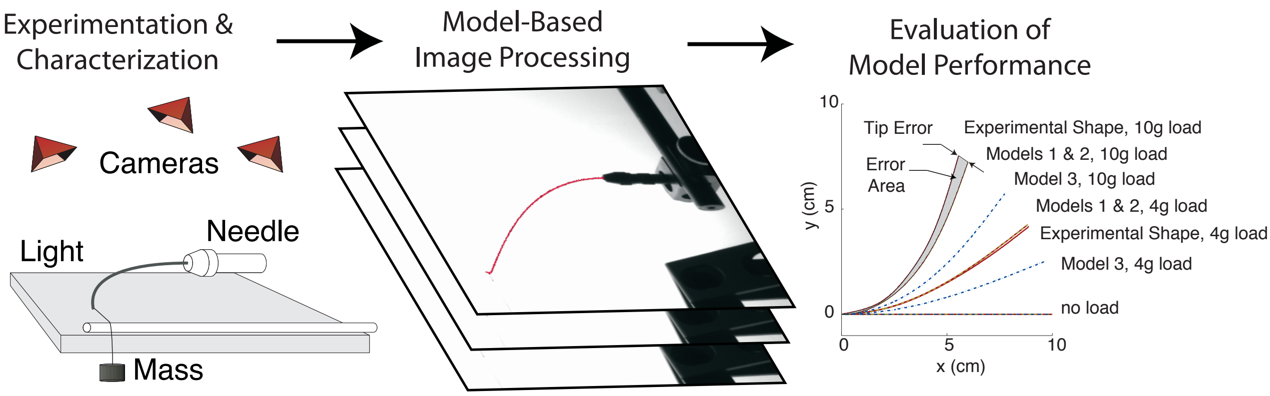

Abstract:

A needle with an asymmetric tip naturally deflects when inserted into tissue. With image guidance, such a needle can be steered to acquire a target or avoid an obstacle through a combination of insertion and rotation about the needle's long axis. Path planners and controllers for needle steering require models of needle deflection, which can also facilitate needle segmentation within medical images. This study considered seven needle deflection models for both initially straight and pre-curved Nitinol asymmetric-tip steerable needles:

- linearly and quadratically interpolating tetrahedral finite element models
- quadratically interpolating hexagonal finite element models
- linearly and quadratically interpolating Timoshenko beam models
- cubically interpolating Euler-Bernoulli beam models, and
- elastica models.

The contributions of this study are (1) comparison of the performance of a wide set of needle deflection models, (2) implementation of deformable model-based image segmentation and curve fitting algorithms that capture needle shape despite occasional needle occlusion, and (3) evaluation of the models' ability to predict large deflections of initially straight and curved needles made of superelastic Nitinol.

Three-point bending experiments characterized needle material properties, and cantilevered needle deflection experiments illustrated the models' predictive abilities. Finite element and analytic models were both used in deformable-model and optimization based image-processing algorithms. The models were evaluated for their prediction accuracy, solution speed, complexity, and sensitivity to model parameters. With one exception, all the models predicted similar needle deflections. Elastica models did not easily generalize, and linearly interpolating Timoshenko beam finite elements were the most efficient. The models were accurate for small to moderate tip loads (up to 70mN and 196mN for the initially straight and pre-curved needles, respectively), but they significantly erred for large needle deflections, indicating the linear constitutive model assumed in all known needle deflection models fundamentally limits model performance.