

# LABORATORY FOR COMPUTATIONAL SENSING + ROBOTICS



JOHNS HOPKINS  
WHITING SCHOOL  
*of* ENGINEERING



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# Advancing Discovery:

Robotics at Johns Hopkins University's  
Whiting School of Engineering

Johns Hopkins University's Whiting School of Engineering stands at the forefront of technological innovation in robotics, and its faculty and students are advancing discoveries that are revolutionizing fields ranging from medicine and manufacturing to national security.

Improving the efficacy and efficiency of health care, making complex surgeries safer and more widely available, reducing risks to first responders, enabling the exploration of outer space and of the ocean's depths, and expanding our understanding of climate change are just some of the ways Johns Hopkins roboticists are addressing critical societal challenges.

The Whiting School of Engineering is one of the world's largest and most technologically advanced robotics research and educational centers. Our faculty are world-renowned leaders in the areas of medical robotics, autonomous systems, and bio-inspired robots, and lead collaborations and translational research in partnership with affiliate clinicians and scientists from across Johns Hopkins divisions, including the Johns Hopkins School of Medicine, the Bloomberg School of Public Health, and the Johns Hopkins University Applied Physics Laboratory, as well as with international peer institutions, government, and industry.

# AREAS OF IMPACT

## Medical Robotics

**Problem:** Whether it is suturing shape-changing and fragile soft tissue, performing a procedure in a person's long, narrow throat, or manipulating delicate retinal tissue during an eye procedure, surgeons face significant challenges to their precision, control and accuracy when performing surgical procedures.

**Solution:** Roboticists at Johns Hopkins are developing robotic surgical assistants, from a snake-like robot that allows surgeons to operate more effectively in a patient's narrow throat or upper airways to a steady-hand robot, which mitigates tiny human hand tremors and permits doctors to inject vision-saving medication into tiny blood vessels within the eye. Whiting School researchers have developed force-sensing microsurgical instruments that can measure the forces exerted on eye and other delicate tissue, providing surgeons with haptic feedback and improving surgical accuracy in a number of procedures.

## Manufacturing / Human-machine interaction

**Problem:** In the manufacturing process, there exist manipulation tasks that are impossible for autonomous robots to perform, but that are repetitive, injury-causing, and dangerous for humans. One example from the commercial airline industry involves wiring harnesses for commercial airplanes. This process involves a tying operation, now carried out by humans, that not only results in uneven product quality, but also carries a risk of repetitive-motion injuries.

**Solution:** Johns Hopkins researchers are investigating ways to improve human-robot teamwork in this setting by developing a way to incorporate robots into this process to reduce such problems, increase work efficiency, and set an example for future manufacturing innovations. Included in the solution is the development of virtual reality technology that allows humans to control the robots from a safe distance.

## Robotics in extreme environments

**Problem:** Scientists use autonomous underwater vehicles to explore some of the world's most remote underwater environments in order to map the ocean floor, document the discovery of new species, and investigate ocean chemistry in the search for insights to global climate change. Among the technological challenges such exploration presents are the need quickly to transmit large amounts of data from AUV to the mother ship and the need to know where the vehicle is, although global positioning system signals do not travel through water, in order to make the data useful to the scientists.

**Solution:** Robotics researchers at Johns Hopkins have developed an acoustical system that enables them to track with tremendous accuracy the exact position of the AUV and, over time, its trajectory, in environments including on the floor of the Mariana Trench and beneath the polar ice cap. They also have developed a tethering system that uses a fiber optic cable, just a few times thicker than a human hair to transmit data between it and the mother ship at the speed of light. This cable provides a gigabit Ethernet data stream to the surface, as well as a high-definition video feed that allows scientists to observe the under-ice world as never before and as close to firsthand as is presently possible.

## Bio-robotics

**Problem:** From war zones to areas devastated by nuclear accidents and natural disasters, many environments and situations are extremely dangerous for human beings to navigate. However, machines that can actually replace humans in these areas by skillfully climbing over rubble, digging out survivors, opening doors, clearing debris, and climbing stairs (among other things) simply don't yet exist.

**Solution:** Researchers in the LCSR's Terradynamics Laboratory are studying how animals, from cockroaches and spider crickets to reptiles, take advantage of mechanical contact with the environment to better traverse difficult and rough terrain, such as mountain boulders, desert sand, and the forest floor. Their aim is to translate that knowledge into the development of mobile robots who can successfully navigate farmland, factories, and the cluttered rubble of buildings shattered by natural disaster, war, or fire to help human beings.



# LCSR Laboratories:

## **Biomechanical- and Image-Guided Surgical Systems Lab**

DR. MEHRAN ARMAND

The Biomechanical- and Image-Guided Surgical Systems (BIGSS) laboratory is a collaboration between researchers at the Johns Hopkins University and the Johns Hopkins University Applied Physics Laboratory. This laboratory focuses on developing innovative computer-aided surgical guidance systems involving novel robots, advanced imaging, and real-time biomechanical assessments to improve surgical outcomes.

## **Photoacoustic & Ultrasonic Systems Engineering Lab**

DR. MUYINATU BELL

The PULSE Lab, directed by Dr. Muyinatu A. Lediju Bell, integrates light, sound, and robots to develop innovative biomedical imaging systems that simultaneously address unmet clinical needs and improve patient care. Our emphasis is diagnostic and surgical ultrasound and photoacoustic technologies, with applications in neurosurgery, cancer detection and treatment, and women's health. We maintain a constant eye toward interfacing our technologies with real patients to facilitate clinical translation. The PULSE Lab is affiliated with the Laboratory for Computational Sensing and Robotics, the Malone Center for Engineering in Healthcare, and the Carnegie Center for Surgical Innovation, with dedicated laboratory space at both the Johns Hopkins University Homewood Campus and the Johns Hopkins Hospital School of Medicine.

## **Medical UltraSound Imaging and Intervention Collaboration**

DR. EMAD BOCTOR

The MUSiiC research lab, headed by Dr. Emad Boctor, develops innovative ultrasound technologies for medical applications ranging from prostate and breast cancer treatment to liver ablation and brachytherapy, among others. The group is based on a collaboration among researchers from Johns Hopkins Medical School, Johns Hopkins Whiting School of Engineering, and partners from other academic institutions and industry.

## **Haptics and Medical Robotics Lab**

DR. JEREMY D. BROWN

The Haptics and Medical Robotics (HAMR) Laboratory seeks to extend the current knowledge surrounding the human perception of touch, especially as it relates to applications of human/robot interaction and collaboration. We are particularly interested in medical robotics applications such as minimally invasive surgical robots, upper-limb prosthetic devices, and rehabilitation robots. To solve many of the problems in these areas, we apply techniques from human perception, human motor control, neuromechanics, and control theory.

## **Robot and Protein Kinematics Lab**

DR. GREGORY CHIRIKJIAN

Dr. Gregory Chirikjian directs the Robot and Protein Kinematics Lab in LCSR. This lab is involved in research in computational structural biology (in particular, computational mechanics of large proteins), conformational statistics of biological macromolecules, developed theory for 'hyper-redundant' (snakelike) robot motion planning, hyper-redundant robotic manipulator arms, modular self-reconfigurable robots, applied mathematics (applications of group theory in engineering), self-replicating robotic systems.

## **Locomotion In Mechanical and Biological Systems**

DR. NOAH COWAN

The LIMBS laboratory, directed by Noah J. Cowan, strives to uncover principles of animal and robot sensory guidance. For animals this is an analysis problem: we reverse engineer the biomechanical and neural control principles underlying animal movement. For robotics, this is a design problem: we incorporate biological inspiration and engineering insights to synthesize new approaches to robot control. This research program includes several projects.

### **Computational Interaction and Robotics Lab**

DR. GREGORY HAGER

The Computational Interaction and Robotics Laboratory, directed by Dr. Gregory Hager, is devoted to the study of problems that involve dynamic, spatial interaction at the intersection of imaging, robotics, and human-computer interaction. The laboratory has a number of ongoing projects in this area. The Language of Motion project is seeking to develop new methods to recognize and evaluate skilled human manipulation, with a particular emphasis on surgery. Data is collected using a da Vinci Surgical robot, and processed into gesture-based models that support skill evaluation, training, and human-robot collaborative task execution. The Manipulating and Perceiving Simultaneously (MAPS) project seeks to apply principles of computer vision to tactile sensing, with the goal of developing new methods for haptic object recognition. The lab's most recent work aims to develop Generic Perception to support general-purposes manipulation of objects in the physical world. The laboratory also works in the area of medical imaging. Interactive computer-aided diagnostic systems based on images are also an area of interest.

### **Advanced Medical Instrumentation, and Robotics**

DR. IULIAN IORDACHITA

The Advanced Medical Instrumentation and Robotics Research Laboratory (AMIRO), directed by Dr. Iulian Iordachita, conducts research to aid and support the robotic assisted medical technology encompassing medical diagnosis and therapy, and clinical research. The main goal is to create the future medical robots and devices that will help clinicians to deliver earlier diagnosis and less invasive treatments at lower cost and in shorter time.

### **Sensing, Manipulation, and Real-Time Systems Lab**

DR. PETER KAZANZIDES

Dr. Peter Kazanzides heads the SMARTS lab, which works on components and integrated systems for computer-assisted surgery. This includes the integration of real-time imaging, such as video and ultrasound, to enable robotic assistance in more challenging environments, such as minimally invasive surgery and microsurgery. Research in component technologies includes high-performance motor control, electromagnetic and inertial sensing, and sensor fusion. The lab also performs research in system architectures, applying component-based software engineering concepts to provide a uniform programming model for multi-threaded, multi-process, and multi-processor systems.

### **Autonomous Systems, Control, and Optimization Lab**

DR. MARIN KOBILAROV

The Autonomous Systems, Control and Optimization Laboratory (ASCO), directed by Dr. Marin Kobilarov, aims to develop intelligent robotic vehicles that can perceive, navigate, and accomplish challenging tasks in uncertain, dynamic, and highly constrained environments. The lab performs research in analytical and computational methods for mechanics, control, motion planning, and reasoning under uncertainty, and in the design and integration of novel mechanisms and embedded systems. Application areas include mobile robots, aerial vehicles, and nano satellites.

### **Terradynamics Lab**

DR. CHEN LI

Aero- and hydrodynamics have helped us understand how animals fly and swim and develop aerial and aquatic vehicles that work well. By contrast, we know little about how animals move so well through almost any terrain, and even the best robots struggle in terrain like building rubble or loose Martian soil. Analogous to aero- and hydrodynamics, we are creating terradynamics, new physics models of locomotor-terrain interactions, to understand animal locomotion and improve robotic mobility in complex terrain common in the real world.

### **Computer Aided Medical Procedures**

DR. NASSIR NAVAB

The CAMP laboratory aims at developing the next generation solutions for computer assisted interventions. The complexity of surgical environments requires us to study, model and monitor surgical workflow enabling the development of novel patient and process specific imaging and visualization methods. Due to the requirements of flexibility and reliability we work on novel robotized multi-modal imaging solutions and to satisfy the challenging usability requirements we focus on data fusion and its interactive representation within augmented reality environments. The lab creates a bridge across the Atlantic ocean by hosting researchers working at both of Prof. Navab's groups at JHU in Baltimore and TUM in Germany.

### **Computer Integrated Interventional Systems Lab**

DR. RUSSELL TAYLOR

Professor Russell Taylor directs the Computer Integrated Interventional Systems (CIIS) laboratory. This lab exists to develop surgical systems that integrate novel computer and human/machine interface technologies that will revolutionize surgical procedures, extending the surgeon's abilities to achieve better outcomes at lower costs. Some of the recent research projects include robot assisted microsurgery (steady hand eye robot), surgical control and planning, snake robot, deformable human anatomical models, smart surgical instruments, treatment plan optimization in radiation oncology, image overlay, laparoscopic-assisted robot system, robot assisted ultrasound and MRI compatible robotics.

### **Dynamical Systems and Control Lab**

DR. LOUIS WHITCOMB

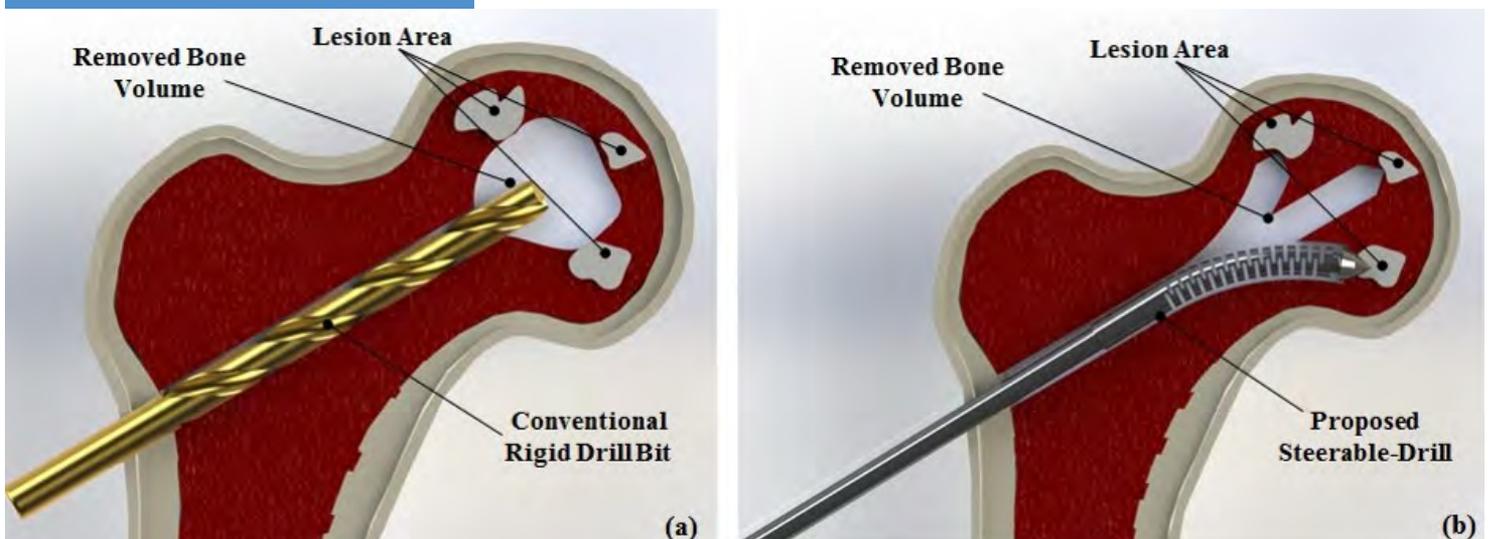
Professor Louis Whitcomb directs the DSCL lab and research focusing on problems in the navigation, dynamics, and control of linear and nonlinear dynamical systems, observers, nonlinear systems analysis, modeling, and sensing relevant to robots that interact dynamically in extreme environments. The principal focus is on problems motivated by two application areas that share a common underlying mathematical framework - underwater robot vehicles and robot manipulators.

## Snake-Like Manipulators for Minimally-Invasive Surgery: Applications to Orthopaedics and ENT

### Core decompression of Femoral Osteonecrosis

Accomplishment: In conventional core decompression of osteonecrosis, surgeons cannot successfully reach the entire lesion area within the femoral head with the existing rigid instruments. To address this issue, we are designing and fabricating a novel steerable drill using a continuum dexterous manipulator (CDM) and two different flexible cutting tools passing through the instrument channel of the CDM. The feasibility of the approach for S-shape and multi-branch drilling have been successfully demonstrated using human cadaveric specimens. Status: Prototype CDM, appropriate tools and actuation unit exists; application demos for treatment of osteonecrosis is developed; integrating system components underway; patents pending applications filed.

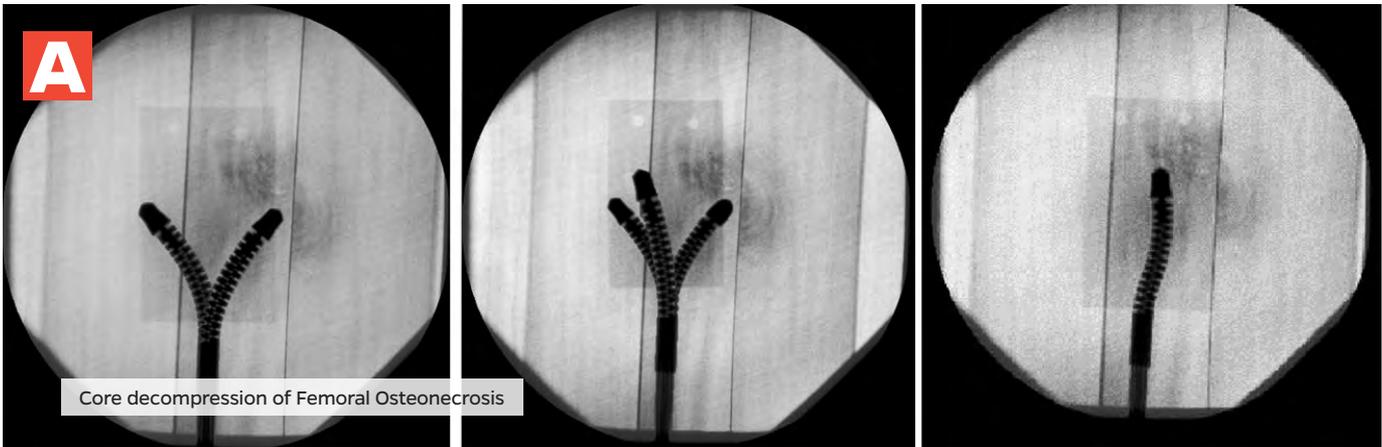
Funding: NIH/NIBIB



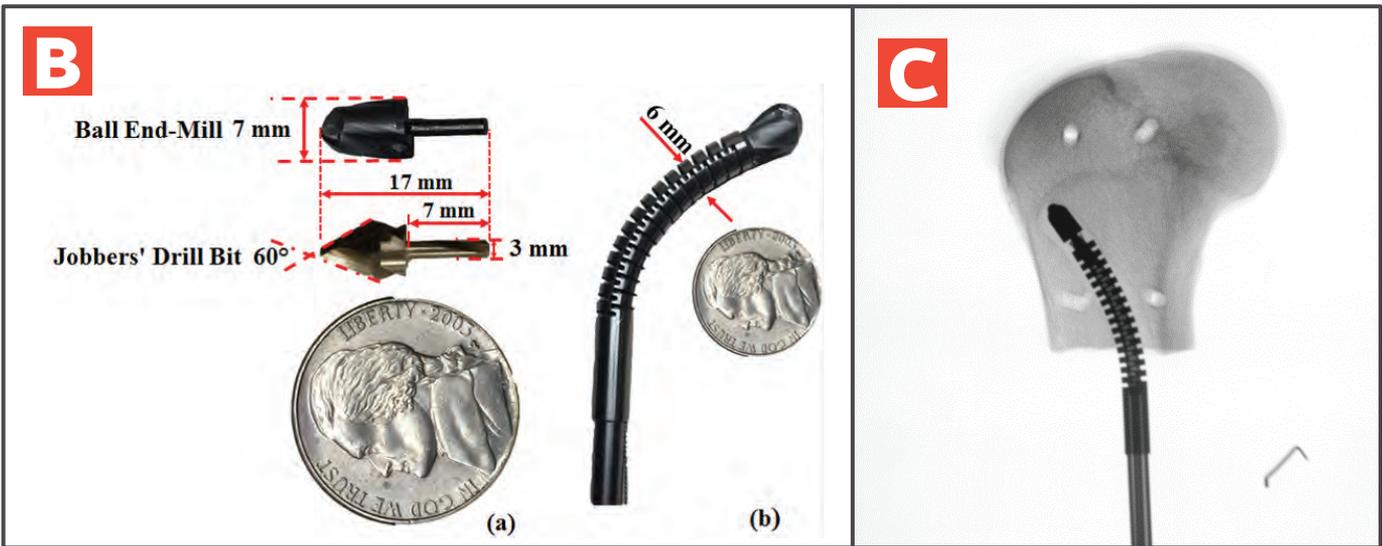
Key Personnel: (APL) Mehran Armand (WSE) Farshid Alambeigi, Shahriar Sefati, Russell Taylor, Iulian Iordochita (SOM) Harpal Khanuja

To find out more: <https://bigss.lcst.jhu.edu>

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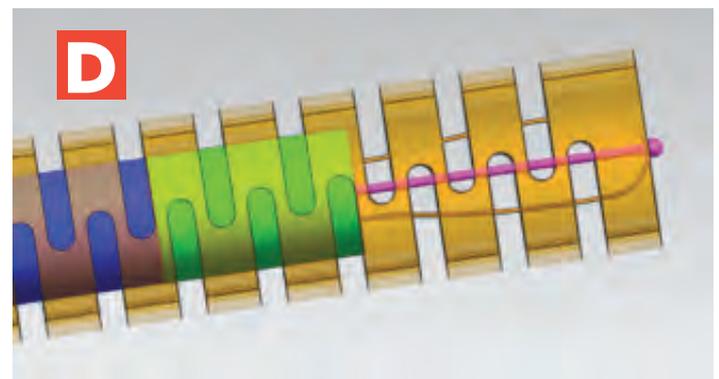
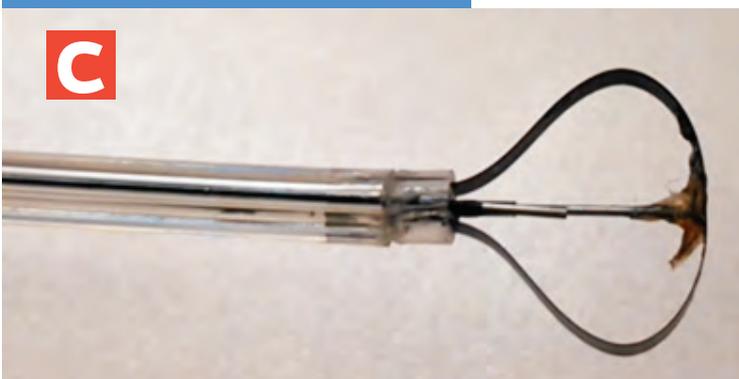
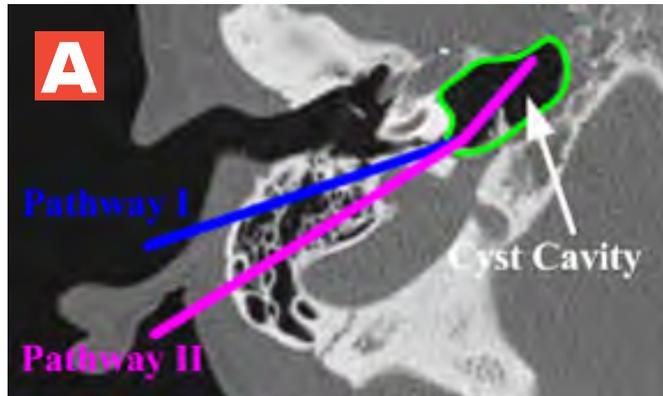


A) X-ray images of a two-branch, three-branch and an S-shape curved drilling tunnel made by the steerable drill.  
 B) Two types of the cutting tool used for making the flexible cutter and integration of the CDM with the flexible cutter.  
 C) X-ray image of a curved drilling experiment on human femur medial epicondyle

