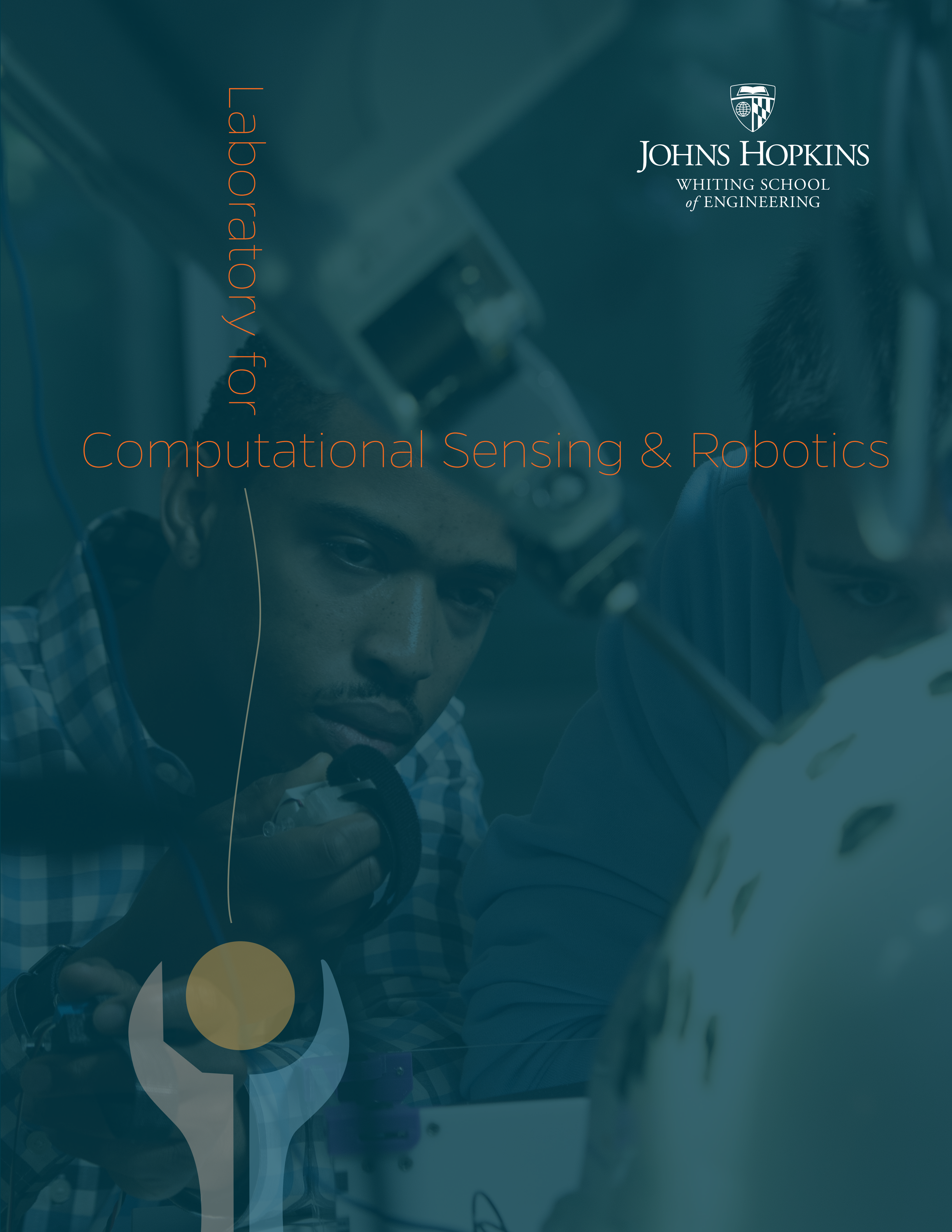


Laboratory for Computational Sensing & Robotics

Johns Hopkins
Whiting School of Engineering

Advancing Discovery:

Robotics at Johns Hopkins Whiting School of Engineering

Johns Hopkins University's Whiting School of Engineering stands at the forefront of technological innovation in robotics, and comprises one of the largest and most technologically advanced robotics research and educational centers in the world. Its faculty and students work collaboratively and across traditional disciplinary boundaries to advance the discoveries that are revolutionizing fields ranging from national security and medicine to manufacturing.

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.

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. The power of this truly cross-disciplinary, collaborative approach is profound.

Areas of Impact

Advancing Medical Robotics

Even the best surgeons face significant challenges to their precision, control, and accuracy when performing procedures involving delicate body tissue, or within the body's narrowest conduits.

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.

Advancing Human-Machine Interaction to Improve Manufacturing

When it comes to heavy lifting, repetitive motions, and manufacturing work that requires an absolutely steady hand, robots can outperform most humans. Even so, there are manipulation tasks that are impossible for autonomous robots to perform, and which pose significant dangers (from outright injury to repetitive motion conditions) to humans.

Johns Hopkins researchers are working to improve human-robot teamwork in manufacturing settings. They are investigating ways to incorporate robots in order to reduce the risk of injury, increase work efficiency, and set an example for future manufacturing innovations. Included in these solutions is the development of virtual reality technology that allows humans to control the robots from a safe distance.

Advancing Robotics in Extreme Environments

Johns Hopkins roboticists are using autonomous underwater vehicles to venture into some of the world's most remote underwater environments. They are mapping the ocean floor, documenting the discovery of new species, and investigating ocean chemistry in search of insights into global climate change. Among the technological challenges such exploration presents are the need quickly to transmit large amounts of data from an 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 scientists.

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. A fiber-optic cable a few times thicker than a human hair transmits data to the mother ship at the speed of light.

Advancing Bio-Robotics

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

Hopkins researchers 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.

Research Laboratories

Biomechanical- and Image-Guided Surgical Systems

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

DR. MUYINATU BELL

The PULSE Lab 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 School of Medicine.

Medical UltraSound Imaging and Intervention Collaboration

DR. EMAD BOCTOR

The MUSiiC research lab develops innovative ultrasound technologies for medical applications ranging from prostate and breast cancer treatment to liver ablation and brachytherapy, among others. This group is a collaboration between researchers from the Johns Hopkins Whiting School of Engineering, the Johns Hopkins School of Medicine, and partners from other academic institutions and industry.

Haptics and Medical Robotics

DR. JEREMY D. BROWN

The Haptics and Medical Robotics (HAMR) Laboratory seeks to extend 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

DR. GREGORY CHIRIKJIAN

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), and self-replicating robotic systems.

Locomotion In Mechanical and Biological Systems

DR. NOAH COWAN

The LIMBS laboratory 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 in robot and animal (including human) sensing, navigation, and control.

Network and Spatially Distributed Systems

DR. DENNICE GAYME

The NSDS lab is concerned with characterizing, predicting, and controlling spatially distributed and networked systems in order to ensure stability and manage disturbances, while also optimizing efficiency and performance. These systems are typically represented as dynamical systems interacting over a graph (e.g. transportation, communication or power networks) or as partial differential equations (e.g. wind farms, wall-turbulence and power system oscillations). We develop theory and computational approaches for applications that lie at the interdisciplinary intersections of dynamical systems, controls and fluid mechanics, e.g. coordinated control of wind farms and grid integration of renewable energy.

Computational Interaction and Robotics

DR. GREGORY HAGER

The Computational Interaction and Robotics Laboratory 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 seeks 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.

Intuitive Computing

DR. CHIEN-MING HUANG

The Intuitive Computing Laboratory seeks to innovate interactive robot systems to provide physical, social, and behavioral support personalized to people with various characteristics and needs. We are an interdisciplinary team that designs, builds, and studies intuitive interaction capabilities of robotic systems to improve their utilities and user experience. We draw on principles and techniques from human-computer interaction, robotics, and machine learning in our research and are interested in using our systems to address problems in the fields of health care, education, and collaborative manufacturing.

Advanced Medical Instrumentation and Robotics

DR. IULIAN IORDACHITA

The Advanced Medical Instrumentation and Robotics Research Laboratory (AMIRo) 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. Application areas include robot-assisted microsurgery, MRI-compatible mechatronic systems, image-guided procedures, optical fiber-based force and shape sensing, and small animal research platforms.

Sensing, Manipulation, and Real-Time Systems

DR. PETER KAZANZIDES

The SMARTS lab works on components and integrated systems for computer-assisted surgery and robotics in extreme environments. This includes the development of mixed reality user interfaces and the integration of real-time sensing to enable robotic assistance in challenging environments, such as minimally invasive surgery, microsurgery, and outer space. Research in component technologies includes high-performance motor control, sensing, sensor fusion, and head-mounted displays. 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

DR. MARIN KOBILAROV

The Autonomous Systems, Control and Optimization Laboratory (ASCO) 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

DR. CHEN LI

Aero- and hydrodynamics have helped us understand how animals fly and swim and to develop aerial and aquatic vehicles that move through air and water rapidly, agilely, and efficiently. By contrast, we know surprisingly little about how terrestrial animals move so well in nature, and even the best robots still struggle in complex terrains like building rubble, forest floor, mountain boulders, and cluttered indoor environments. In our lab, we are developing experimental tools and theoretical models to create the new field of terradynamics that describe complex locomotor-terrain interactions, and use terradynamics to better understand animal locomotion and to advance robot locomotion in complex terrains.

Computer Aided Medical Procedures

DR. NASSIR NAVAB

The CAMP laboratory develops 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. In order to satisfy 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 Dr. Navab's groups at JHU in Baltimore and at TUM in Germany.

Computer Integrated Interventional Systems

DR. RUSSELL TAYLOR

This lab develops 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 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

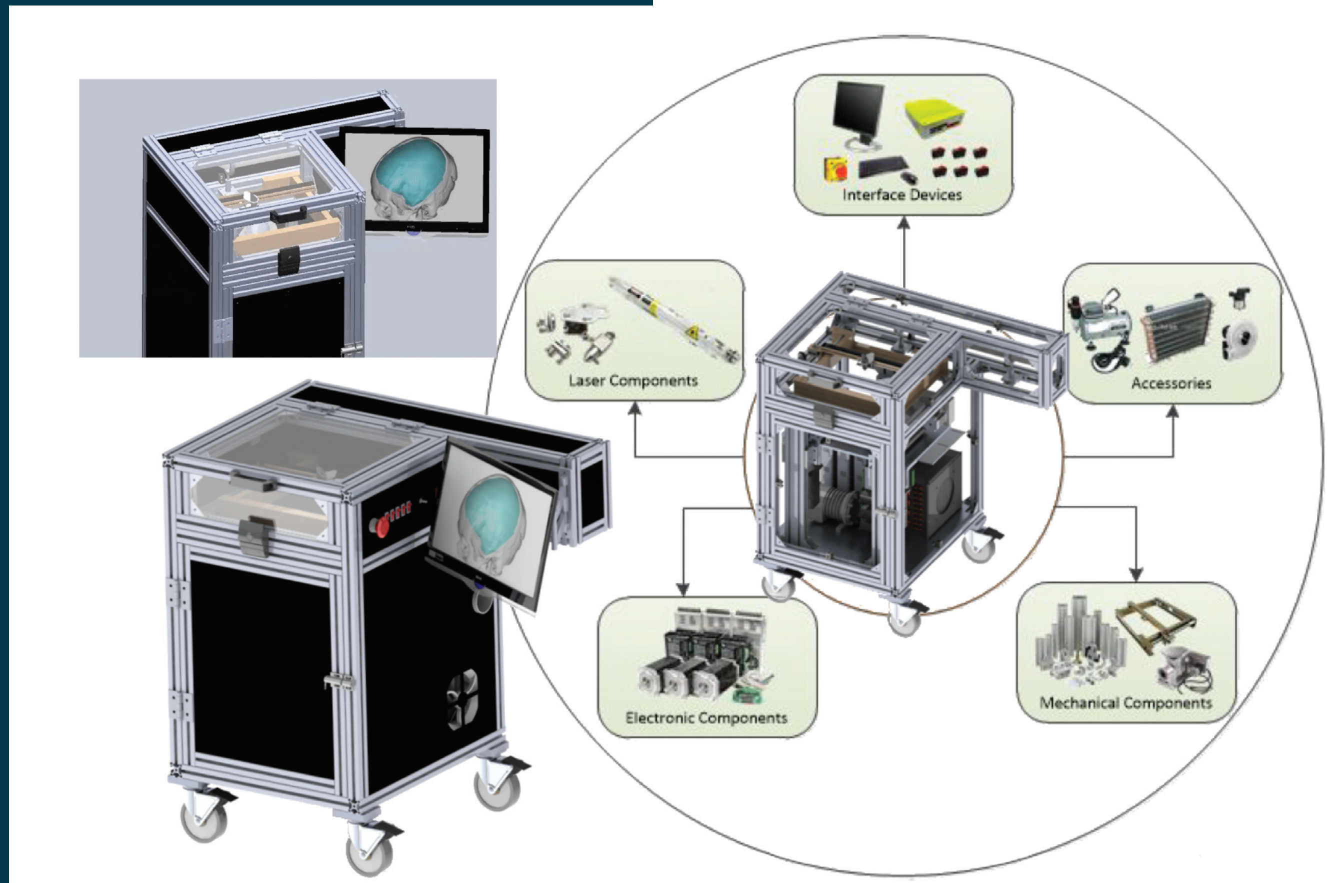
DR. LOUIS WHITCOMB

The DSCL lab focuses 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. We focus on problems motivated by several application areas that share a common underlying mathematical framework including underwater robotics, space telerobotics, and medical robotics. Dr. Whitcomb and his students have participated in the development of numerous underwater vehicles for oceanographic science missions, including the Nereus hybrid underwater vehicle that dove to the bottom of the Mariana Trench in 2009, and Nereid Under-Ice (NUI) hybrid underwater vehicle that was deployed under Arctic sea ice at 87 degrees North in 2016. Our methodology is to address fundamental theoretical issues with concise mathematical analysis, and to experimentally validate our research results in actual working systems.

Projects

5-axis Cranial Laser Cutting System:

Applications to Cranioplasty and Making Customized Implants



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Accomplishment: We have developed a 5-axis cranial implant cutting system. This system can assist single-stage cranioplasty by cutting the customized cranial implant (CCI) intraoperatively. The system features automatic, five-axis laser cutting capability that enables three-dimensional modification of the cranial implant. Besides, a laser-based cutting system has no direct contact with the implant as the entire surgical procedure is required to be performed under a sterile environment. The system can also be used for making customized cranial implants that requires certain manufacturing techniques, like pocket milling, drilling, etc.

Status: Physical system built; control software integrated; preliminary experiments for cutting conducted.

Robots and Computer
Assisted Surgical Technology

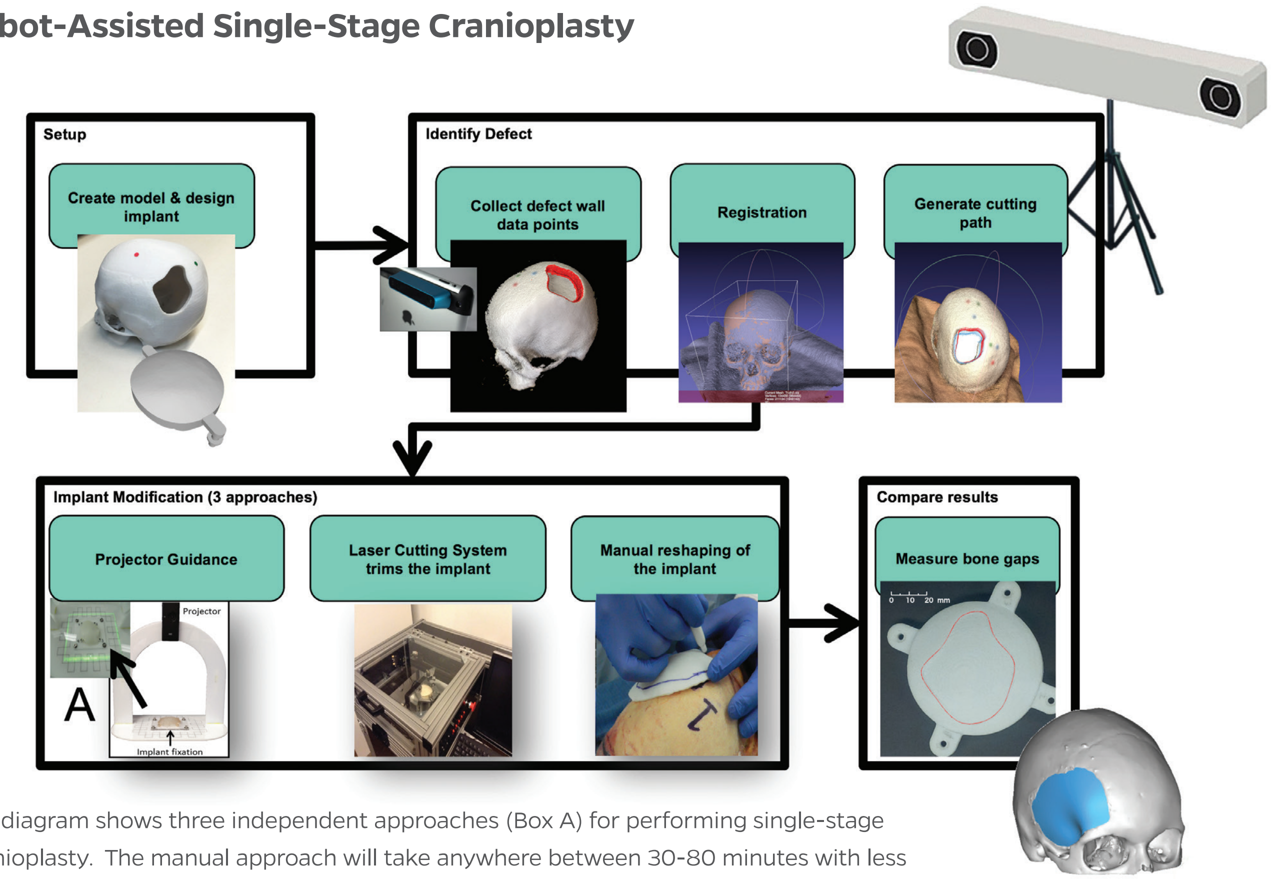
Funding: N/A

Key Personnel: Joshua Liu, Jerry Fang, Ryan Murphy, Chad Gorden, Mehran Armand

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

J. Liu, J. Fang, R. Murphy, C. Gordon, and M. Armand, *Design and Development of 5-Axis Cranial Implant Laser Cutting System*. ASME, 2017, pp. V001T02A051–V001T02A051.

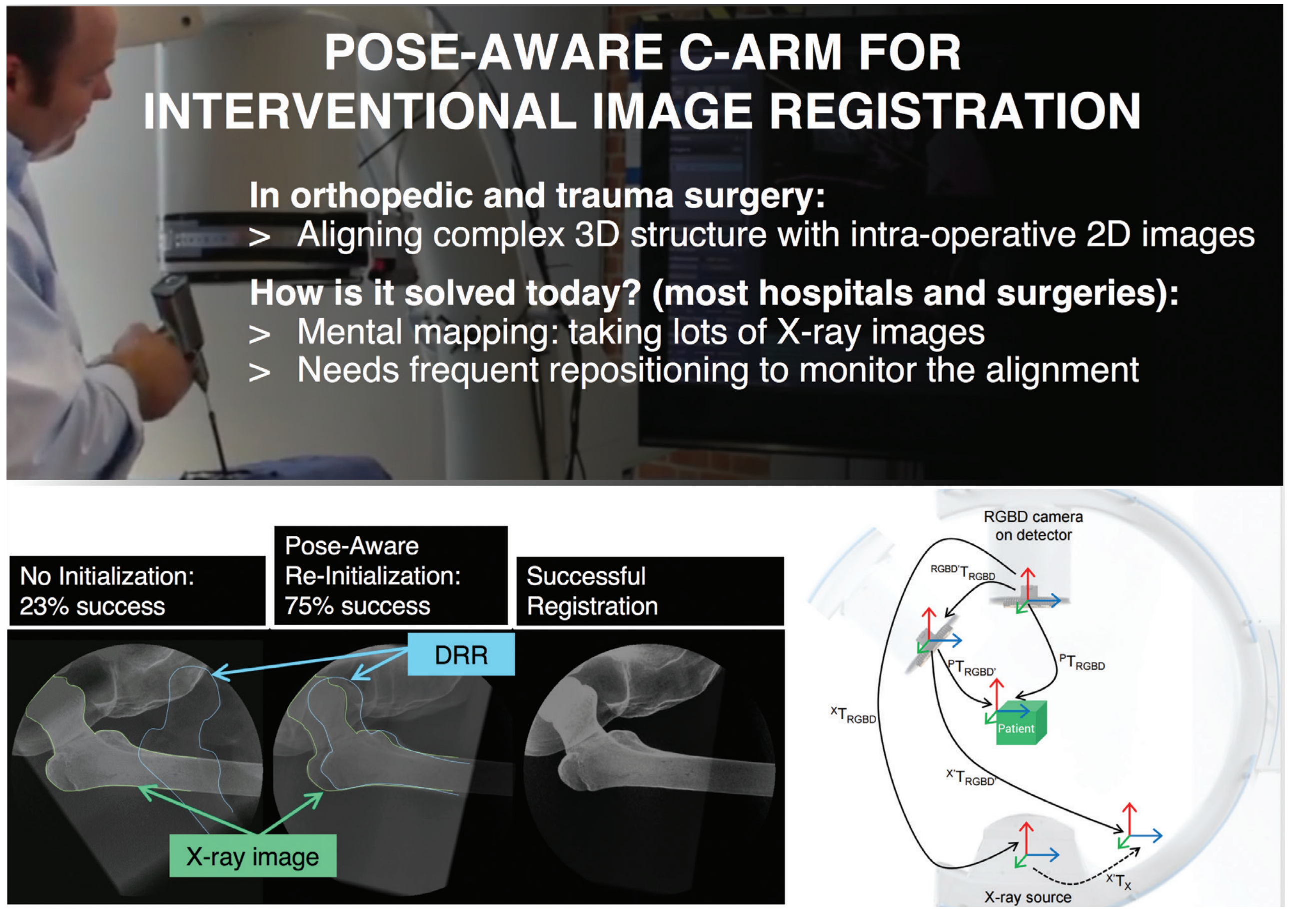
Robot-Assisted Single-Stage Cranioplasty



The diagram shows three independent approaches (Box A) for performing single-stage Cranioplasty. The manual approach will take anywhere between 30-80 minutes with less accuracy. The use of optical tracking system improved the accuracy and reduced the reshaping time to 3-10 minutes. The use of laser cutting machine is expected to further improve accuracy and the timing as well as potential surgical errors, and provide the ability to reshape the side bevels and , therefore, significantly improving the fitting of the implant. The five-axis laser cutter will also improve the reshaping of implants with multi-curvature designs (such as the implants including the orbit).

Robots and Computer
Assisted Surgical Technology

Opto/X-ray Image Fusion for Computer-Assisted Surgery



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Accomplishment:

Purpose: In minimally invasive interventions assisted by C-arm imaging, there is a demand to fuse the intra-interventional 2D C-arm image with pre-interventional 3D patient data to enable surgical guidance. The commonly used intensity-based 2D/3D registration has a limited capture range and is sensitive to initialization. We propose to utilize an opto/X-ray C-arm system which allows to maintain the registration during intervention by automating the re-initialization for the 2D/3D image registration. Consequently, the surgical workflow is not disrupted and the interaction time for manual initialization is eliminated.

Methods: We utilize two distinct vision-based tracking techniques to estimate the relative poses between different C-arm arrangements: (1) global tracking using fused depth information and (2) RGBD SLAM system for surgical scene tracking. A highly accurate multi-view calibration between RGBD and C-arm imaging devices is achieved using a custom-made multimodal calibration target.

Results: Several in vitro studies are conducted on pelvic femur phantom that is encased in gelatin and covered with drapes to simulate a clinically realistic scenario. The mean target registration errors (mTRE) for re-initialization using depth-only and RGB+depth are 13.23 mm and 11.81 mm, respectively. 2D/3D registration yielded 75% success rate using this automatic re-initialization, compared to a random initialization which yielded only 23% successful registration.

Conclusion: The pose-aware C-arm contributes to the 2D/3D registration process by globally re-initializing the relationship of C-arm image and pre-interventional CT data. This system performs inside-out tracking, is self-contained, and does not require any external tracking devices.

