NSF Award Number: 0932272
Title: Image Guided Robot-Assisted Medical Interventions

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MINIMALLY INVASIVE SURGERIES

Minimally invasive surgeries have emerged as an alternative to traditional open surgeries, since they contribute to improving patient management and cost effectiveness. Among the important factors for their further advancement are robust, scalable and efficient computational methodology for integrating (i) multimodal sensing (including real-time imaging), (ii) controlled robotic manipulators, and (iii) the interventionalist or operator (e.g., surgeon, cardiologist etc). Motivated by the aforementioned potential impact of minimally invasive surgeries in the present and future healthcare, and within the framework of this CPS, we are pursuing the development of a novel cyber-physical system for performing Multimodal Image-guided RObot-assisted Surgeries (MIROS).

SCIENTIFIC DIRECTIONS

The scientific directions and the associated specific research objectives of the MIROS project is its reliance on true sensing of the physical world with multi-contrast imaging and distributed force/bending-sensors, to maneuver a steerable surgical robotic manipulator inside the continuously changing environment of a patient while offering a comprehensive perception of the Area of Operation (AoO) to the operator via a visuo-haptic interface.

THE TEAM

INVESTIGATORS

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EMERGING TRENDS IN INTERVENTIONAL MEDICINE

1. Use of new non-traditional modalities for guidance MRI, Optical Imaging
2. Multimodality Approaches
   - Complementary information about pathology
3. Real-time Imaging
   - On-the-fly adjustment of the acquisition protocol
4. Robotic Manipulator Assistance
5. Automated Real-time image Processing

WHY MRI GUIDANCE?

1. Excellent Soft Tissue Contrast
2. Lack of Ionizing Radiation
3. Endogenous "absolute" coordinate system of the MR scanner
4. True 3D or multislice 2D and arbitrary definition of imaging planes/volumes
5. On-the-fly: adjustment of imaging planes and/or contrast mechanism

WHY ROBOTIC MANIPULATORS?

1. Access to the patient who remains inside the scanner during the entire or part of the procedure
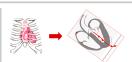2. Real-time Image Guidance
   - On-the-fly adjustment of the trajectory.
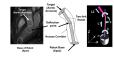   - Multi-modality co-registration (optical imaging, US, endoscopy)
3. Use with High Field (1 - 4 x Tesla) Scanners!

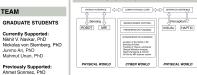## INTRACARDIAC SURGERY

Capability to:

1. Follow a non-linear path of Access to the target or targets
2. Access and intervene to moving tissue (i.e. heart)
3. MR-Compatible steerable catheters
4. MR Image based real-time tissue tracking

CARDIAC SURGERIES ON BEATING HEART

SYSTEM OVERVIEW

PHYSICAL WORLD | CYBER WORLD | PHYSICAL WORLD

THIRD YEAR AREAS OF FOCUS

COMPUTATIONAL CORE
- Backbone Planning/Control Code
- Surgical Planning and Visualization
- New Algorithms for Force-Feedback Rendering
- Image-based generation of 4D Access Corridor in moving tissues for Robot Maneuvering
- Multi-threaded implementation for real-time image processing and robot control

HAPTIC INTERFACE

SENSOR-LEVEL
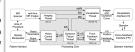- Robot assisted Molecular Level MR/Optical Imaging Probe
- Dynamic MR Raw Data Collection Strategies

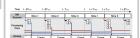**ENABLING METHODOLOGY**
- Robot for Cardiac Surgeries

SUPPORTING METHODOLOGY
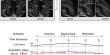- Actuated cardiac-motion mimicking Phantom

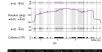## ARCHITECTURE OF CURRENT COMPUTATIONAL CORE

Computational framework for an image-guided robot-assisted telemanipulated surgical system for cardiac interventions. Integrates physical components (MR scanner, slave robotic manipulator, operator's interface consisting of GUI and force-feedback equipped master controllers) with cyber components consisting of routines for on-the-fly image processing, virtual fixture generation, robot guidance and control, and rendering visual-force-feedback information to the operator interfaces.

HAPTIC INTERFACE

Photographs of the prototype and its different sub-assembles

Control scheme for the Force-feedback device.

Representative example of image processing by the imaging thread pipeline:

(a) Representative results of the recorded stream of the simulated surgical task of transapical aortic valve implantation.
(b) Five selected frames from the recorded stream.

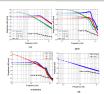Comparison of the position of the end effector and its projection measured for a surgical task with and without guidance fixture (and in presence of visual guidance).