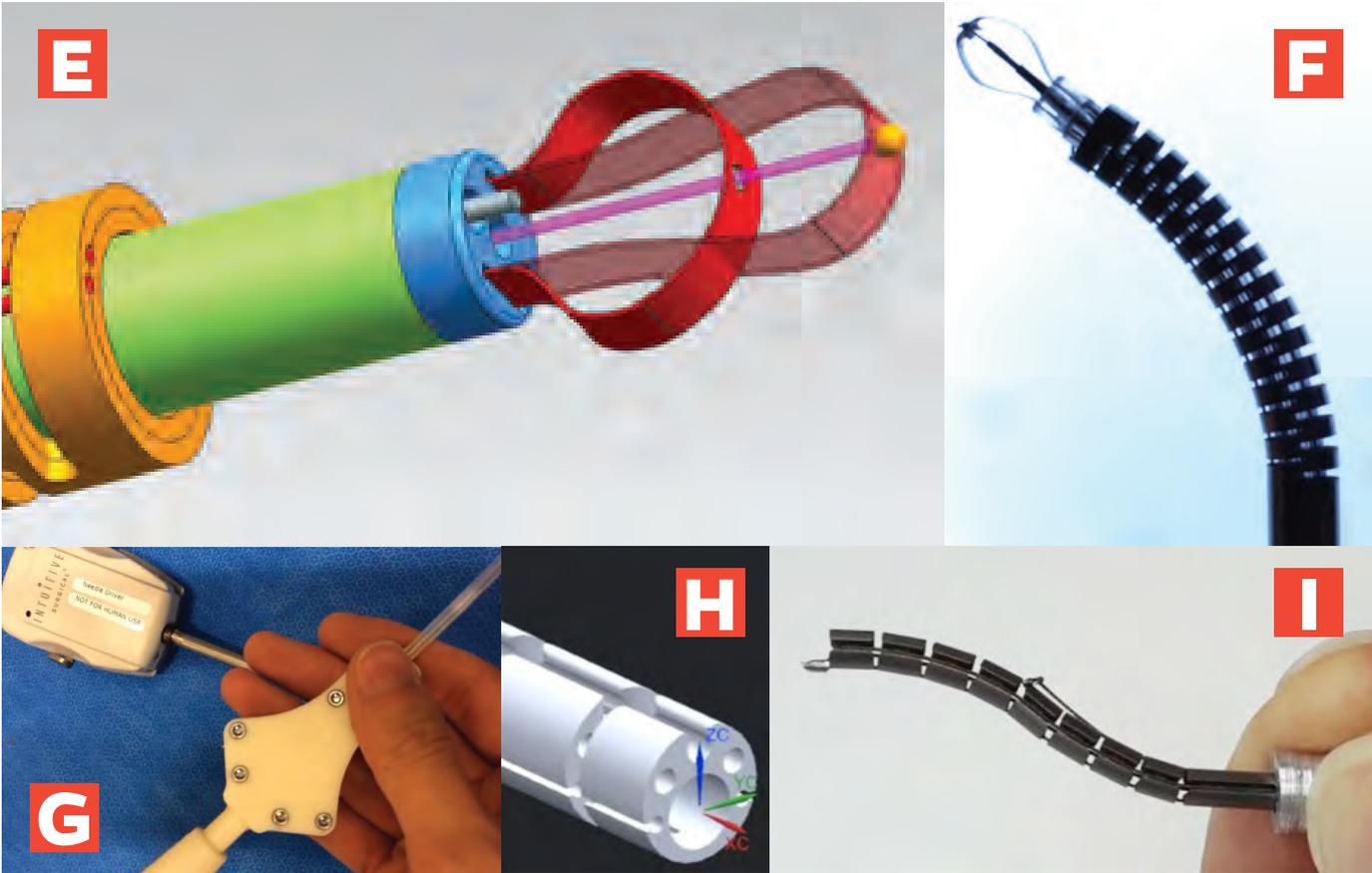


# Snake-Like Manipulators for Minimally-Invasive Surgery: Applications to Orthopaedics and ENT

## Robot-Assisted Skull Base Surgery

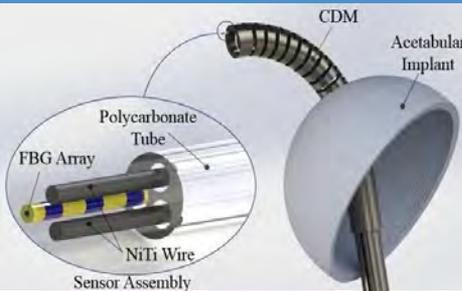
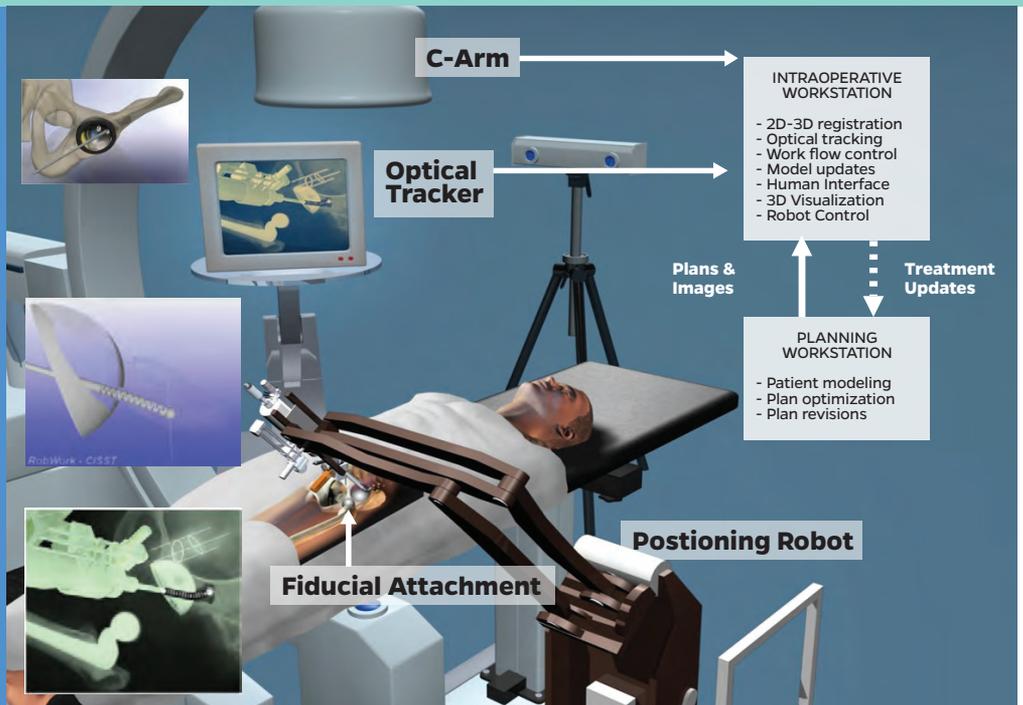


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Applied Physics Laboratory,  
Merle A Tuve Associate Research  
Professor of Mechanical Engineering  
with joint appointment in  
Orthopaedic Surgery,  
Director of Biomechanical- and  
Image-Guided Surgical Systems  
(BIGSS) Laboratory



- A) CT image of petrous apex; two typical pathways for reach the cyst cavity in mid brain is shown. The CDM should pass within a triangle of critical organs. The maximum diameter of the CDM for passing through this triangle must be less than 4 mm.
- B) A video of the CDM using Davinci robot's drive mechanism for manual control of the shape
- C) An active ring tool mechanism made from Nitinol plates for scraping the wall of the petrous apex.
- D) Ring tool passing through the lumen of the CDM
- E) Ring tool expands once it reaches inside the cavity of the petereous apex using its drive mechanism
- F) A picture of the Ring tool and the CDM
- G) The video shows the ring tool and the snake working together
- H) CAD model of a novel CDM with 3 mm outer diameter, 1.7 mm lumen for tools and thru holes for drive cables, Borescope, and FBG shape sensor fibers
- I) The novel 3 mm CDM producing S-shape

# Snake-Like Manipulators for Minimally-Invasive Surgery: Applications to Orthopaedics and ENT



Sensor assembly (FBG array containing three active areas and two Nitinol wires inserting through the polycarbonate tube) embedded in the SDM

**ACCOMPLISHMENT:** We are developing robot-assisted surgical workstations including Continuum Dexterous Manipulators (CDM) attached to a positioning robot with accompanying tools and sensors for orthopaedic and ENT skull base surgery. We have designed and fabricated CDMs and associated tools that can pass through the relatively large instrument channel of the CDM. The CDM can be driven manually or using a positioning robot such as UR5, UR10, or Kuka. For the treatment of osteolysis (as shown) the CDM operates through the screw holes of well-fixed an acetabular implant. Large-deflection shape sensors are designed and tested to track and control the shape of the CDM during the surgical procedure. Furthermore, we have developed 2D-3D registration techniques to update the pose of the CDM with respect to the lesion space using multiple x-ray images anytime at the request of the surgeon. We have also developed model-less control algorithm to control the SDM shape in real-time using the feedback from shape sensors and the x-ray image.

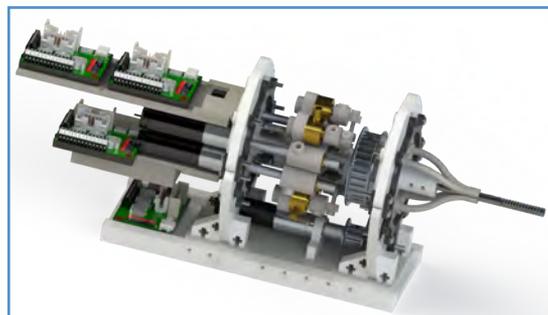
**STATUS:** Prototype SDM exists; application demos for treatment of osteolysis; integrating system components for operating room application and cadaver studies; patents issued and others in prosecution.

**FUNDING:** NIH/NIBIB

**KEY PERSONNEL:** (APL) Ryan Murphy, Mehran Armand (WSE) Farshid Alambeigi, Shahriar Sefati, Amir Farvardin, Robert Grupp, Paul Wilkening, Russell Taylor, Iulian Iordochita (SOM) Simon Mears, Harpal Khanuja

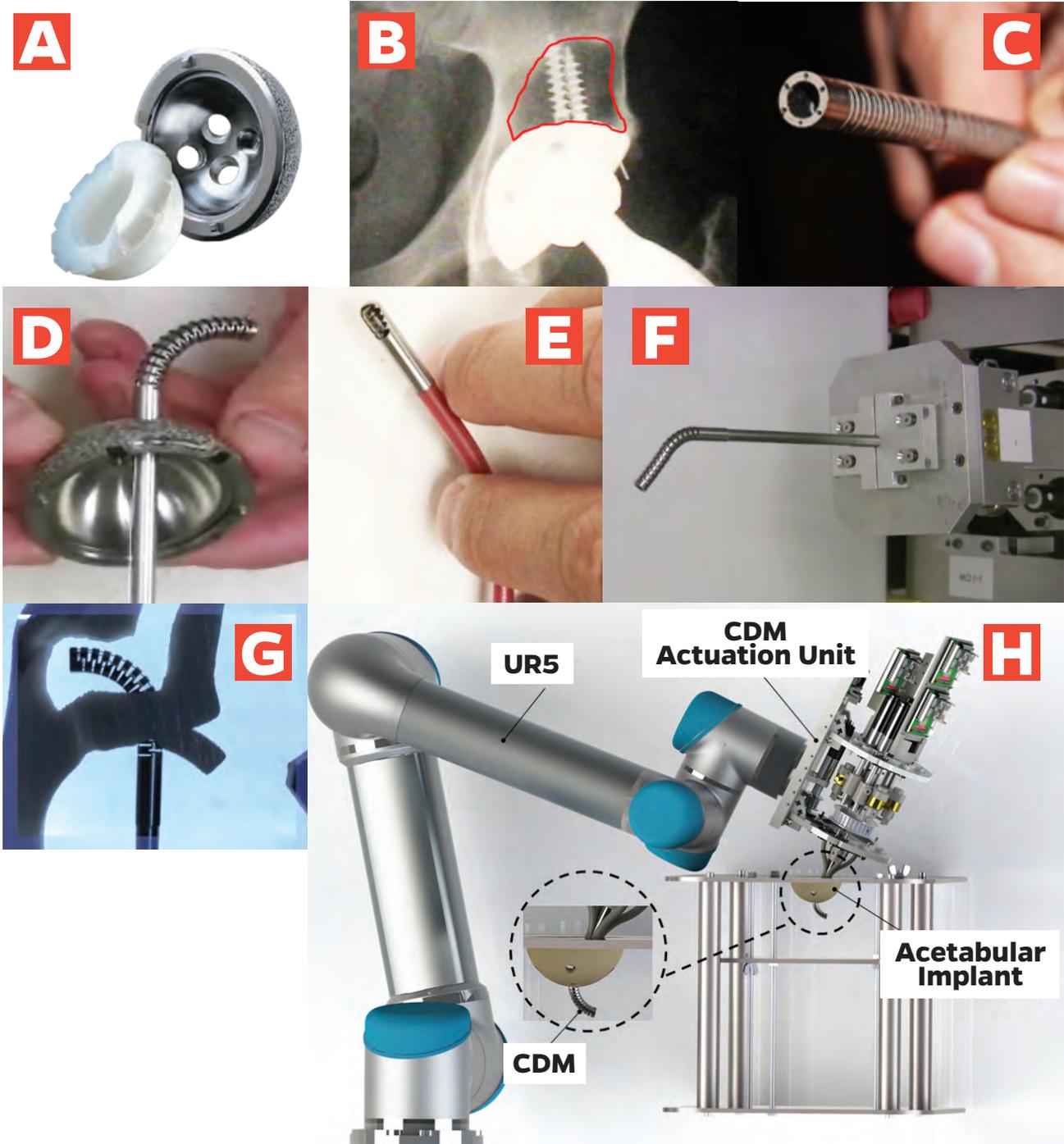
**TO FIND OUT MORE:** [bigss.lcst.jhu.edu](http://bigss.lcst.jhu.edu)

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Merle A Tuve Associate Research Professor of Mechanical Engineering with joint appointment in Orthopaedic Surgery,  
Director of Biomechanical and Image-Guided Surgical Systems (BIGSS) Laboratory



Designed and fabricated actuation unit for controlling the SDM shape

## Robot-Assisted Treatment of Osteolysis



A) Acetabular implant demonstrating the three 8 mm screw holes

B) X-ray image of the pelvis osteolysis behind the acetabular implant (outlined in red)

C) The cable-driven CDM with 6 mm outer diameter and 4 mm lumen for tools and six thru holes housing drive cables, and FBG fibers for shape sensing. The main advantages of the JHU CDM is its structural strength especially for orthopaedic applications and large lumen / outer diameter ratio supporting relatively larger tools.

D) The CDM passing through the screw holes.

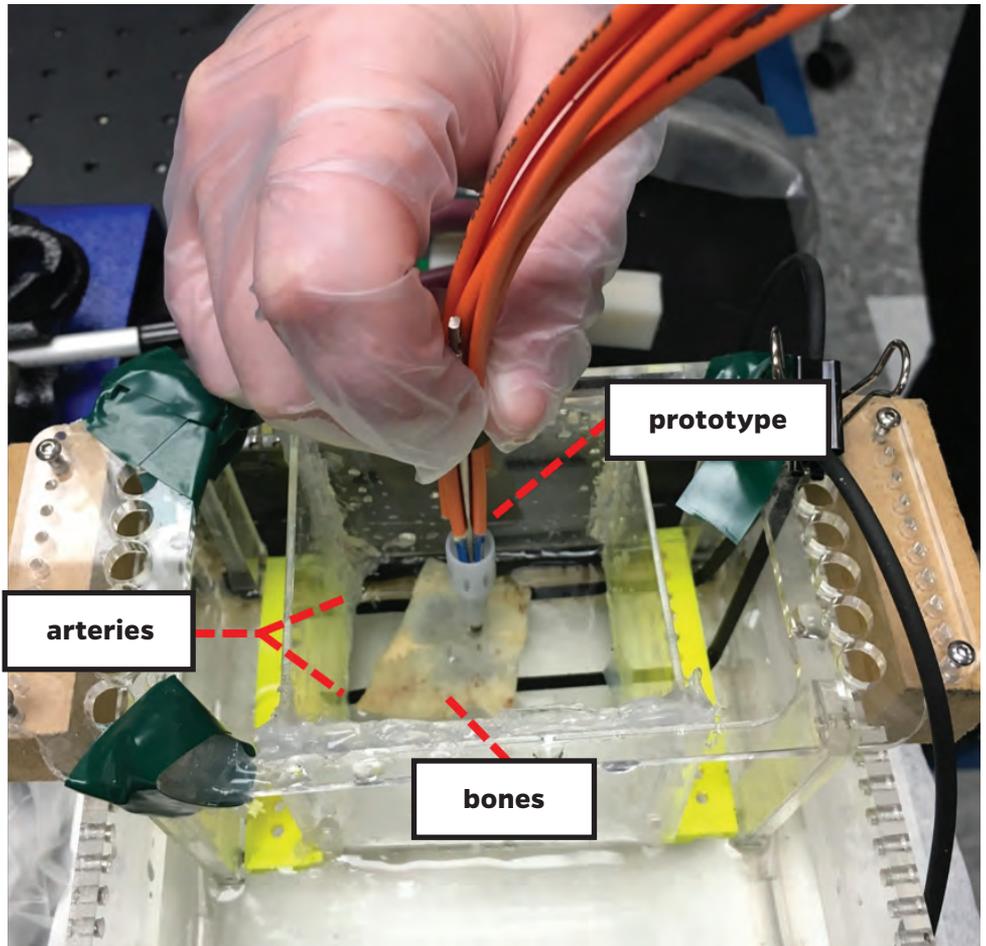
E) The shaving tool with outer diameter of 3.5 mm. the shaving tool pathways for water circulation and vacuum for removing debris.

F) A video of the CDM producing S shape configuration

G) A video of the CDM demonstrating its reach within the simulated lesion

H) The CDM working with UR5 positioning robot

## Specialized Light Delivery for Photoacoustic-Guided Surgery



**ACCOMPLISHMENT:** We used optical simulations to design and build a specialized light delivery system that surrounds a neurosurgical drill. Our goal is to enable photoacoustic guidance and navigation around critical anatomical features in real time during surgery.

**STATUS:** This design was successfully tested with phantoms and ex vivo bone samples. Next steps include testing with in vivo tissue and ultimately investigating specialized light delivery systems for an entire suite of surgical tools.

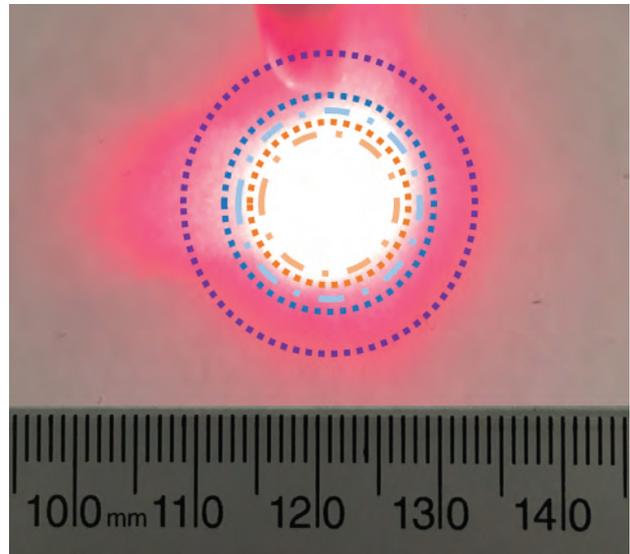
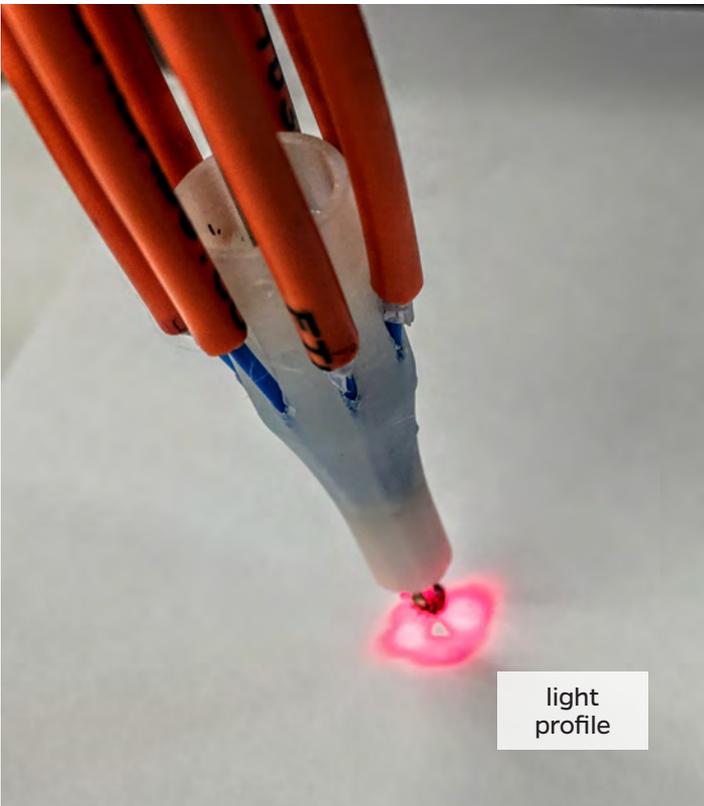
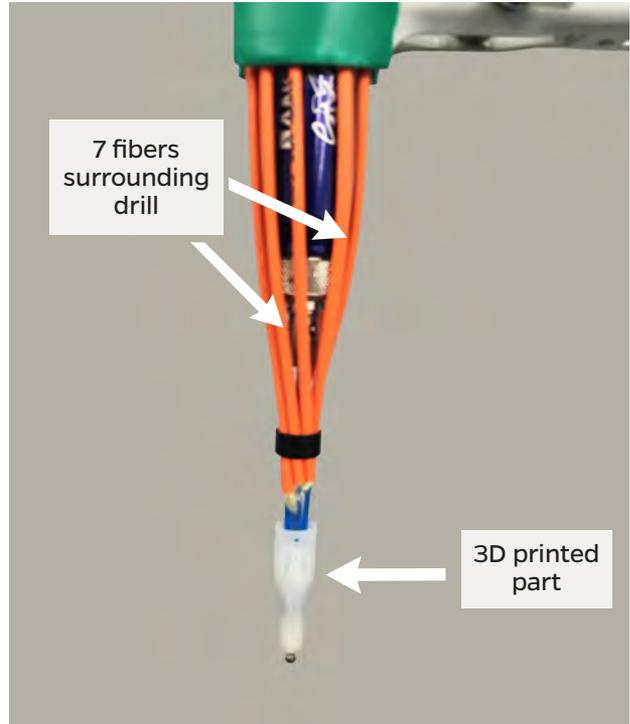
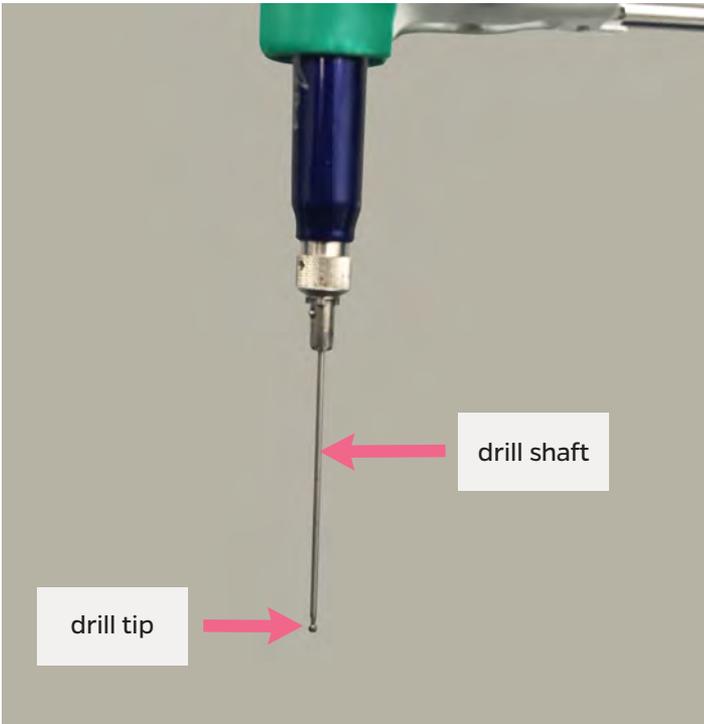
**FUNDING:** NIH, NSF

**KEY PERSONNEL:** Muyinatu A. Lediju Bell, Blackberrie Eddins

**TO FIND OUT MORE:** B Eddins, MAL Bell, "Design of a multifiber light delivery system for photoacoustic-guided surgery," J. Biomed. Opt. 22(4), 041011 (2017), doi: 10.1117/1.JBO.22.4.041011.