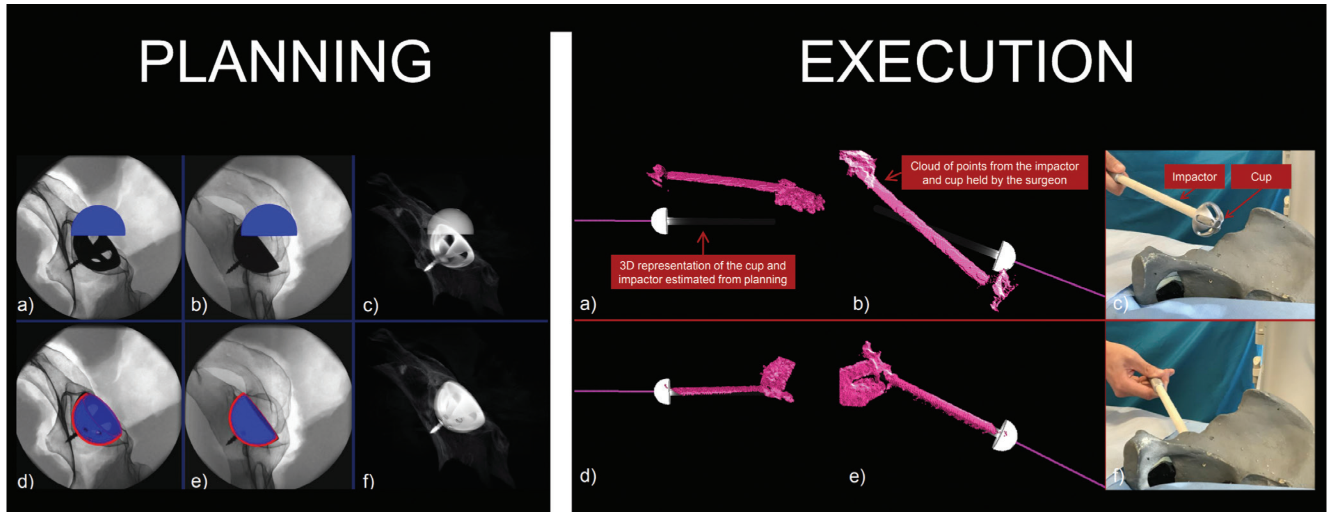
Status: Prototyping finished. Being deployed to the Bayview Hospital for cadaver studies

Funding: Research reported in this publication was partially supported by NIH/NIAMS under Award Number T32AR067708, NIH/NIBIB under the Award Numbers R01EB016703 and R21EB020113, and Johns Hopkins University internal funding sources.

Key Personnel: Javad Fotouhi, Bernhard Fuerst, Alex Johnson, Sing Chun Lee, Russell Taylor, Greg Osgood, Nassir Navab, Mehran Armand

To find out more: https://camp.lcsr.jhu.edu/

Plan in 2D, Execute in 3D: An Augmented Reality Solution for Total Hip Arthroplasty



Accomplishment: Reproducibly achieving proper implant alignment is a critical step in total hip arthroplasty (THA) procedures that has been shown to substantially affect patient outcome. In current practice, correct alignment of the acetabular cup is verified in C-arm X-ray images that are acquired in an anterior-posterior (AP) view. Favorable surgical outcome is, therefore, heavily dependent on the surgeon's experience in understanding the 3D orientation of a hemispheric implant from 2D AP projection images. This work proposes an easy to use intra-operative component planning system based on two C-arm X-ray images that is combined with 3D augmented reality (AR) visualization that simplifies impactor and cup placement according to the planning by providing a real-time RGBD data overlay. We evaluate the feasibility of our system in a user study comprising four orthopedic surgeons at the Johns Hopkins Hospital, and also report errors in translation, anteversion, and abduction as low as 1.98 mm, 1.10 mm , and 0.53 mm, respectively. The promising performance of this AR solution shows that deploying this system could eliminate the need for excessive radiation, simplify the intervention, and enable reproducibly accurate placement of acetabular implants.

Status: Prototyping finished. Being deployed to the Bayview Hospital for cadaver studies

Funding: Research reported here was partially supported by NIH/NIBIB under the Award Number R21EB020113 and Johns Hopkins University internal funding sources

Key Personnel: Javad Fotouhi, Clayton Alexander, Mathias Unberath, Giacomo Taylor, Sing Chun Lee, Bernhard Fuerst, Alex Johnson, Greg Osgood, Russell H. Taylor, Herpal Khanuja, Mehran Armand, and Nassir Navab

To find out more: https://camp.lcsr.jhu.edu/

Papers : Fotouhi, Javad, et al. , "Plan in 2D, Execute In 3D: An Augmented Reality Solution For Cup Placement in Total Hip Arthroplasty", accepted for publication at the Journal of Medical Imaging

AR in OR: From Monitor to Head-Mounted-Display in the Operating Room

Accomplishment: Integrating the use of optical-see-through head-mounted-display into the surgical workflow for orthopedic and trauma surgeries. The goal of this project is to co-calibrate the head-mounted-display on the surgeon's head with the patient, and then render 3D pre- and intra-operative patient data on the patient.

Status: Calibration completed. Implementing the components for closing the calibration loop.

Funding: No funding support for this project

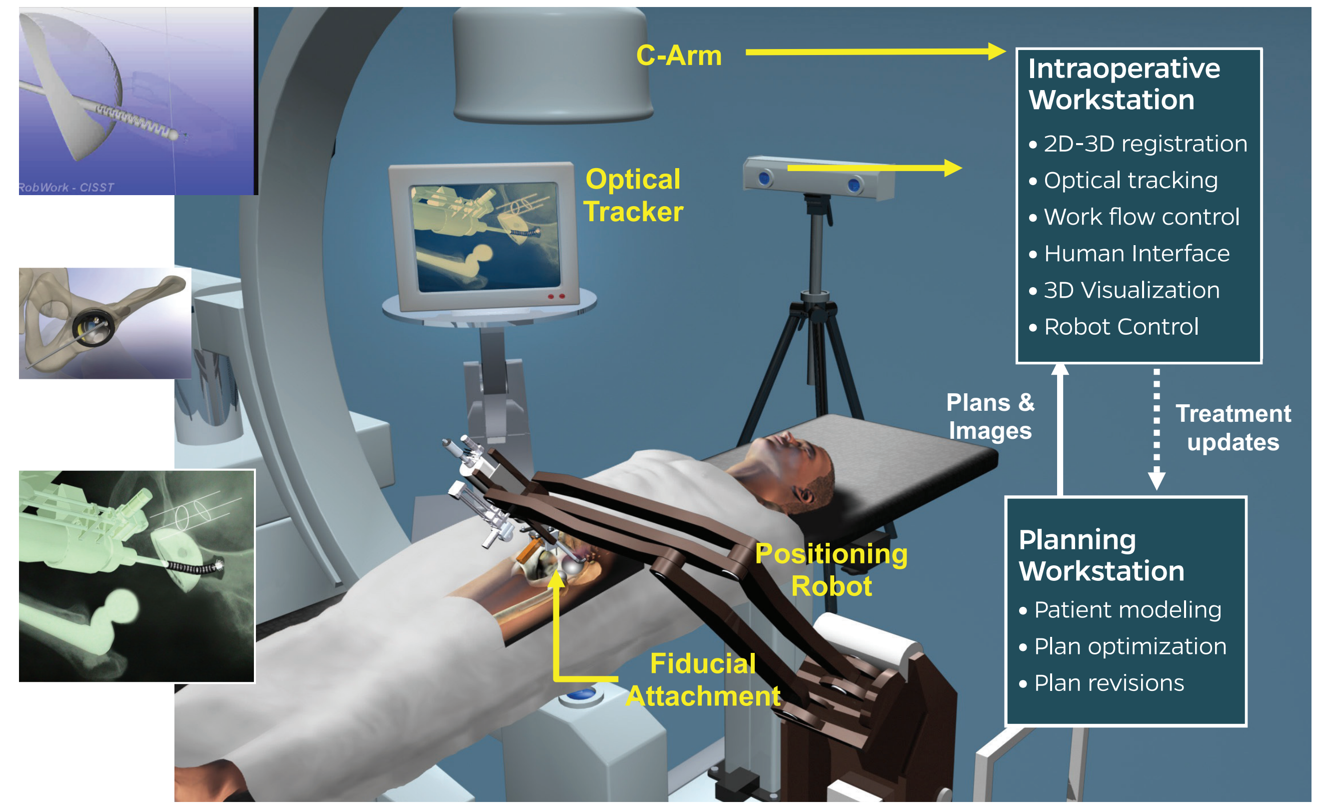
Key Personnel: Javad Fotouhi, Mathias Unberath, Nassir Navab, Mehran Armand

To find out more: https://camp.lcsr.jhu.edu/

Robots and Computer
Assisted Surgical Technology

Continuum Robots, Tools, and Algorithms for Tissue Manipulation for Minimally Invasive Surgery

Continuum Manipulators for Minimally Invasive Surgery



Accomplishment: We are developing robot-assisted surgical workstation including snake-like manipulators attached to a positioning robot (e.g. Kuka or UR10) with accompanying tools and sensors for orthopaedic (minimally-invasive treatment of osteolysis) and ENT skull base surgery. We have designed and fabricated snake-like manipulators with large lumen and associated sizable ring currette and shaving tools that can pass through the relatively large lumen of the Continuum dexterous manipulator (CDM). The CDM is driven manually or using a positioning robot such as LARS, UR5, 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

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are designed and tested to track and control the shape of the CDM during the operation within the lesion. Furthermore, we have developed 2D-3D registration techniques to update the pose of CDM with respect to lesion space using multiple x-ray images at certain points during the surgery.

Status: Prototype CDM exists; application demos for treatment of osteolysis; integrating system components for OR application and cadaver studies; patents issued and others in prosecution.

Funding: NIH/NIBIB

Key Personnel: (APL) Ryan Murphy, Michael Kutzer, Mehran Armand (WSE) Yoshito Otake, Farshid Alambeigi, Amir Farvardin, Robert Grupp, Paul Wilkening, Anzhu Goa, Hoa Liu, Russell Taylor, Iulian Iordochita (SOM) Simon Mears, Harpal khanuja

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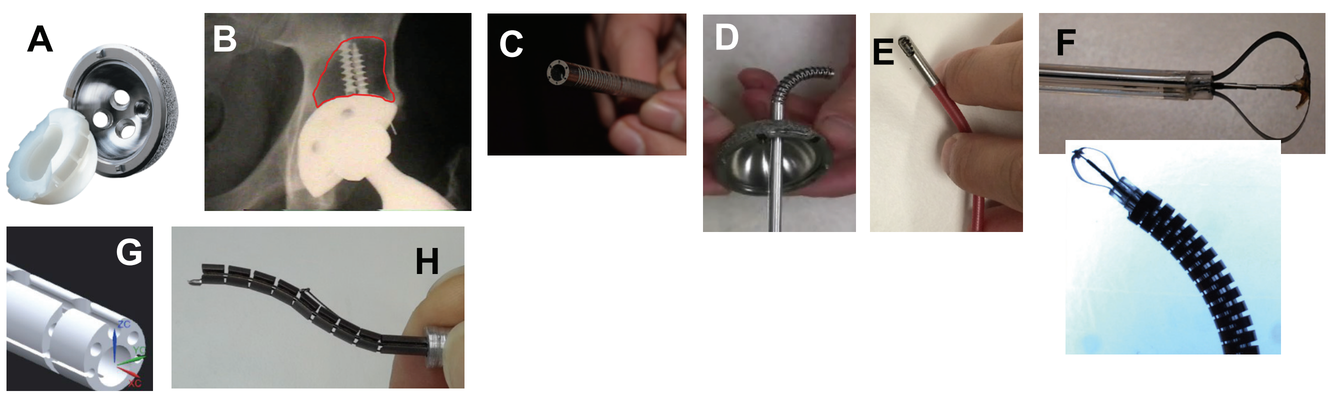
Robot-Assisted Treatment of Osteolysis



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) Cable-driven snake-like manipulator (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 SDM 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 .

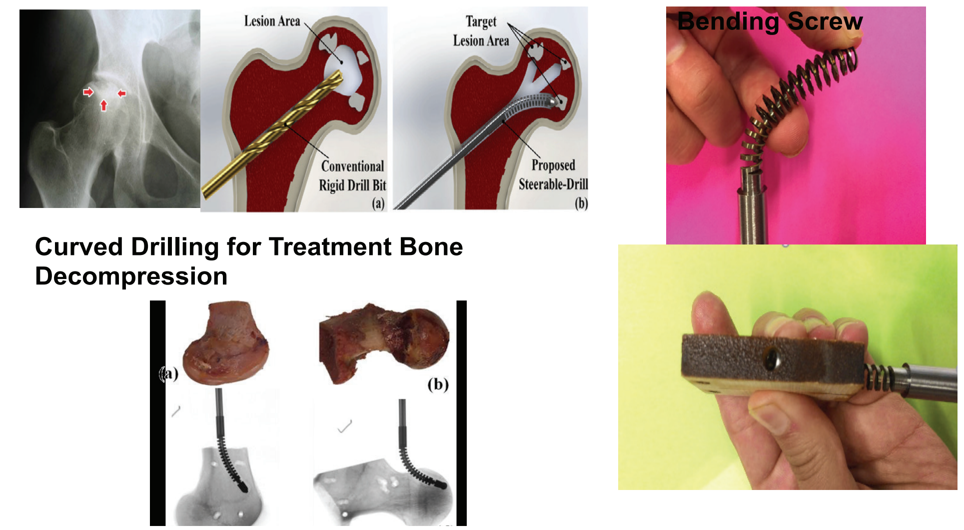
E) The shaving tool with outer diameter of 3.5 mm. the shaving tool pathways for water circulation and vacuum for removing debris.

F) An active ring tool mechanism made from Nitinol plates.

G) CAD model of a novel SDM with 3 mm outer diameter, 1.7 mm lumen for tools and thru holes for drive cables, borescope, and FBG shape sensor fibers.

H) The novel 3 mm SDM producing S-shape.

Curved Drilling: Fixation of Hard Tissues with Bending Screws



Accomplishment: We are developing robot-assisted surgical workstation including snake-like manipulators for treatment of Osteonecrosis using curved-drilling approach. To fill the created curved tunnel and connect the fragments, we use a combination of filing the lesion with augmenting material and newly designed and fabricated bending screws.

Status: Curved drilling was demonstrated in the cadaver specimens. Prototype Screw was fabricated and tested on simulated bones, disclosure submitted. patents issued and others in prosecution.

Funding: NIH/NIBIB

Key Personnel: (APL) Farshid Alambeigi, Mehran Armand

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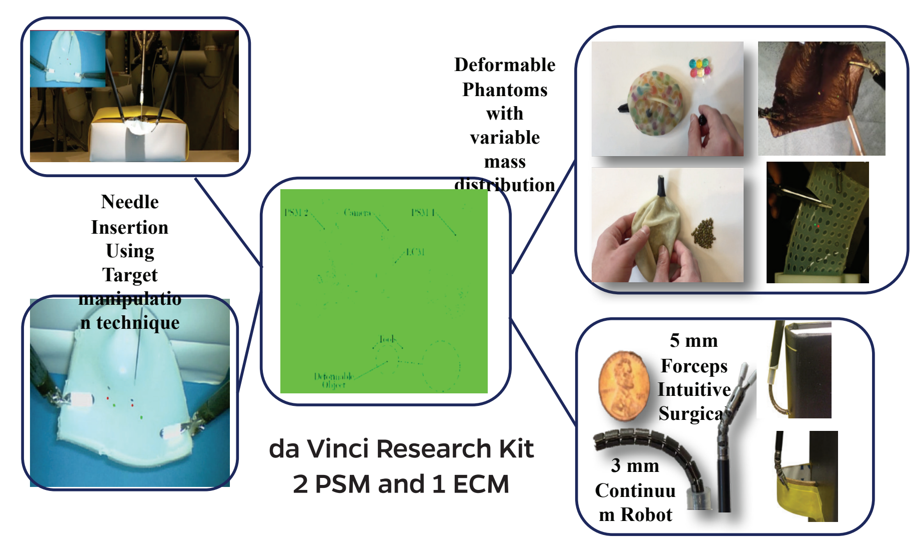
Autonomous Unknown Deformable-Object Manipulation



Accomplishment: We are developing frameworks for autonomous manipulation of unknown deformable objects. This object can be a Snake-like robot or a deformable tissue working in an unstructured environment.

Status: The framework has been successfully tested on the dVRK system and for various tasks.

Funding: NIH/NIBIB

Key Personnel: (APL) Farshid Alambeigi, Zerui Wang, Yun-Hui Liu, Russell Taylor, Mehran Armand

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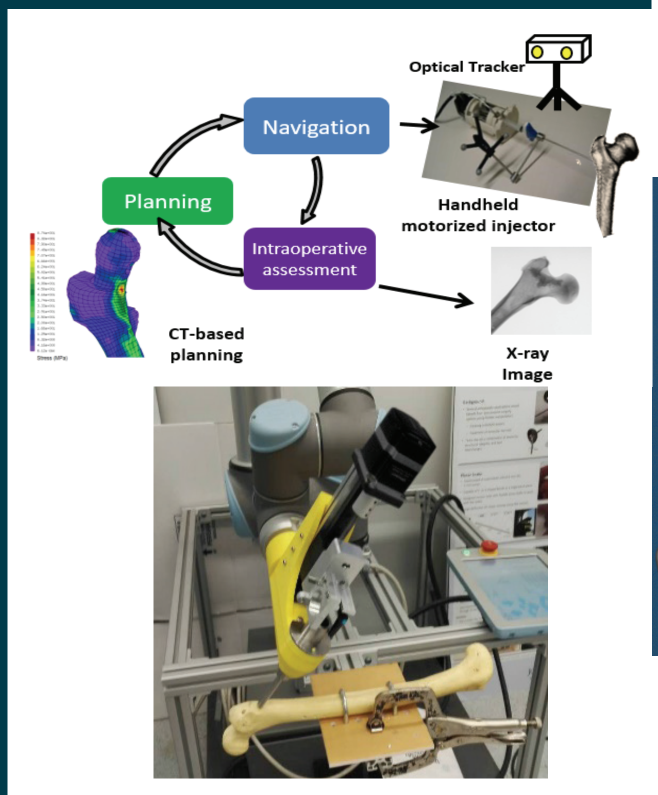
Robots and Computer
Assisted Surgical Technology

Biomechanical Planning for Robot-Assisted Augmentation of Osteoporotic Femurs



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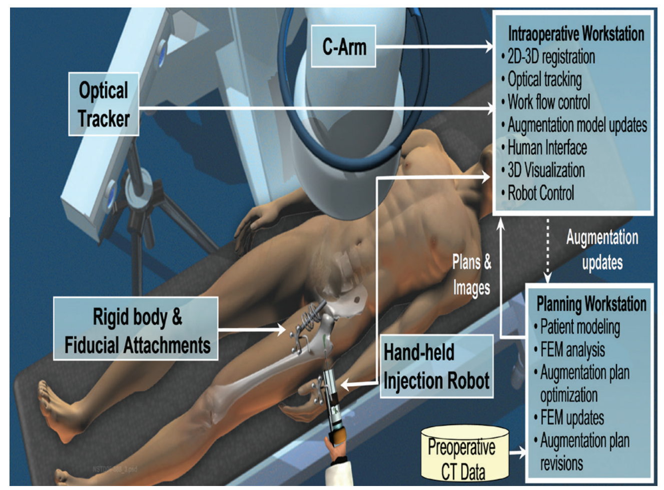

Accomplishment: We have developed an image-guidance system for femoral bone augmentation surgery that implements a novel concept of intraoperative feedback and tested on three cadaver experiments. The system consists of surgical planning using hydrodynamics-based bone cement diffusion model, surgical navigation involving 2D/3D registration of preoperative CT scans to the augmented hip bone, real-time tracking, a handheld motorized bone cement delivery device, and an intraoperative monitoring system of the cement shape from X-ray images (Fig. 1). Current system advancements include automated positioning of the drill and injection system using a six degree of freedom robotic arm (UR10, Universal Robots Inc.) We have also modified a planning paradigm for femoroplasty to lower the injection volume as compared to the previous work . This will likely reduce the risk of thermal necrosis caused by exothermic polymerization of PMMA.

Status: Prototype robot exists; application demos for treatment of femoroplasty; integrating system components for OR application and cadaver studies; developing new system for Robot integration and cement injection, developing cooling system to decrease the temperature after the injection, developing finite element simulation for temperature evaluation and cooling system

Funding: NIH/NIBIB

Key Personnel: (APL) : Amirhossein Farvardin, Mahsan Bakhtiarinejd, Ryan Murphy, Ehsan Basafa, Gang Zhu, Russell Taylor, Simon Mears, Harpal Khanuja, Mehran Armand

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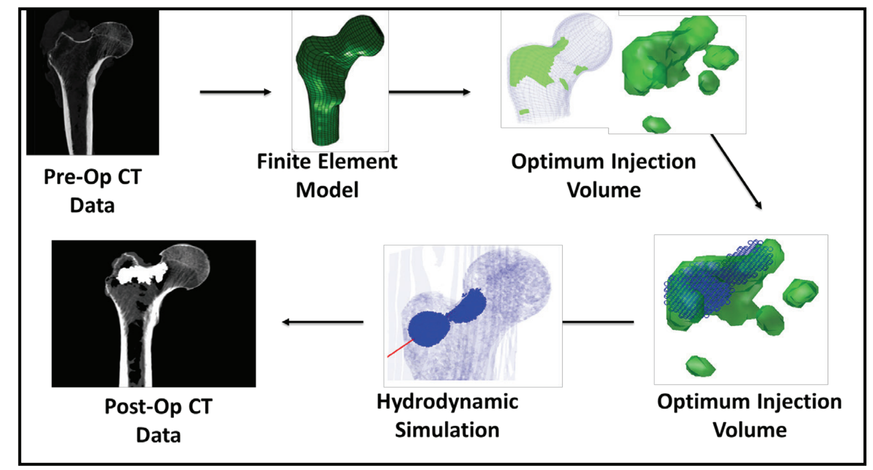
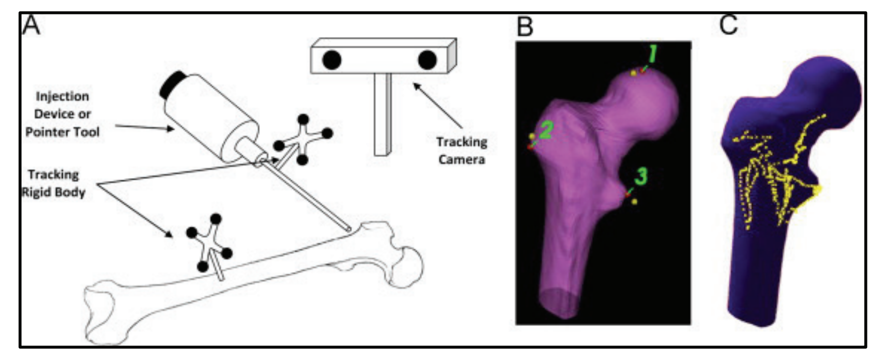
Planning Mode for Osteoporotic Bone Augmentation and Surgical Execution



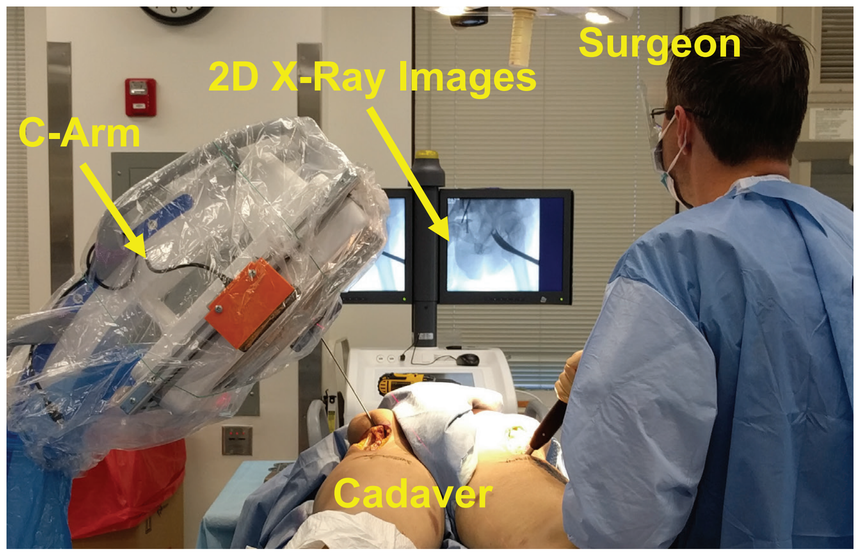


This slide shows the overview of our planning. We start by taking a pre-operative CT of the femur. We then create a Finite Element model of that femur and run several iterations of finite element to find the ideal injection profile. Once we know the ideal profile, we try to match that we spheroids or injection blobs that lay on a single path of injection. We then do a hydrodynamic simulation of the cement to see how it diffuses inside the bone and do an intra-operative or a post-operative assessment of the cement profile.