Average errors measured over the duration of a surgical task for the four guidance schemes.

ENABLING METHODOLOGY
"Robot for Cardiac Surgery"

A new 6 DoF MR-compatible robot under development for surgical and interventional procedures with real-time MR guidance. An important innovation we are pursuing is a new method of actuation that resembles pneumatic/hydraulic actuators but without air or fluid! This we anticipate that successful development of this actuation may offer a unique new and low cost way to actuate medical robotics.

Open loop frequency response of the device vs. the vibration detection threshold of the hand for (a)yaw, (b)pitch, (c) translation, (d)roll and (e)tip bending axes, scaled by the corresponding DC motors' maximum continuous torque values.
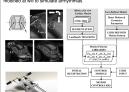
SUPPORTING METHODOLOGY
"Actuated cardiac-motion mimicking Phantom"

Purpose: To mimic the motion of cardiac landmarks pertinent to a transapical surgery under controlled laboratory conditions. The trajectories are extracted from MR images, as well as can modified at will to simulate arrhythmias.

The Dimensions and range of motion are those of the human heart (extracted from MR images)
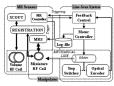
3D Model of the Actuated Phantom

SENSOR LEVEL WORK:
THE "RoboScanner" PROJECT

Purpose: Develop an approach for biosensing at the molecular and near-cellular level compatible with robotic surgeries
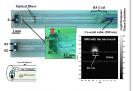
Approach: Implement a method that mechanically scans miniature MR and optical sensors so the raw data are inherently co-registered

MRS: magnetic resonance spectroscopy
Current sensor: miniature RF coil (i.e. antenna for MR signal)

PUBLICATIONS

Intellectual Property:

Nikolaos V. Tsekos and Ahmet Sonmez "Devices, systems and methods for multimodal biosensing and imaging", US Patent Application Filing Date: Sep 8, 2011 (number: 13/199,741; Publication number: US 20120095322 A1)

Nikolaos V. Tsekos "Robotic Device, and Methods, Software and Hardware for Image-Guided and Robot-Assisted Surgeries and Minimally Invasive Interventions" Patent Application Filing Date: Aug 27, 2012

Nikolaos V. Tsekos and Nikhil V. Navkar "Methods, Software and Hardware for Image-guided and Robot assisted Surgeries and Minimally Invasive Interventions" US Provision Patent Application Filing Date: Aug 27, 2012

Papers at Journals:

A Framework for Visual-Force-Feedback Interfacing of Robot-Assisted Interventions using real-time MRI.
N.V. Navkar, Z. Deng, D.J. Shah, and N.V. Tsekos.
IEEE Transaction on Biomedical Engineering, (Accepted with Minor Revision), 2013

A system for endoscopic mechanically scanned localized proton MR and light-induced fluorescence emission spectroscopies.
A.E. Sonmez, A. Webb, W.M. Spees, A. Ozcan, and N.V. Tsekos.
Journal of Magnetic Resonance, 2012.

An approach for preoperative planning and performance of minimally invasive MR-guided interventions with a manually-operated robotic device.
Seimenis, N. V. Tsekos, C. Keroglou, E. Eracleous, C. Pitris, and E. Christoforou.
Cardiovascular and Interventional Radiology, 2011 (In Press).

Context-Aware Motion Simulation for Crowds Simulation.
Qin Gu and Zhigang Deng.
IEEE Computer Graphics and Applications (CG&A), 2010.

Papers at Refereed Conferences:

Image Guided Mechanically Scanned and Coregistered Localized Optical and MR Spectroscopies.
A.E. Sonmez, A. Webb, and N.V. Tsekos.
In IEEE International Conference on Bioinformatics and BioEngineering (BIBE), 2012.

Robot-assisted Mechanical Scanning and Co-registration of Magnetic Resonance Imaging and Light-Induced Fluorescence.
A.E. Sonmez, A. Webb, W.M. Spees, A. Ozcan, Z. Deng, A. Webb, and N.V. Tsekos.
In IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2012.
FINALIST FOR BEST STUDENT PAPER AWARD

An Actuated Phantom for Developing and Studying MRI-Guided Interventions in Dynamic Environments.
N.C. von Sternberg, Y.S. Hedayati, H.M. Zald, E. Yeniaras, E. Christoforou, and N.V. Tsekos.
In IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), 2012.