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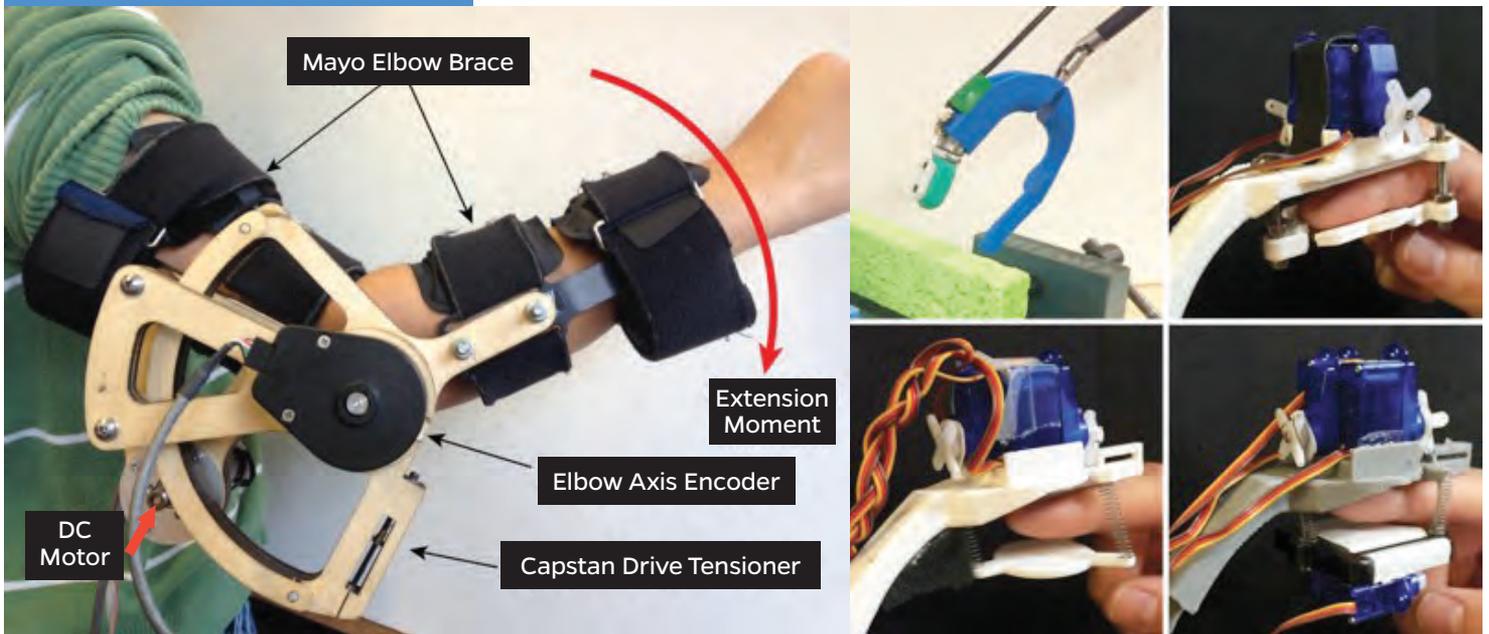


- Surgical complications include accidental damage to critical anatomical structures, such as arteries and nerves
- The PULSE Lab is developing specialized light delivery systems that surround surgical tools to navigate around these structures

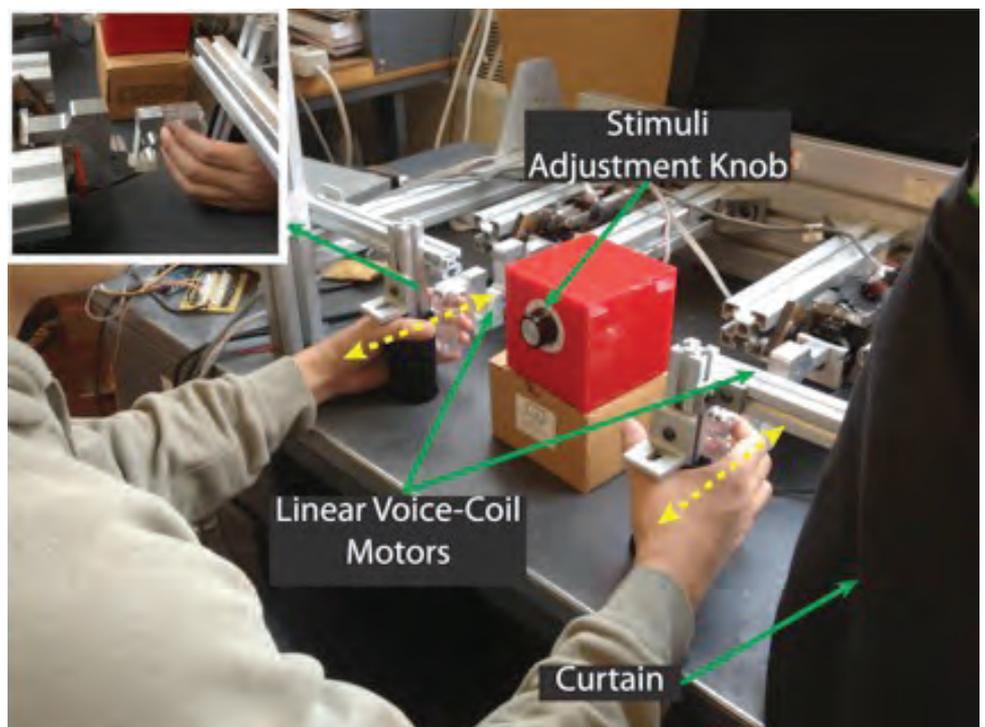
# The Haptics and Medical Robotics (HAMR) Laboratory

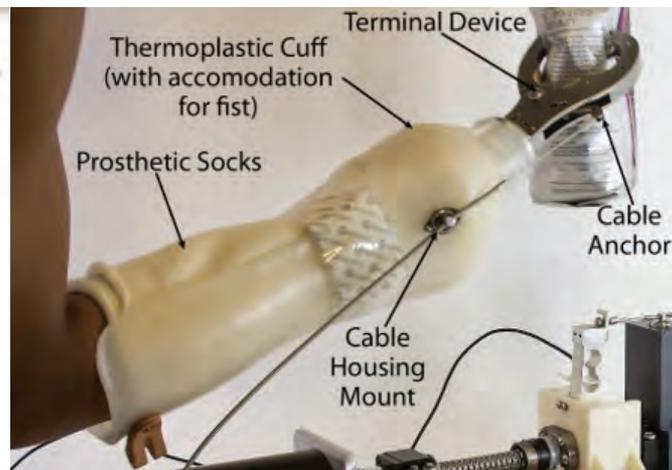
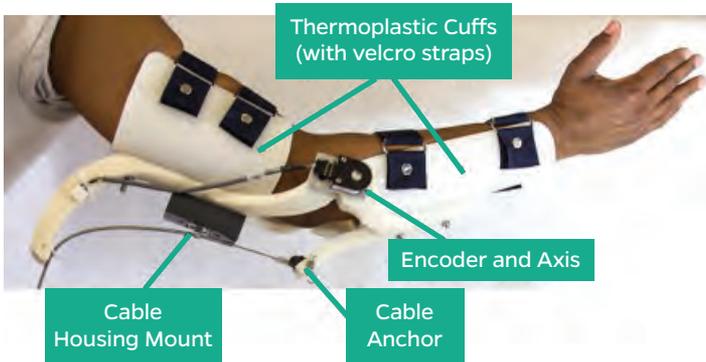
## THE HAPTICS AND MEDICAL ROBOTICS (HAMR) LABORATORY

seeks to extend the current knowledge surrounding the human perception of touch, especially as it relates to applications of human/robot interaction and collaboration. We are particularly interested in medical robotics applications such as minimally invasive surgical robots, upper-limb prosthetic devices, and rehabilitation robots. To solve many of the problems in these areas, we apply techniques from human perception, neuromechanics, and biomechanics.



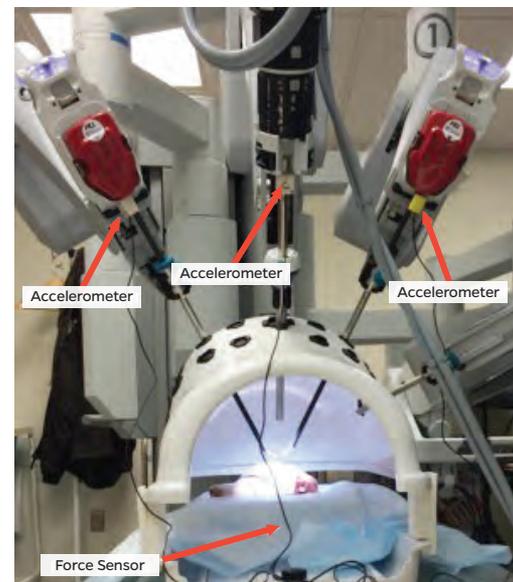
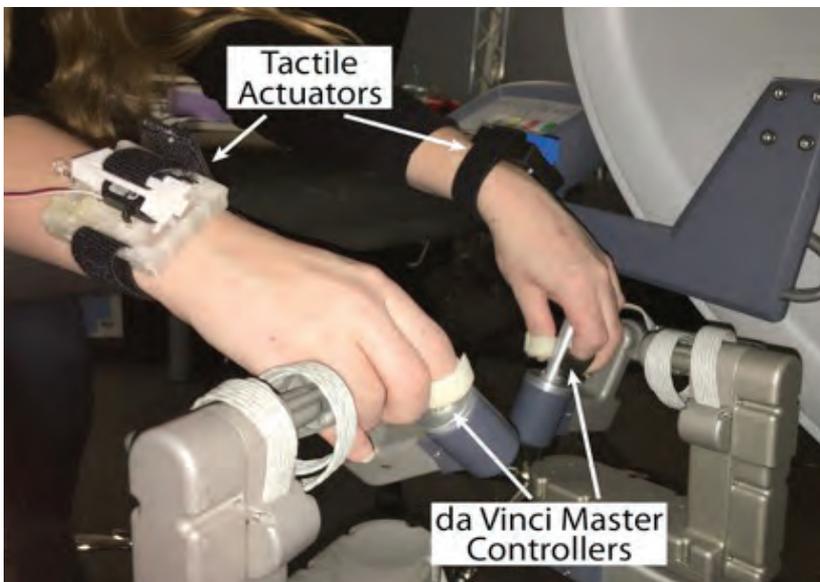
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### UPPER-LIMB PROSTHETIC

Previous research by Dr. Brown in the area of upper-limb prosthetics has demonstrated that myoelectric prosthetic hands with low mechanical impedance allow users to apply force control strategies akin to what our natural limbs do. His research has also provided an empirical evaluation of the utility of body-powered prosthetic grippers, which feature inherent force feedback.

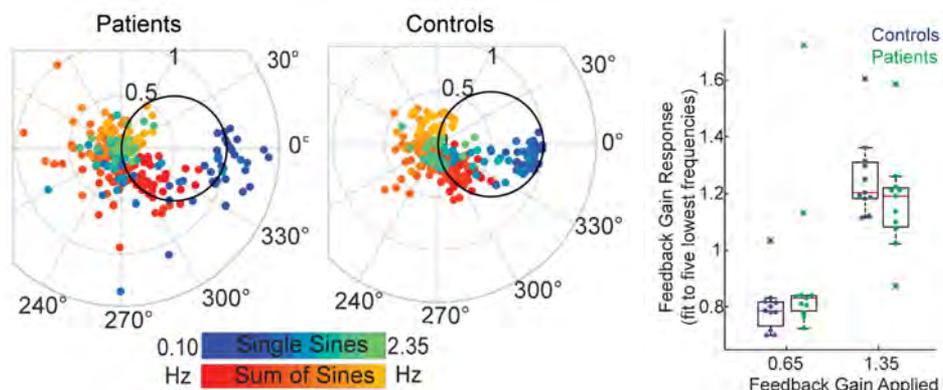
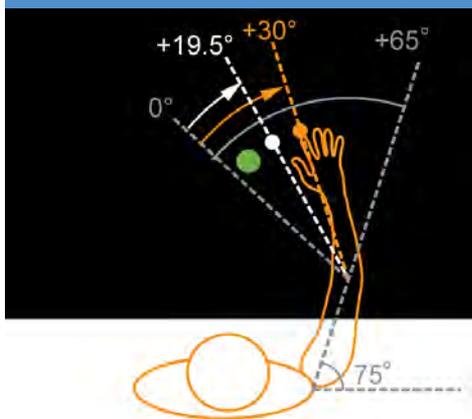
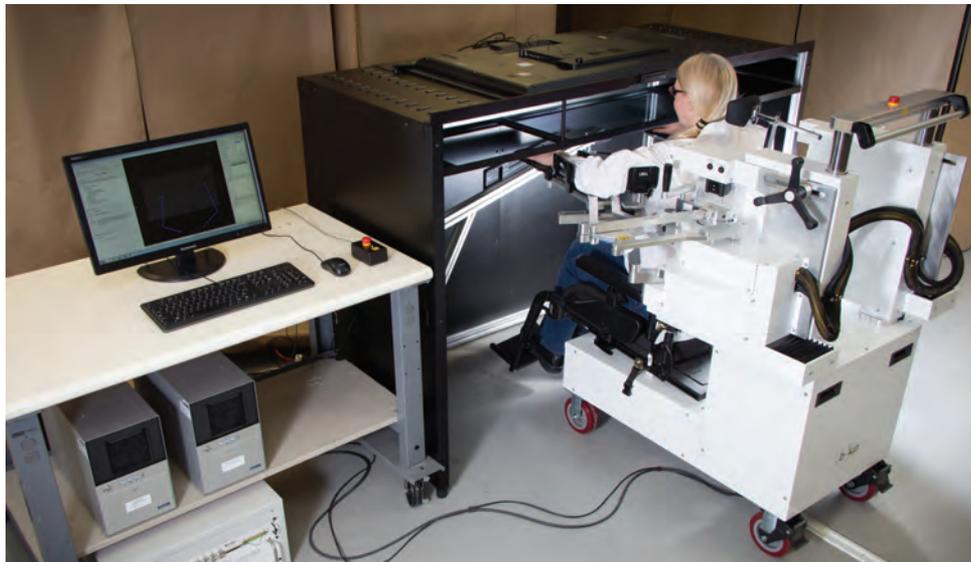


### ROBOTIC MINIMALLY INVASIVE SURGERY

Previous research by Dr. Brown in the area of robotic minimally invasive surgery has led to the development of advanced training platforms which provide automatic assessment of skill based on the manner in which a surgical trainee brings the robot in physical contact with the training environment, and which provide trainees with tactile feedback of those physical interactions.

# The Locomotion in Mechanical and Biological Systems (LIMBS) Laboratory

## DOES CEREBELLAR ATAXIA IMPAIR FEEDBACK CONTROL?



Noah Cowan, Ph.D.  
Associate Professor  
of Mechanical Engineering  
limbs.lcsr.jhu.edu

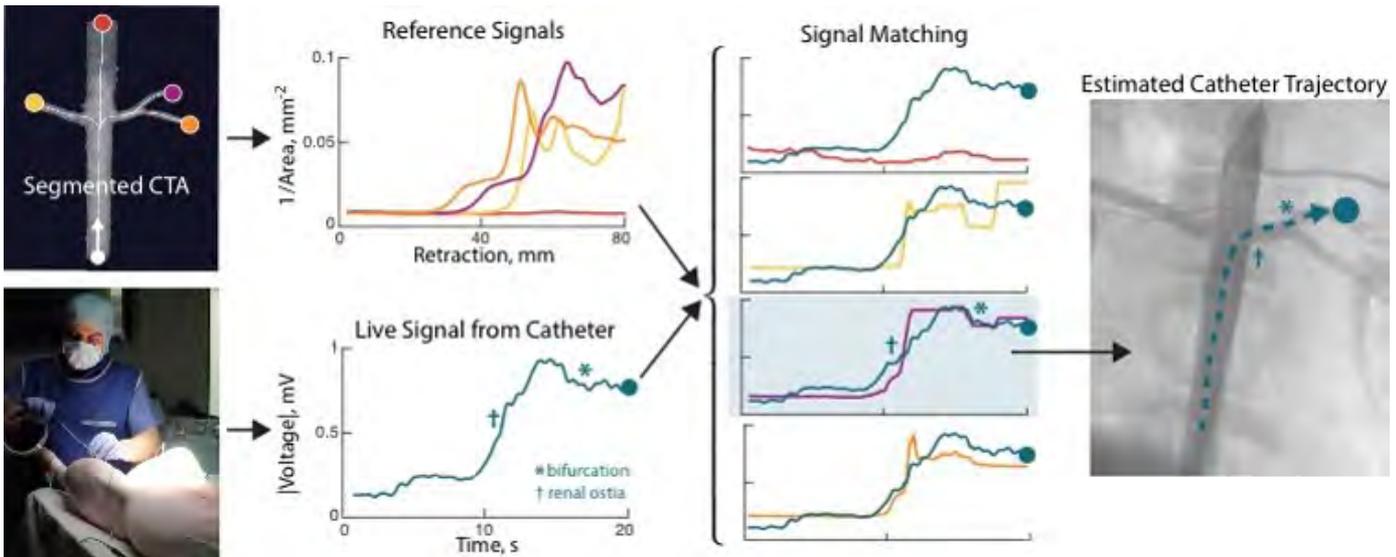
**ACCOMPLISHMENT:** Patients with cerebellar damage may experience ataxia, a movement disorder that can most easily be described as moving in a "drunken" pattern. In addition, damage to the cerebellum results in motor learning deficits, which yields typical physical therapy largely ineffective. From an engineering perspective, the oscillating movements exhibited by these patients are reminiscent of a poorly tuned control system. Using the mathematical tools from the system identification literature, we were able to demonstrate that these patients have an intact feedback controller. We conducted followup experiments using virtual reality augmentation of patients' arm motions to stabilize their control systems and reduce their ataxia.

**STATUS:** Finalizing data collection (2 more subjects) and writing journal publications

**FUNDING:** Applied Physics Lab Graduate Fellowship

**KEY PERSONNEL:** A. Edwards, A. Bastian, N. Cowan

## BIOLOGICALLY INSPIRED ACTIVE CATHETER FOR NON-FLUOROSCOPIC ENDOVASCULAR SENSING AND NAVIGATION



**ACCOMPLISHMENT:** Minimally invasive treatment of vascular disease demands dynamic navigation through complex blood vessel pathways and accurate placement of an interventional device, which has resulted in increased reliance on fluoroscopic guidance and commensurate radiation exposure to the patient and staff. Here we introduce a guidance system inspired by electric fish that incorporates measurements from a newly designed electrogenic sensory catheter with preoperative imaging to provide continuous feedback to guide vascular procedures without the need for ionizing radiation, image registration, or external tracking. Electrodes near the catheter tip simultaneously create a weak electric field and measure the impedance, which changes with the internal geometry of the vessel as the catheter advances through the vasculature. The impedance time series is then mapped to a preoperative vessel model to determine the relative position of the catheter within the vessel tree. We have validated the system with navigation in a synthetic vessel tree and ex vivo biological tissue based on our mapping technique. Our latest experiments in a porcine model demonstrated the sensor's ability to detect cross-sectional area variation in vivo. These initial results demonstrate the capability and potential of this novel bioimpedance-based guidance technology as a non-fluoroscopic technique to navigate intravascular devices.

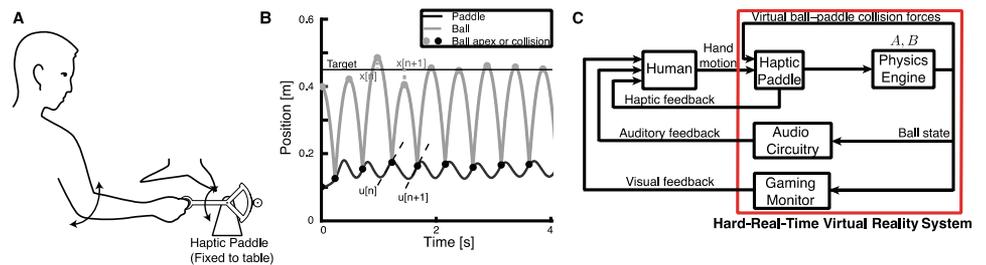
**STATUS:** R21 Pending. Patent application submitted. Journal paper in preparation. Conference paper published:

B. Fuerst\*, E.E. Sutton\*, R. Ghotbi, N.J. Cowan, and N. Navab. Bioelectric navigation: A new paradigm for intravascular device guidance. In Sébastien Ourselin, William Wells, Mert R. Sabuncu, Gözde Unal, and Leo Joskowicz, editors, *Medical Image Computing and Computer-Assisted Intervention*, volume 9902 of LNCS. Springer, 2016. (\* joint first authors)

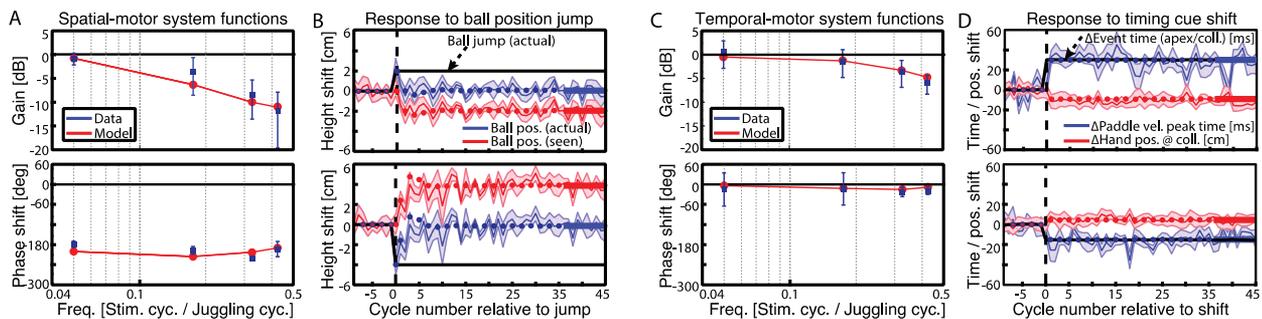
**KEY PERSONNEL:** Erin E. Sutton, Bernhard Fuerst, Clifford R. Weiss, Reza Ghotbi, Noah J. Cowan, and Nassir Navab

# The Locomotion in Mechanical and Biological Systems (LIMBS) Laboratory

## UNDERSTANDING HUMAN RHYTHMIC MOTOR CONTROL



**ACCOMPLISHMENT:** Rhythmic arm movements are critical to tool use and other activities of daily life. We have designed and implemented a virtual reality paddle juggling (ball bouncing) task to understand how the human brain uses spatial and timing sensory information to control rhythmic movements. Using a hard-real-time platform, we perturb spatial (vision) and timing (audio, touch) cues at high precision, and analyze how the brain processes these changes to sensory information to affect motor control. Our research thus far has shown that spatial and timing information have separable and complementary roles in task performance. We have also developed models of how spatial and timing error affects juggling behavior, which predict responses to novel perturbations to spatial or timing information.



**STATUS:** We have one published study and are finalizing a second manuscript. Further studies are in progress to study how task dynamics can alter weighting of spatial and timing cues, and how humans modify their behavior in response to external timing signals. Results from these studies can be used to design therapies or virtual reality simulations that leverage the brain's information processing capabilities to improve human motor control programs or train new ones.

M. M. Ankarali, H. Tutkun Şen, A. De, A. M. Okamura, and N. J. Cowan. "Haptic feedback enhances rhythmic motor control by reducing variability, not improving convergence rate". J Neurophysiol, 111(6):1286-1299, 2014.