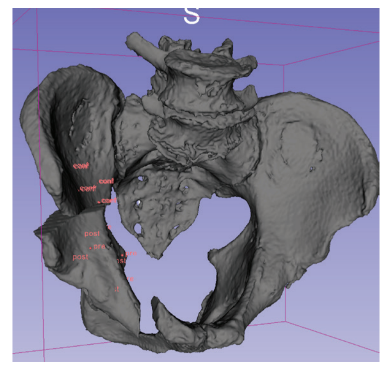
The modified planning paradigm involves three steps: 1) finite element (FE) optimization of the PMMA distribution, 2) geometric optimization for approximating the FE-optimized model geometry with spheroids, and 3) hydrodynamic simulation to predict the resulting PMMA distribution in the bone . FE models of the femora were created using CT scans obtained from the specimens following the procedure described earlier . The boundary conditions simulated a fall to the side.

For the surgical execution and tracking system, we remove the soft tissue from the femora that has been selected for augmentation. We then attach a tracking rigid body with reflective markers (NDI, Waterloo, ON, Canada) to the femur. We then utilize an in-house navigation system to register the bone to its CT volume. For this purpose, we first identify three landmarks on the femur utilizing a tracking digitizer and perform a rigid transformation from the camera coordinates to the CT. We then digitize several surface points and perform a point cloud-to surface registration utilizing the iterative closest point (ICP) method.

Intraoperative Feedback for Periacetabular Osteotomy Using Implanted Markers



Intraoperative 3D Visualization



Intraoperative Workflow

- Markers intraoperatively implanted about iliac wing and acetabular joint
- 3D marker models created using several 2D X-ray views
- Ostoetomies performed and fragment relocated
- Movement of 3D marker models estimated using 2D X-ray views
- Fragment visualization and biomechanical feedback provided to surgeon

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Accomplishment: Periacetabular osteotomy (PAO) is a procedure used to treat developmental hip dysplasia (DDH), in which the acetabulum is relocated to provide greater coverage of the femoral head. We have developed a computer-aided system to provide the operating surgeon with real-time intraoperative 3D visualization and biomechanical feedback during periacetabular osteotomy procedures. Surgeons can use the information provided by the system to help them orient the acetabular fragment for the best patient outcome. The system relies on a series of 2D/3D registrations of the patient's full pelvis to determine relative poses of the C-Arm imager. After soft tissue dissection, the clinician uses a specialized tantalum BB injector to insert markers into the patient's pelvis. Prior to any osteotomies, a series of X-Ray images are registered to the patient's pelvis, and used to create a model of the BBs in the pelvis coordinate frame. After osteotomies and fragment relocation, X-Ray images are collected, registered to the patient's pelvis, and the movement of the BB model is determined. This movement is used to intraoperatively illustrate the 3D motion of the acetabular fragment and provide and biomechanical analysis to the surgeon. It is important to note that this method does not rely on the shape of the acetabular fragment, or the locations of the osteotomies. Similar to radiostereometric analysis (RSA), the rigid implantation of BBs should allow longitudinal studies to measure stability of the relocated joint.

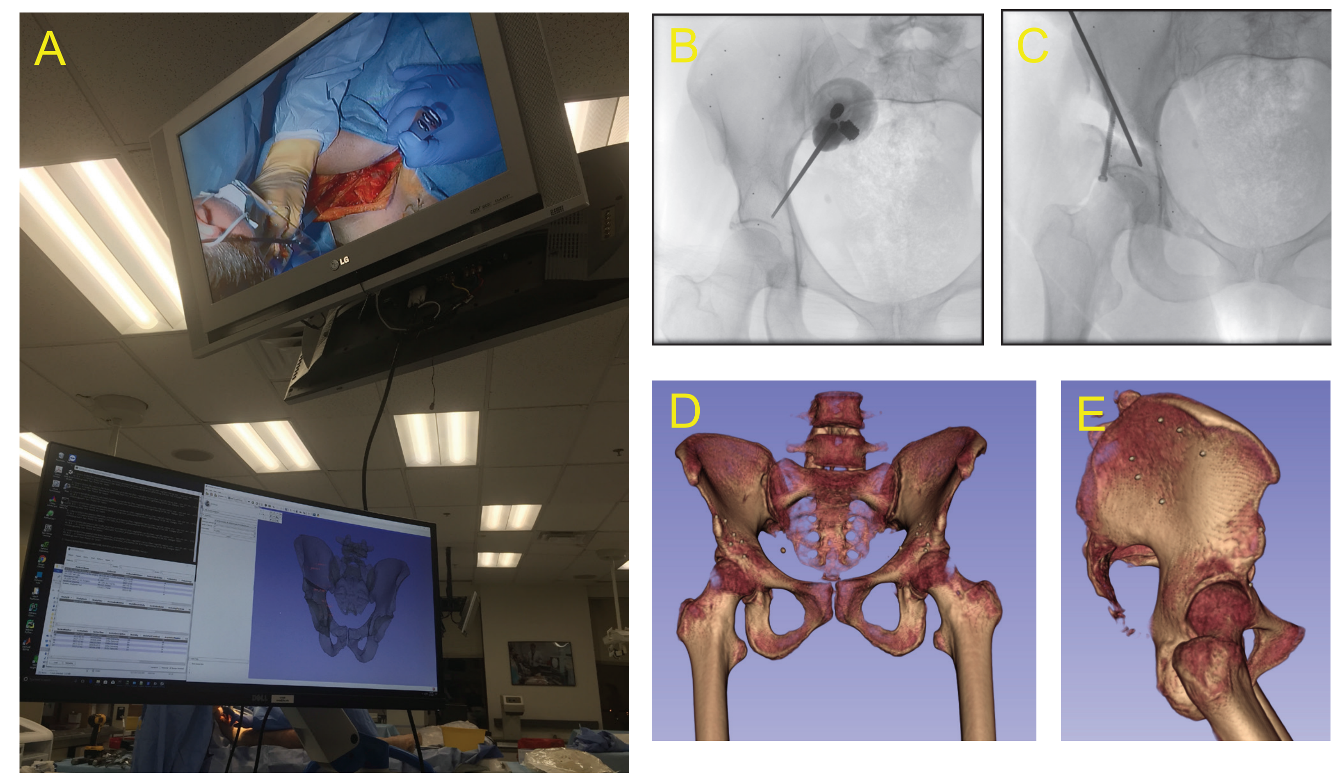
Status: We have performed successful cadaver procedures with prototypes of the system components; working towards reducing time and human input needed to provide intraoperative feedback.

Funding: NIH/NIBIB grants R21EB020113, R01EB006839, JHU APL Graduate Student Fellowship

Key Personnel: (APL) Rachel Hegeman, Ryan Murphy, Mehran Armand (WSE) Robert Grupp, Russell Taylor (UT-Austin) Benjamin McArthur

To find out more: https://bigss.lcsr.jhu.edu

Fragment Localization & Visualization



A) Surgical workstation

B) X-Ray taken during BB insertion

C) X-Ray taken after fragment repositioning

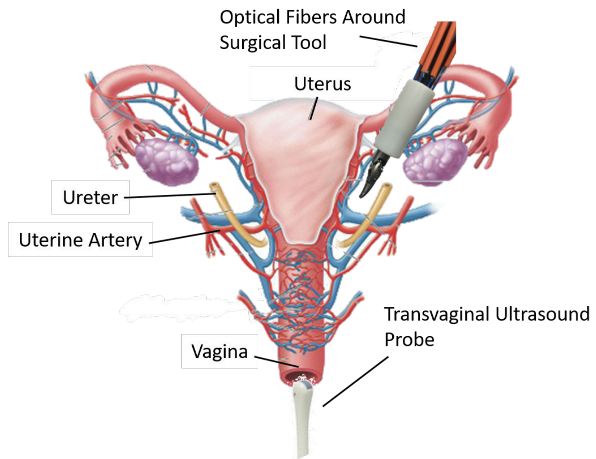
D) Acetabulum BB 3D Visualization

E) Illium BB 3D Visualization

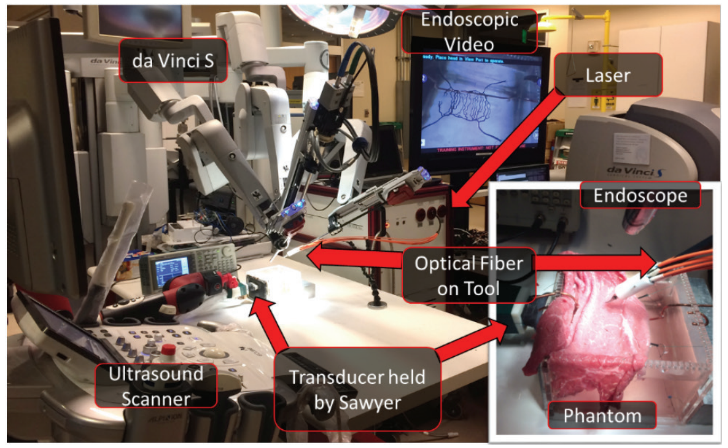
Feasibility of Teleoperated Photoacoustic-Guided Hysterectomy

- Approximately 50–70% of ureter injuries are undetected during surgery
- One common complication of hysterectomies is accidental injury to the ureters located within millimeters of the uterine arteries that are severed and cauterized to hinder blood flow and enable full uterus removal
- This work explores the feasibility of using photoacoustic imaging to visualize the uterine arteries (and potentially the ureter)

Concept



Experimental Setup



Accomplishment: We developed a specialized light delivery system to surround a da Vinci curved scissor tool and an ultrasound probe was placed externally, representing a transvaginal approach, to receive the acoustic signals. Photoacoustic images were acquired while sweeping the tool across our custom 3D uterine vessel model covered in ex vivo bovine tissue that was placed between the 3D model and the ber, as well as between the ultrasound probe and the 3D model. Four tool orientations were explored, and the robot kinematics were used to provide tool position and orientation information simultaneously with each photoacoustic image acquisition.

Status: This design was successfully tested with phantoms and *ex vivo* tissue samples. Next steps include testing *in vivo* with an animal model.

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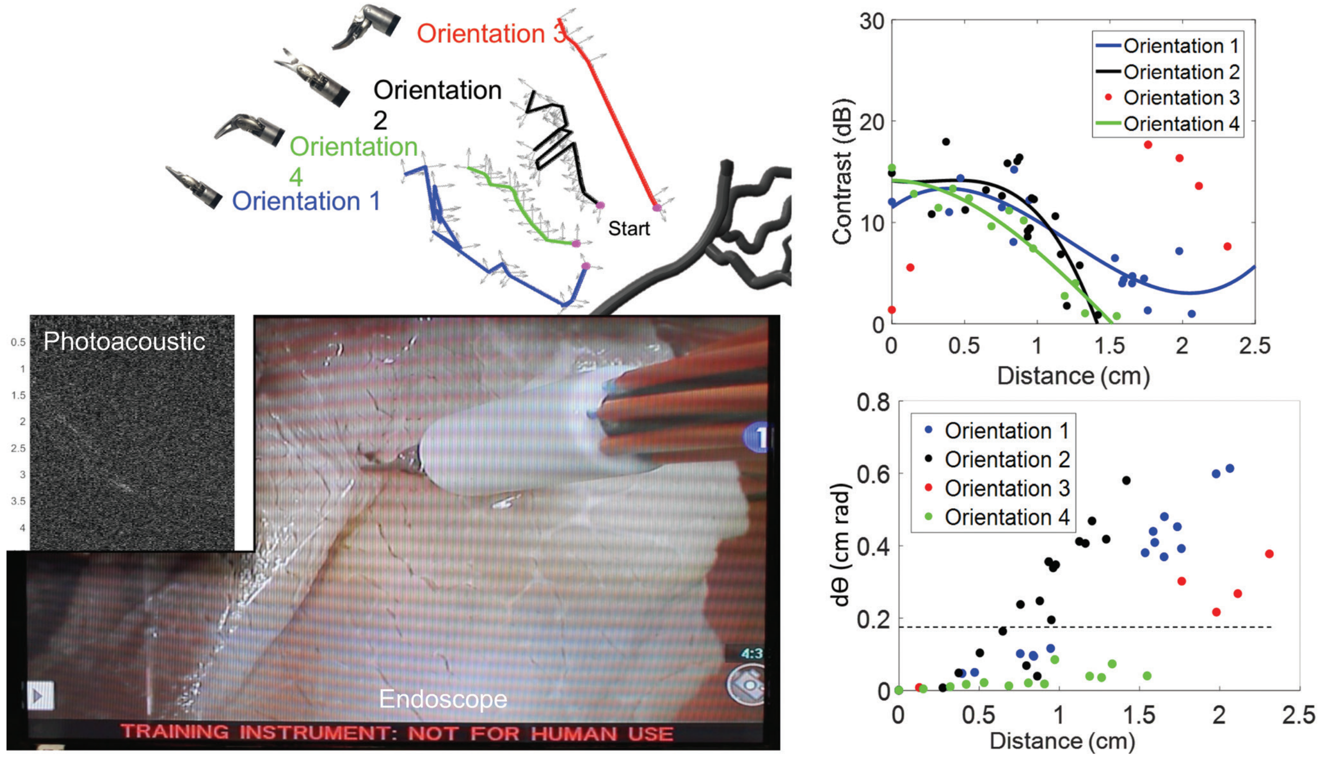
Robots and Computer Assisted Surgical Technology
Human-Machine Collaborative Systems

Teleoperated Photoacoustic-Guided Hysterectomy

- This work explores the feasibility of using photoacoustic imaging to visualize the uterine arteries (and potentially the ureter)



Key Personnel: Muyinatu A. Lediju Bell, Margaret Allard, Joshua Shubert

To find out more: M Allard, J Shubert, MAL Bell, Feasibility of photoacoustic guided hysterectomies with the da Vinci robot, SPIE Medical Imaging 2018

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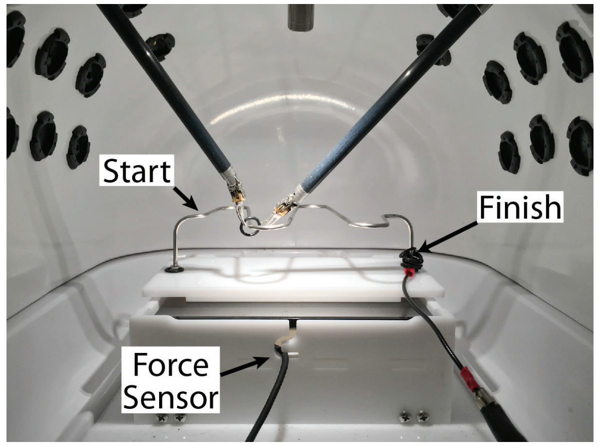
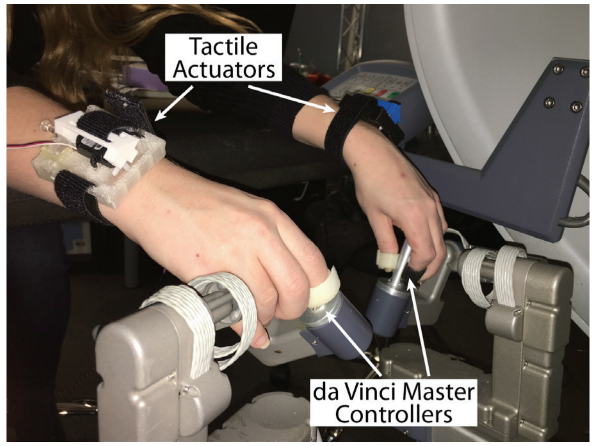
Haptic Feedback for Robotic Surgery Training





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Accomplishments: We developed a haptic feedback system for robotic surgery training that provides bimanual wrist-squeezing feedback of the interaction forces between the surgical instruments and the training task. Bimanual feedback is provided by a custom circuit that monitors the interaction of electrocautery instruments with the conductive task materials. 27 participants were recruited in a user study to evaluate the utility of the system.

Status: Sensor improvements are being made based on the results of the previous study. The improved system will be evaluated again over the next few months.

Funding: Hopkins internal, NSF (CSMR REU program)

Key Personnel: Jeremy D. Brown (PI), Katherine J. Kuchenbecker (Co-PI, Max Planck Institute for Intelligent Systems), Brett Wolfinger (JHU BME undergraduate student), Zachary Patterson (University of Pittsburgh undergraduate student - CSMR REU)

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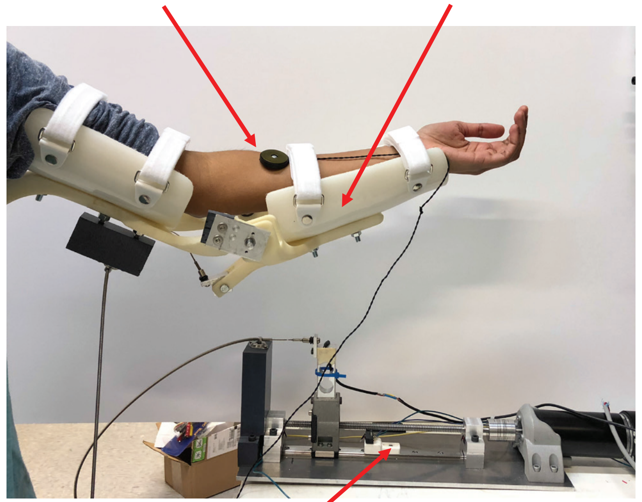
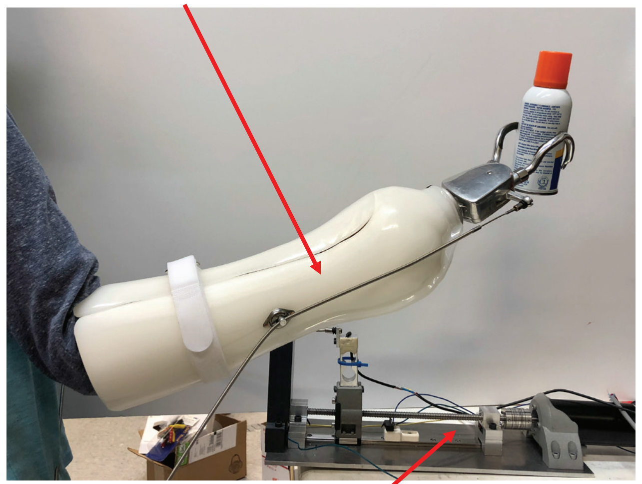
Haptic Feedback for Upper-Limb Prostheses





Accomplishments: We have developed a prototype experimental apparatus that will allow for in-depth studies of the contributions of haptic feedback and EMG-control on the ability of amputees to dexterously manipulate an upper-limb prosthesis. The apparatus is capable of being worn by both amputee and able-bodied individuals and will facilitate comparisons of various control strategies and haptic feedback methodologies. Results from these studies will be used to design improved control algorithms and haptic feedback systems for commercially available prosthetic limbs.

Status: The prototype system exists and is currently undergoing pilot testing. Results from the pilot tests will be used to further improve the system.

Funding: JHU internal funds

Key Personnel: Jeremy D. Brown (PI), Neha Thomas (JHU doctoral student), Jacob Carducci (JHU robotics masters student)

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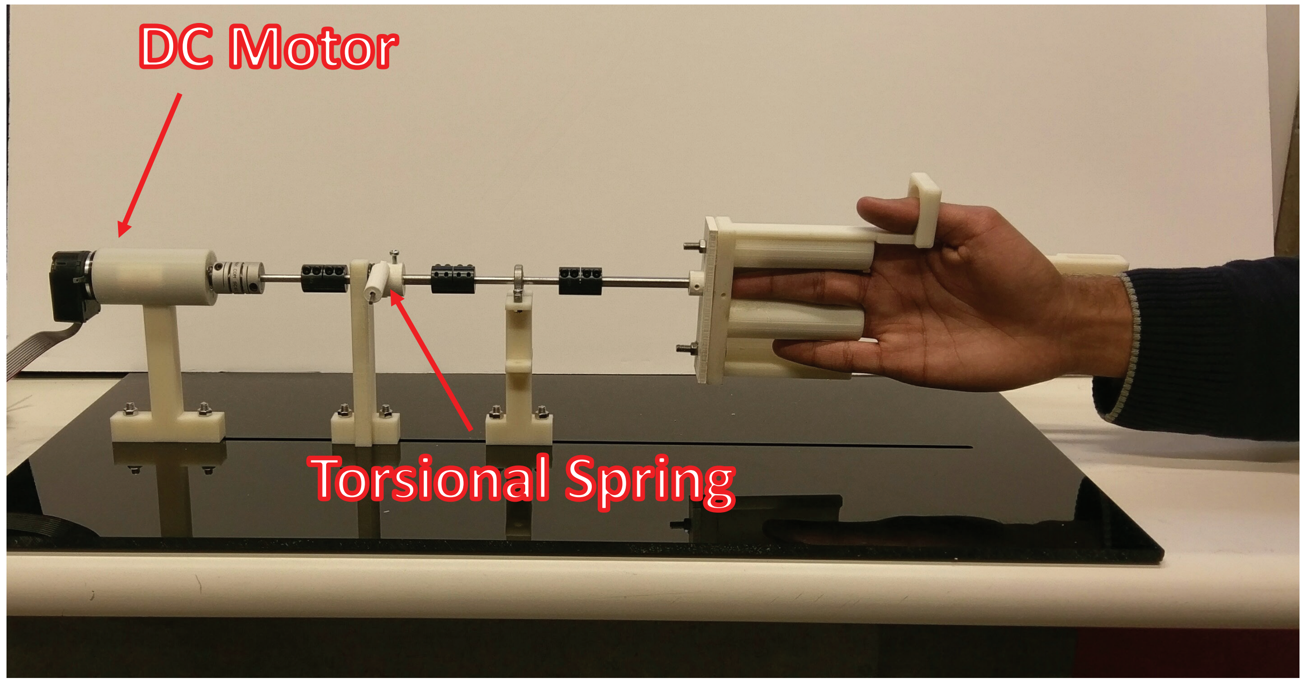
User-Sensitive Haptic Display



Accomplishments: We have developed a prototype experimental apparatus that will allow for in-depth studies of the contributions of human-body dynamics and robot dynamics on haptic perception and human-robot interaction. Human-body dynamics are based on measures of muscle activation and limb kinematics. Results from these studies will be used to design improved control algorithms and robotic systems for virtual reality, telerobotics, and rehabilitation robotics.

Status: The prototype system exists and is currently undergoing pilot testing. Results from the pilot tests will be used to further improve the system.

Funding: JHU internal funds, NSF (CRII Award)

Key Personnel: Jeremy D. Brown (PI), Mohit Singhala (JHU doctoral student)

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Conformational Probabilities: A Bridge Between Innate Knowledge and Action Recognition

Goals/Objectives:

To automate the classification of common human actions observed by robots so as to facilitate human-robot interaction in close proximity

To apply these same methods for robots to understand the actions of other robots (friend or foe) when direct communication is not available

Technical approach:

Basic classes of actions are defined by collections of conformational/configurational trajectories.

Conformational probabilities capture information about all trajectories in each class of actions, and classes are obtained through a quotient mapping.

Developing methods for statistical inference on these spaces and applying to ML frameworks on these lower-dimensional non-Euclidean Spaces has potential advantages in grounding these systems.

Insights, Accomplishments, and Expected Results:

Action classification can be viewed as a quotient operation, and conformational probabilities capture variations in actions.