Visual and Force-Feedback Guidance for Robot-Assisted Interventions in the Beating Heart with Real-Time MRI.
N.V. Navkar, Z. Deng, D.J. Shah, K.E. Bekris, and N.V. Tsekos.
In Proceedings of IEEE International Conference on Robotics and Automation (ICRA), 2012.
FINALIST FOR BEST MEDICAL ROBOTICS PAPER AWARD

Dynamic Simulation of Blood Flow Effects on Flexible Manipulators During Intra-Cardiac Procedures on the Beating Heart.
A. Salimi, J. Mohammadpour, K. Grigoriadis, and N.V. Tsekos.
In Proceedings ASME Conference on Dynamic Systems & Control (DSC), 2011.

Linear Parameter Varying Control of a Robot Manipulator for Aortic Valve Implantation.
A. Ramezanifar, A. Salimi, J. Mohammadpour, K. Grigoriadis, and N.V. Tsekos.
In Proceedings ASME Conference on Dynamic Systems & Control (DSC), 2011.

MR-based Real Time Path Planning for Cardiac Operations with Transapical Access.
E. Yeniaras, N.V.Navkar, A.E.Sonmez, D.J.Shah, Z.Deng, and N.V.Tsekos.
In Proceedings of International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI), pages 25-32, 2011.

Generation of 4D Access Corridors from Real-Time Multislice MRI for Guiding Aortic Valvulplastes.
N.V.Navkar, E.Yeniaras, D.J.Shah, N.V.Tsekos, and Z.Deng.
In Proceedings of International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI), pages 249-256, 2011.

Simulations and Experimental Demonstration of Coupling Molecular and Macroscopic Level Modalities with a Robotic Manipulator.
A.E. Sonmez, Y.Hedayati, A.Ozcan, W.M.Spees, N.V.Tsekos.
In International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pages 7446-7449, 2011.

Cardiac MRI Intervention and Diagnosis via Deformable Collaborative Tracking.
Y. Zhou, N. Tsekos, and I. Pavlidis.
In Proceedings of 6th International Conference on Functional Imaging and Modeling of the Heart (FIMH), pages 188-194, 2011.

Robot-facilitated Scanning and Co-registration of Multi-modal and Multi-level Sensing; Demonstration with Magnetic Resonance Imaging and Spectroscopy.
A.E.Sonmez, A.Ozcan, W.M.Spees, N.V.Tsekos.
In Proceedings of IEEE International Conference on Robotics and Automation (ICRA), pages 1133-1138, 2011.

Virtual Reality Enhanced Control of A Robotic Manipulator for Image Guided Interventions in the Beating Heart.
E. Yeniaras, J.Lamaury, N.V.Navkar, D.J.Shah, K.Chin, Z.Deng, and N.V.Tsekos.
In Proceedings of IEEE International Conference on Robotics and Automation (ICRA), pages 6270-6275, 2011.

Extracting Geometric Features of Aortic-Valve Annulus Motion from Dynamic Cardiac MRI for Guiding Interventions.
N.V.Navkar, E.Yeniaras, D.J.Shah, N.V.Tsekos, and Z.Deng.
In Proceedings of IEEE International Symposium on Biomedical Imaging (ISBI), pages 1302-1305, 2011.

A Novel Virtual Reality Environment for Preoperative Planning and Simulation of Image Guided Intracardiac Surgeries with Robotic Manipulators.
E. Yeniaras, Z.Deng, M.A. Syed, M.G Davies and N.V. Tsekos.
In Proceedings of Medicine Meets Virtual Reality (MMVR), pages 716-722, 2011.

A Shape-Driven MRF Model for the Segmentation of Organs in Medical Images.
D.R. Chittajallu, S. Shah, I.A. Kakadiaris.
In Proceedings of IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pages 3233 - 3240, 2010.

Design of an actuated phantom to mimic the motion of cardiac landmarks for the study of image-guided intracardiac interventions.
N. von Sternberg, Y. Hedayati, E. Yeniaras, E. Christoforou, and N. V. Tsekos.
In Proceedings of the 2010 IEEE International Conference on Robotics and Biommetrics (ROBIO), pages 856-861, 2010.

Towards A Novel Cyber-Physical System for MRI-Guided and Robot-Assisted Cardiac Procedures.
E. Yeniaras, J. Lamaury, Z. Deng, and N.V. Tsekos.
In Proceedings of 10th IEEE International Conference on Information Technology and Applications in Biomedicine (ITAB), pages 1-5, 2010

Design and Analysis of a Haptic Interface in Minimally Invasive Cardiac Surgery.
A. Kilicarslan, J. Mohammadpour, K. Grigoriadis, and N.V.Tsekos.
In Proceedings of 10th IEEE International Conference on Information Technology and Applications in Biomedicine (ITAB), 2010.