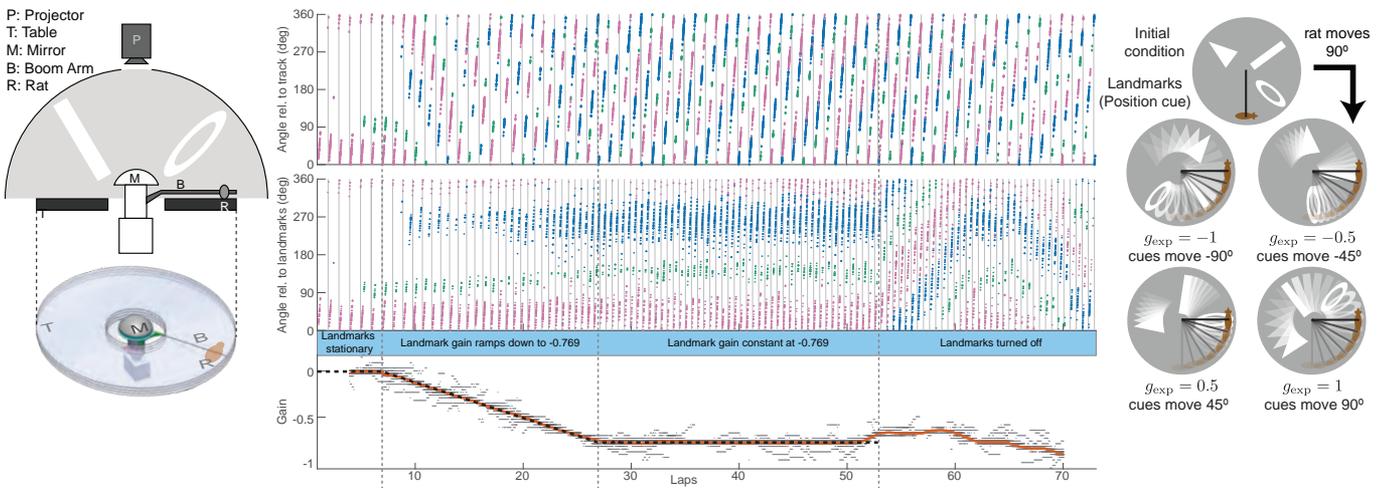
**FUNDING:** NSF (including Graduate Research Fellowship to R. Nickl)

**KEY PERSONNEL:** Robert Nickl, Mert Ankarali, Nicole Ortega, Noah Cowan

**TO FIND OUT MORE:** [limbs.lcsr.jhu.edu/human](http://limbs.lcsr.jhu.edu/human)

Noah Cowan, Ph.D.  
Associate Professor  
of Mechanical Engineering  
[limbs.lcsr.jhu.edu](http://limbs.lcsr.jhu.edu)

## CONTROL THEORETIC ANALYSIS OF HIPPOCAMPAL NAVIGATION



**ACCOMPLISHMENT:** Neurons in the hippocampus, a region of the mammalian brain, fire at specific locations in an environment, and are thus called ‘place cells.’ These, along with similarly spatially selective cells across the hippocampal formation, constitute the so-called ‘cognitive map’ in the brain, thought to be responsible for representation of space and time, and enabling navigation. Using a novel, planetarium-style virtual reality apparatus, we were able to alter the location of firing of place fields in rats in a predictable way and demonstrate that moving landmarks also causes the brain to ‘recalibrate’ its path integration system, effectively weighting each step more or less depending on how fast or slow the visual landmarks are moving relative to the rat. Using this apparatus, we seek to manipulate and thereby understand the relative contribution of different sensory inputs towards forming the cognitive map.

**STATUS:** Finalized first set of data collection (5 rats) and analyzing towards journal publication

**FUNDING:** NIH R21, Johns Hopkins University Discovery award.

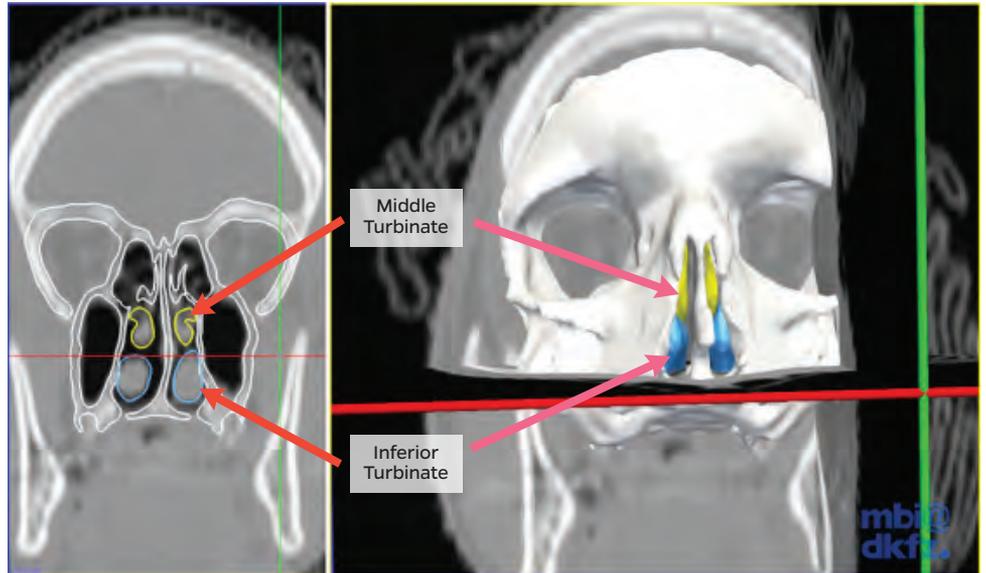
**KEY PERSONNEL:** Manu Madhav, Ravikrishnan Jayakumar, Francesco Savelli, James Knierim, Noah Cowan

**TO FIND OUT MORE:** [limbs.lcsr.jhu.edu/dome](http://limbs.lcsr.jhu.edu/dome)

# Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis

Sinha, Liu, Vágvölgyi, Leonard, Reiter, Ishii, Taylor, Hager

**Gregory D. Hager, Ph.D.**  
Mandell Bellmore Professor of Computer Science, with secondary appointments in Mechanical Engineering, Electrical and Computer Engineering, and Surgery, Founding Director: Malone Center for Engineering in Healthcare  
hager@cs.jhu.edu

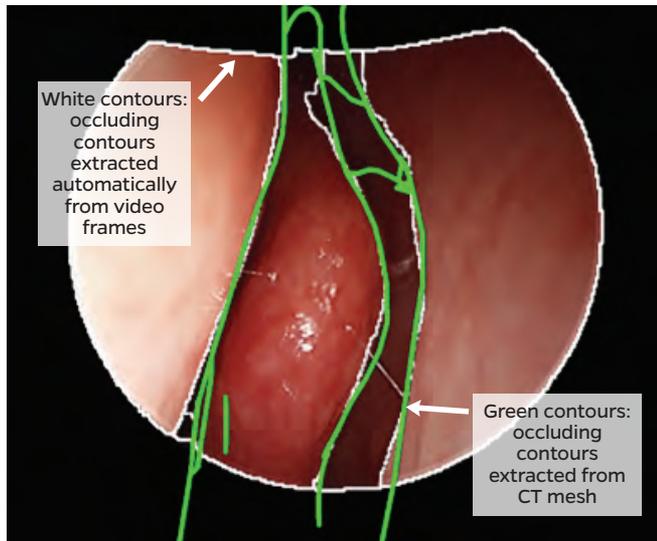


## Pre-op CT

Automatically segmented to extract relevant structures as 3D meshes which can be used to compute occluding contours.

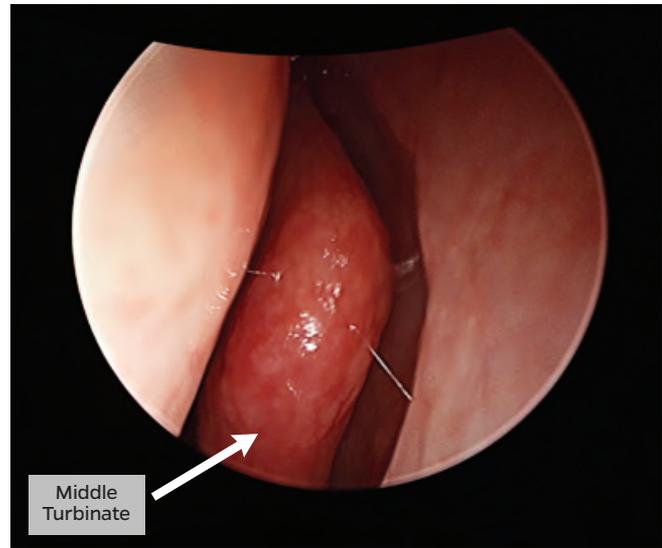
**ACCOMPLISHMENTS:** We developed a data collection system which automatically captures both the endoscopic video and the endoscope motion tracking data. We used this system to collect several videos from patients at the Johns Hopkins Outpatient Center who agreed to participate in our IRB approved study. CT images of these patients were also collected and used, along with the video data, to develop and test our segmentation, reconstruction, and registration algorithms. We developed a system for fast structure from motion reconstruction using multiple video frames to produce sparse reconstructions, as well as a framework for photometric reconstruction using neural networks to produce dense reconstructions from a single video frame. Another framework was developed to automatically segment CT images to extract structures of interest in the nasal airway and the sinuses, as well as to statistically model each structure with high accuracy using data from multiple patients. Finally, the two modalities were brought together using our novel registration algorithm, video iterative most likely oriented point (V-IMLOP) algorithm, which consistently produces registrations with sub-millimeter accuracy. We also performed a thorough evaluation of trimmed ICP on multiple datasets, as well as an evaluation of the uncertainty of the registrations produced.





### Registration

Our goal is to register pre-op data to the intra-op data to inform the surgeon of his/her precise location in the nasal airway or sinuses as he/she is performing the endoscopy.



### Intra-op Video

Pre-processed to extract features such as structure from motion (SfM) points and occluding contours.



**STATUS:** We published 4 papers last year and 1 already this year based on work done in this project. Currently, our work is focused on improving reconstruction from video, using a larger number of shapes to build better statistical models, and also on extending our registration framework to incorporate the statistical models in order to estimate deformation.

**FUNDING:** This project has been funded by National Institutes of Health Grant No. R01 EB015530: Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis.

**KEY PERSONNEL:** Ayushi Sinha, Xingtong Liu, Balázs P. Vágvölgyi, Simon Leonard, Austin Reiter, Masaru Ishii, Russell H. Taylor, Gregory D. Hager

**TO FIND OUT MORE:**  
[cirl.lcsr.jhu.edu/research/enhanced-endoscopic-navigation/](http://cirl.lcsr.jhu.edu/research/enhanced-endoscopic-navigation/)

## Language of Surgery: Understanding Activity and Improving Performance

### A DATASET AND BENCHMARKS FOR SEGMENTATION AND RECOGNITION OF GESTURES IN ROBOTIC SURGERY

**ACCOMPLISHMENT:** State-of-the-art techniques for surgical data analysis report promising results, study-specific data, and validation metrics, making assessment of progress across the field extremely challenging. We address two major problems for surgical data analysis: (1) lack of uniform shared datasets and benchmarks and (2) lack of consistent validation processes. We address the former by presenting the JHU-ISI Gesture and Skill Assessment Working Set (JIGSAWS), a public dataset we have created to support comparative research benchmarking. We address the latter by presenting a well documented evaluation methodology and reporting results for six techniques for automated segmentation and classification of time-series data on JIGSAWS.

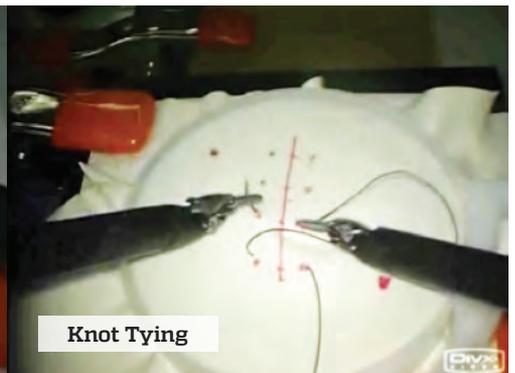
#### Different training tasks in JIGSAWS



Suturing



Needle Passing



Knot Tying

**STATUS:** JIGSAWS was released in September 2014 and has since been cited in 26 scholarly articles along with more than 60 downloads across the globe. A subsequent journal article has been published in IEEE Transactions on Biomedical Engineering, 2017.

**FUNDING:** NSF 0534359, NSF IIS-0748338, NSF-OIA 0941362, NSF-CSN 0931805, Sloan Foundation, NSF Graduate Research Fellowship Program (CER); Talentia Fellowship Program of the Andalusian Regional Ministry of Economy, Innovation and Science (Bejar); European Research Council grant VideoWorld (Vidal); NSF grant DGE-1232825 (Lea)

**KEY PERSONNEL:** Narges Ahmidi, Lingling Tao, Shahin Sefati, Yixin Gao, Colin Lea, Benjamín Béjar, Luca Zappella, Sanjeev Khudanpur, René Vidal, Gregory D. Hager

**TO FIND OUT MORE:** [cirl.lcsr.jhu.edu/jigsaws](http://cirl.lcsr.jhu.edu/jigsaws), [ieeexplore.ieee.org/document/7805258/](http://ieeexplore.ieee.org/document/7805258/)

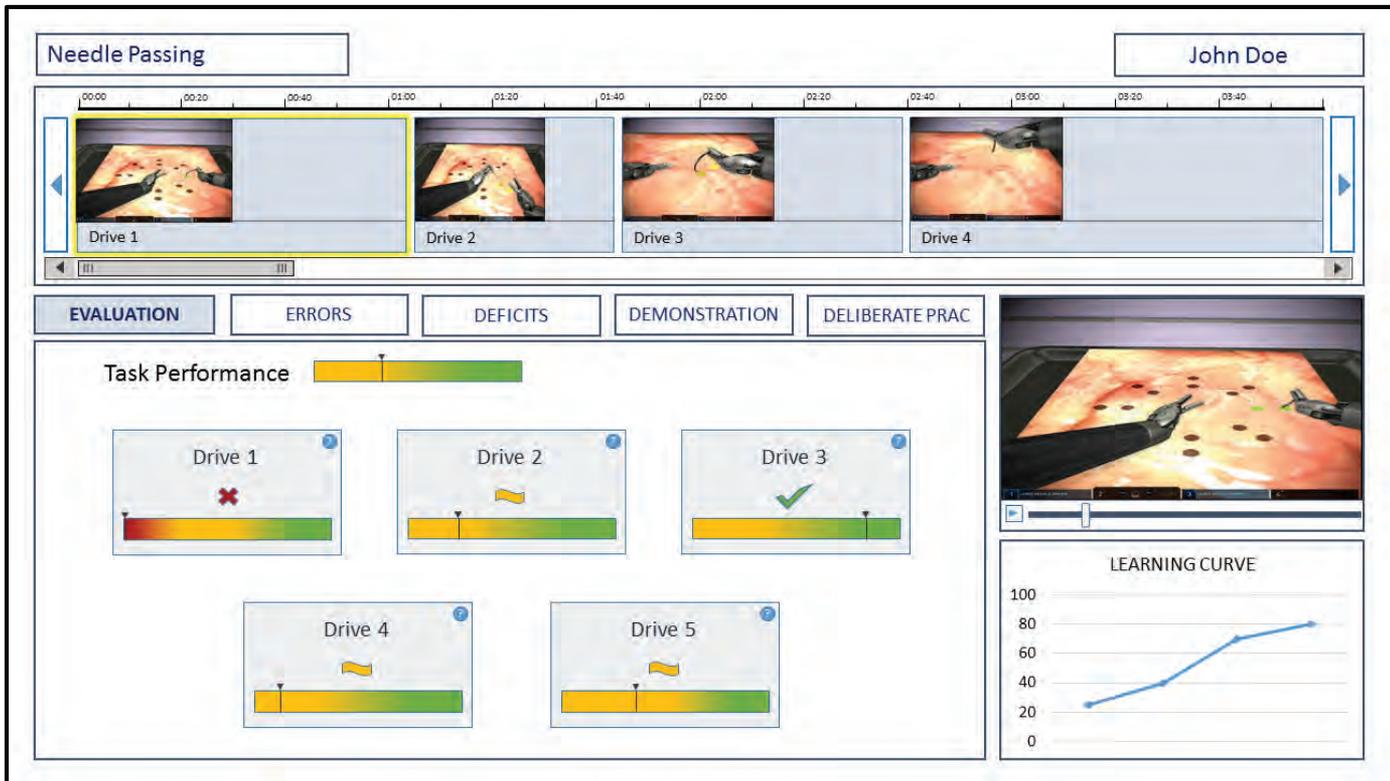
**DISCLOSURES:** None

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Task / Goal	Best Performance (framewise accuracy)		
	Suturing	Needle Passing	Knot Tying
Segmentation and Classification	81.6	74.8	78.9
Classification only	83.0	67.1	86.5

Current benchmarks for gesture recognition tasks in JIGSAWS

## AUTOMATED VIRTUAL COACH FOR SURGICAL TRAINING



**ACCOMPLISHMENT:** Surgical educators have recommended individualized coaching for acquisition, retention and improvement of expertise in technical skills. But, current approaches are resource intensive and limited to scale. We formulate automated methods using surgical data science tools to provide effective and efficient coaching that is relevant, targeted, critical and individualized. We present an integration of core coaching activities in a score card (shown above) towards the first end-to-end automated virtual coach for surgical training.

**STATUS:** Various components of the score card have been developed including activity segmentation, segment-level evaluation, real-time teaching and feedback and their validations have been published in multiple conference proceedings and journals. Work is underway to conduct effectiveness and usability studies of such a virtual coach.

**FUNDING:** Link Foundation Fellowship for Modeling, Simulation & Training, JHU Science of Learning Institute Research Grant, Intuitive Surgical Student Fellowship, JHU internal funds.

**KEY PERSONNEL:** Anand Malpani, S. Swaroop Vedula, Gregory D. Hager

**TO FIND OUT MORE:** [cirl.lcsr.jhu.edu/research/hmm/](http://cirl.lcsr.jhu.edu/research/hmm/)

**DISCLOSURES:** None

**PAPERS:** A. Malpani, "Automated Virtual Coach for Surgical Training", Ph.D. Thesis, The Johns Hopkins University, Baltimore, Maryland, 2017.

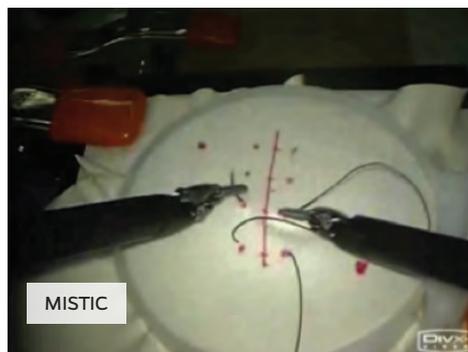
## Language of Surgery: Understanding Activity and Improving Performance

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### RECOGNIZING SURGICAL ACTIVITIES WITH RECURRENT NEURAL NETWORKS (RNNs)

**ACCOMPLISHMENT:** Automated surgical-activity recognition is an important step toward objective skill assessment and toward providing targeted feedback to trainees. In this work, we focus on recognizing both gestures, short, low-level activities, and maneuvers, longer, high-level activities. By applying recurrent neural networks to this task, we improve significantly over previous state-of-the-art techniques. For example we increase activity-recognition accuracy from 80% to 90% in the context of robotic minimally invasive surgery.

#### DATA



**STATUS:** This work was accepted at MICCAI 2016 as an oral presentation, (but it is of course far from complete). Next, we would like to apply methods that incorporate global structure (such as fully-connected conditional random fields) to further improve results.

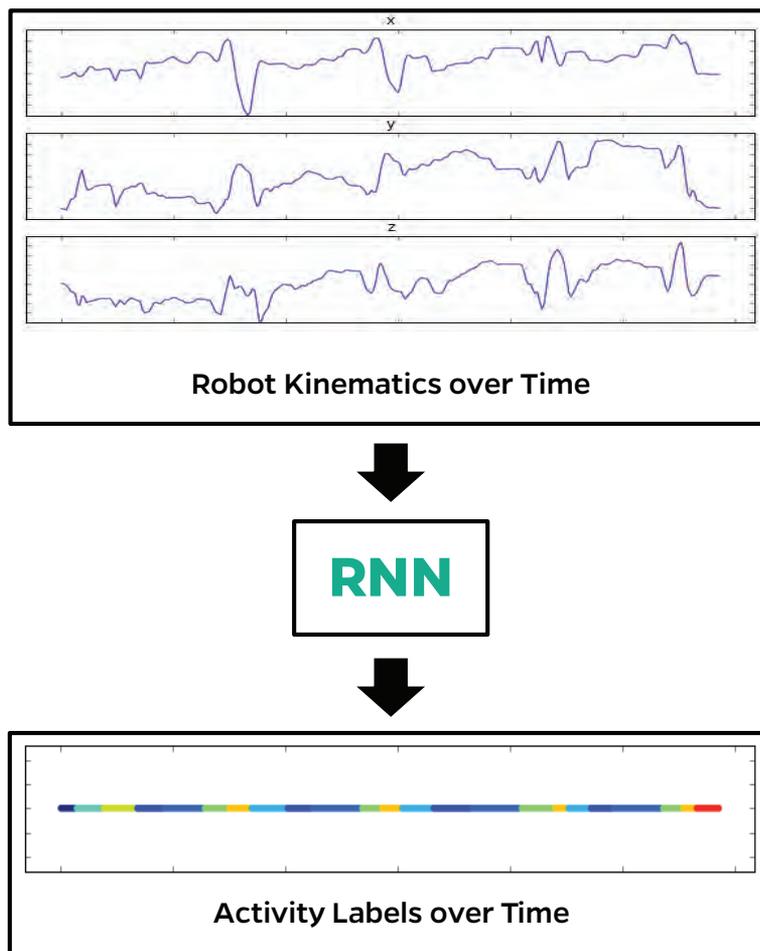
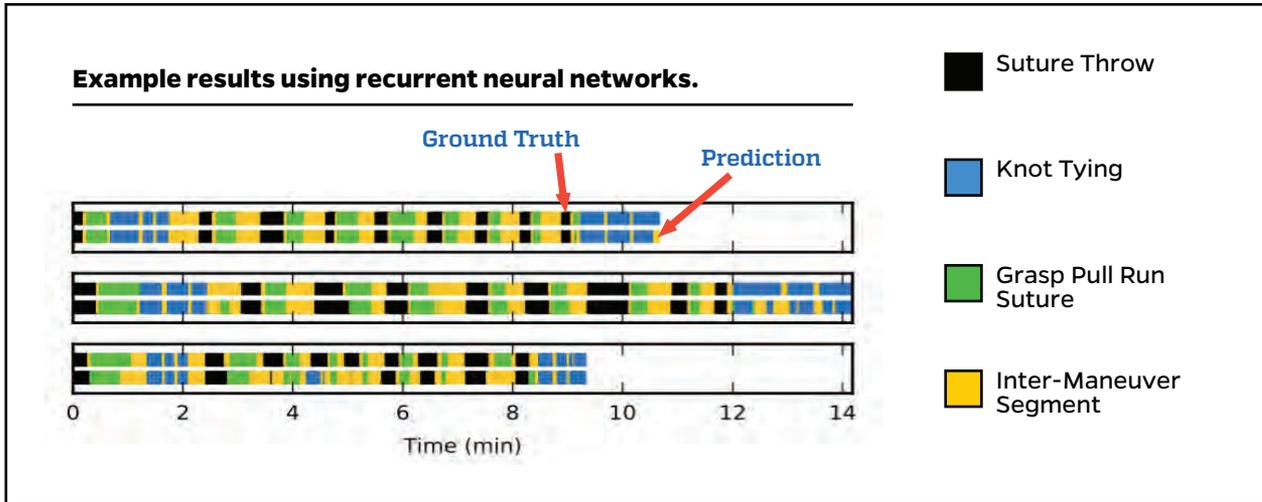
**FUNDING:** JHU Science of Learning Institute Research Grant, National Science Foundation

**KEY PERSONNEL:** Robert DiPietro, Colin Lea, Anand Malpani, Narges Ahmidi, S. Swaroop Vedula, Gyusung I. Lee, Mija R. Lee, and Gregory D. Hager

**TO FIND OUT MORE:** [arxiv.org/abs/1606.06329](https://arxiv.org/abs/1606.06329)

**DISCLOSURES:** None

**PAPERS:** R. DiPietro et al., “Recognizing surgical activities with recurrent neural networks,” in Medical Image Computing and Computer-Assisted Intervention – MICCAI 2016, Springer International Publishing, 2016, pp. 551–558.