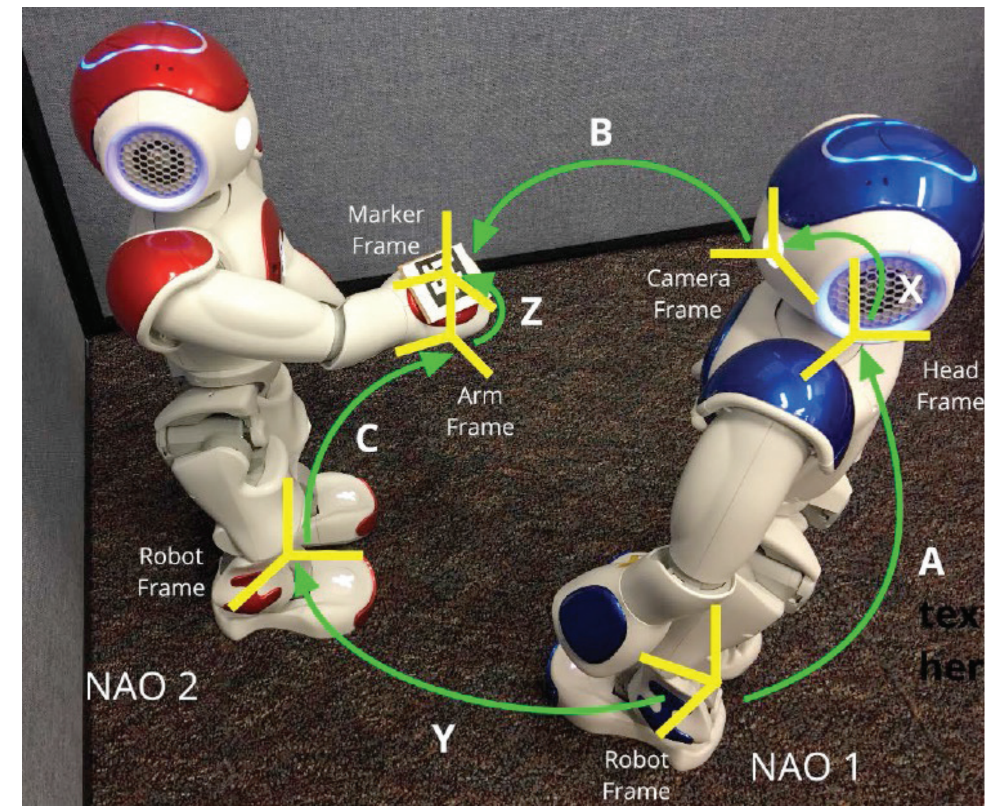
The mapping between observed actions to classes in the quotient space has been formalized

This framework will be developed further and will be demonstrated on a robotic testbed (displayed in figure) which is currently under development

Funding: ONR Award N00014-17-1-2142

Personnel: G. Chirikjian, Sipu Ruan, Thomas Mitchell, Mengdi Xu, Can Kocabalkani

A Humanoid Robot Assessing the Motions of Another



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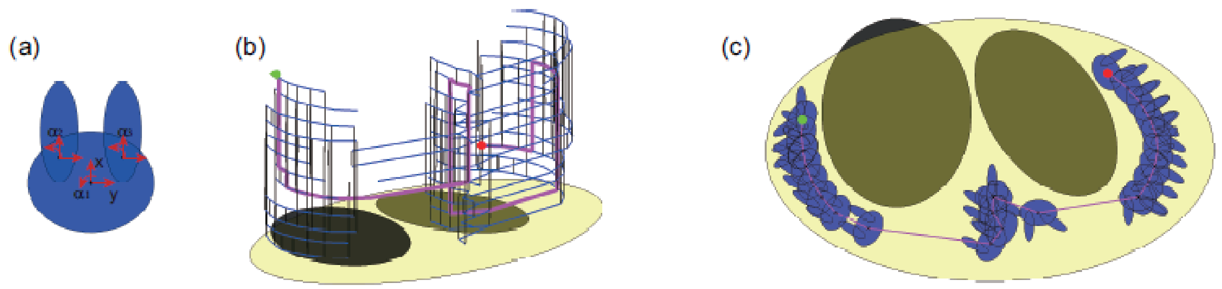
A Paradigm for Motion Planning Based on Parameterization of Free Space

Ellipsoids have closed-form implicit and parametric descriptions: $\Phi(\mathbf{x}) \doteq \mathbf{x}^T A_1^{-2}\mathbf{x} = 1$ and $\mathbf{x} = A_1\mathbf{u}(\phi)$

Though these equations have been known for centuries, it was discovered only recently that the Minkowski sum $P_1 \oplus P_2 \doteq \{p_1 + p_2 \mid p_1 \in P_1, p_2 \in P_2\}$ (and Minkowski difference) of two ellipsoids can be parameterized in closed form as:

$$\mathbf{x}_{1\oplus 2}(\phi) = A_1\mathbf{u}(\phi) + A_2\frac{A_2A_1^{-1}\mathbf{u}(\phi)}{\|A_2A_1^{-1}\mathbf{u}(\phi)\|}$$

This means that the collision-free regions of configuration spaces of articulated models constructed from ellipsoids can be parameterized in closed form, therefore providing a new tool to improve motion planning in narrow passages, as depicted below.



Funding: NSF IIS-1619050

Participants: Sipu Ruan, Mengdi Xu

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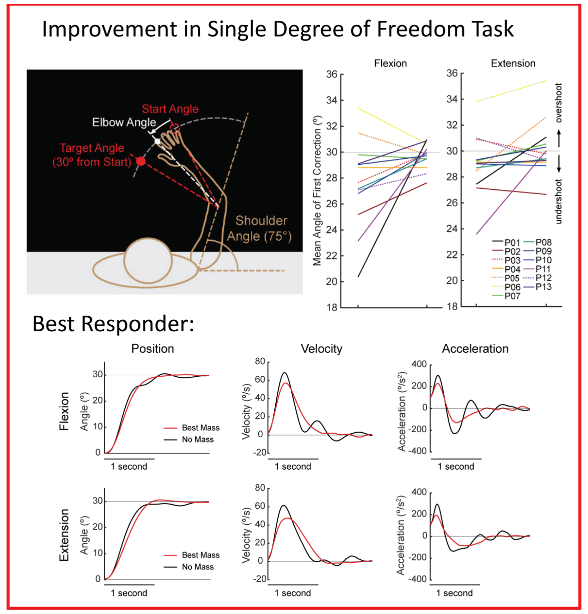
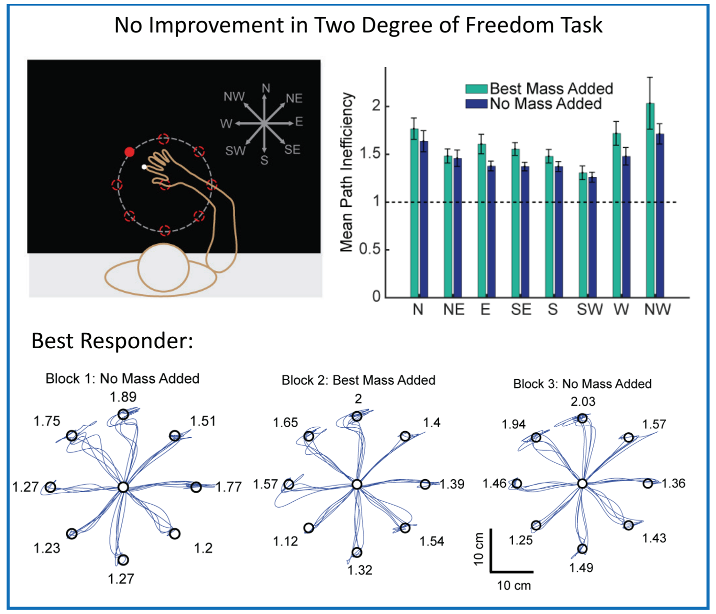
Patients with Cerebellar Ataxia Do Not Benefit from Limb Weights

Accomplishment: Treating patients with cerebellar ataxia by the addition of mass to the limbs is a debated practice with a limited scientific history. We hypothesized that addition of mass would only be effective in reducing dysmetria in hypometric patients when mass was added along the length of the limb segment about the center of mass of that segment. Cerebellar patients were challenged with making a single joint, single degree of freedom reaching movement while various limb masses were tested. In this task, reaches were indeed improved by adding a patient-specific mass. However, this improvement did not translate to multi-joint movements. In multi-joint movements, the “best” patient-specific masses (as determined in a single joint task) generally exacerbated subjects’ dysmetria in a multi-joint reaching task. This finding raises doubts as to the merits of adding limb weights as a therapy to mitigate the effects of dysmetria.





Status: We have submitted these results to The Cerebellum under the title “Patients with Cerebellar Ataxia Do Not Benefit from Limb Weights.”

Funding: National Institute of Child Health and Human Development (HD040289 to Amy J. Bastian), Applied Physics Lab Graduate Fellowship (FNACCX19 to Amanda M. Edwards), and James S. McDonnell Foundation Complex Systems Scholar Award (to Noah J. Cowan)

Key Personnel: Amanda M. Edwards, Noah J. Cowan, Amy J. Bastian

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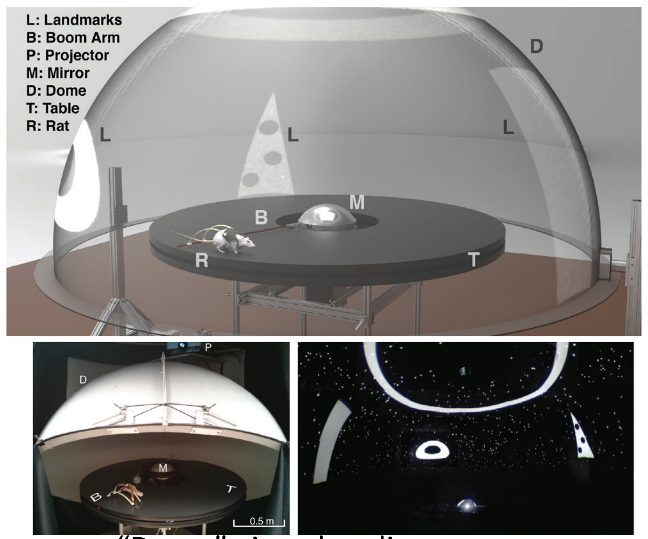
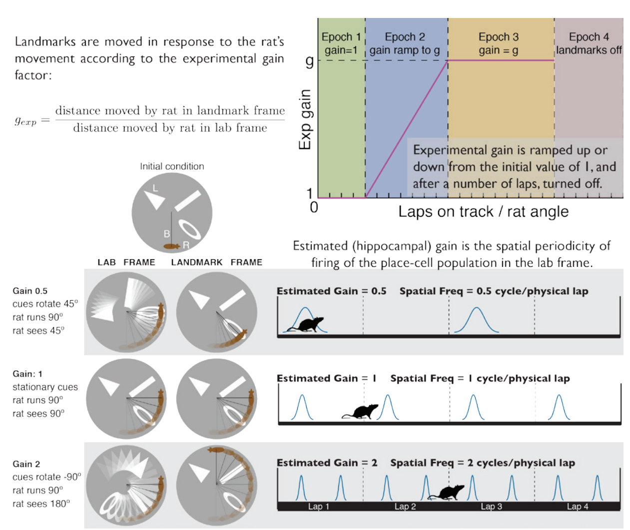
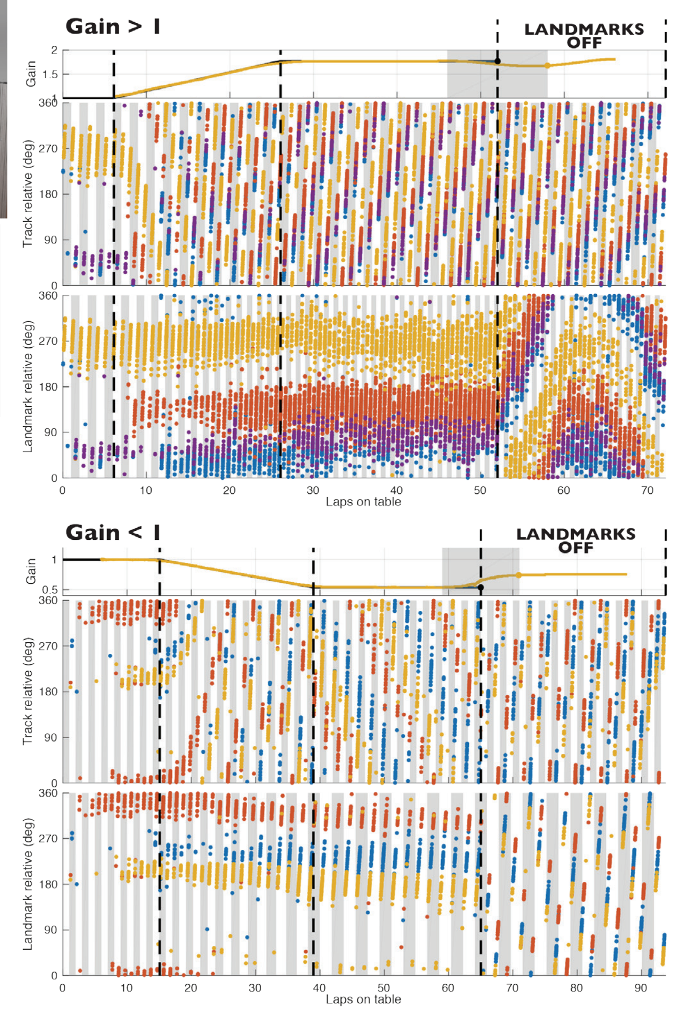
Recalibration of the Path Integrator in Virtual Reality as Revealed in CA1 Place Cells



“Dome” virtual reality apparatus





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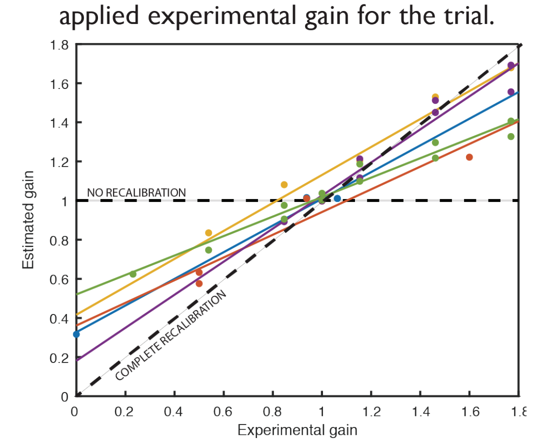
When landmarks are on and moving, place fields fire in the same location in the landmark frame of reference, not the lab frame of reference.

When landmarks are turned off, the place cells do not revert back to spatial firing in the lab frame of reference.

The estimated (hippocampal) gain when landmarks are turned off is generally between 1 (no manipulation) and the applied experimental gain for the trial.



(Each color represents a rat)

The path integrator gain (how much the spatial representation of allocentric position moves with each unit of movement in the real world) is **recalibrated** by the prior experience of experimental gain manipulation.

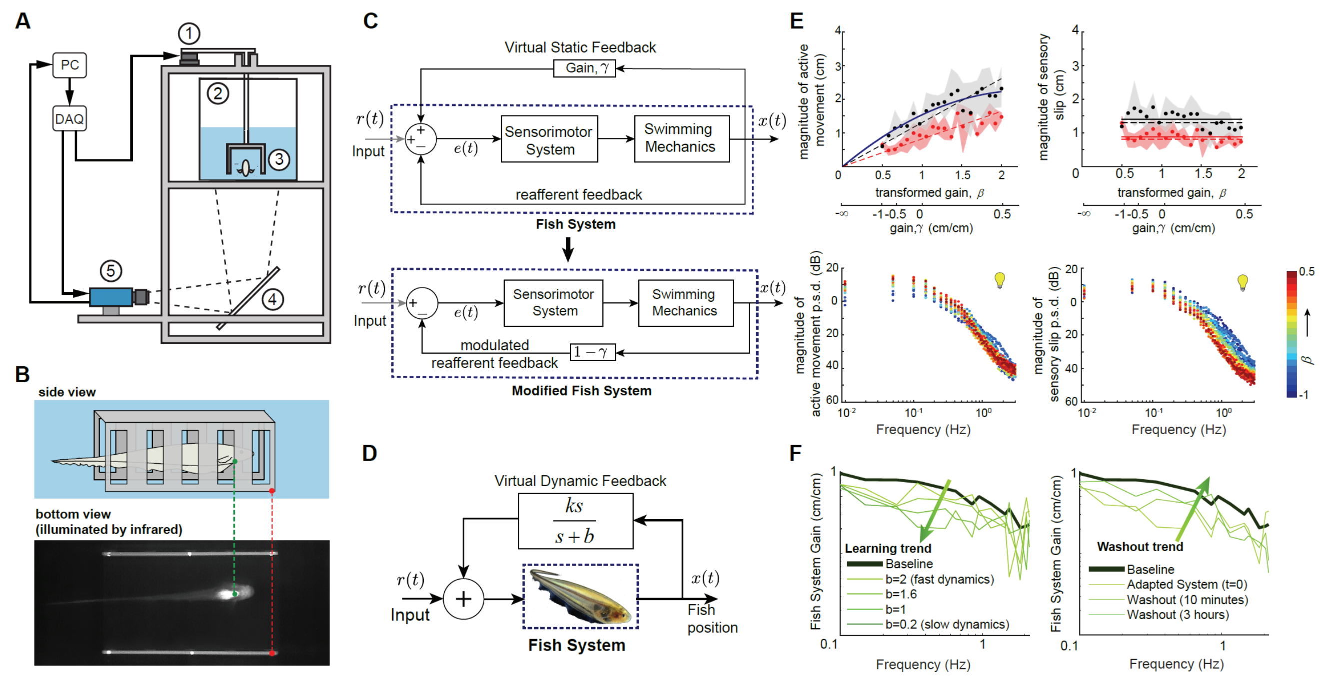
Accomplishment: The rodent hippocampal formation combines information from both landmark and self-motion cues into an allocentric representation of its environment. We designed and used a planetarium-style virtual reality dome to examine the relative influence of these two types of cues on the firing fields of place cells. We tested whether the brain recalibrates the relationship between self-motion cues perceived by the rat during movement and the update of position encoded by CA1 place cells. We call this relationship the ‘internal gain’ of the path integrator and showed that this is a plastic variable learned via feedback from landmark cues. By slowly changing the rate of movement of visual stimuli in relation to the movement of the rat, we can recalibrate the internal gain to a particular value, and moreover show that this value persists when landmarks are turned off after this manipulation.

Status: We have presented the equipment, experimental design, and partial results at Society for Neuroscience (2015,2016,2017) and ICRA 2015. We are drafting a manuscript on the recalibration results, and planning another publication on the modification of representation of velocity in relation to EEG theta waves in the virtual reality apparatus. We have also commenced recording from head-direction cells in the thalamus of rats using the same paradigm.

Funding: NIH grants R01 MH079511, R21 NS095075 and R01 NS102537, Johns Hopkins University Discovery Award, Johns Hopkins Kavli Neuroscience Discovery Institute Postdoctoral Distinguished Fellowship.

Key Personnel: Ravikrishnan Jayakumar, Manu Madhav, Francesco Savelli, Macauley Breault, H. Tad Blair, James Knierim, Noah Cowan

Active Sensing and Adaptive Control in Electric Fish under Virtual Feedback



Accomplishment: *(1) Active Sensing.* Animals regulate the stimulation of their sensory receptors by using purposeful motor commands to modulate reafferent feedback, a process known as active sensing. The closed-loop coupling between sensory input and the motor output makes understanding the underlying strategies for active sensing a difficult problem. Our experimental setup enables us to directly alter the dynamics of reafferent feedback during refuge tracking in the weakly electric fish *Eigenmannia virescens*, providing new insight into the behavioral mechanisms for the control of active sensing. We found that *Eigenmannia* maintains robust sensory slip during station-keeping behavior by altering its active movements as necessary. *(2) Adaptive Control.* We also observed that introducing novel dynamics with through such virtual feedback triggers a quantifiable adaptive response in the fish's control system. When the novel dynamics were removed, the fish regains its original controller over a post-adaption period of several hours, a process known as "washout".

Status: We presented our findings on active sensing at SICB 2017 and the manuscript on the detailed work is in preparation for a journal publication. We will present our recent work on understanding how the fish learns novel locomotion dynamics at SICB 2018.

Funding: Complex Systems Scholar Award to NJC from the James McDonnell Foundation under Grant No. 112836, a NSF Award to NJC and ESF under Grant No. 1557858

Key Personnel: Debojyoti Biswas, Ismail Uyanik, Sarah A. Stamper, Balázs P. Vágvölgyi, Kyle Yoshida, Luke Arend, Eric S. Fortune, Noah J. Cowan

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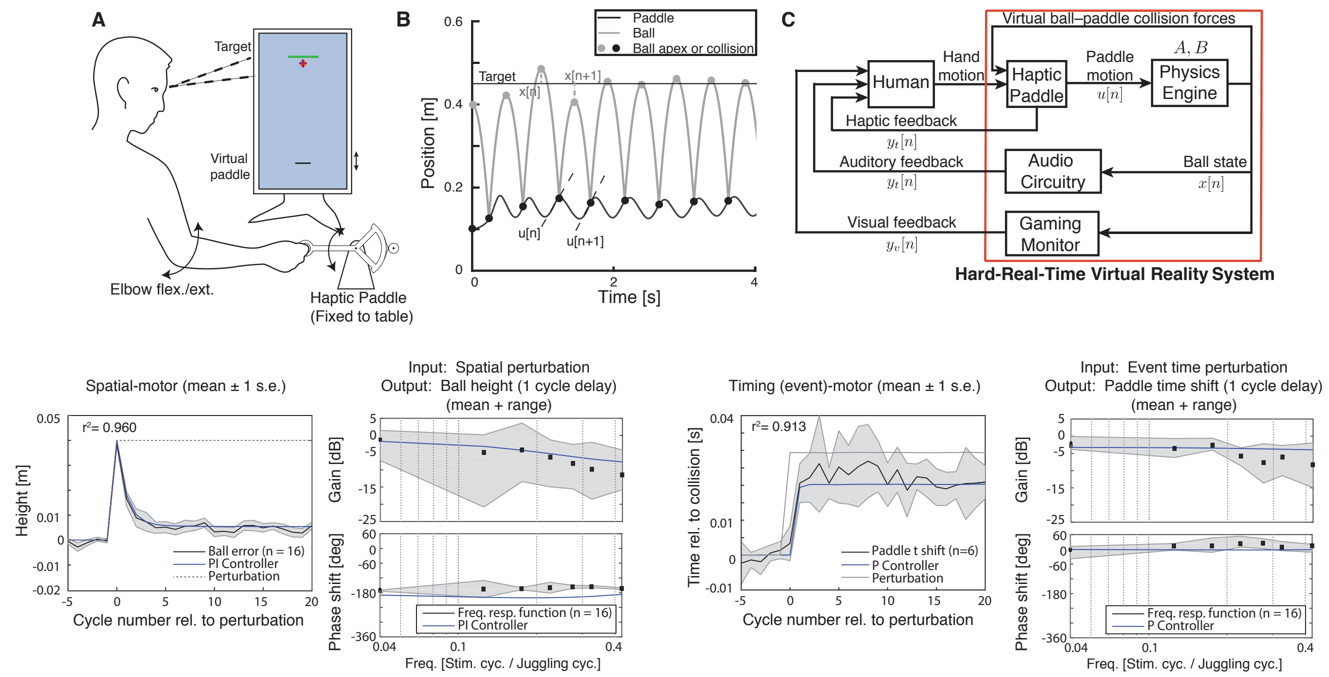
Understanding Human Rhythmic Motor Control



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 other classes of spatial or timing perturbations.

Status: We have one published study and are finalizing a second manuscript. Further studies are in progress to study 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), Link Foundation Fellowship (to R. Nickl)

Key Personnel: Robert Nickl, Mert Ankarali, Nicole Ortega, Noah Cowan

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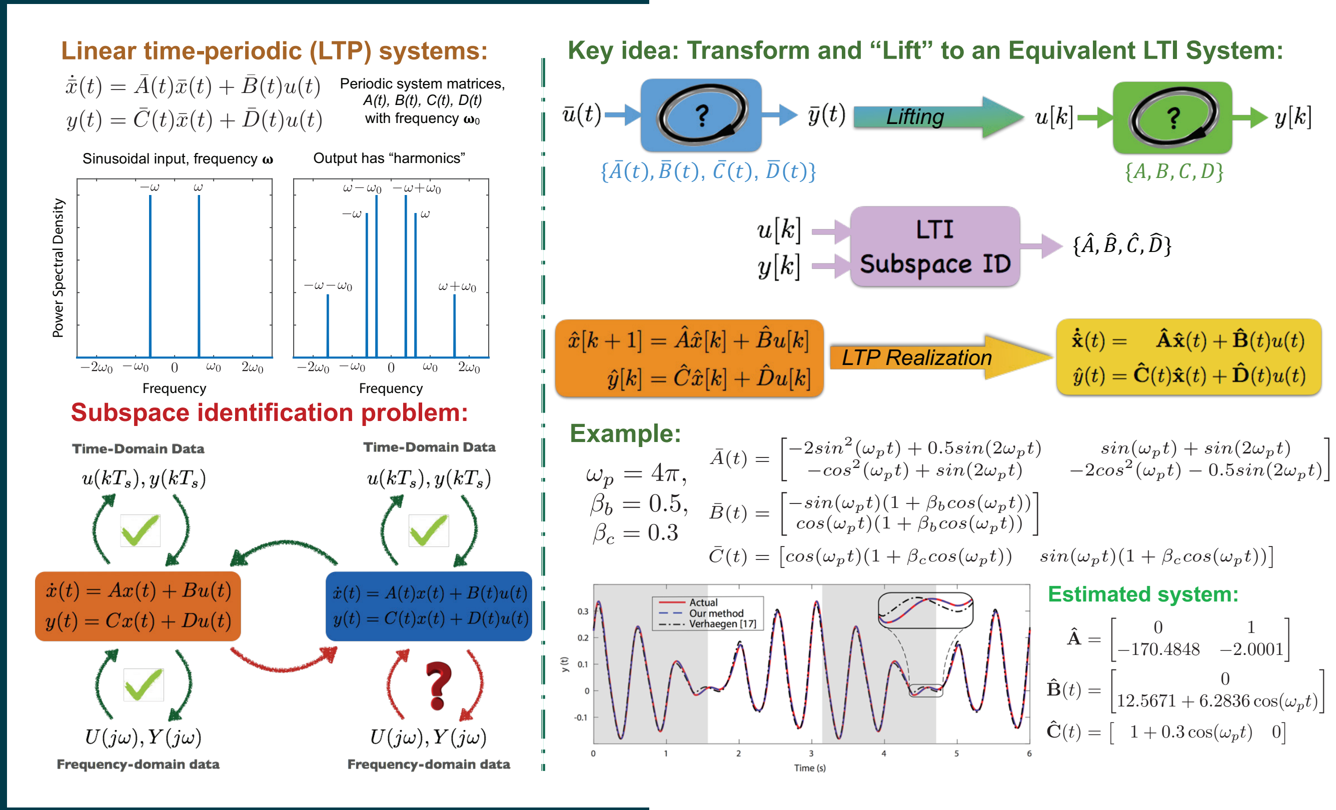
Frequency-Domain Subspace Identification of Linear Time-Periodic (LTP) Systems

Accomplishment: We developed a new methodology for frequency-domain subspace-based state-space identification for linear time-periodic (LTP) systems with three main components. (1) Lifting: We proposed a methodology for transforming the LTP systems to an equivalent discrete-time LTI system by utilizing tools from the literature. (2) Subspace Identification: We utilize LTI frequency-domain subspace identification techniques to estimate LTI equivalents of LTP systems. (3) LTP realization: We propose a novel method to find time-periodic realizations of lifted LTI systems based on the specific structural form of Fourier series coefficients in lifted LTI system matrices. A key property of the proposed method is that it provides estimation of Floquet transformed forms of LTP systems using data-driven techniques.