Collaborative tracking for MRI-guided robotic intervention on the beating heart.
Y. Zhou, E. Yeniaras, P. Tsiamyrtzis, N.V. Tsekos, and I. Pavlidis.
In Proceedings of the 13th International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI), pages 351-358, 2010.

A Computational System for Performing Robot-assisted Cardiac Surgeries with MRI Guidance.
E. Yeniaras, N.V. Navkar, M.A. Syed, and N.V. Tsekos.
In Proceedings of 15th Society for Design and Process Science (SDPS) International Transformative Systems Conference (ITSC), 2010.

Robot-Assisted Scanning for Macrostructural Interventions with Straight Access.
N.V.Navkar, J.N.Stafford, J.S.Weinberg, and Z.Deng.
In Proceedings of International Conference on Information Processing in Computer-Assisted Intervention (IPCAI), pages 1-11, 2010.

Book Contributions:

Image based methodologies and their integration in a cyber-physical system for minimally invasive and robotic cardiac surgeries.
E. Yeniaras and N.V. Tsekos.
In Biomedical Engineering: Healthcare Systems, Technology and Techniques. Editors: S. Suh, M.M. Tanik, V. Gurupur: Springer, (to appear), 2011.

A robot-assisted method for coupling molecular, near-cellular and macroscopic modalities.
A.E.Sonmez, E.Yeniaras, Y.Hedayati, Z.Deng and N.V.Tsekos.
In Computational Surgery and Dual Training II. Editors: M. Garbey, B.L. Bass, C. Collet, M. Mathelin, R. Tran-Son-Tay: Springer, (to appear), 2011.

Integration of Virtual Reality Enhanced MRI Guidance and Visuo-Haptic Interface: A Novel Cyber-Physical System for Cardiovascular Surgeries.
E. Yeniaras, N.V. Navkar, A.E. Sonmez, J. Lamaury, A. Kilicarslan, Z. Deng, K. Grigoriadis and N.V. Tsekos.
In Computational Surgery and Dual Training II. Editors: M. Garbey, B.L. Bass, C. Collet, M. Mathelin, R. Tran-Son-Tay: Springer, (to appear), 2011.

Robot-Assisted Procedures with MRI Guidance.
M.G. Davies, N.V. Tsekos and E. Yeniaras.
In Pumps and Pipes. Editors: M.G. Davies, A.B. Lumsden, W.E. Cline, I. Kakadiaris. Springer, pages 21-31, 2010.

MRI-Guided Robot-Assisted Interventions: An Opportunity and a Challenge in Computational Surgery.
N.V. Tsekos, E. Yeniaras and A.E. Sonmez.
In Computational Surgery and Dual Training. Editors: M. Garbey, B.L. Bass, C. Collet, M. Mathelin, R. Tran-Son-Tay: Springer, pages 171-190, 2010.

A General-Purpose MR-Compatible Robotic System.
N. V. Tsekos and E. Christoforou.
In Biomedical Engineering Book Series "Advances in Medical Physics". Editors: A.B. Wolbarst, K.L. Mossman, and W.R. Hendee. Medical Physics Publishing, pages 73-87, 2010.

Papers at Abstract Based Conferences:

Prototype cyber-physical system for magnetic resonance based, robot assisted minimally invasive intracardiac surgeries.
E. Yeniaras, J. Lamaury, Y. Hedayati, N. von Sternberg, and N.V. Tsekos.
In International Journal of Computer Assisted Radiology and Surgery (IJCARS), (to appear), 2011.

Novel methodology and software tool for the preoperative planning of minimally invasive MRI-guided interventions.
Seimenis, C. Keroglou, N.V. Tsekos, E. Eracleous, and E. Christoforou.
In proceedings of European Congress of Radiology, Vienna, Austria, 2011

MR-compatibility of a robotic system for minimally invasive interventional procedures under real-time MRI guidance: A novel approach.
Seimenis, C. Keroglou, E. Eracleous, N.V. Tsekos, E.G. Christoforou.
In Proc. of European Congress of Radiology, Vienna, Austria, 2010.

An Approach for MRI Based Pre-operative Planning of Cardiac Interventions via Transapical Access.
E.Yeniaras, N.V.Navkar, M.A.Syed, N.V.Tsekos.
In 18th scientific Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM-ESMRMB) Joint Annual Meeting, page 3771, 2010.

An approach for planning interventions in the brain with straight access paths.
N.V.Navkar, Z.Deng, J.R.Stafford, J.S.Weinberg, and N.V.Tsekos.
In 18th scientific Meeting of the International Society for Magnetic Resonance in Medicine (ISMRM-ESMRMB) Joint Annual Meeting, page 7162, 2010.