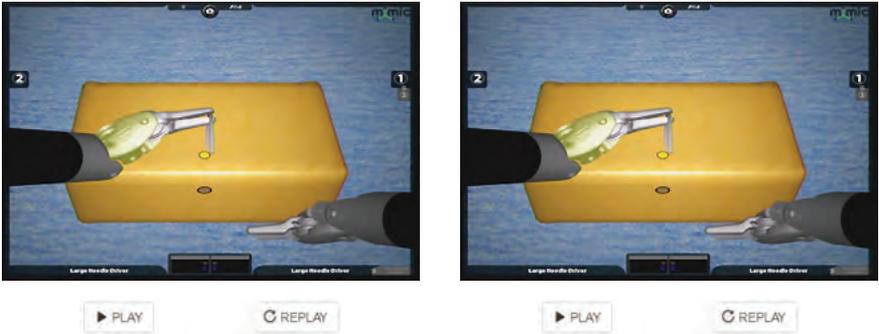


# Language of Surgery: Understanding Activity and Improving Performance

## SEGMENT-LEVEL EVALUATION OF SURGICAL PERFORMANCE USING PAIRWISE COMPARISONS

### Crowdsourced Comparisons

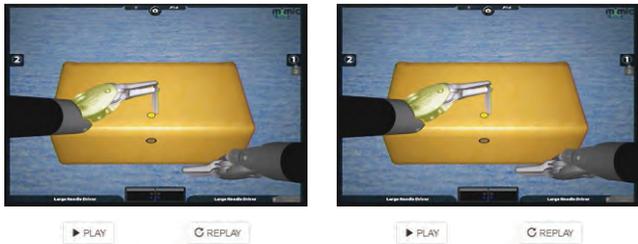
Which performance is better? 1 or 2?



Video 1 Video 2

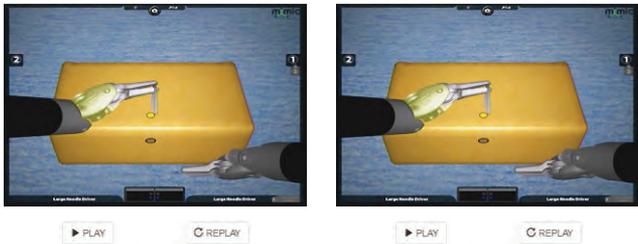
### Machine-predicted Comparisons

Which performance is better? 1 or 2?



Video 1 Video 2

Which performance is better? 1 or 2?



Video 1 Video 2

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**ACCOMPLISHMENT:** While automation and objectiveness are desirable properties of surgical skill assessments, providing only a skill score or expertise label is not sufficient to train or coach surgeons. The question of “where was I wrong?” still remains unsolved. Segment-level evaluation is not only useful to provide targeted feedback about which segments need improvement but can lead to reliable overall evaluations as well. We present a novel scoring method to generate automated skill scores of segment-level and task-level performances using crowdsourced pairwise comparisons and machine learning approaches.

**STATUS:** Multiple validation studies have been conducted with successful outcomes supporting the framework on offline data sets. Future steps will explore the effectiveness of such scores in delivering targeted feedback and effective learning. There have been multiple publications at IPCAI'14 and a journal article in IJCARS, 2015.

**FUNDING:** JHU Science of Learning Institute Research Grant, Intuitive Surgical Student Fellowship, JHU internal funds.

**KEY PERSONNEL:** Anand Malpani, S. Swaroop Vedula, C. C. Grace Chen, Gregory D. Hager

**TO FIND OUT MORE:** [link.springer.com/article/10.1007/s11548-015-1238-6](http://link.springer.com/article/10.1007/s11548-015-1238-6)

**DISCLOSURES:** None



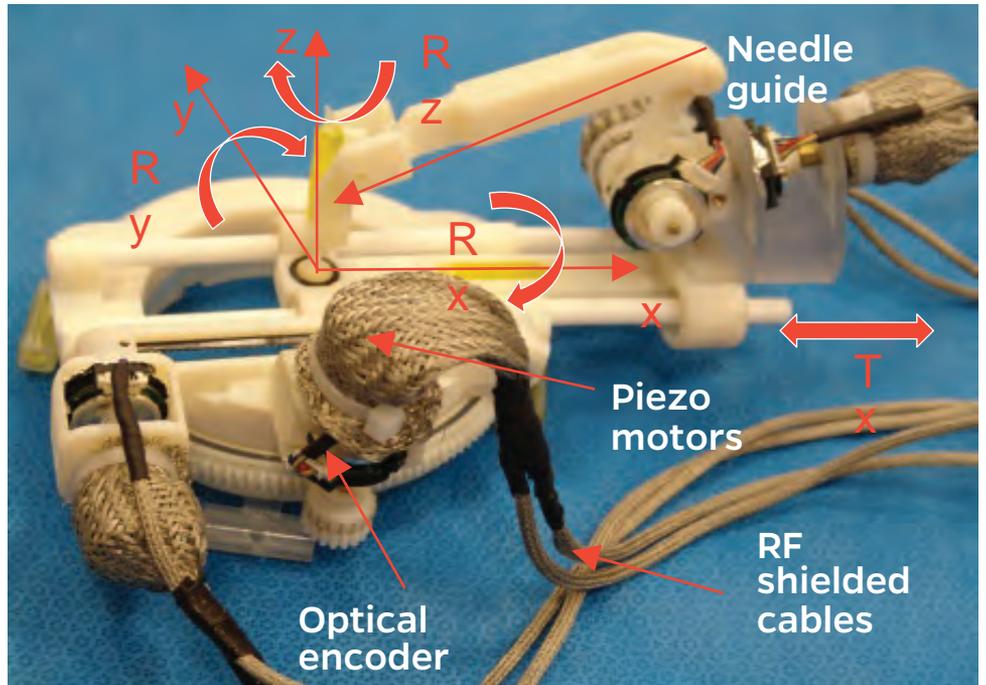
**Ranking (percentile score)**

**PAPERS:**

1. A. Malpani, "Automated Virtual Coach for Surgical Training", Ph.D. Thesis, The Johns Hopkins University, Baltimore, Maryland, 2017.
2. A. Malpani, S. S. Vedula, C. C. G. Chen, and G. D. Hager, "A study of crowdsourced segment-level surgical skill assessment using pairwise rankings," Int J CARS, vol. 10, no. 9, pp. 1435–1447, Jun. 2015.
3. A. Malpani, S. S. Vedula, C. C. G. Chen, and G. D. Hager, "Pairwise comparison-based objective score for automated skill assessment of segments in a surgical task," in Information Processing in Computer-Assisted Interventions, D. Stoyanov, D. L. Collins, I. Sakuma, P. Abolmaesumi, and P. Jannin, Eds. Springer International Publishing, 2014, pp. 138–147.

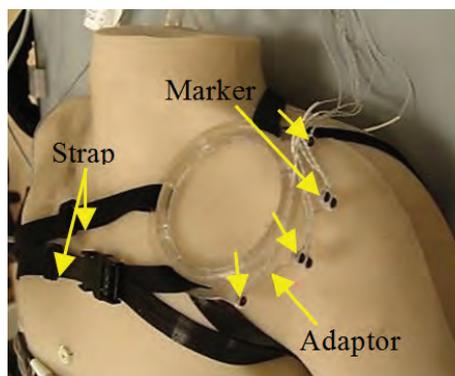
# MRI Compatible Body-mounted Robot to Streamline Pediatric Shoulder Arthrography

Monfaredi, Sharma, Kim,  
Iordachita, Cleary (PI)

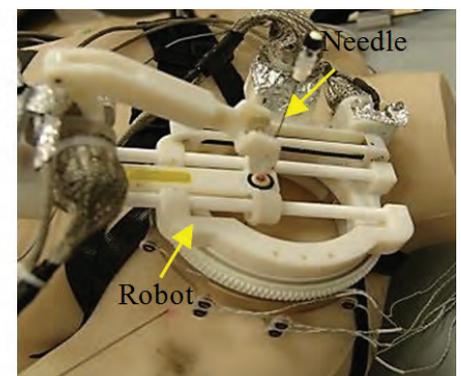


MRI-compatible 4-dof needle placement manipulator

**ACCOMPLISHMENT:** The goal is to develop and test a new patient-mounted MRI-compatible shoulder arthrography robot for needle guidance in pediatric interventional procedures. The second prototype of a 4 degrees of freedom (DOF) body-mounted robot was developed. Robot accuracy and mounting system stability were evaluated in laboratory environment. The maximum positioning and orienting error for the robot was  $\pm 0.6$  mm and  $\pm 0.5$  degree; respectively. Experimental results for mounting stability gave a maximum displacement of the base of the robot with respect to a target point inside the shoulder of the body phantom as 1.12 mm. IRB approval for a clinical trial of MRI-guided shoulder arthrography using this robot has been granted.

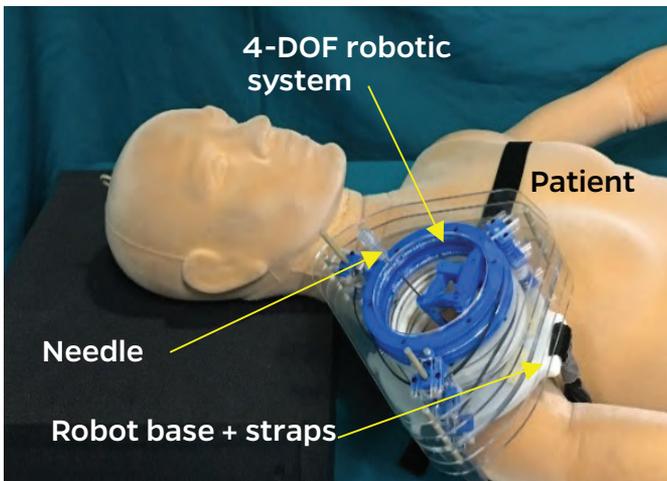


Proposed mounting method

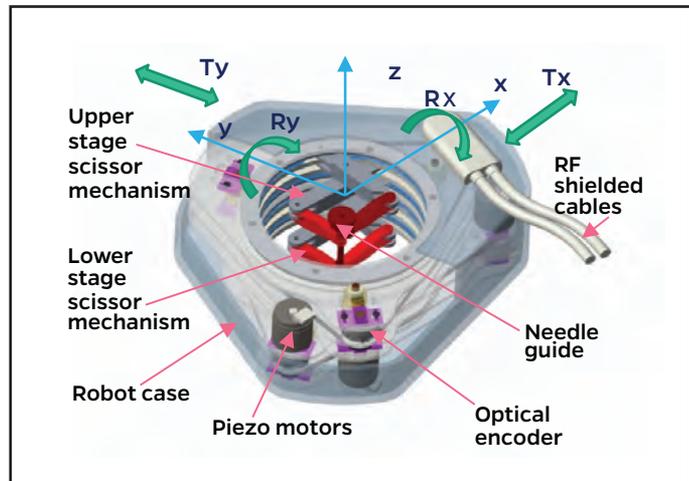


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New design concept with a parallel structure



CAD model for the new 4-DOF parallel robot

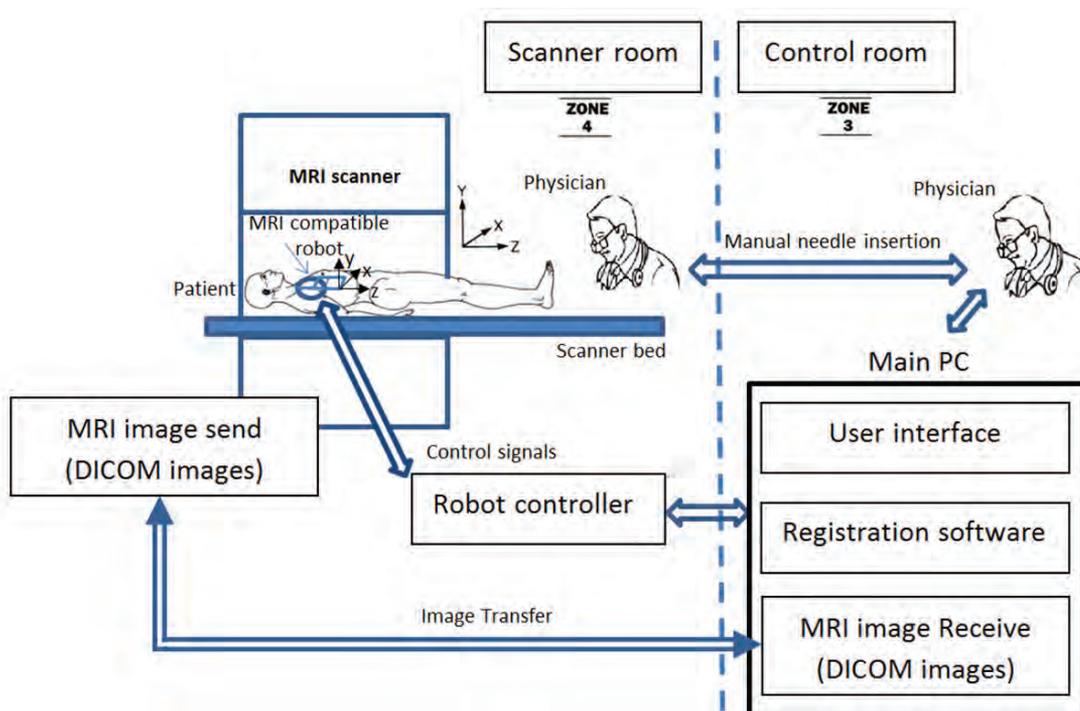
**STATUS:** Refinements and further engineering evaluations ongoing

**FUNDING:** NIH R01 EB020003-01, Children's National Health System, Sheikh Zayed Institute for Pediatric Surgical Innovation, and JHU internal funds

**KEY PERSONNEL:** (CNMC) Monfaredi R., Sharma K., Cleary K., (JHU) Iordachita I., Kim J.S.

**TO FIND OUT MORE:** [amiro.lcsr.jhu.edu/main/Research](http://amiro.lcsr.jhu.edu/main/Research)

## System configuration



# MRI-guided Robot for In-Bore Prostate Interventions: Clinical Trials

Tokuda, Tuncali, Fischer, Iordachita, Burdette, Hata, Tempany (PI)

## Clinical Trials at BWH

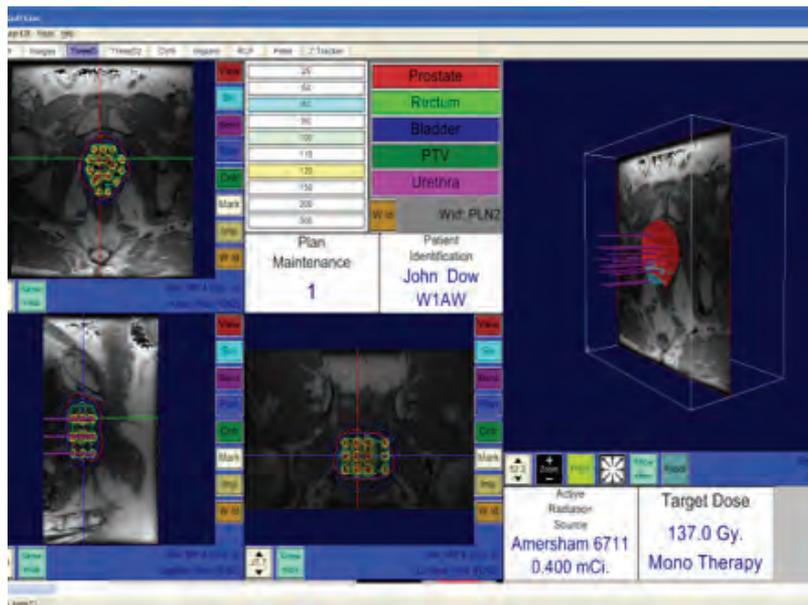
**ACCOMPLISHMENT:** The goal is to evaluate the clinical feasibility of our MRI-compatible 4-DOF needle-guide manipulator for in-bore MRI-guided transperineal prostate biopsy. A total of 26 men were biopsied in a 3T MRI scanner using this manipulator. All 26 procedures were successfully performed. The targeting errors were consistent with other clinical studies. In conclusion, in-bore MRI-guided prostate biopsy using the manipulator was feasible.

**STATUS:** Clinical trials, results evaluation ongoing

**FUNDING:** NIH R01CA111288, R01EB020667, and P41EB015898

**KEY PERSONNEL:** (BWH) Tokuda J., Tuncali K., Hata N., Tempany C.M., (WPI) Li G., Patel N., Fischer G.S., (JHU) Iordachita I., (ACM) Burdette E.C., Heffter T.

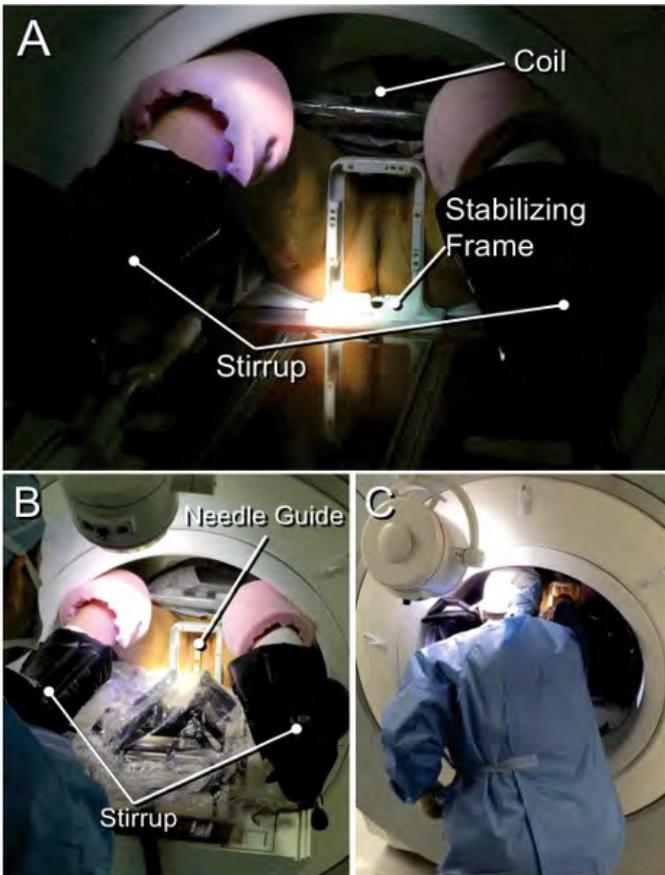
**TO FIND OUT MORE:** [amiro.lcsr.jhu.edu/main/Research](http://amiro.lcsr.jhu.edu/main/Research)



GUI of the RadVision Software

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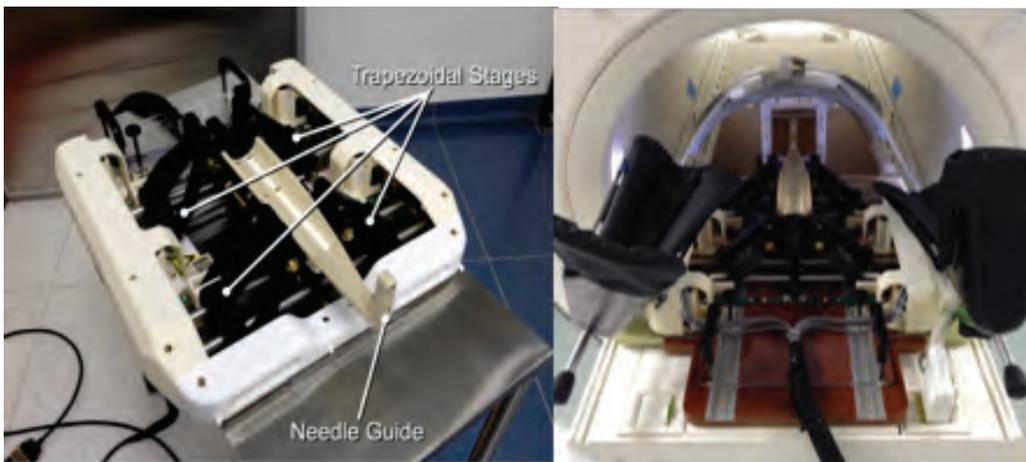




Clinical workflow of MRI-guided prostate biopsy

**RESULTS:**

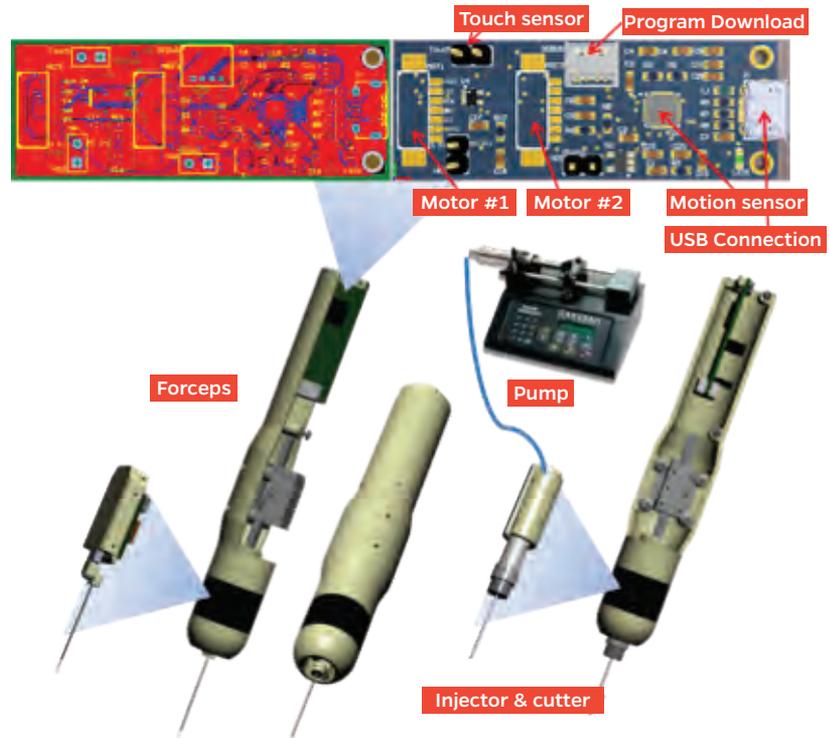
- 26 men were biopsied in a 3T MRI scanner
- All the procedures were successfully performed
- Number of targets/case: 1.615
- Number of cores/target: 2.476
- Number of attempts/core: 2.010
- Targeting error (all attempts):  $7.724 \pm 4.916$  mm
- Targeting errors (1st attempt):  $8.003 \pm 5.034$  mm
- Biopsy error (all attempts):  $8.611 \pm 7.209$  mm
- Biopsy error (1st attempt):  $10.506 \pm 7.260$  mm



MRI-compatible 4-DOF needle placement manipulator

# Optical Coherence Tomography Image and Sensor Guided Microsurgical Tools

Jin U. Kang (PI), Soohyun Lee, Berk Gonenc, Jeremy Chae, Russell H. Taylor



Smart microsurgical tool designs, including a control board and an example of a prototype micro-forceps and injector

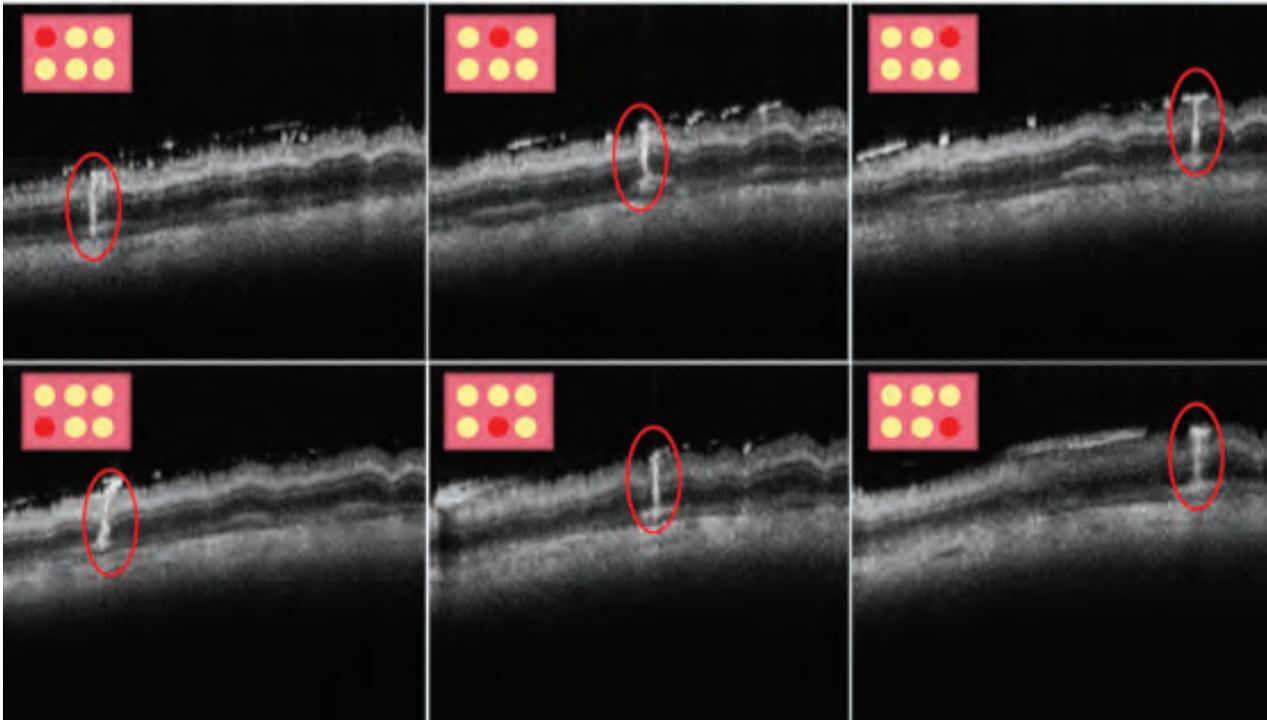
**SUMMARY:** We are developing a new class of handheld “smart” microsurgical tools combining fiber optic common-path OCT sensors with automatic high-precision fine axial movement of the tool tip to ensure safety and axial tool control beyond the human capability. These include a microinjection cannula that will allow precise delivery of micro-volumes of therapeutic agents such as stem cells and genes directly into the desired layers in intra-retinal space. Currently, we are actively pursuing commercialization of these technologies for clinical use.