Status: The outcomes of this work was submitted to IEEE Transactions on Automatic Control and it is currently under review.

Key Personnel: Ismail Uyanik, Uluc Saranli, M. Mert Ankarali, Noah J. Cowan, and Omer Morgul.

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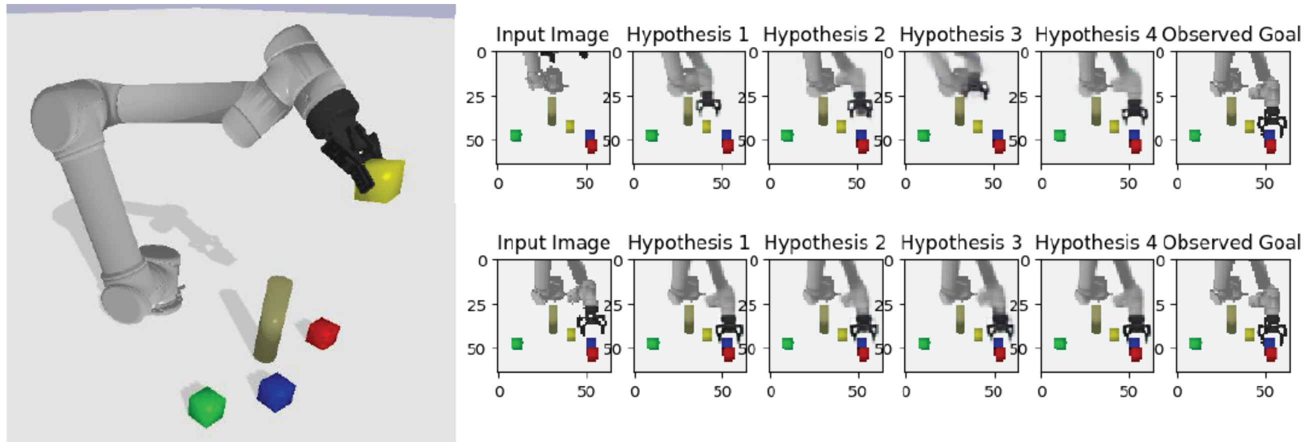
Learning to “Imagine” for Robot Task Planning



Demonstration of robot planning using “imagination.” The right side shows how the predicted images converge as the robot moves closer to the target block.

Accomplishment: JHU and APL have developed algorithms that enable robot task planning based on “imagination.” Our approach is inspired by the observation that humans observe a situation, generate several hypothetical actions that could accomplish the task and then select the actions with the highest probability of success. We show that it is feasible to generate predictions of future actions based on past observations without a reliance of a predefined model. The novelty of this approach is to use multiple hypothesis prediction and an autoencoder network to generate predicted changes in the environment many time steps in the future. To date, this work has been successfully applied to robotic manipulation and navigation scenarios in simulation.

Status: We have generated preliminary results for manipulation tasks in simulation. We are currently refining the algorithms to generate more accurate predictions and performing hardware evaluation.

Funding: NSF – Award Number 1637949
APL Independent Research and Development Funds

Key Personnel: Chris Paxton, Kapil Katyal, Gregory D. Hager

To find out more: Link to a web page, You can also add something about key publications if you like
https://cirl.lcsr.jhu.edu/research/human-machine-collaborative-systems/

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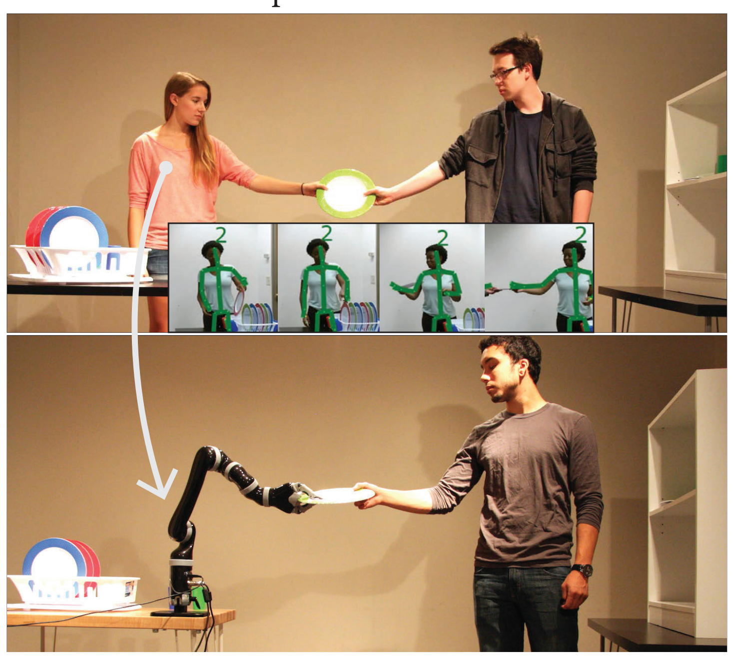
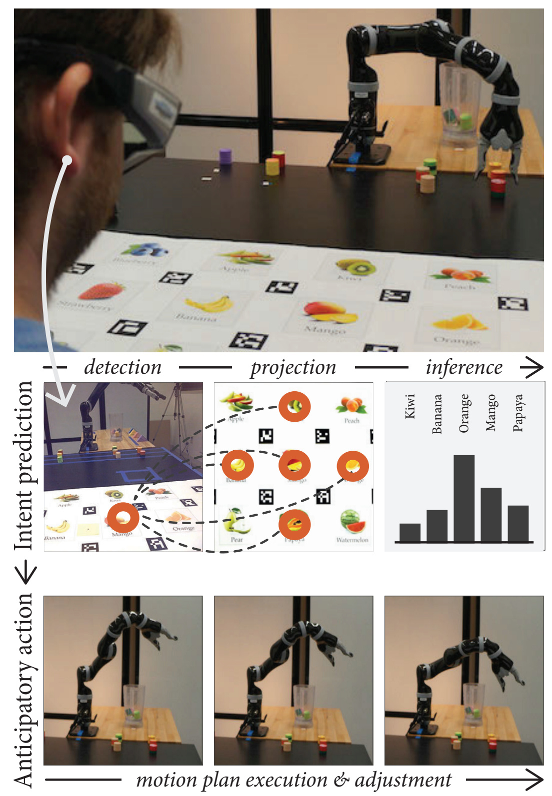
Intuitive Computing Laboratory Using Socially Intuitive Robots to Empower People

Human-Robot Teaming

Human-inspired action coordination





From Perception to Anticipation and Coordination

Dr. Huang's research in this area focuses on developing collaborative robots that can infer human internal states based on observable behavioral cues and then act accordingly to achieve shared goals. His work has explored action coordination and anticipation in a human-robot team, demonstrating improved team performance and desirable user experience.

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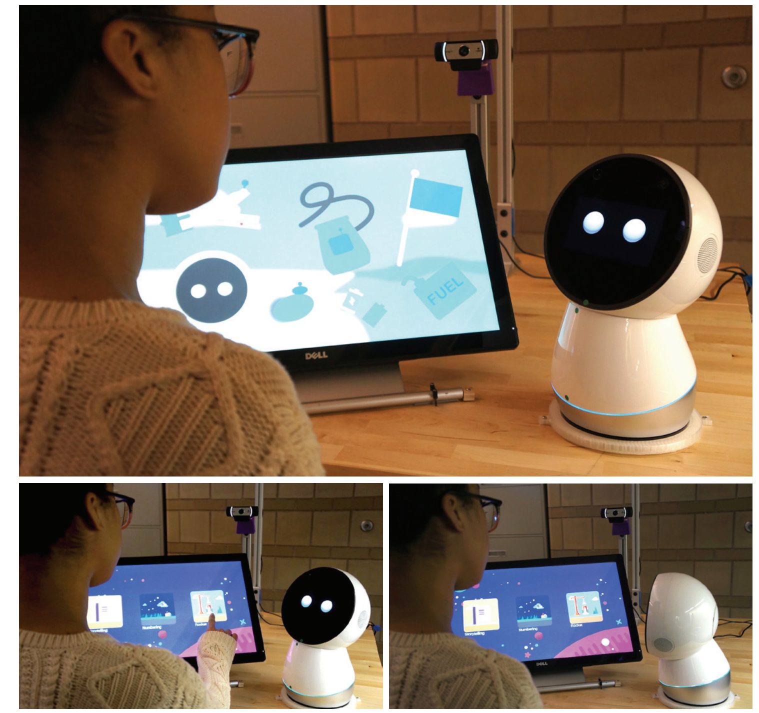
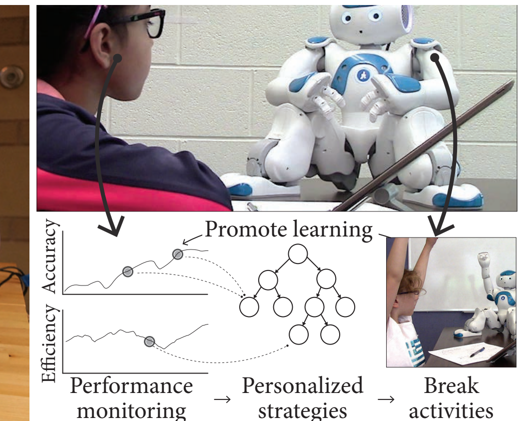
Robots for Children with Special Needs

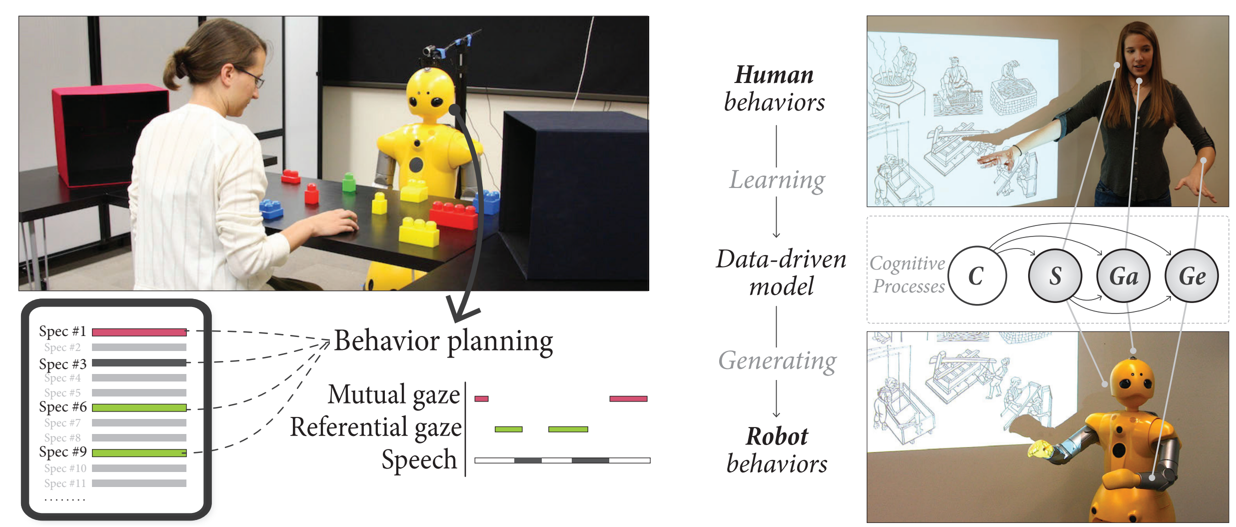




Personalized Intervention

Dr. Huang's research in this area focuses on creating personalized, playful robot-mediated intervention for children with special needs, such as children with autism spectrum disorders (ASD). Social robots provide a unique opportunity to deliver effective behavioral intervention to children with ASD, as evidence has shown their involvement in interaction with technologies. We seek to use social robots to help children with ASD improve social and communication skills.

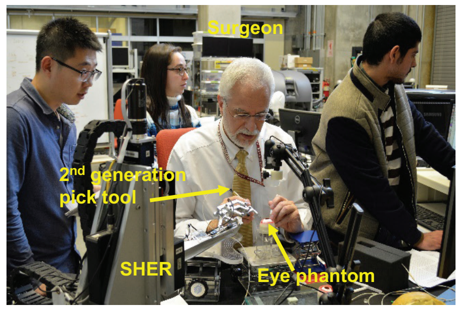
Synthesis of Intuitive Robot Behaviors: Helping Humans Understand Robots



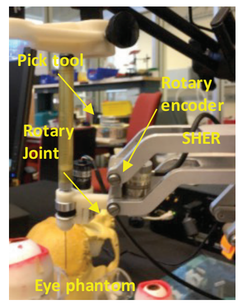
Dr. Huang's research in this area focuses on generating social behaviors for robots to interact with people effectively and intuitively. The aim is to create natural interaction protocols where people are comfortable and familiar with for human-robot teams. These human-inspired designs have shown measurable improvements in task performance and user experience.

Robots and Computer Assisted Surgical Technology

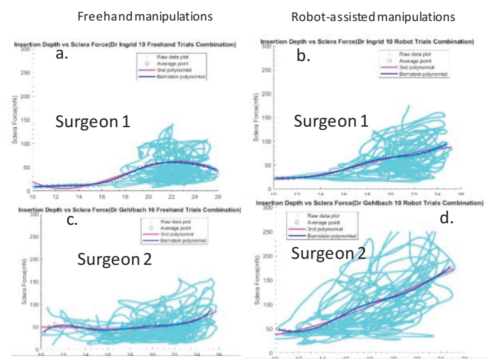
Enabling Technology for Safe Robot-assisted Surgical Micromanipulation



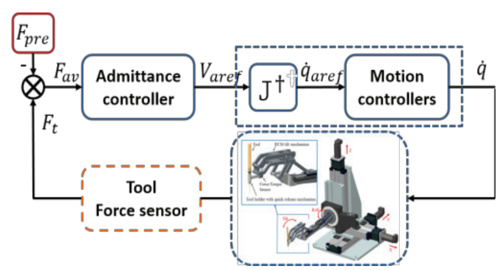
Experimental setup



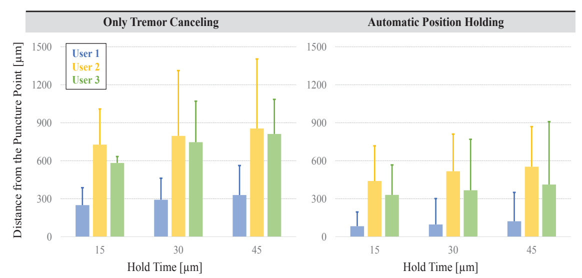
Hardware update



Sclera force to insertion depth variation



Block diagram of admittance controller for SHER



Automatic position holding with a handheld manipulator

Accomplishment: The central goal of this proposal is to develop enabling technology for safe robot-assisted retinal surgery. Factors such as involuntary patient motion, inconsistent tissue properties, high or variable tool velocities, and changing manipulation directions can dramatically increase undesirable forces applied to the delicate retinal tissue. We are addressing these factors by integrating a previously-developed robotic system, with multifunction force-sensing tools to sense tool-to-tissue interactions at both, tool tip and sclera. We shown, for the first time ever, the relationship between sclera force and tool insertion depth, during freehand and robot-assisted tool manipulations inside eye phantoms. Also, a new control method was implemented to actively compensate unintended movements of the operator, and to keep the cannulation device securely inside the vein following cannulation.

Status: Refinements and further engineering evaluations ongoing

Hardware:

Encoded rotary joint has been added to the existing 5 degree-of-freedom SHER

Second generation pick tool has been developed and calibrated

Experimental setup for multi-user trails on eye phantoms under evaluation

Software:

Tool-to-robot registration procedure with rotary encoder ongoing

New FBG-interrogator interfaced with the SHER

Began implementing control strategy for safe sclera force-based manipulation

Funding: NIH 1R01EB023943-01 and JHU internal funds

Key Personnel: Iordachita I., Kobilarov M., Gehlbach P., Taylor R., Gonenc B., Patel N.

To find out more: https://amiro.lcsr.jhu.edu/main/Research

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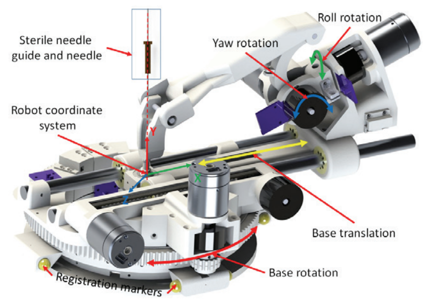
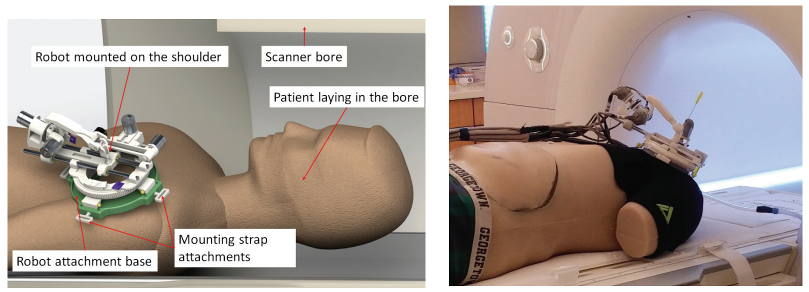
Robots and Computer Assisted Surgical Technology

MRI Compatible Body-Mounted Robot to Streamline Pediatric Shoulder Arthrography

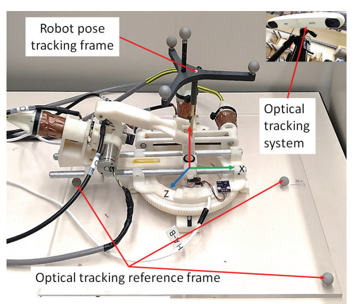
Accomplishment: The goal is to develop and test a new patient-mounted MRI-compatible shoulder arthrography robot for needle guidance in pediatric interventional procedures. The third prototype of a 4 degrees of freedom body-mounted robot is under development. Robot accuracy was evaluated in laboratory environment. Maximum positioning and orienting error at needle insertion point was ±0.6 mm and ±1.0 degree, respectively. Maximum positioning error at needle tip (50 mm insertion depth) in air was 1.22 mm. IRB approval for a clinical trial of MRI-guided shoulder arthrography using this robot has been granted.



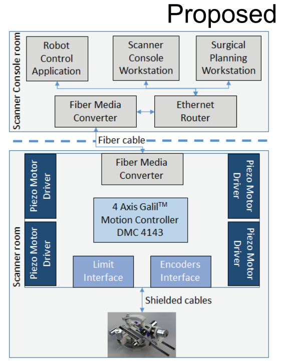
Robot structure



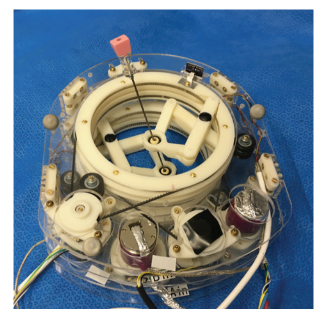
Proposed mounting method



Accuracy assessment



System architecture



Parallel robot prototype

Status: Refinements and further engineering evaluations ongoing

Hardware: Improved rigidity and reliability of some of the joints; 4 new limit switches for repeatable homing procedure; A clinical grade prototype is under development

Software: Predefined home offsets for robot home (zero) pose; Real-time updated MATLAB application; Complete homing procedure for each axis; Forwards and inverse kinematics for task-space poses

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., Patel N., Azimi E.

To find out more: https://amiro.lcsr.jhu.edu/main/Research

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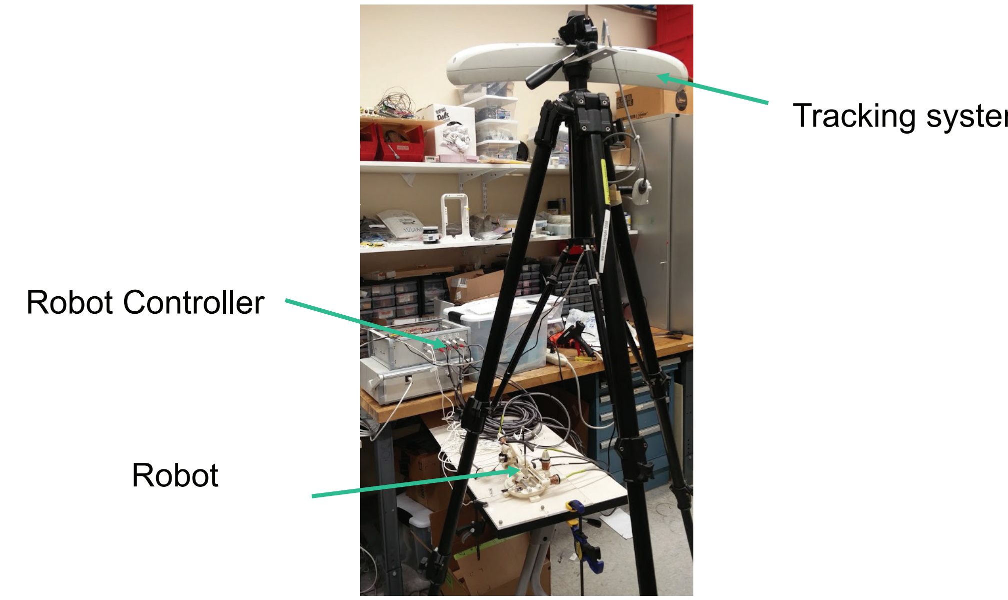
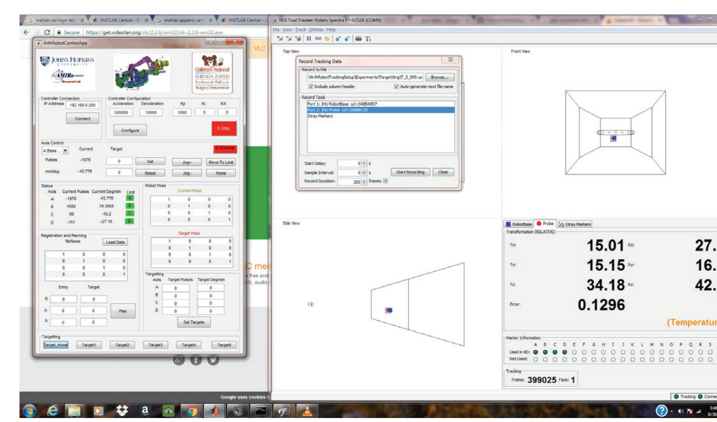
Serial robot accuracy assessment – Experiment Setup

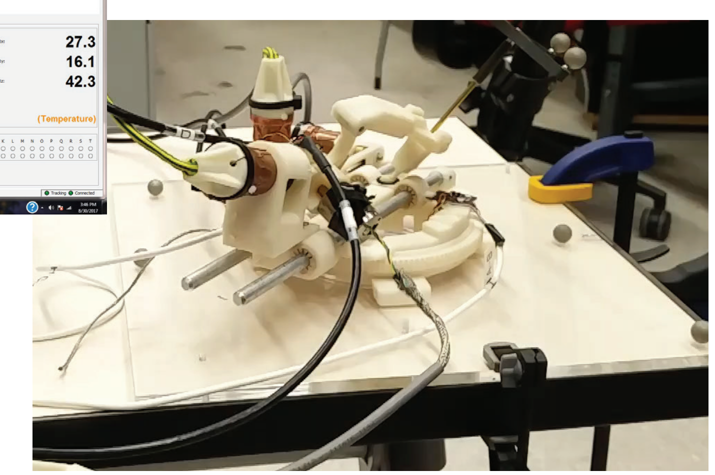


MRI Compatible body-mounted robot to streamline pediatric shoulder arthrography

Serial robot accuracy assessment



Robot new GUI

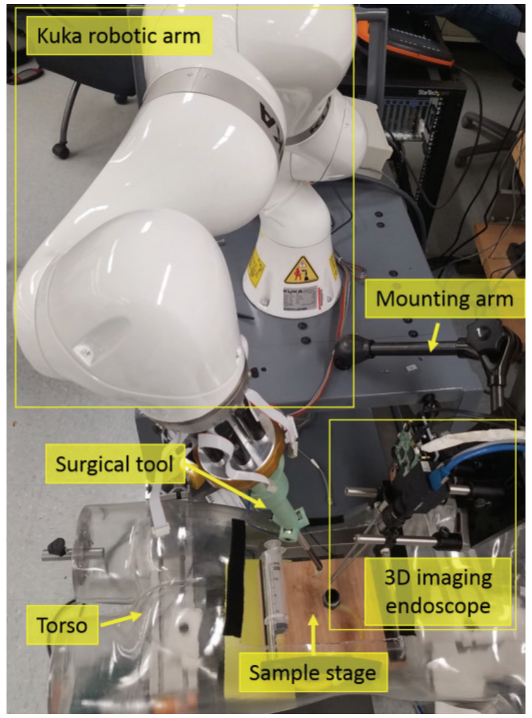


Accuracy assessment

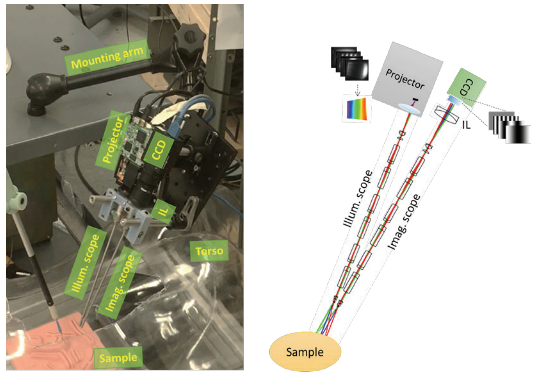
The Next Generation of Surgical Imaging and Robotics for Supervised Autonomous Soft Tissue Surgery

Accomplishment:
Successful completion of targeting and cutting tasks using laparoscopic constraints demonstrate feasibility of this technology to complete semi-autonomous electro-surgery in minimally invasive procedures.

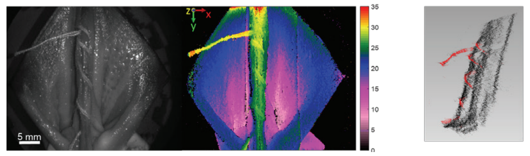
Future works: Enhance the accuracy on the focal of semi-autonomous suturing task with NIR marker navigation



3D imaging endoscope with quantitative depth measurement for minimally invasive surgery



Intestinal imaging with looping sutures



To find out more:

[1] Shaderman et al. Science Translational Medicine, 8 (337): 337ra64
[2] Leonard et al, ICRA: 1889-1894.
[3] Le *et al*, CLEO: AW1A.4.
[4] Le *et al*, Chinese Optics Letter, 15 (5).

Key personnel: Jin U. Kang (PI), Hanh N. D. Le, Justin Opfermann, Simon Leonard, Axel Krieger

Funding: National Institute of Biomedical Imaging and Bioengineering of the National Institute of Health under award number 1R01EB02061

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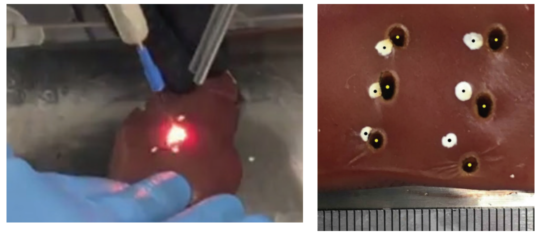
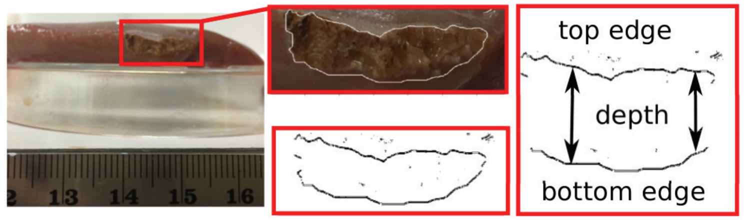
Robots and Computer Assisted Surgical Technology

Accuracy tests



#	Fiducial		Burned Mark		Error (mm)
	X (mm)	Y (mm)	X (mm)	Y (mm)	
1	8.94	26.43	10.38	27.45	1.76
2	20.02	27.41	22.68	30.73	4.25
3	10.13	20.65	11.86	20.21	1.78
4	21.88	20.73	24.6	22.79	3.40
5	11.42	14.83	13.18	13.43	2.25
6	23.17	13.94	26.18	13.78	3.01

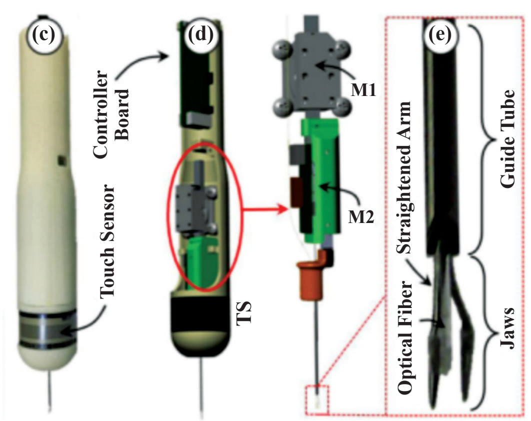
Average x-y positional error: 2.74± 0.99 mm

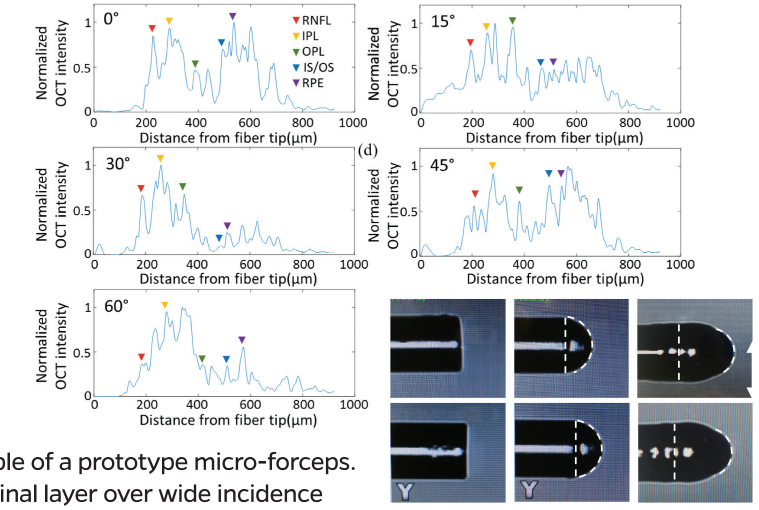


Average cutting depth accuracy: 0.56 ± 0.34 mm

Optical Coherence Tomography Image and Sensor Guided Microsurgical Tools

Accomplishment: We are developing a new class of hand-held "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 and a micro-forceps used for epiretinal membranectomy.





(Left) Smart microsurgical tool designs, an example of a prototype micro-forceps. (Right) Lensed fiber and identification of each retinal layer over wide incidence angle.

Status: We are researching on automatic identification of each retinal layers for delivery of therapeutic agents into a targeted layer and actively pursuing commercialization of these technologies for clinical use.

To find out more: http://engineering.jhu.edu/biophotonics/

1) J. U. Kang, J.J. Chae, S. Lee, G. Cheon, B. Gonenc, C. Lee, P.L .Gehlbach, Investigative Ophthalmology & Visual Science 58 (8), 1187-1187

2) G. W. Cheon , B. Gonenc, R. H. Taylor, P. L. Gehlbach, and J. U. Kang, IEEE/ASME Trans. Mechatronics 22(6) 2440 (2017)

Key personnel: Jin U. Kang (PI), Soohyun Lee, Shoujing Guo, Berk Gonenc, Jeremy Chae, Russell H. Taylor

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

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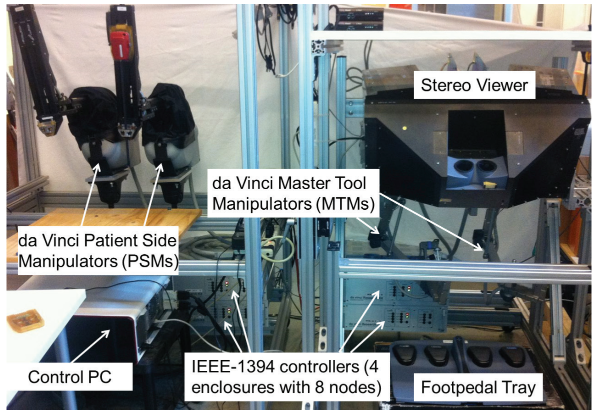
da Vinci Research Kit (dVRK)

Open source research platform based on first-generation da Vinci system, disseminated to 30 research institutions around the world

dVRK



Surgeon panel at IROS 2017 Workshop on Shared Platforms for Medical Robotics Research

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.

Status: This platform now exists at 30 institutions worldwide, with more in process. We organized several community events, including a PI Meeting at the Hamlyn Symposium, a Workshop at IROS 2017, and a User Group Meeting prior to IROS 2017. We are also extending the software framework to other collaborative robotic systems.

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.

Current Key Personnel: Peter Kazanzides, Russell Taylor, Anton Deguet, Jie Ying Wu, 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.

Earlier Collaborators: Zihan Chen, Long Qian, Simon Leonard, Balazs Vagvolgyi, Paul Thienphrapa, Ankur Kapoor

To find out more: https://github.com/jhu-dvrk, https://github.com/collaborative-robotics

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Human-Machine
Collaborative Systems

Calibration and Tracking for Augmented Reality Head-Mounted Displays

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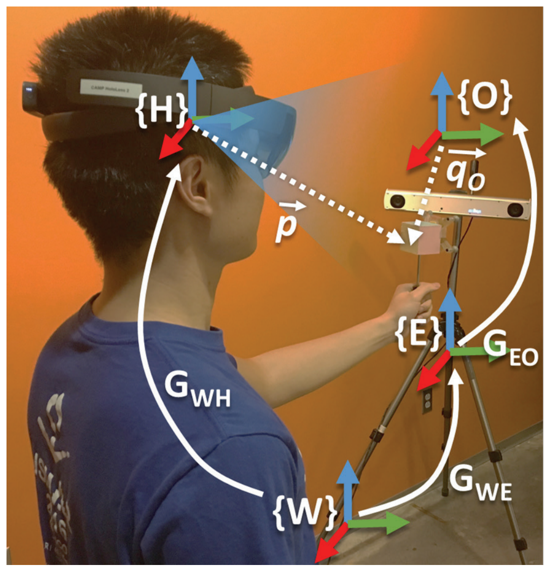
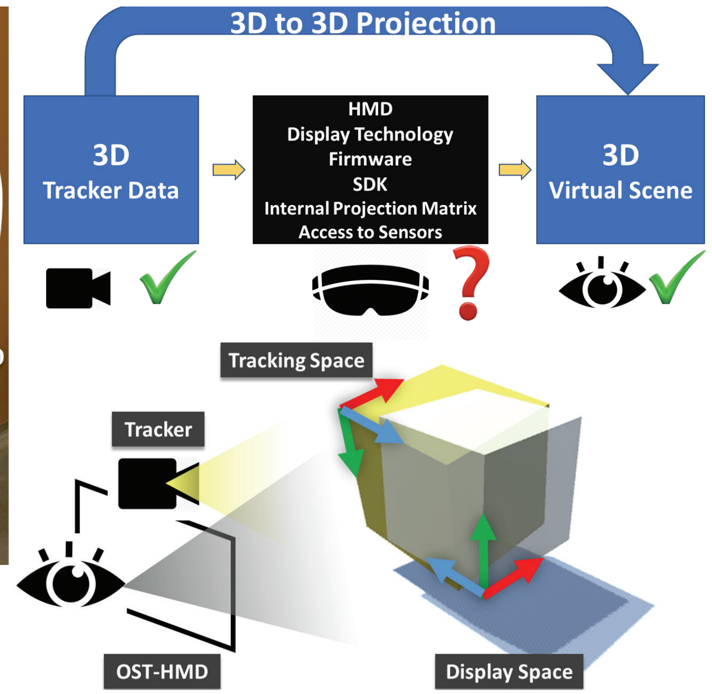




- Left: User performing calibration using external tracking system
- Right : (Top) Approach to solve the display calibration (Bottom) Resolving the misalignment between the tracking space and virtual scene

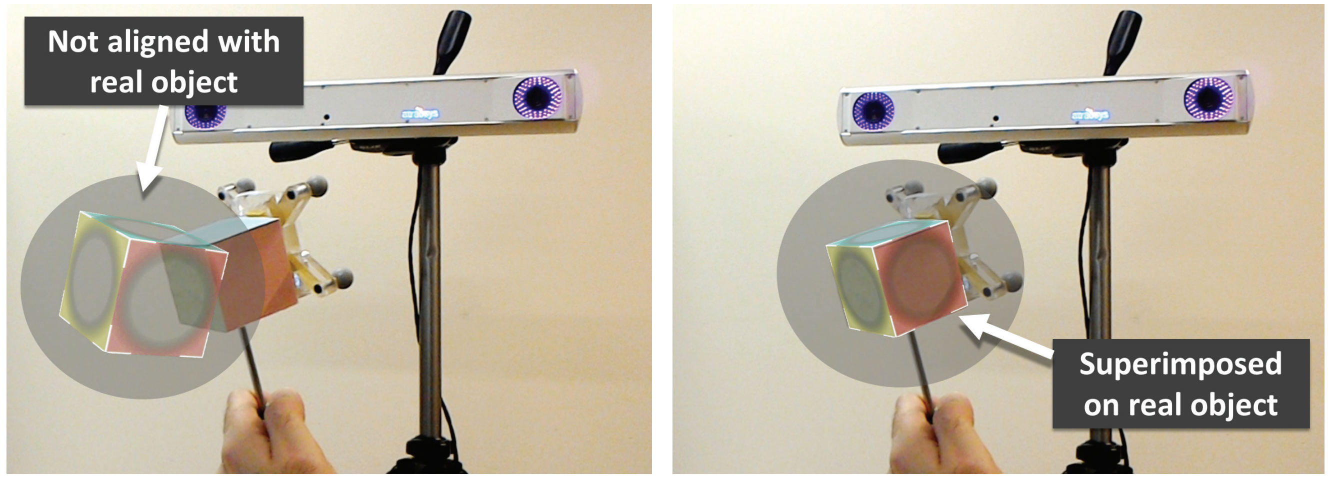
Accomplishment: For an optical see-through head-mounted display (OST-HMD), calibration is required to align virtual objects with respect to the real world, as observed by the user's eyes. Tracking of real-world objects is required to maintain this relationship for moving objects. We developed a tracking method that uses markers consisting of two strips of three small dots, which is less obtrusive and more robust, with respect to partial occlusions, than conventional AR tags. We also developed a general-purpose calibration method for OST-HMDs that uses a 3D virtual scene and the pose obtained from a tracking system, which can be internal (using an HMD camera) or external. To improve the accuracy, a general anisotropic noise model was considered, with optimization based on Mahalonobis distance. We also integrated different interaction methods, including eye gaze, speech recognition and mouse clicks to interact with the HMD.

Status: Completed two-year project. Plan to use developed methods for other applications.

Funding: Supported by DoD W81XWH-15-C-0156.

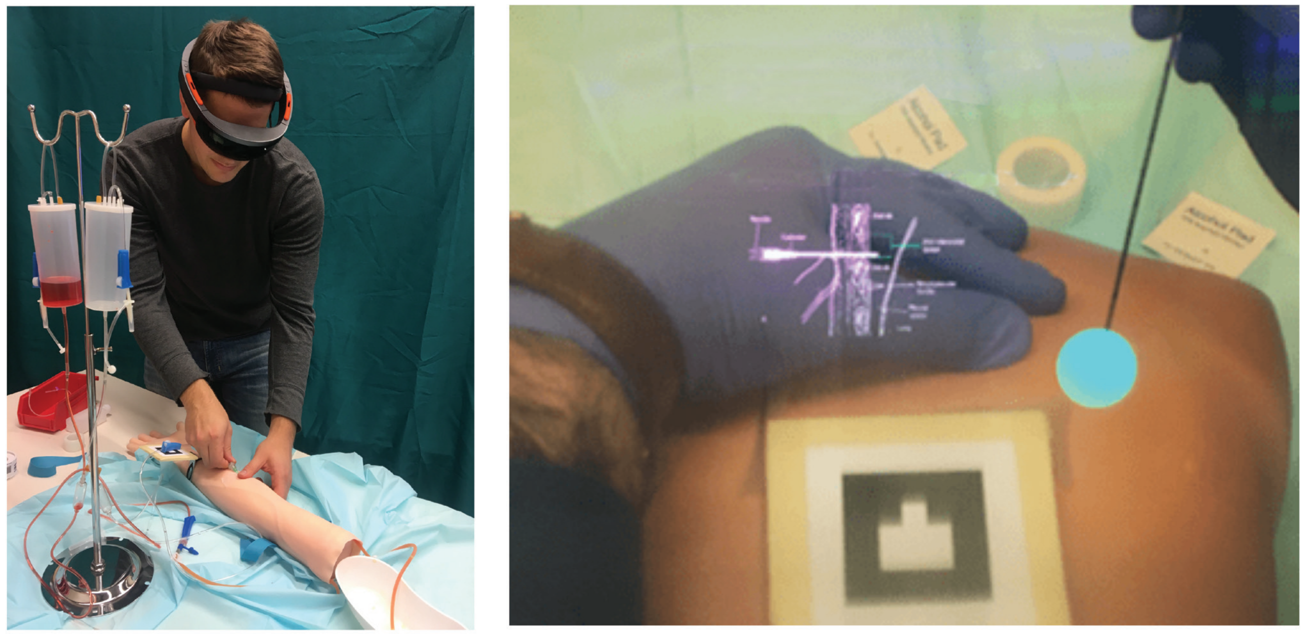
Key Personnel: Peter Kazanzides, Nassir Navab, Ehsan Azimi, Long Qian, Balazs Vagvolgyi

To find out more: https://smarts.lcsr.jhu.edu/research/augmented-reality-hmd-research/



Left: Before Calibration (Virtual and real cube are misaligned)
Right: After Calibration (Virtual and real cube are well aligned)

Augmented Reality Head-Mounted Display for Medical Training



Left: subject in multi-user study using augmented reality HMD during training for intravenous (IV) catheter insertion.
Right: augmented reality overlay for needle decompression, with green circle indicating second intercostal space.

Accomplishment: Developed general-purpose application software in Unity 3D, configured via JSON files, to provide augmented reality assistance for training or performance of a task. Modular architecture allows the course developers to incorporate their desired material and load it on the HMD without any change to the application. Software is portable to different head mounted displays (HMDs), including Microsoft HoloLens and Epson Moverio BT-200/BT-300, and supports display-anchored and feature-anchored overlays, where the latter rely on integrated tracking using the HMD camera. Interaction with the UI is handled via voice commands. Performed multi-user study to evaluate the effectiveness for training of emergency medical procedures, such as needle decompression and intravenous (IV) catheter insertion.

Status: Completed two-year project. Plan to use developed system for other applications.

Funding: Supported by DoD W81XWH-15-C-0156.

Key Personnel: Peter Kazanzides, Nassir Navab, Ehsan Azimi, Long Qian, Emerson Tucker, Alexander Winkler, Manyu Sharma; collaboration with Jayfus Doswell, Saboor Salaam and others at Juxtopia LLC.

To find out more: https://smarts.lcsr.jhu.edu/research/augmented-reality-hmd-research/

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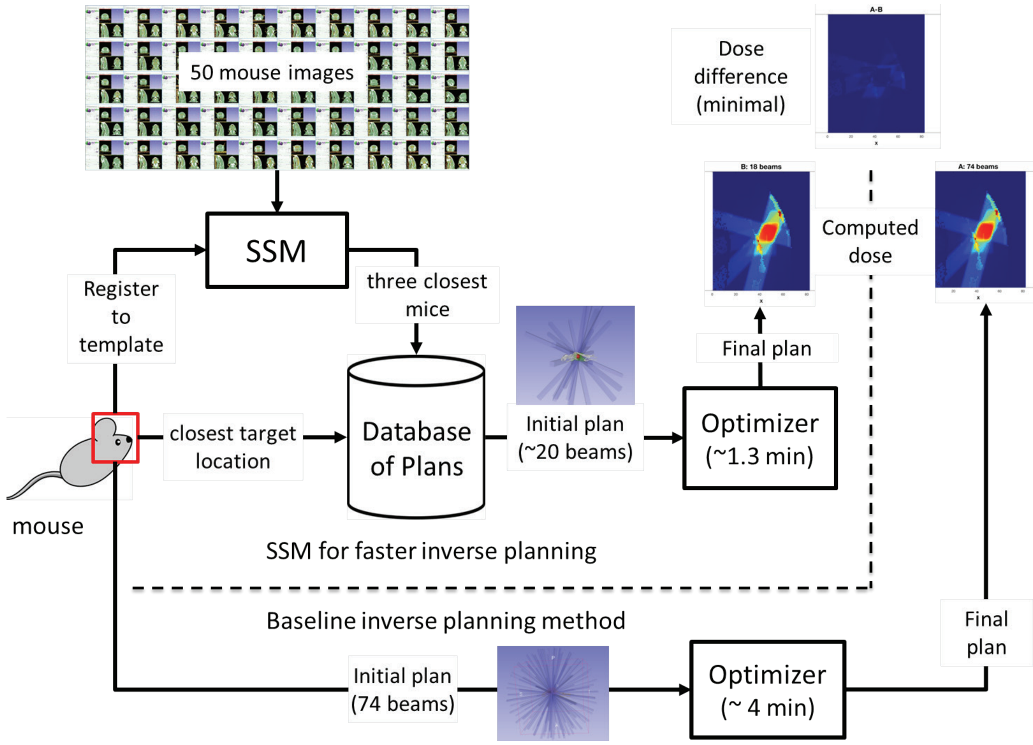
Inverse Treatment Planning for Small Animal Radiation Research



Using a Statistical Shape Model (SSM) to accelerate inverse treatment planning for small animal radiation research.

Accomplishment: We developed inverse planning solutions for the Small Animal Radiation Research Platform (SARRP) treatment planning system, which includes a GPU dose engine that can compute dose for a single beam within a few seconds. For inverse planning, the researcher specifies the target that should receive high dose and (optionally) organs at risk that should receive minimal dose, and the software computes the treatment plan that achieves these objectives. In contrast to clinical practice, the workflow for small animal research allows only a few minutes for treatment planning. The GPU dose engine enables an inverse planning approach that considers a large number of initial beams to optimize both beam directions and weights. For example, the system can consider an initial arrangement of 74 uniformly distributed beam directions and compute an optimal solution, typically containing less than 20 beam directions, in less than 5 minutes. Computation time can be further reduced by creating a statistical shape model (SSM) of mouse anatomy and a database of treatment plans to select a better initial distribution of beam directions. We demonstrated a threefold reduction in computation time (from about 4 minutes to about 1.3 minutes) for mouse glioblastoma irradiation, using a SSM of the mouse skull created from 50 mouse cone-beam CT images and a database of precomputed treatment plans.

Status: Research has been completed and is described in the PhD thesis of Nathan Cho (October 2017).

Funding: Xstrahl PhD Fellowship

Key Personnel: Peter Kazanzides, Russell Taylor, John Wong, Nathan Cho

To find out more: https://smarts.lcsr.jhu.edu/research/small-animal-radiation-research-platform-sarrp/

Patents and Disclosures: SARRP mechanical design and software and GPU dose computation software have been licensed to Xstrahl, Inc.