**TO FIND OUT MORE:** [engineering.jhu.edu/biophotonics](http://engineering.jhu.edu/biophotonics)

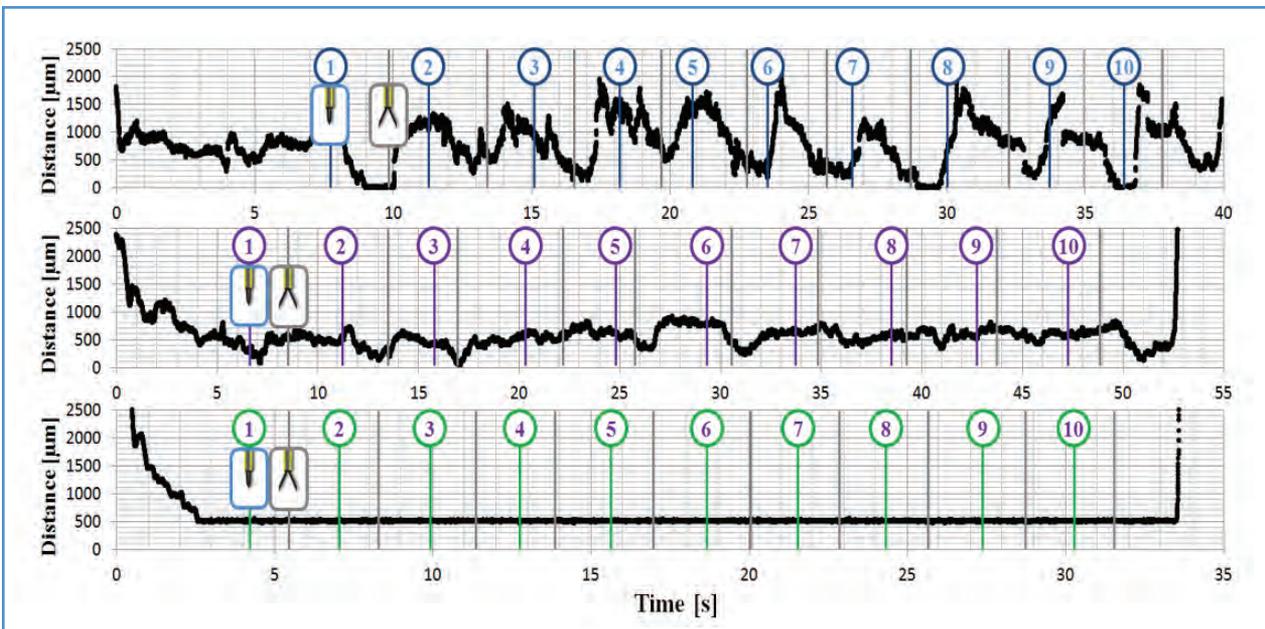
**FUNDING:** NIH R01, NIH R21, ERC MIRTHE, Coulter Foundation, Maryland Innovative Initiative (MII)

**KEY PERSONNEL:** Jin U. Kang (PI), Soohyun Lee, Berk Gonenc, Jeremy Chae, Russell H. Taylor

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 Department of Dermatology,  
 Kevli Neuroscience  
 Discovery Institute,  
 Engineering Research Center  
 for Mid-IR Technologies for  
 Health and Environment



OCT image of intra-retinal Injection using SMART injector

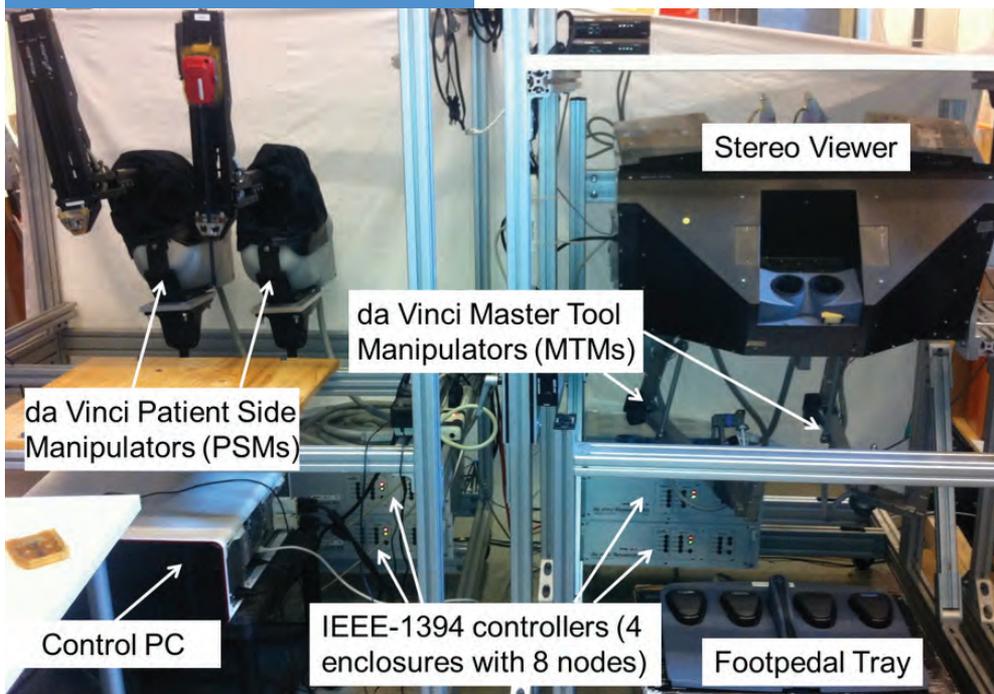


Motion of micro-forceps during grasping action (10 grasps/case): (a) using a standard manual micro-forceps, using SMART micro-forceps (actuated via the touch sensor) (b) without and (c) with the motion compensation

## da Vinci Research Kit: Community Infrastructure

Peter Kazanzides, Russell Taylor, Anton Deguet, Zihan Chen, Jie Ying Wu

**ACCOMPLISHMENT:** We developed open source electronics and software to control the mechanical components of a first-generation da Vinci Surgical Robot. As this mechanical hardware has become available to other researchers, we have replicated our hardware and software to support a growing research community. With NSF support, we have partnered with Worcester Polytechnic Institute (WPI) and University of Washington to create an open source framework around the dVRK, Raven II, and other robot systems. The availability of these robust, common platforms enables education and collaborative research in cutting edge robotics areas such as semi-autonomous teleoperation.



- Open source research platform based on first-generation da Vinci system

- Growing international user community: 25 existing sites and more in process

- Extending software framework to other robots and devices.

Peter Kazanzides, Ph.D.  
Research Professor  
of Computer Science  
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**STATUS:** This platform now exists at 25 institutions worldwide, with more in process. The open source controller is used both for the da Vinci Research Kit (subset of a complete da Vinci) as well as for complete da Vinci systems. We are currently extending the software framework to include other robots and devices.

**FUNDING:** Current support via NSF NRI 1637789 and DVRK Consortium; previous support from: NSF EEC 9731748 (CISST ERC), EEC 0646678 (SAW Supplement), and MRI 0722943.

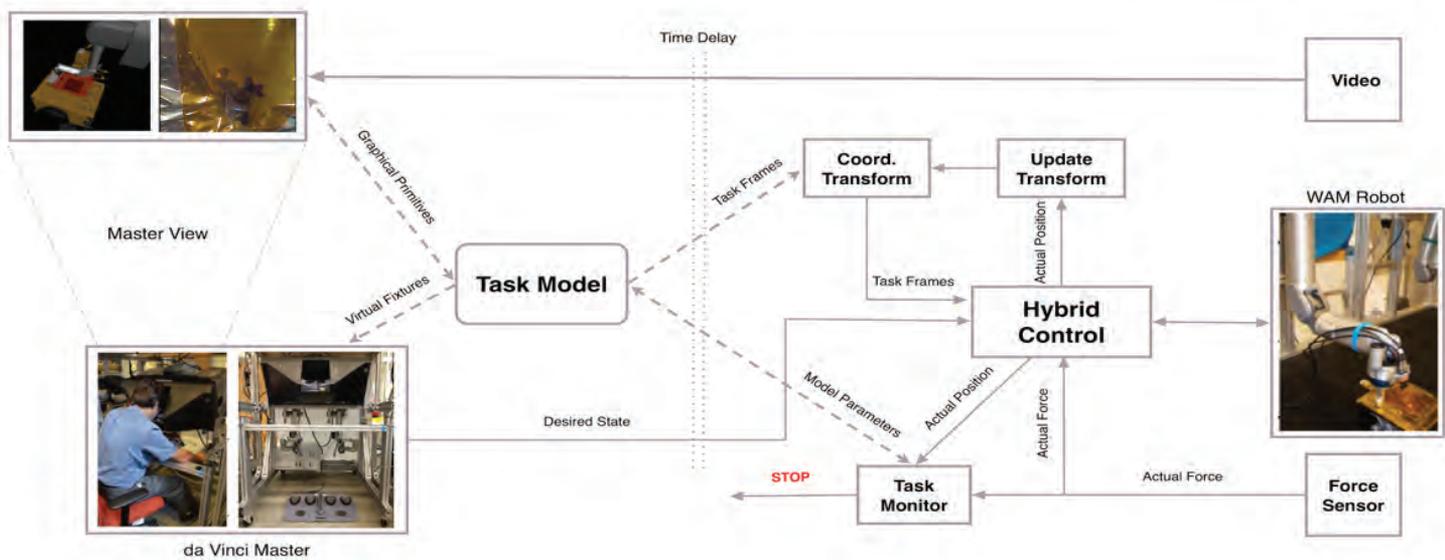
**KEY PERSONNEL:** Peter Kazanzides, Russell Taylor, Anton Deguet, Zihan Chen, Jie Ying Wu, Simon Leonard, Long Qian, Paul Thienphrapa; collaboration with Simon DiMaio and others at Intuitive Surgical; collaboration with Greg Fischer at Worcester Polytechnic Institute (WPI) and Blake Hannaford at University of Washington.

**TO FIND OUT MORE:** [research.intusurg.com/dvrkwiki/](http://research.intusurg.com/dvrkwiki/), <http://github.com/jhu-dvrk>

# Telerobotic Satellite Servicing

Peter Kazanzides,  
Louis Whitcomb, Simon  
Leonard, Greg Hager

**ACCOMPLISHMENT:** We have developed and demonstrated a system to enable ground-based control of an on-orbit robot for satellite servicing, with communication delays of several seconds. We adopt a model-based approach, where the ground-based operator performs the (simulated) task in an augmented reality environment constructed from a registered 3D model of the satellite augmented with projections of images from the remote cameras. The results are sent to the remote robot, which uses sensor-based control to replicate the simulation. The remote robot includes a task monitor that compares measured interaction forces with those estimated from a task model, so that the robot can be stopped if discrepancies are detected. It also contains a component to estimate and correct for registration errors between the task model and satellite. Several multi-user experiments (HIRB 00000701) have been performed to study the performance of different control methods and user interaction modes.



**STATUS:** System components have been developed and individually tested. Current efforts focused on:

- (1) multi-user experiments to compare performance with all components enabled to baseline scenario (no assistance), and
- (2) generation of virtual 3D satellite model from multiple 2D views and CAD model of satellite internal structure.

**FUNDING:** NASA NNG10CR16C, NNG14CR58C, NNG 15CR66C, NSF NRI 1208540

**KEY PERSONNEL:** Peter Kazanzides, Louis Whitcomb, Simon Leonard, Greg Hager, Balazs Vagvolgyi, Zihan Chen, Tian Xia, Anton Deguet, Jonathan Bohren, Steve Vozar, Isha Kandaswamy, Amy Blank, Ryan Howarth, Paul Wilkening, Wenlong Niu

**TO FIND OUT MORE:** T. Xia, S. Leonard, I. Kandaswamy, A. Blank, L. Whitcomb, P. Kazanzides, "Model-Based Telerobotic Control with Virtual Fixtures For Satellite Servicing Tasks," IEEE Intl. Conf. on Robotics and Automation (ICRA), Karlsruhe, Germany, May 2013.

S. Vozar, S. Leonard, P. Kazanzides, L. Whitcomb, "Experimental Evaluation of Force Control for Virtual-Fixture-Assisted Teleoperation for On-Orbit Manipulation of Satellite Thermal Blanket Insulation," IEEE Intl. Conf. on Robotics & Automation (ICRA), Seattle, USA, May 2015.

- Ground-based control of on-orbit robotic servicing spacecraft, subject to communication delays of several seconds
- Approach: model-based teleoperation, where operator uses da Vinci master console to perform task in virtual world while remote robot uses sensor-based control to replicate simulation
- Augmented reality and augmented virtuality interfaces to improve operator situation awareness.

## Photoacoustic Image Guidance for Robotic Surgery

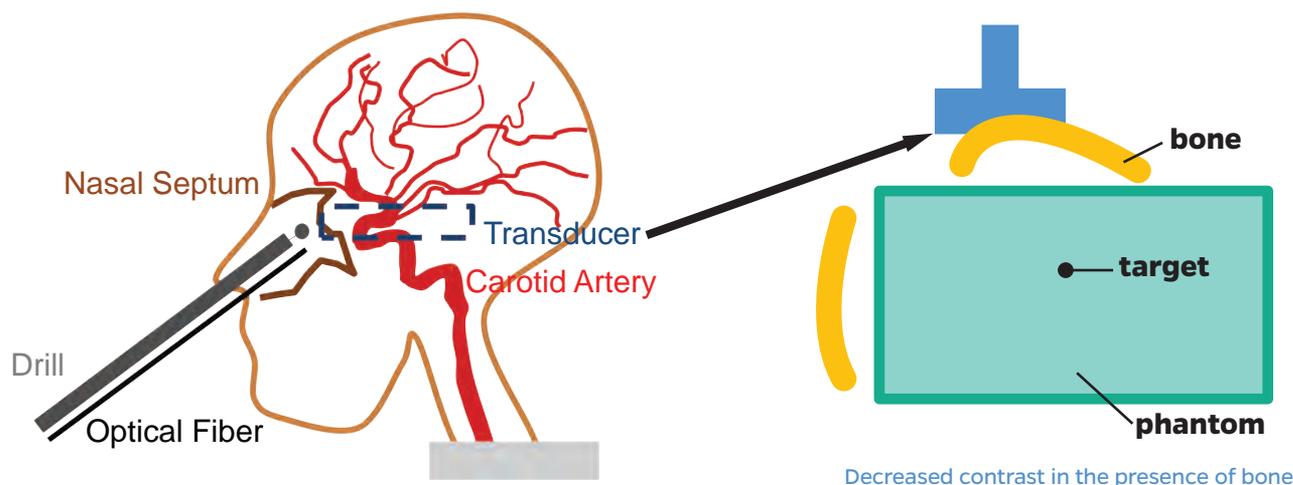
Peter Kazanzides,  
Muyinatu A. Lediju Bell,  
Sungmin Kim

**ACCOMPLISHMENT:** We developed and demonstrated the use of photoacoustic imaging to detect critical structures, such as the carotid artery, during endonasal skull base surgery. In this system, an optical fiber is integrated with the surgical instrument (drill) and directs a pulsed laser into the tissue that causes blood vessels to generate acoustic waves. These waves are detected by an ultrasound probe held by a second robot arm. In benchtop experiments, we demonstrated that photoacoustic imaging can locate blood vessels behind several millimeters of bone, whereas conventional B-mode ultrasound fails to image those vessels. We demonstrated an integrated system composed of a da Vinci robot (open-source da Vinci Research Kit), an ultrasound scanner, a pulsed laser, and the 3D Slicer visualization software.

**STATUS:** System has been tested on phantoms. Next steps include testing with more realistic phantoms (based on human skull), improved light delivery systems, and better mapping of intraoperative anatomy.

**FUNDING:** NSF NRI 1208540 (PI: Kazanzides), NIH K99-EB018994 (PI: Bell)

### PROPOSED IMAGING SYSTEM



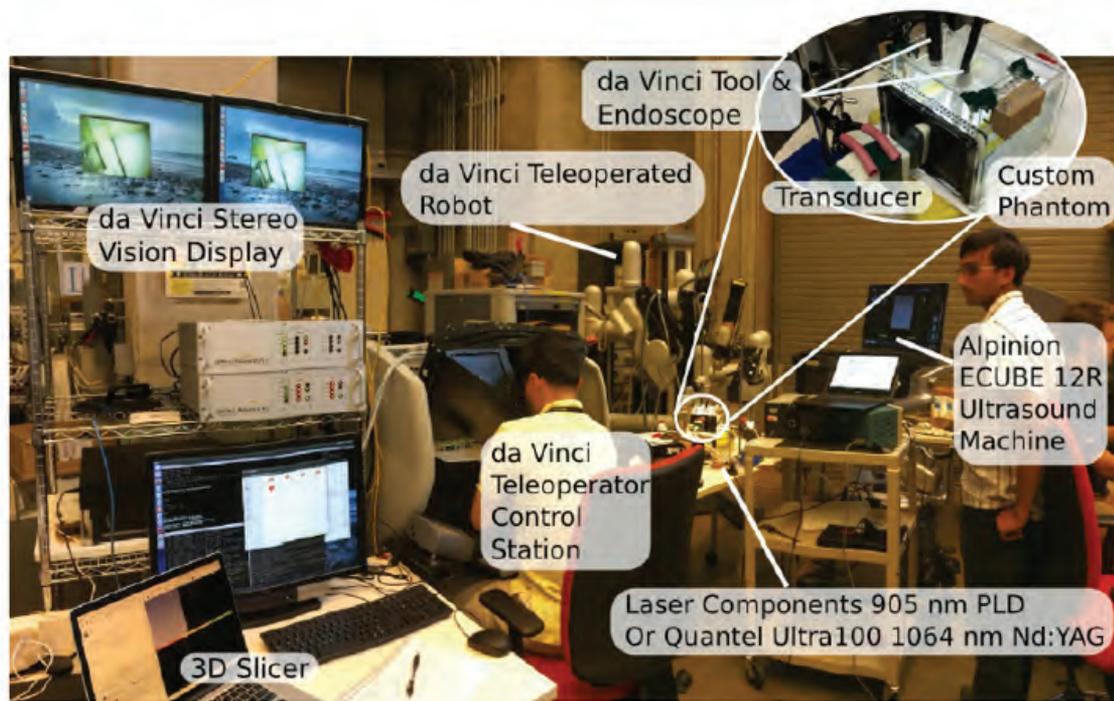
**Peter Kazanzides, Ph.D.**  
Research Professor  
of Computer Science  
pkaz@jhu.edu  
pulselab.jhu.edu/research  
smarts.lcsr.jhu.edu/research

**KEY PERSONNEL:** Peter Kazanzides, Muyinatu A. Lediju Bell, Sungmin Kim, Blackberrie Eddins; previous participants include: Neeraj Gandhi, Anastasia Ostrowski, Alicia Dagle, Youri Tan, Emad Boctor

**TO FIND OUT MORE:** mledijubell@jhu.edu, sungminkim@jhu.edu, pkaz@jhu.edu

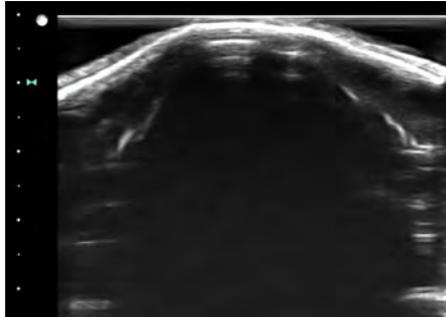
Bell MAL, Ostrowski AK, Li K, Kazanzides P, Boctor EM, “Localization of transcranial targets for photoacoustic-guided endonasal surgeries”, *Photoacoustics*. 3 (2), 78-87, 2015.

Kim S, Kang HJ, Cheng A, Bell MAL, Boctor EM, Kazanzides Peter, “Photoacoustic Image Guidance for Robot-Assisted Skull Base Surgery”, *IEEE Intl. Conf. on Robotics and Automation (ICRA)*. Seattle, WA, 2015.