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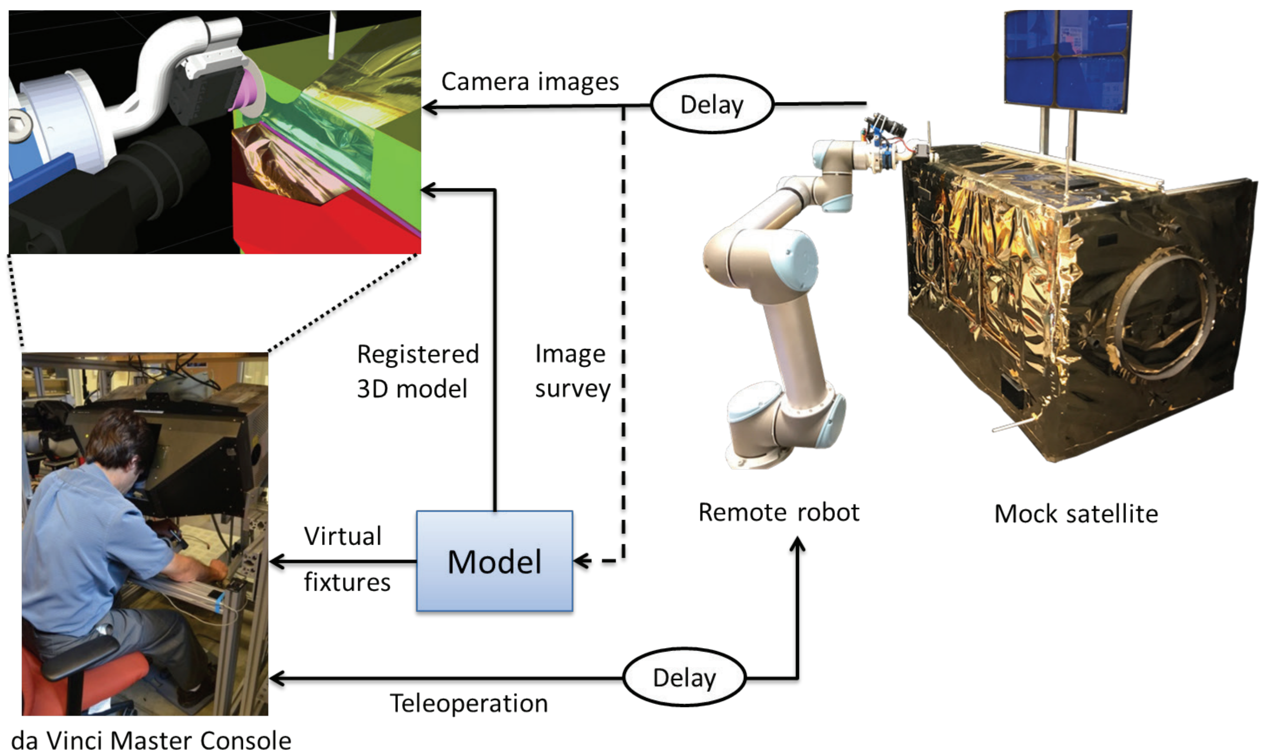
Telerobotic Satellite Servicing

- Ground-based control of on-orbit robotic servicing spacecraft, subject to communication delays of several seconds
- Approach: model-based teleoperation, where operator uses master console to perform task in virtual world, augmented with real camera images from remote robot (augmented virtuality).



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Accomplishment: We have developed a proof of concept system to demonstrate ground-based teleoperation of an on-orbit robot for satellite servicing, subject to communication delays of several seconds. This is in support of the NASA Restore-L mission to refuel Landsat-7. We focus on one challenging task, which is to cut the multilayer insulation (MLI) blanket that covers the satellite fill/drain valves. We adopt a model-based approach, where the ground-based operator performs the task in an augmented virtuality environment constructed from a registered 3D model of the satellite augmented with projections of images from the remote cameras. This solves several problems with teleoperation using tool cameras, such as the unintuitive eye-in-hand configuration, loss of situation awareness due to the limited field of view, lack of stereo visualization, and possible obstruction of the camera view. We developed a Vision Assistant software application for intrinsic and extrinsic camera calibration, registration of a 2D image survey to a 3D model, and reconstruction of unknown features, such as the MLI cover on the fill/drain valves. Several multi-user experiments (HIRB 00000701) have been conducted to study the performance of different control methods and user interaction modes.

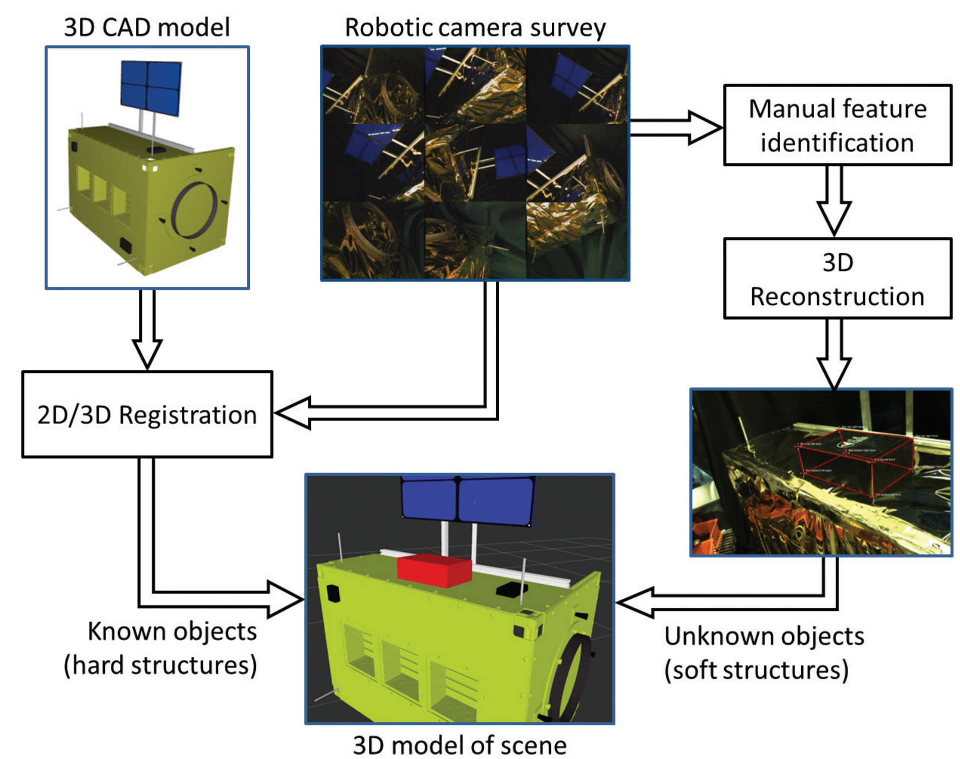
Status: System components have been developed and tested. Our current efforts focus on improving the fidelity of the ground-based test platform, refinements to the augmented virtuality user interface, and development of methods for dynamic model updates.

Funding: NASA NNG 15CR66C

Current Key Personnel: Peter Kazanzides, Louis Whitcomb, Simon Leonard, Greg Hager, Balazs Vagvolgyi, Anton Deguet, Will Pryor

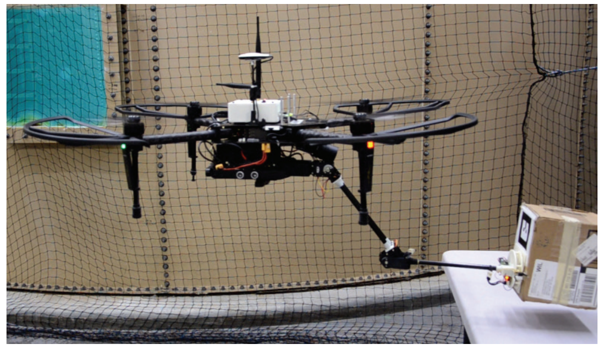
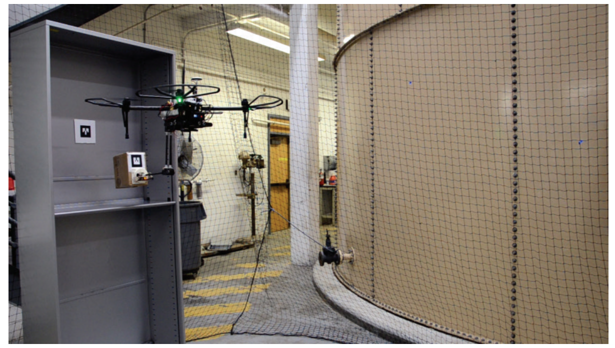
Earlier Collaborators: Zihan Chen, Tian Xia, Jonathan Bohren, Steve Vozar, Isha Kandaswamy, Amy Blank, Ryan Howarth, Paul Wilkening, Wenlong Niu

To find out more: https://smarts.lcsr.jhu.edu/research/telerobotic-satellite-servicing/

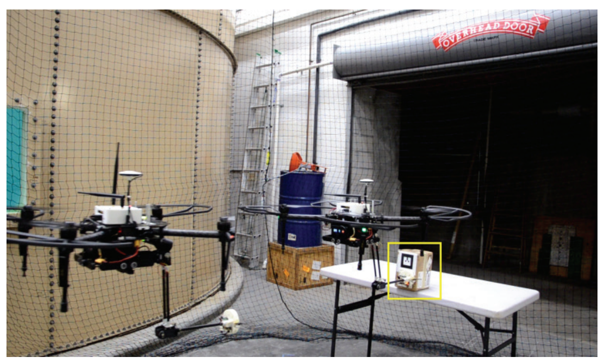


Scene modeling based on robotic camera survey: (1) registration of camera images to known objects, such as satellite structure, and (2) 3D reconstruction of unknown objects, such as soft insulation covers, from features identified in camera images.

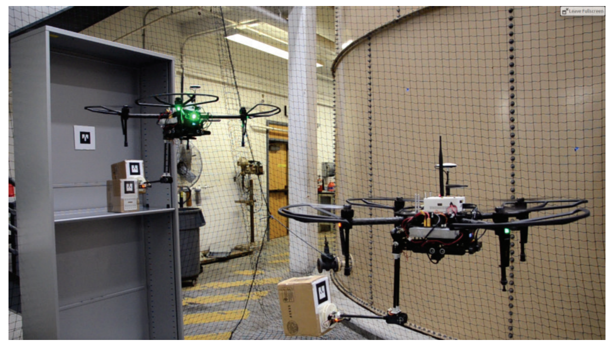
Autonomous Object Manipulation with Aerial Robots

Still pictures of picking and placing objects



Picking time-lapse



Placing time-lapse

Accomplishment: we have developed aerial vehicles equipped with a manipulator arm capable of grasping and transporting objects from the air autonomously.

Status: we are currently applying the system to automated object transport in an industrial setting as well as in natural outdoor conditions.

Funding: NSF

Key Personnel: Gowtham Garimella, Matthew Sheckells, Marin Kobilarov

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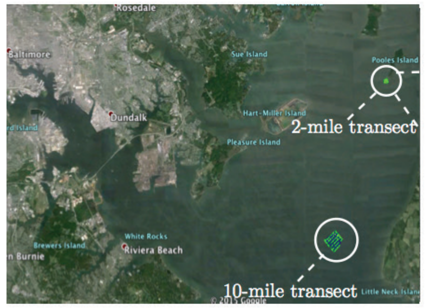
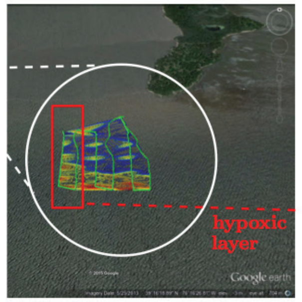
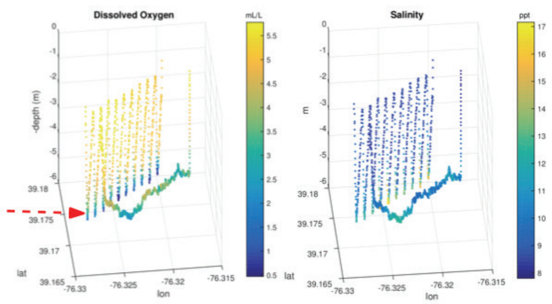
Water Quality Sampling with Autonomous Underwater and Aerial Vehicles







Accomplishment: we have instrumented underwater and aerial vehicles with water quality sensing instruments and performed initial tests for identifying hypoxic regions in the Chesapeake Bay.

Status: we are currently extending the system to operate over larger regions and in full 3-d volumes.

Funding: NSF and USDA

Key Personnel: Paul Stankiewicz, William Tan, Marin Kobilarov

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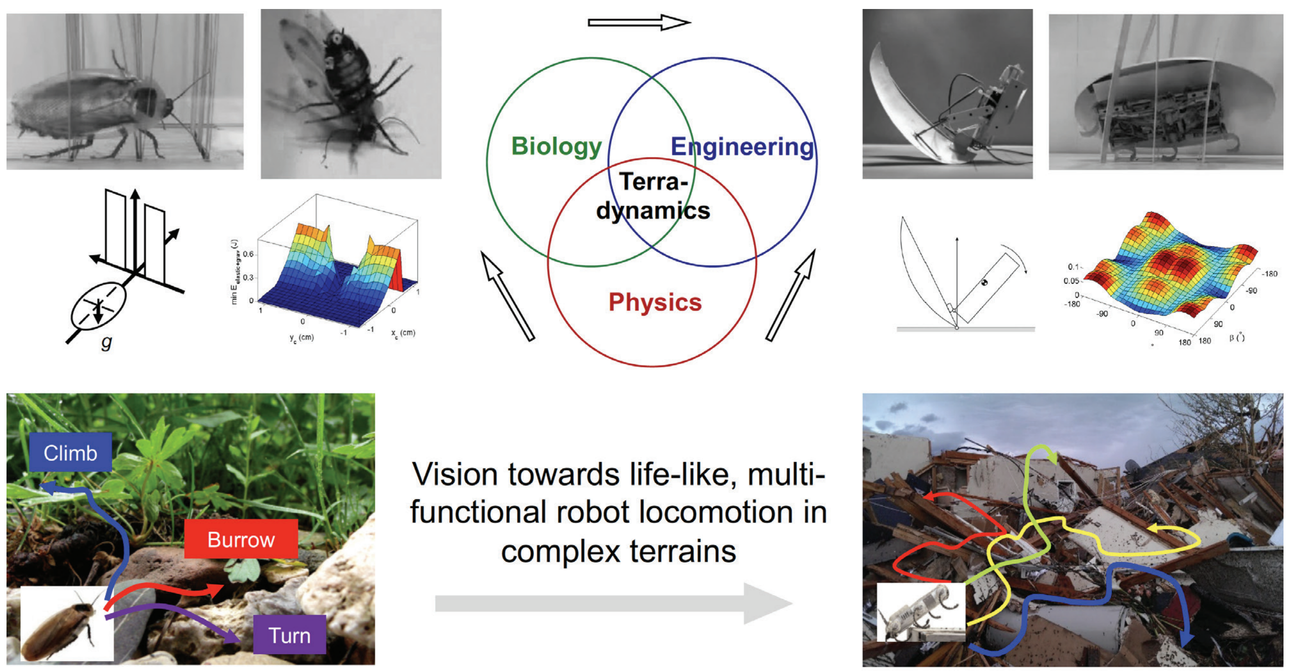
Terradynamics of Animal and Robot Locomotion in Complex Terrain



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

Accomplishment & Status: We established our lab in 2016 and expanded our research program in 2017. We have expanded our group to one postdoc and five PhD students. 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 collected a lot of data and are in the process of analyzing them to discover general terradynamic principles of locomotion in complex terrain. We have created a few theoretical and preliminary computational models for locomotor-terrain interaction. We are further developing our experimental and theoretical tools and systematically collecting and analyzing more data towards new predictive terradynamic models.

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Bio-Robotics | Modeling, Dynamics, Navigation, and Control | Robotics in Extreme Environments

Publications:

*Li C, Kessens CC, Fearing RS, Full RJ (2017). Mechanical principles of dynamic terrestrial self-righting using wings, *Advanced Robotics*, DOI: 10.1080/01691864.2017.1372213 (Invited Paper)

*Li C, Kessens CC, Young A, Fearing RS, Full RJ (2016). Cockroach-inspired winged robot reveals principles of ground-based dynamic self-righting, *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2128-2134 (Highlight Paper of IROS 2016, 20 out of 840)

Abstracts:

Gart SW, Winey N, Obert RDLT, *Li C (2017), Dynamic traversal of high bumps and large gaps by a small legged robot, *Bulletin of the American Physical Society 62*

Othayoth R, Xuan Q, *Li C (2017), Induced vibrations increase performance of a winged self-righting robot, *Bulletin of the American Physical Society 62*

Han Y, Wang Z, *Li C (2017), Body shape helps legged robots climb and turn in complex 3-D terrains, *Bulletin of the American Physical Society 62*

Thoms G, Yu S, Kang Y, *Li C (2017), Induced vibrations facilitate traversal of cluttered obstacles, *Bulletin of the American Physical Society 62*

Gart SW, *Li C (2017), Dynamic traversal of large gaps and high bumps by cockroaches, *Integrative and Comparative Biology 56*

Othayoth R, Xuan Q, *Li C (2017), Leg vibrations help cockroaches self-right using wings, *Integrative and Comparative Biology 56*

Han Y, Luo Y, Bi J, *Li C (2017) Body shape affects yaw and pitch motions of insects traversing complex 3-D terrains, *Integrative and Comparative Biology 56*

*Li C, Fearing RS, Full RJ (2016). Cockroaches inspire exoskeletal shells and wings that help robots traverse obstacles and self-right, *International Congress of Entomology*

*Li C, Fearing RS, Full RJ (2016). Obstacle traversal and self-righting of bio-inspired robots reveal the physics of multi-modal locomotion, *Bulletin of the American Physical Society 61*

*Li C, Tian R, Porter W, Hammond Z, Strachan-Olson D, Kooker AW, Olivas J, Kessens CC, Jayaram K, Fearing RS, Full RJ (2016). Cockroach-inspired self-righting robots, *Integrative and Comparative Biology 56*

Funding:

Army Research Office Young Investigator Award

Burroughs Wellcome Fund Career Award at the Scientific Interface

Key Personnel: PI: Chen Li (PI), Postdoc: Sean Gart, PhD students: Ratan Othayoth, Yuanfeng Han, Qihan Xuan, Qiyuan Fu, Hongtao Wu; collaborators: Jin-Seob Kim & Greg Chrikjian at Hopkins; Chad Kessens at Army Research Lab

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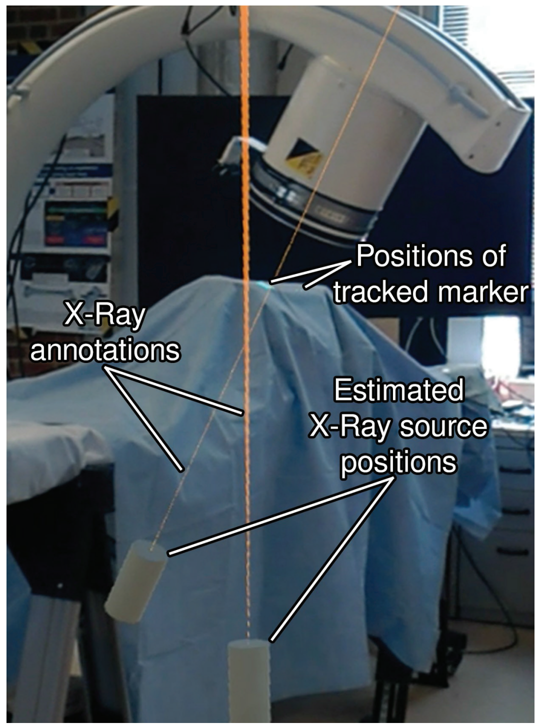
On-the-fly Augmented Reality for Surgery



AR in unprepared operating rooms

- See-through head-mounted display: Displays virtual content
- C-arm fluoroscopy system: Acquires intra-op. images
- Multi-modal marker: Visible in X-ray and RGB

▶ Co-calibration enables AR guidance in unprepared environments

Accomplishment: Providing meaningful guidance to surgeons is complicated and requires cumbersome calibration procedures, dedicated tracking systems, and prepared environments. Despite many efforts, these systems are not well received by surgeons and were not successfully established in clinical practice. However, guidance as such is considered useful.

We propose an on-the-fly guidance system based on augmented reality that is easy to use and introduces little to no change to the surgical workflow. The system builds upon a multi-modality fiducial marker that is visible by both the interventional C-arm X-ray imaging device and the optical see-through head-mounted display (HMD). The marker is introduces into the X-ray beam path when standard images are acquired and, thus, allows for co-calibration of the C-arm to the HMD domain. Annotations on the X-ray images can then be rendered on the HMD in 3D, providing on-the-fly augmented reality to the surgeon.

Status: Guidance is working and very effective, yet, some problems need to be addressed: tracking of the HMD is not very reliable such that the virtual content is not perfectly locked in place, real objects do not interact with virtual content making the alignment of tools difficult, larger studies necessary.

Funding: No dedicated funding, T32

Key Personnel: Nassir Navab, Alex Johnson, Sebastian Andress, Alexander Winkler, Mathias Unberath

To find out more: https://camp.lcsr.jhu.edu/

Disclosures: 2 Patents pending

Papers: Accepted to the SPIE JMI special issue on computer aided surgery, Technical Note in SPIE Medical Imaging Conference

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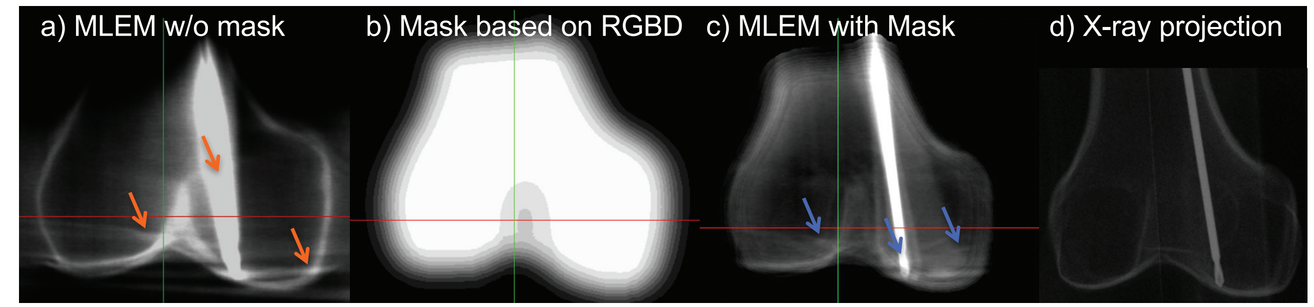
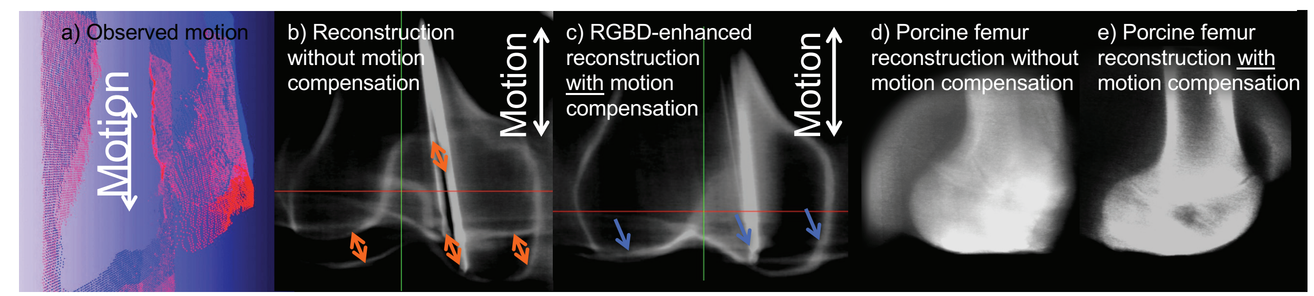
Can RGBD Imaging Enhance CBCT?

Improving the quality of reconstruction by incorporating surface information of the patient



Implicit correction for in-voluntary patient movement in real-time



Accomplishment:

Purpose: Cone-Beam Computed Tomography (CBCT) is an important 3D imaging technology for orthopedic, trauma, radiotherapy guidance, angiography, and dental applications. The major limitation of CBCT is the poor image quality due to scattered radiation, truncation, and patient movement. In this work, we propose to incorporate information from a coregistered Red-Green-Blue-Depth (RGBD) sensor attached near the detector plane of the C-arm to improve the reconstruction quality, as well as correcting for undesired rigid patient movement.

Methods: Calibration of the RGBD and C-arm imaging devices is performed in two steps: (i) calibration of the RGBD sensor and the X-ray source using a multimodal checkerboard pattern, and (ii) calibration of the RGBD surface reconstruction to the CBCT volume. The patient surface is acquired during the CBCT scan and then used as prior information for the reconstruction using Maximum-Likelihood Expectation Maximization. An RGBD-based simultaneous localization and mapping method is utilized to estimate the rigid patient movement during scanning.

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Results: Performance is quantified and demonstrated using artificial data and bone phantoms with and without metal implants. Finally, we present movement-corrected CBCT reconstructions based on RGBD data on an animal specimen, where the average voxel intensity difference reduces from 0.157 without correction to 0.022 with correction.