### NO BONE (CONTROL)

ultrasound



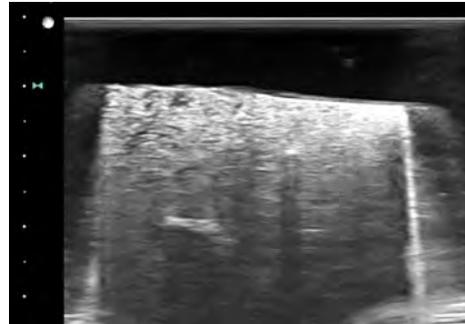
photoacoustic



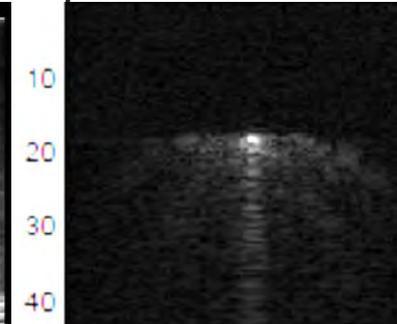
Target is visible in photoacoustic image with decreased contrast

### TEMPORAL BONE

ultrasound



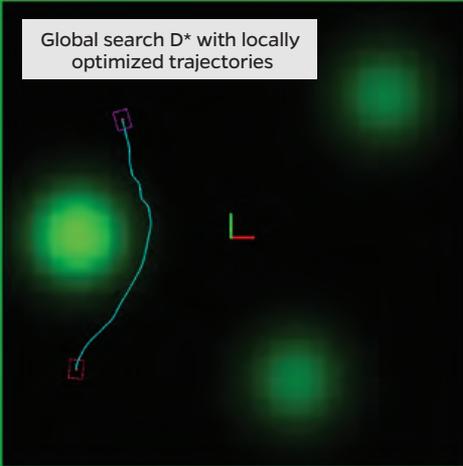
photoacoustic



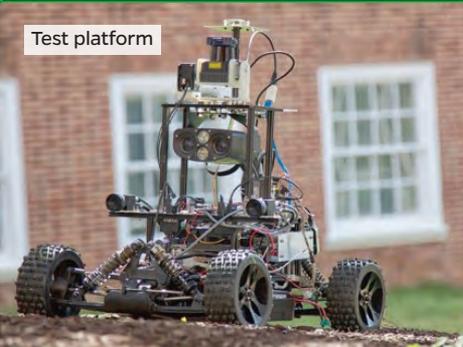
Target is visible in both images with excellent contrast in photoacoustic image

# Autonomous Systems, Control, and Optimization Laboratory (ASCO)

Global search D\* with locally optimized trajectories



Test platform



**Marin Kobilarov, Ph.D.**  
Assistant Professor  
of Mechanical Engineering,  
Autonomous Systems, Control and  
Optimization (ASCO) Lab  
[asco.lcsr.jhu.edu](http://asco.lcsr.jhu.edu)

## TOWARDS AGILE AERIAL MANIPULATION

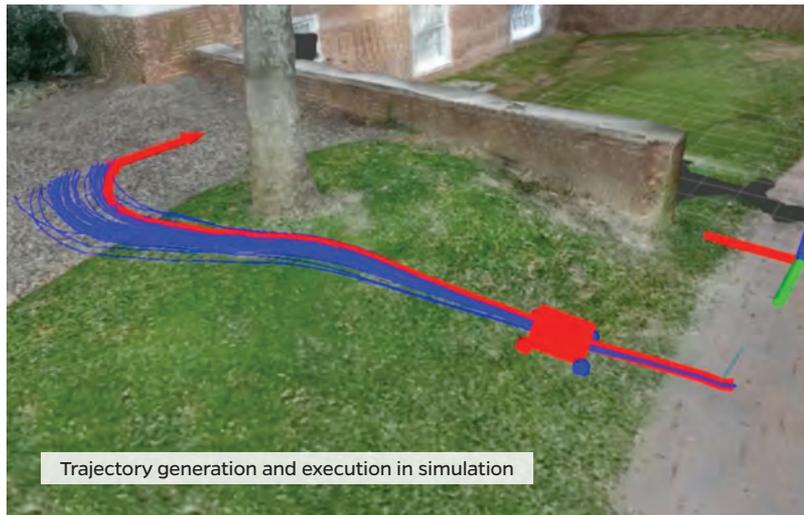
**ACCOMPLISHMENT:** This work develops planning and control algorithms for autonomous navigation of ground vehicles on arbitrary rough terrains. The approach is based on global stochastic optimization and local optimal control of trajectories simulated using a high-fidelity physics engine. Other approaches involve using graph search techniques with locally optimized dynamic primitives.

**STATUS:** The system is currently being deployed on a small-scale ground vehicle at JHU.

**FUNDING:** DARPA

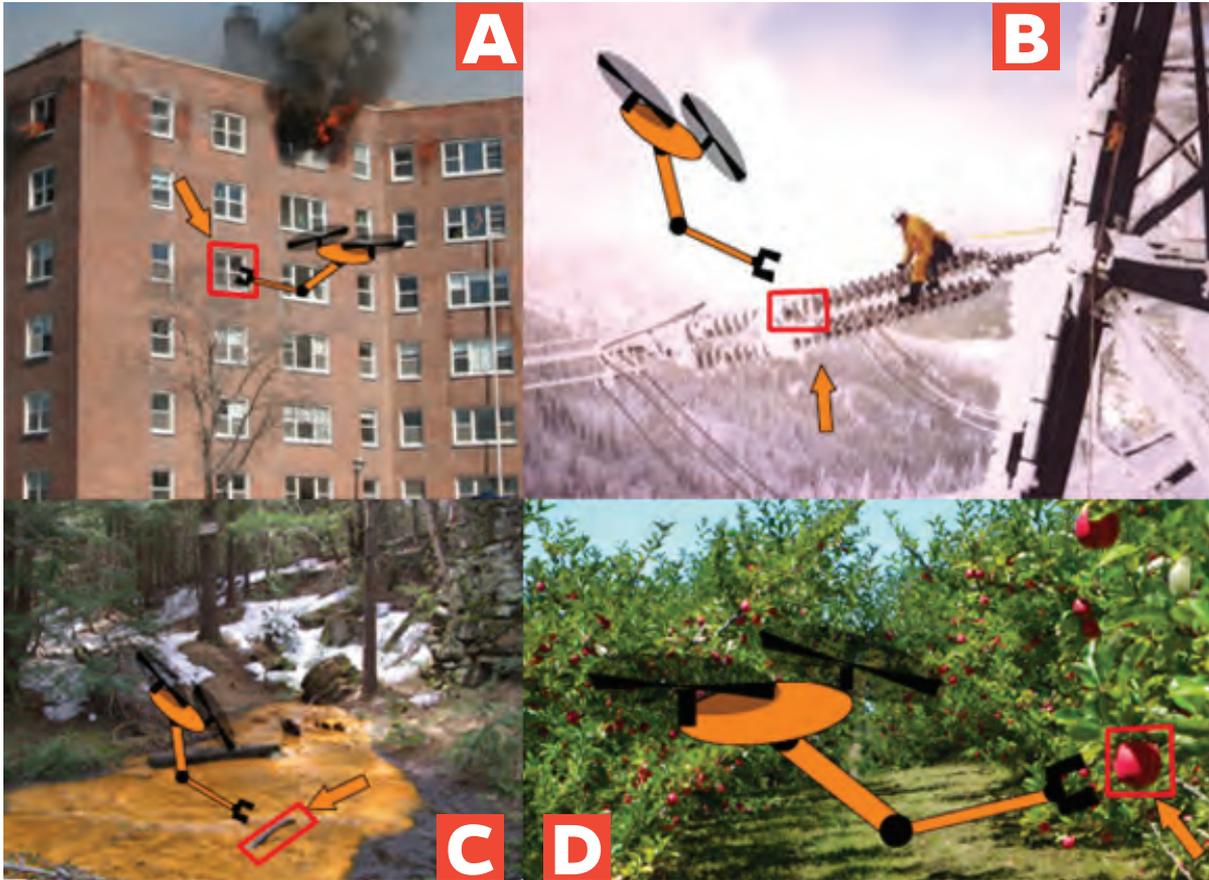
**KEY PERSONNEL:** Subhransu Mishra, Gowtham Garimella, Matthew Sheckells, Marin Kobilarov

**TO FIND OUT MORE:** [asco.lcsr.jhu.edu/rough-terrain-ground-vehicle-control](http://asco.lcsr.jhu.edu/rough-terrain-ground-vehicle-control)

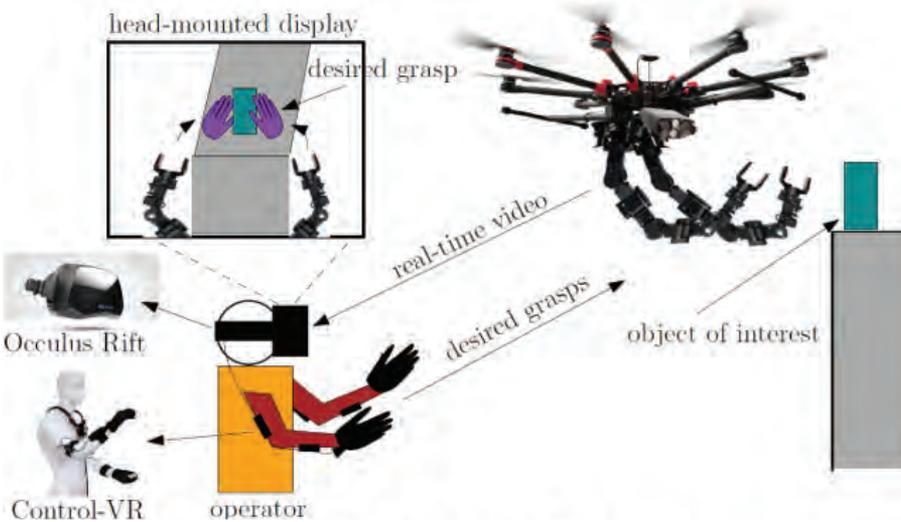


**AGILE OFF-ROAD SMALL VEHICLE NAVIGATION**

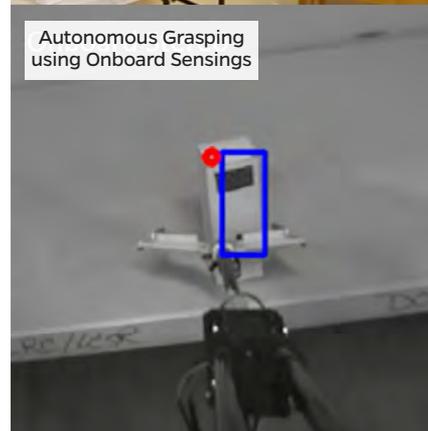
S. Mishra, G. Garimella, M. Sheckells, M. Kobilarov, et al.



**Manipulation Concepts:** A) Search-and-rescue, B) Infrastructure repair, C) Environmental sampling, D) Agriculture

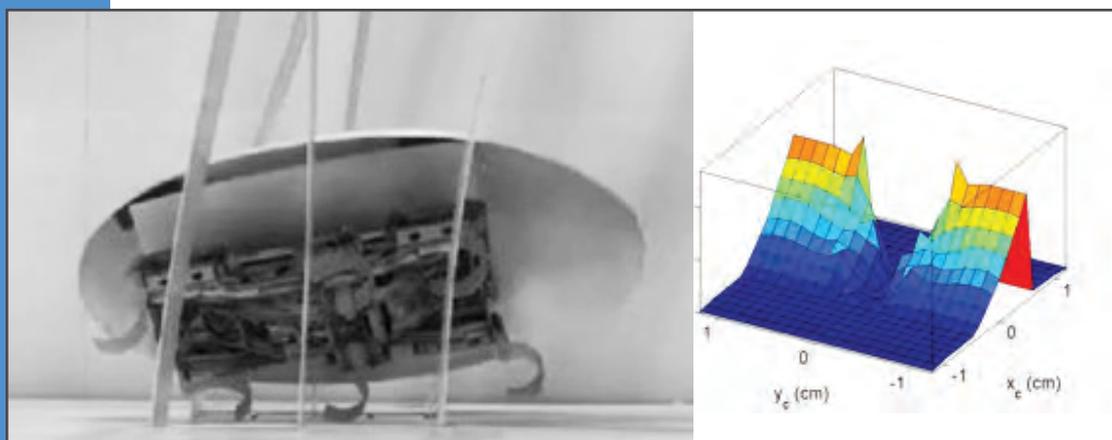


**Human-assisted Manipulation using Augmented Reality**



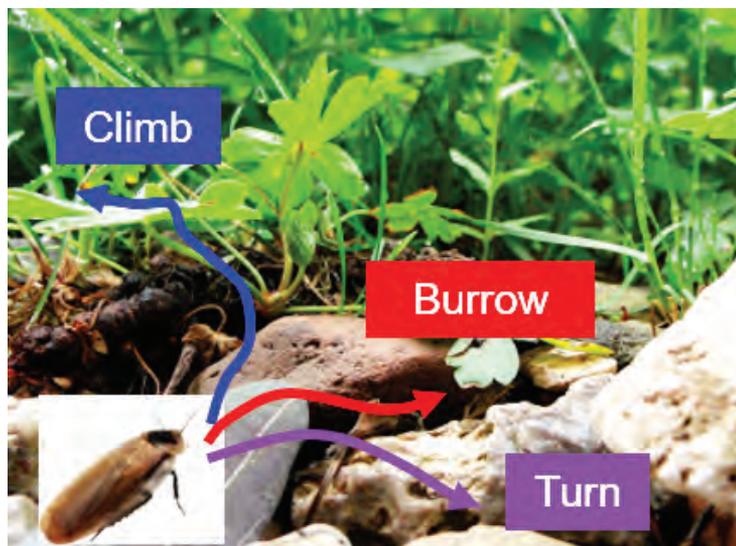
Autonomous Grasping using Onboard Sensings

# Terradynamics Lab



Analogous to aero-/hydrodynamics for flight and swimming, Prof. Chen Li's Terradynamics Lab studies the physics of animal/robot-terrain interaction to better understand biological locomotion and improve robotic mobility in the real world.

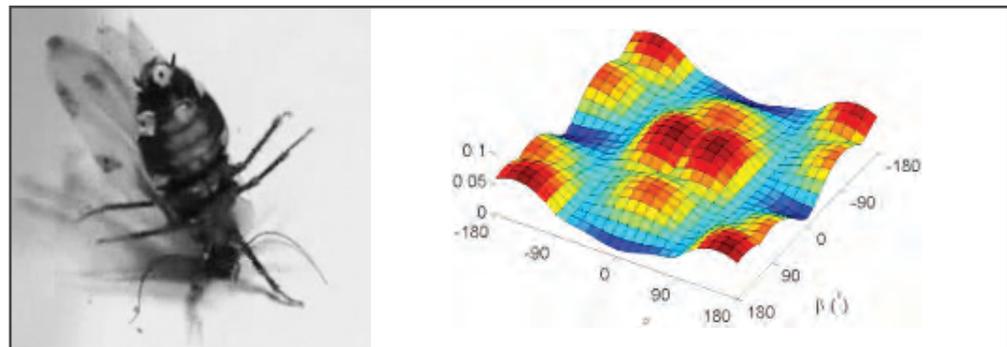
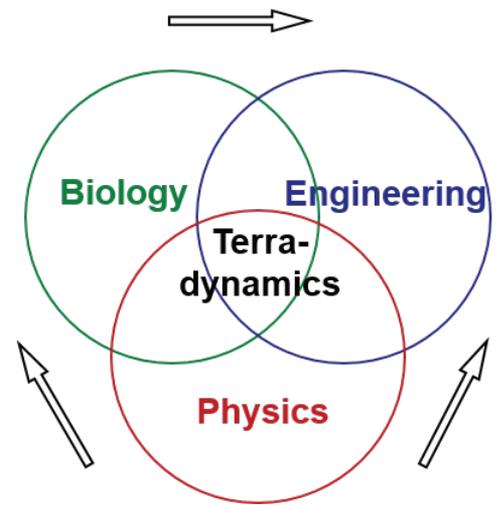
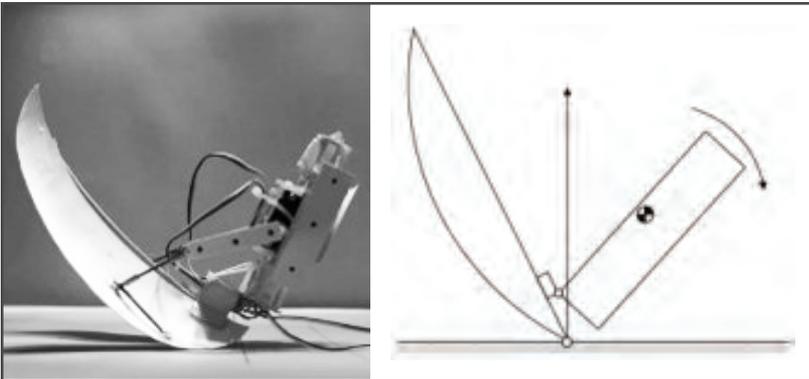
**Chen Li, Ph.D.**  
 Assistant Professor of  
 Mechanical Engineering  
[chen.li@jhu.edu](mailto:chen.li@jhu.edu)



Vision towards life-like, multi-functional robot locomotion in complex terrains



**ACCOMPLISHMENT:** We established our lab in 2016. We have created several novel experimental platforms for studying animal (insect and reptile) and robot locomotion in complex 3-D terrains. We have developed several novel robotic platforms to systematically perform controlled locomotion experiments. We have created initial theoretical and computational models for locomotor-terrain interaction. We have obtained preliminary data that support our research hypotheses.



**STATUS:** We are further developing our experimental and theoretical tools and systematically collecting data to validate our models, which will allow quantitative predictions.

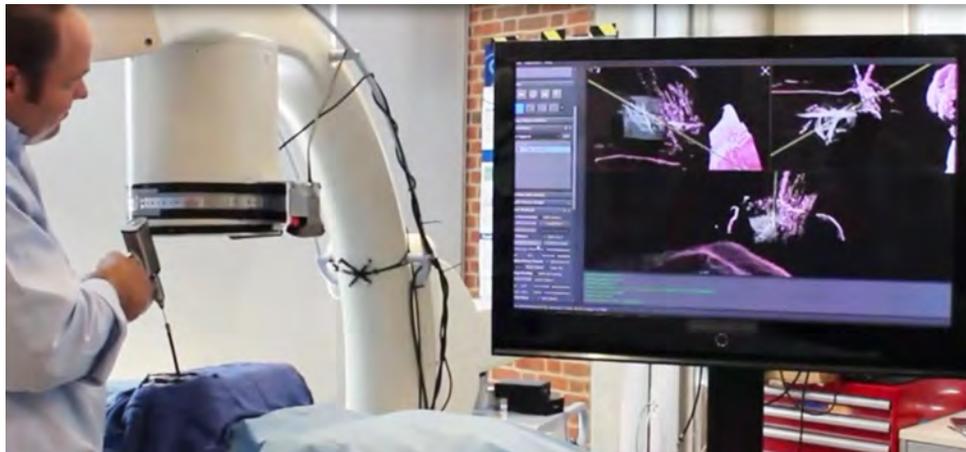
**FUNDING:** Burroughs Wellcome Fund Career Award at the Scientific Interface

**KEY PERSONNEL:** Chen Li, Sean Gart, Ratan Othayoth, Yuanfeng Han; collaboration with Chad Kessens at Army Research Laboratory

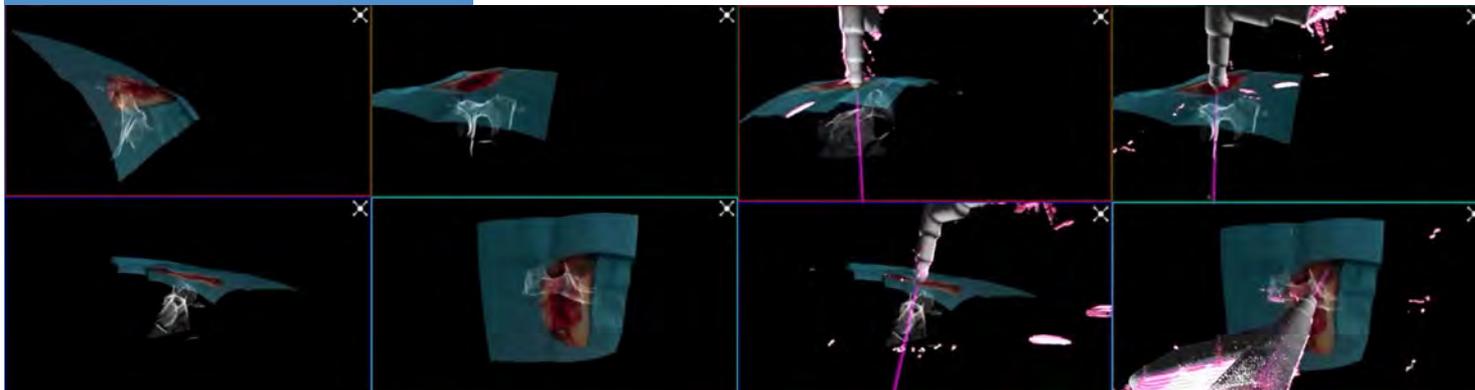
**TO FIND OUT MORE:** [li.me.jhu.edu](http://li.me.jhu.edu)

## Computer Aided Medical Procedures (CAMP) Laboratory

### AUGMENTED ORTHOPEDIC SURGERIES



**ACCOMPLISHMENT:** In many orthopedic surgeries there is a demand for correctly placing medical instruments (e.g. K-wire or drill) to perform bone fracture repairs. The main challenge is the mental alignment of X-ray images acquired using a C-arm, the medical instruments, and the patient, which dramatically increases in complexity during pelvic surgeries. Current solutions include the continuous acquisition of many intra-operative X-ray images from various views, which will result in high radiation exposure, long surgical durations, and significant effort and frustration for the surgical staff. This work conducts a pre-clinical usability study to test and evaluate mixed reality visualization techniques using intra-operative X-ray, optical, and RGBD imaging to augment the surgeon's view to assist accurate placement of tools.



**Nassir Navab, Ph.D.**  
Professor of Computer Science  
nassir.navab@jhu.edu

**METHOD:** We design and perform a usability study to compare the performance of surgeons and their task load using three different mixed reality systems during K-wire placements. The three systems are interventional X-ray imaging, X-ray augmentation on 2D video, and 3D surface reconstruction augmented by digitally reconstructed radiographs and live tool visualization.

**RESULTS:** The evaluation criteria include duration, number of X-ray images acquired, placement accuracy, and the surgical task load, which are observed during 21 clinically relevant interventions performed by surgeons on phantoms. Finally, we test for statistically significant improvements, and show that the mixed reality visualization leads to a significantly improved efficiency.

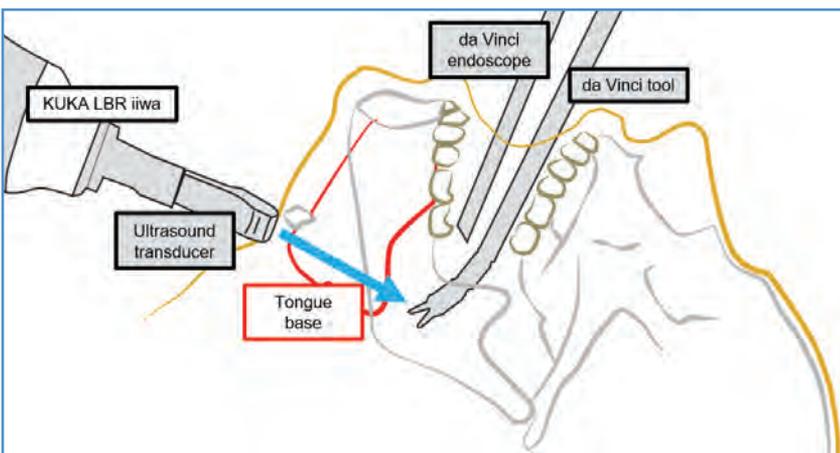
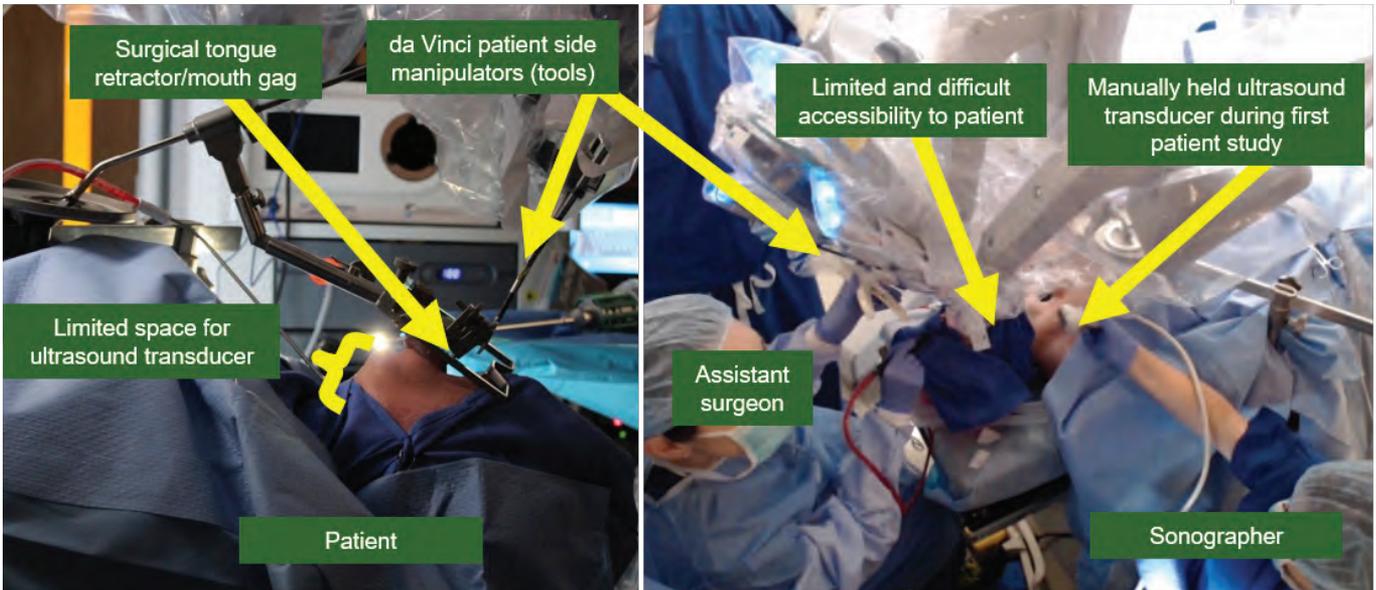
- Patents filed
- Papers accepted at IPCAI and MICCAI

**STATUS:** Pre-clinical validation with surgeons

**FUNDING:** T32 Grant, R21 under review

**KEY PERSONNEL:** N. Navab, P. Kazanzides, B. Fuerst

## ROBOTIC ULTRASOUND FOR TRANSORAL ROBOTIC SURGERY



- Robot follows surgical tools to enable live imaging of intervention
- Smart visualization to guide surgeon by providing just the right information

### ACCOMPLISHMENT:

- IRB approved and first patient's intra-operative data provide promising result
- Robotic Ultrasound successfully implemented and validated on volunteers following IRB approved protocol
- Papers under review for IPCAI and IROS

**STATUS:** pre-clinical validation of usefulness of intra-operative US

**FUNDING:** R21 under review

**KEY PERSONNEL:** N. Navab, B. Fuerst, Clinical Partners J. Richmond, C. Fakhey

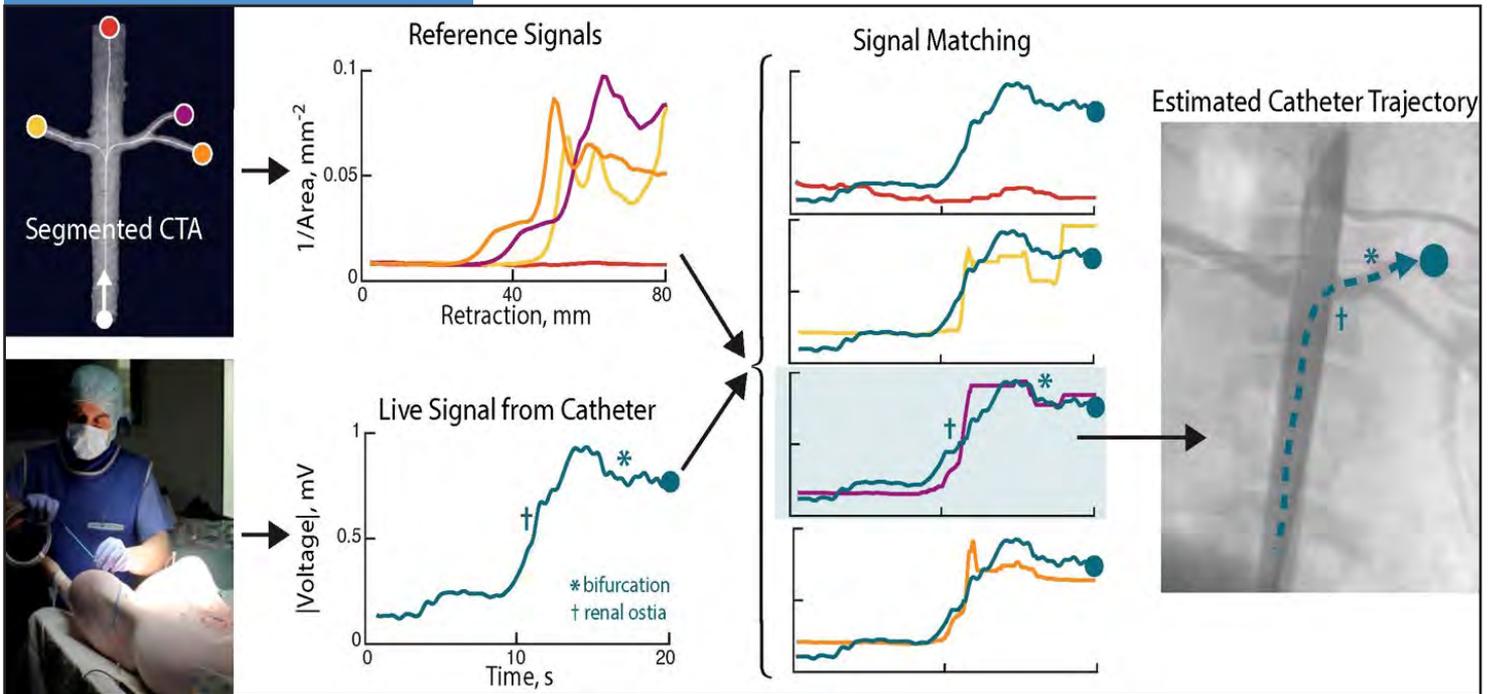
# Computer Aided Medical Procedures (CAMP) Laboratory

## BIOELECTRIC LOCALIZATION AND NAVIGATION FOR ANGIOGRAPHIC PROCEDURES

### ACCOMPLISHMENT:

- US Patent filed in 2013
- Successful testing on plastic phantoms
- Successful testing on plastic phantoms with saline product flowing through the simulated vasculature
- Successful testing on ex-vivo animal parts (realistic electric conductivity variation)
- Successful testing on ex-vivo animal parts with saline product flowing through the vasculature

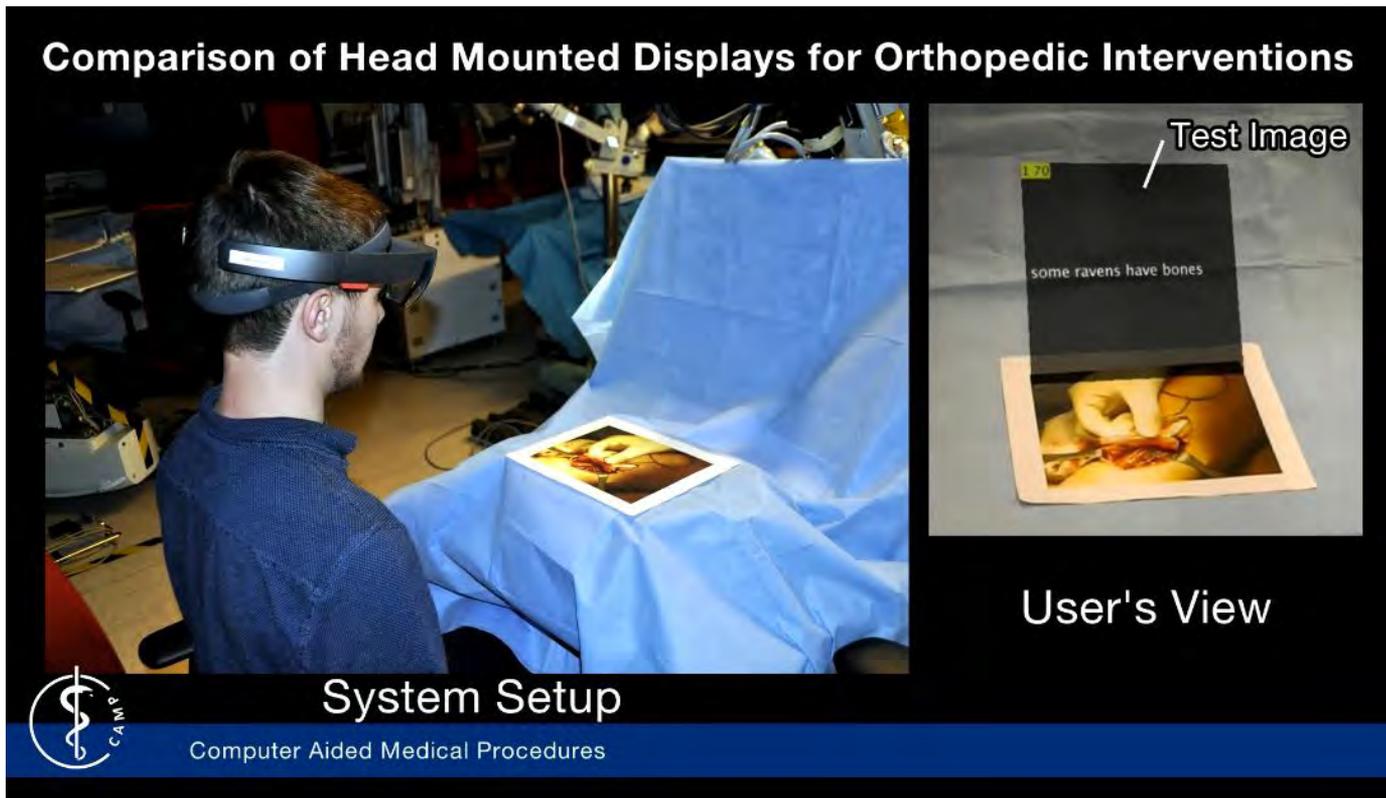
**KEY PERSONNEL:** Nassir Navab, Noah Cowan, Erin Sutton, Bernhard Fuerst



**Nassir Navab, Ph.D.**  
 Professor of Computer Science  
 nassir.navab@jhu.edu



## OPTICAL AND VIDEO SEE-THROUGH HMD FOR AUGMENTED REALITY APPLICATIONS



**ACCOMPLISHMENT:**

- State of art HMD calibration, Advance Visualization
- Both video and optical see-through systems built

**STATUS:** Simultaneous development of novel optical and video see-through hardware and software solutions

**FUNDING:** DOD project funded and in-progres

**KEY PERSONNEL:** Nassir Navab, Peter Kazanzides, Bernhard Fuerst

## The Galen Microsurgery System



**ACCOMPLISHMENT:** We have developed a prototype “steady-hand” robot for head-and-neck microsurgery. The robot was specifically designed for tremor-free operation of long tools reaching into holes while keeping the mechanism as much as possible out of the surgeon’s line of sight. The control resembles power steering in a car. Both the robot and the surgeon hold the tool. The robot senses forces on the tool and moves to comply. Since the robot is doing the motion, there is no tremor, and the robot can also implement “virtual fixtures” to help guide the motion or enforce safety barriers. The robot can also be integrated with surgical navigation systems.

**STATUS:** Prototype robot exists; application demos for laryngeal, sinus, open microsurgery; developing additional components for OR integration and otology; patents issued and others in prosecution; Technology licensed to Galen Robotics, Inc., a startup company making a clinical/commercial version. Advanced R&D work continues in LCSR under a Master Agreement with Galen.



**FUNDING:** JHU internal funds, JHU Cohen Fund, MII Grant; Contract with Galen Robotics, Inc.

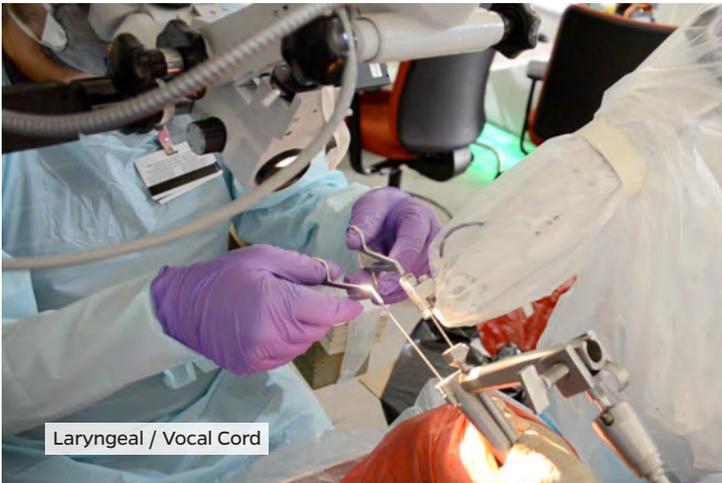
**KEY PERSONNEL:** (Current WSE) Russell Taylor, Iulian Iordachita, Mariah Schrum, Joe Peine, Thomas Keady, Olivia Puelo; (SOM) Kevin Olds, Chris Razavi, Lee Akst, Masaru Ishii, Jeremy Richmon, Matt Stewart, Wade Chien, Henry Brem; (Galen Robotics) Bruce Lichorowic, Dave Saunders, Yunus Sevimli, Paul Wilkening; (Past WSE) Lihang Feng, Preetham Chalasani, Marcin Balicki, Kevin Old, Paul Wilkening

**TO FIND OUT MORE:** [ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research.rems](https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research.rems)

**DISCLOSURES:** Under a license agreement between Galen Robotics, Inc. and the Johns Hopkins University, several of the Key Personnel are entitled to royalty distributions on technology described in this article. Also, Dr. Taylor is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict of interest policies.

**Russell H. Taylor, Ph.D.**  
John C. Malone Professor of Computer Science, with joint appointments in Mechanical Engineering, Radiology & Surgery, Director, Laboratory for Computational Sensing and Robotics  
Director, Engineering Research Center for Computer-Integrated Surgical Systems and Technology  
The Johns Hopkins University  
[rht@jhu.edu](mailto:rht@jhu.edu)





Laryngeal / Vocal Cord

### REMS : Voice Surgery Cadaver Study

This video still shows an experiment performed in our lab by our surgeon collaborator, Dr. Lee Akst, doing a common vocal cord procedure on a cadaveric specimen. Another feature Dr. Akst likes is the ability to position a tool and then have the robot hold it steady until he moves it again.



Sinus Surgery

### REMS: Sinus Surgery with Virtual Fixtures

-This somewhat longer experiment shows the ability of the robot to be integrated with a surgical navigation system, together with its ability to provide virtual fixtures.

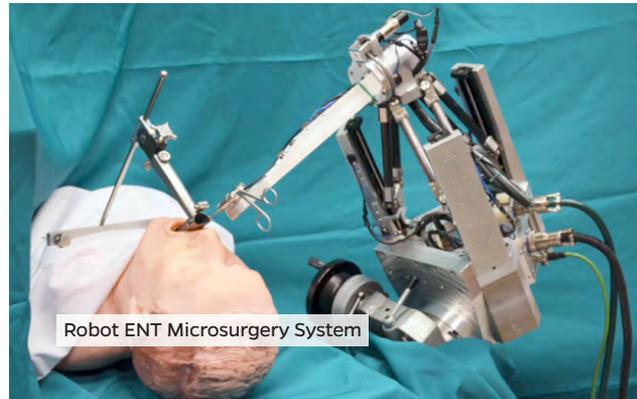
-In this case, we are again using a cadaver, for which we have a CT scan.

-After the CT scan is registered to the robot, the navigational display shows where the tool is relative to the CT images.

-In sinus surgery, surgical instruments must be inserted many times through a complicated path into the nose. Tool-tissue collisions can cause bleeding, so we have implemented a virtual fixture to hold the tool on the desired path while the surgeon advances the tool along it.

-This virtual fixture can either be "hard," in which case the tool will never leave the path, or "soft," in which case the surgeon can deviate from the path but will feel a force nudging the tool back to the path.

-Our surgeon collaborator, Dr. Masaru Ishii, believes that this capability will be especially useful in training surgical residents.



Robot ENT Microsurgery System

### The Robotic ENT Microsurgery System (REMS)

#### User interface:

- Hands-on control, surgeon "in the game"
- Foot pedal-controlled gain

#### Technical specs:

- Up to 0.025 mm precision on-demand
- 6 degrees of freedom
- 125x125x125mm work volume
- Calibrated accuracy ~50-150µm

#### Control modes:

- Free hand
- Remote center of motion
- Virtual fixture avoidance
- Teleoperation



Robot Assisted Open Microsurgery

Robot-Assisted

Freehand

#### Other applications include:

- Otology
- Stapes surgery
- Mastoidectomy
- Cochlear implant
- Craniotomy
- Spine
- Hand

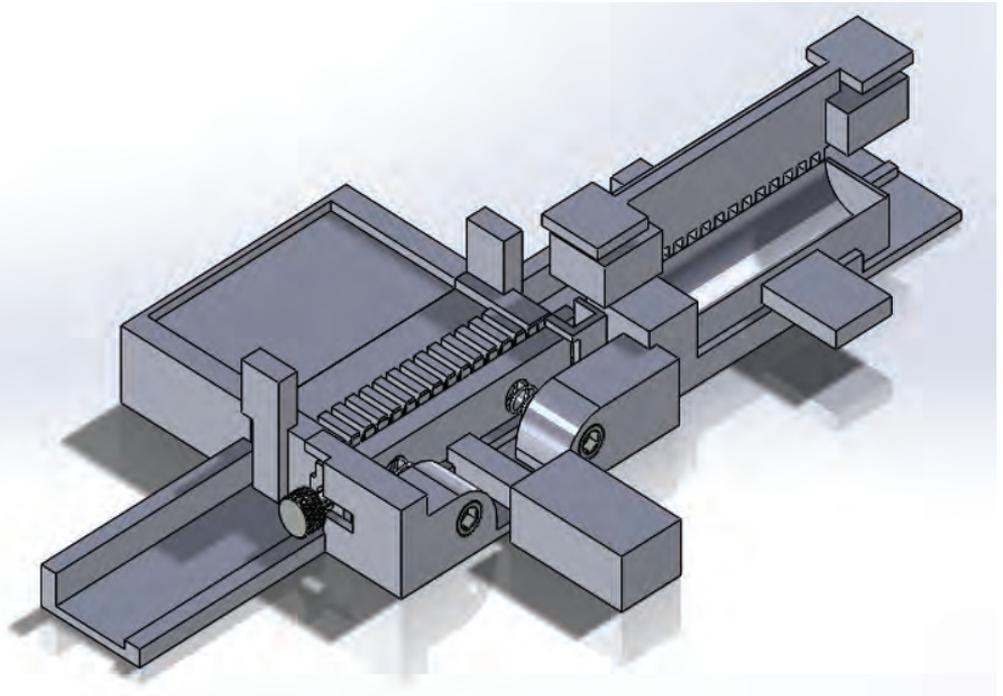
## Mosquito Salivary Gland Extraction

(JHU) Russell Taylor, Amanda Canezin, Mariah Schrum, Suat Coemert, Yunus Sevimli, Greg Chirikjian; (Sanaria) Steve Hoffman, Sumana Chakravarty, Michelle Laskowski



**Russell H. Taylor, Ph.D.**  
John C. Malone Professor of Computer Science, with joint appointments in Mechanical Engineering, Radiology & Surgery, Director, Laboratory for Computational Sensing and Robotics  
Director, Engineering Research Center for Computer-Integrated Surgical Systems and Technology  
The Johns Hopkins University  
rht@jhu.edu

**ACCOMPLISHMENT:** In this undergraduate research project, we have developed novel apparatus to assist in the extraction of salivary glands from mosquitoes. Mosquito-borne diseases such as malaria and yellow fever are among the most serious challenges to public health world-wide, affecting over 700 million people per year. In the case of malaria, one promising approach involves live organisms (*plasmodium falciparum*) harvested from the salivary glands of anopheles mosquitoes. One commercial effort to develop such a vaccine is being undertaken by Sanaria, Inc. ([www.sanaria.com](http://www.sanaria.com)). Although the vaccine is showing promise clinically, one significant barrier to production of sufficient quantities of vaccine for large-scale



trials or inoculation campaigns is the extraction of the salivary glands from large numbers of infected mosquitoes. The current production process used by Sanaria requires the use of tweezers and a hypodermic needle to extract glands one at a time. Working with Sanaria, we have developed production fixtures that enable human operators to perform key steps of this process in parallel, resulting in a very significant reduction in per-mosquito dissection time while also significantly reducing the training time required per production worker.

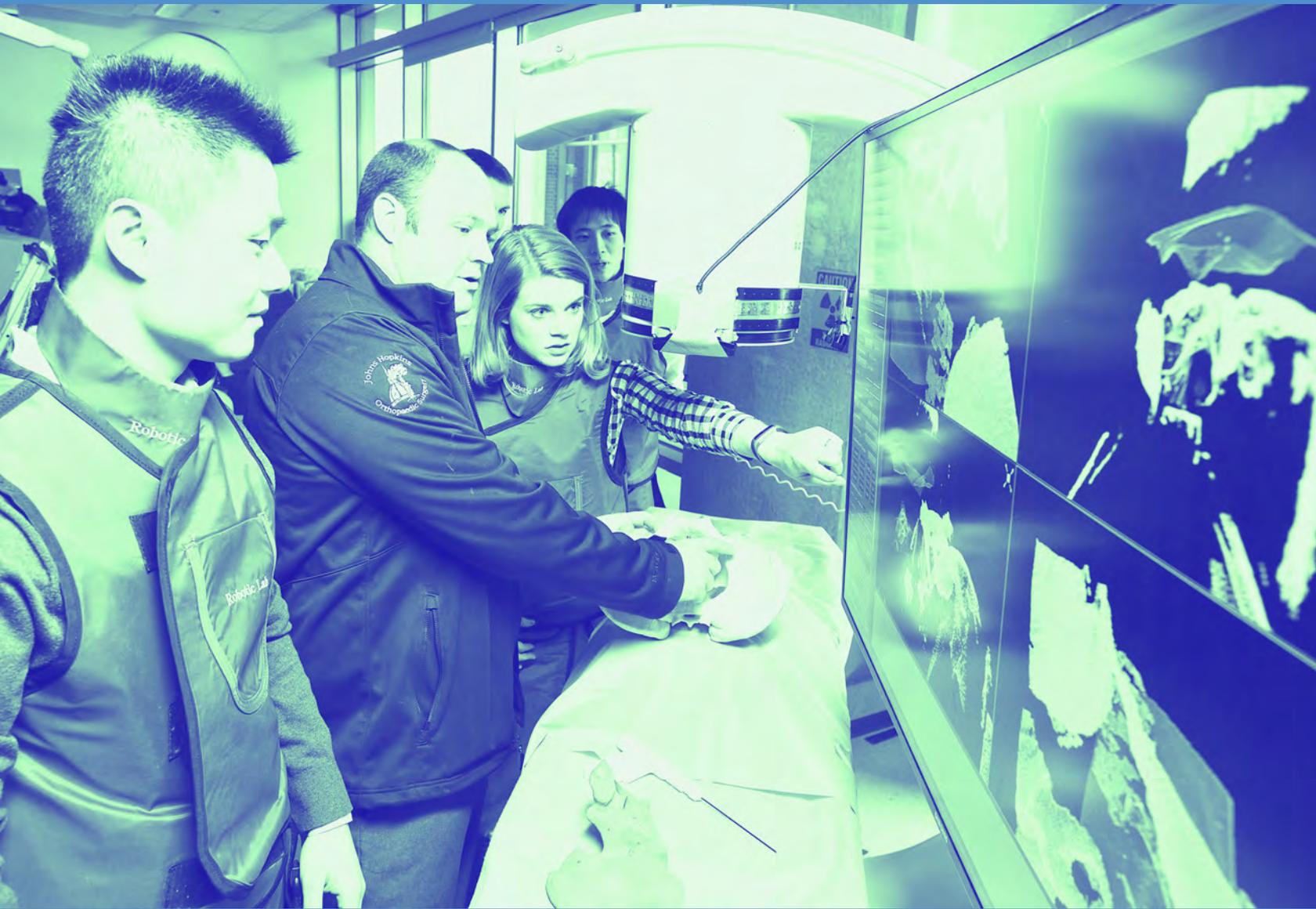




**STATUS:** Work to refine our apparatus and production workflow is continuing with Sanaria and an engineering firm (Keytech, Inc.), with a goal of introducing our apparatus into Sanaria's GMP vaccine production process. A preliminary patent has been filed, and a full utility patent will be filed this spring. Work to develop a more fully automated production process is also beginning, and Sanaria has submitted an NIH SBIR proposal with JHU as a partner to expedite this work.

**FUNDING:** JHU internal funds, Contract from Sanaria, Inc.

**KEY PERSONNEL:** (JHU) Russell Taylor, Amanda Canezin, Mariah Schrum, Suat Coemert, Yunus Sevimli, Greg Chirikjian; (Sanaria) Steve Hoffman, Sumana Chakravarty, Michelle Laskowski



LABORATORY FOR  
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