Conclusion: This work investigated the advantages of a Carm X-ray imaging system used with an attached RGBD sensor. The experiments show the benefits of the opto/X-ray imaging system in: (i) improving the quality of reconstruction by incorporating the surface information of the patient, reducing the streak artifacts as well as the number of required projections, and (ii) recovering the scanning trajectory for the reconstruction in the presence of undesired patient rigid movement.

Status:

Funding: T32

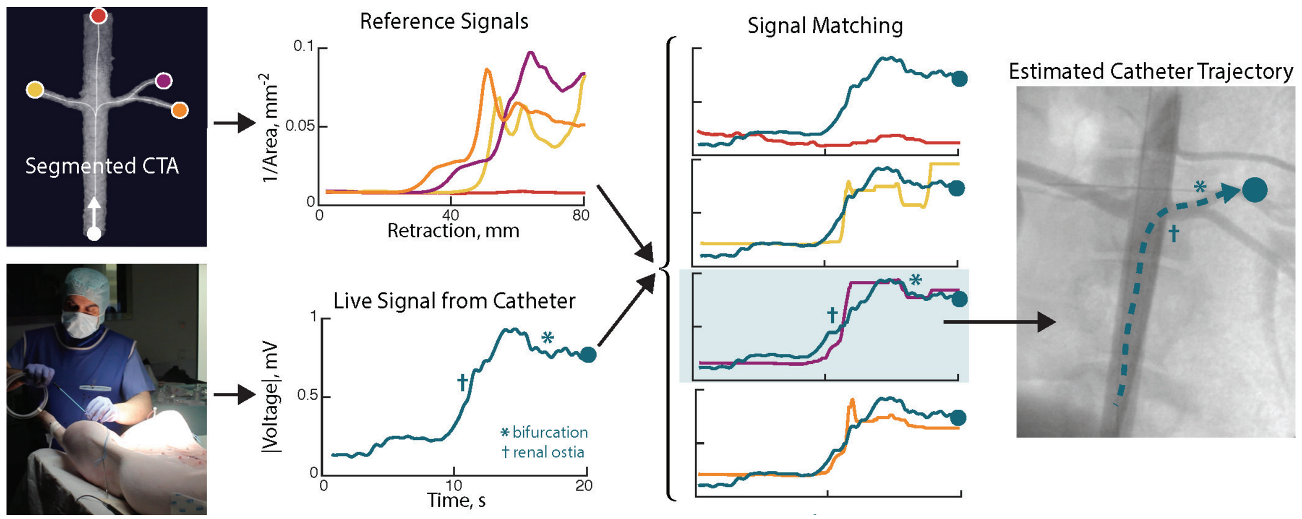
Key Personnel: Nassir Navab, Alex Johnson, Mathias Unberath, Javad Fotouhi

To find out more: https://camp.lcsr.jhu.edu/

Disclosures:

Papers: Fotouhi, Javad, et al. "Can real-time RGBD enhance intraoperative Cone-Beam CT?." *International Journal of Computer Assisted Radiology and Surgery* (2017): 1-9.

Bioelectric Navigation and Sensing



- Impedance signal within vessel is dependent on diameter
- Measure impedance with active catheter to enable navigation
- Vessel centerlines and diameter known from pre-op. data
- Signal matching during intervention enables navigation!

Accomplishment: Use an active catheter equipped with electrodes (voltage supplied to electrodes) to measure the bioelectric impedance of the vessel the catheter is in. This impedance is dependent on the vessel diameter, among others. From pre-operative volumetric data, the expected signal can be extracted via segmentation of the vessel centerline and the respective vessel diameters. During the intervention, navigation then reduces to signal matching of the live catheter signal with the expected/simulated signal profiles. This enables navigation without the need for X-ray imaging thus reducing patient and surgeon dose.

Status: Currently in preparation for an R01 submission, preliminary evidence suggests that the concept is realistic but requires further work, particularly w.r.t. signal matching.

Funding: In submission process for R01.

Key Personnel: Nassir Navab, Noah Cowan, Erin Sutton, Bernhard Fuerst, Mathias Unberath

To find out more: https://camp.lcsr.jhu.edu/

Disclosures: No disclosures

Papers:

Fuerst, Bernhard, et al. "Bioelectric Navigation: A New Paradigm for Intravascular Device Guidance." *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer International Publishing, 2016.

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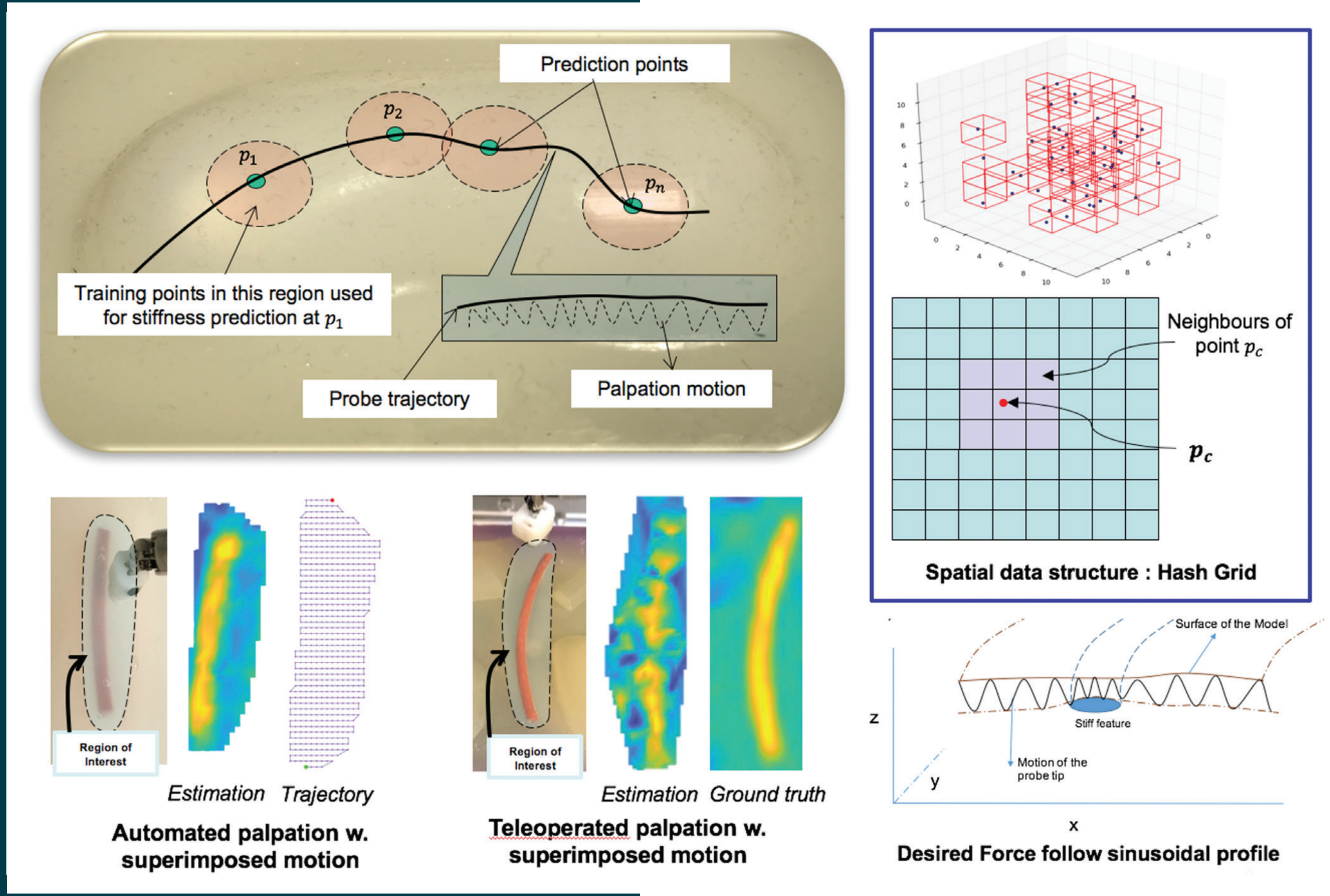
CSA: Real-time Stiffness Estimation Using Gaussian Processes



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Accomplishment: The main goal collaborative project with Carnegie-Mellon University (CMU) and Vanderbilt University) is to establish the foundations for what we call "Computational Situational Awareness (CSA)" . This work emphasizes development of a three way partnership between physicians, technology, and information in minimally-invasive surgery. Specific research goals include 1) real-time sensing during task execution; 2) situational awareness modeling fusing preoperative data, intraoperative sensing, and task models ; and 3) telemanipulation and information assistance provided to the surgeon based on the real-time situational models.

One key capability is robot-assisted palpation in order to locate stiff features such as tumors or arteries beneath the organ surface. We have implemented an assistive behavior where the robot combines a continuous palpation motion into and out of the organ surface with lateral motions across the surface guided by the surgeon. Our sensor fusion strategy requires concurrent real-time estimation of organ stiffness and surface geometry. We use Gaussian processes to estimate forces sensed by the robot in the volume of space near the organ surface, and then uses this force distribution to generate a predicted distribution of organ surface geometry and tissue stiffness. We have implemented a special "hash grid" data structure to enable the stiffness and surface maps to be updated at near video frame rates.

Status: These functions have been implemented and a journal article reporting them is in review. A multiple-user study to evaluate the effectiveness of real-time estimation and augmented reality video overlays in palpation tasks.

Funding: NRI grant (IIS1327566, IIS1327657, IIS1426655)

Key Personnel: (JHU) Russell Taylor, Preetham Chalasani, Peter Kazanzides, Anton Deguet, Marin Kobilarov; (CMU) Howie Choset, Rangaprasad Arun Srivatsan, Nicolas Zevallos, Hadi Salman; (Vanderbilt) Nabil Simaan, Long Wang, Rashid Yasin, Colette Abah

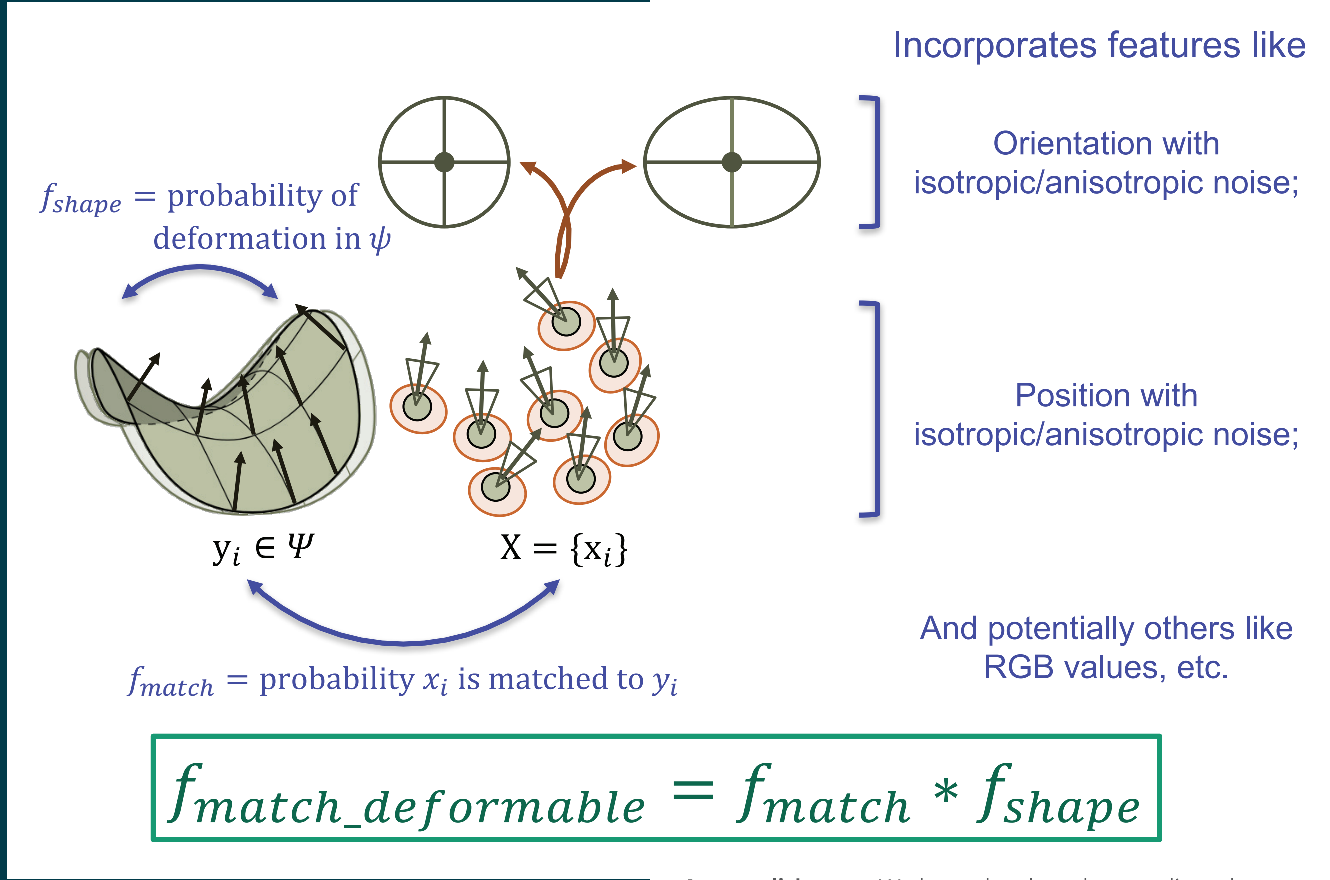
To find out more:
- http://nri-csa.vuse.vanderbilt.edu/joomla/
- https://ciis.lcsr.jhu.edu/dokuwiki/doku.php?id=research
- (video) https://drive.google.com/file/d/13HPrUi3G-G7e-GcuIfV6hSIp2km8-5ZFk/view?usp=sharing

Selected Papers:
Chalasani, Preetham, et al. "Concurrent nonparametric estimation of organ geometry and tissue stiffness using continuous adaptive palpation." *Robotics and Automation (ICRA), 2016 IEEE International Conference on*. IEEE, 2016.

Perception and Cognitive Systems
Robots and Computer Assisted Surgical Technology

Deformable Registration Using Statistical Shape Models

Presenting a paradigm for the development of probabilistic deformable registration algorithms



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Accomplishment: We have developed a paradigm that enables deformable registration between points generated from a shape and a statistical model of that shape, based on extensions of the "most likely point" paradigm introduced by Billings, et al. The purpose of this system is to allow inference of anatomical shapes from partial images. For instance, during an endoscopic examination of the nasal cavity, the field of view of the observer is limited to that of the endoscope, and usually a preoperative CT of the patient is not used for context and localization. Using this registration paradigm, the examiner can gain context cues without the need of a CT by using a statistical model of the nasal cavity to which points from endoscopic video can be deformably registered, and inferring the specific patient's nasal cavity. This paradigm can also be used on non-medical data, for instance, inferring facial expressions using points sampled from faces and deformably registering to a facial expression model. Our current experiments show promising submillimeter results on both simulation and clinic data.

Status: Three different algorithms have been built using this paradigm, and several experiments with simulated and in vivo clinic data have shown that submillimeter registrations and reconstructions can be achieved using these algorithms. A paper introducing our methods is in the process of submission. Work on a pipeline paper to demonstrate its use in endoscopic sinus surgeries is underway, as also is work on inferring unseen anatomy using these methods.

Funding: This project has been funded by National Institutes of Health Grant No. R01 EB015530 (Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis) and JHU Internal Funds.

Key Personnel: Ayushi Sinha, Seth D. Billings, Xingtong Liu, Austin Reiter, Masaru Ishii, Gregory D. Hager, Russell H. Taylor

To find out more: https://cirl.lcsr.jhu.edu/research/enhanced-endoscopic-navigation/

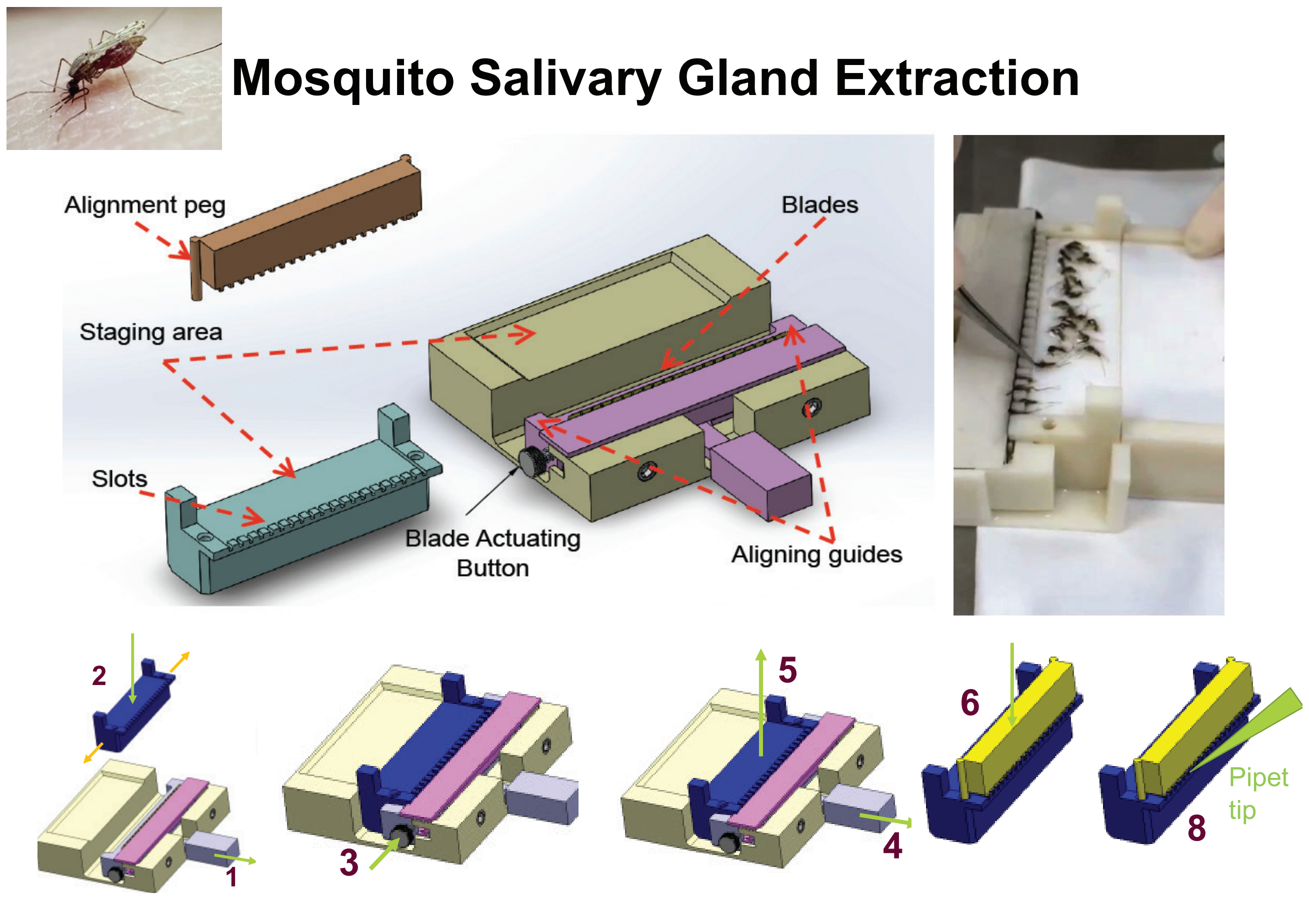
Papers:

[1] S. Billings, E. Boctor, and R. H. Taylor, "Iterative Most-Likely Point Registration (IMLP): A Robust Algorithm for Computing Optimal Shape Alignment", PLOS ONE, vol. 10- 3, pp. (e0117688) 1-45, 2015. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0117688 doi:10.1371/journal.pone.0117688

[2] S. D. Billings, *Probabilistic Feature-Based Registration for Interventional Medicine*, Ph.D. thesis in Computer Science, Johns Hopkins University, August 2015.

[3] Ayushi Sinha, Seth D. Billings , Xingtong Liu , Austin Reiter , Masaru Ishii , Gregory D. Hager , Russell H. Taylor, "The Deformable Most Likely Point Paradigm", (in final preparation for journal submission)

Mosquito Salivary Gland Extraction



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). 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 roughly two-fold increase in per-mosquito dissection rate while also significantly reducing the training time required for a production worker to reach peak proficiency from 29 weeks to 1.5 weeks.

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 patent has been filed.

Work with Sanaria to develop a fully automated mosquito dissection system is underway with NIH SBIR funding.

Funding: JHU internal funds, NIH SBIR 1 R44 AI134500-01

Current Key Personnel: (JHU) Russell Taylor, Amanda Canezin, Mariah Schrum, Suat Coemert, Yunus Sevimli, Greg Chirikjian, Jin Kim, Can, Kocabalkani, Amrita Krishnaraj, Shengnan Lu; (Sanaria) Steve Hoffman, Sumana Chakravarty, Michelle Laskowski

Earlier Collaborators: (JHU) Amanda Canezin, Suat Coemert, Yunus Sevimli; (Sanaria) Michelle Laskowski

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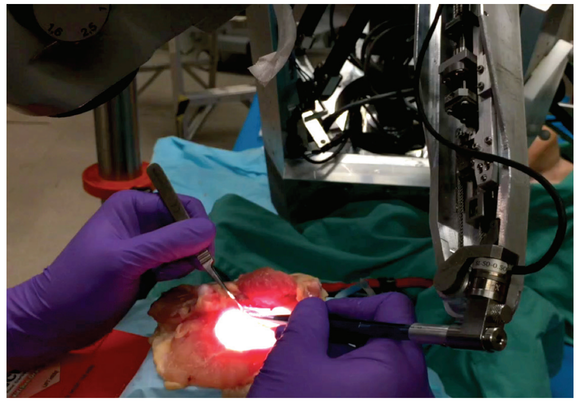
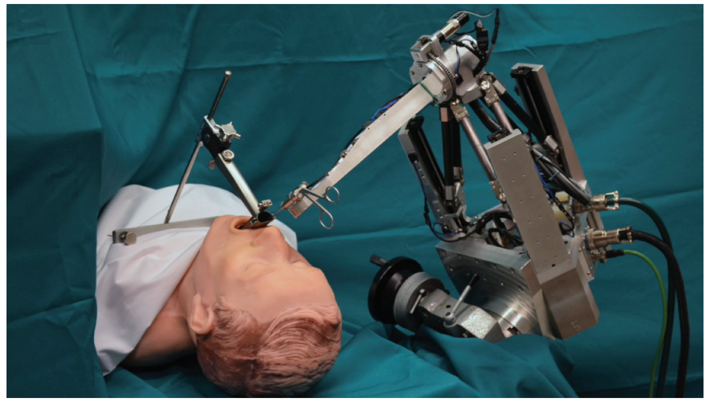
The Galen Microsurgery System



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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

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

To find out more: 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.

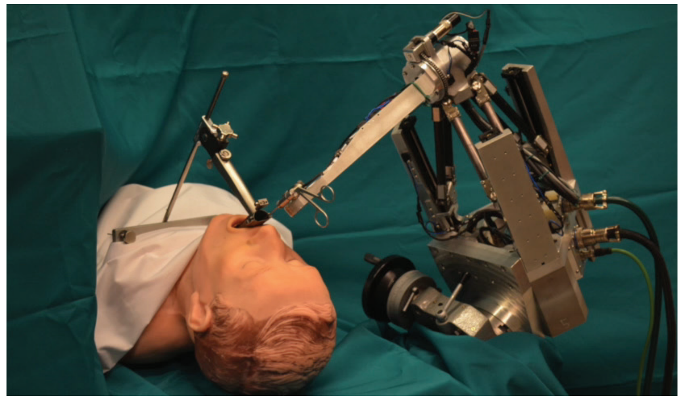
The Robotic ENT Microsurgery System (REMS)

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

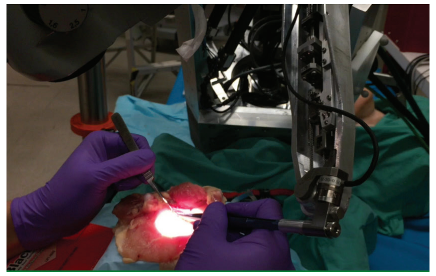


Control modes:

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

REMS Typical Applications

Laryngeal / Vocal Cord



Open Microsurgery

Image-guided sinus surgery with virtual fixtures

Other applications include:

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

REMS: Voice Surgery Cadaver Study

This video shows an experiment performed in our lab by our surgeon collaborator, Dr. Lee Akst, doing a common vocal cord procedure on a cadaveric specimen.

Notice how much more stable the robot-held tool is.

Another feature Dr. Akst likes is the ability to position a tool and then have the robot hold it stably until he moved it again.

Human-Machine Collaborative Systems | Robots and Computer Assisted Surgical Technology

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.

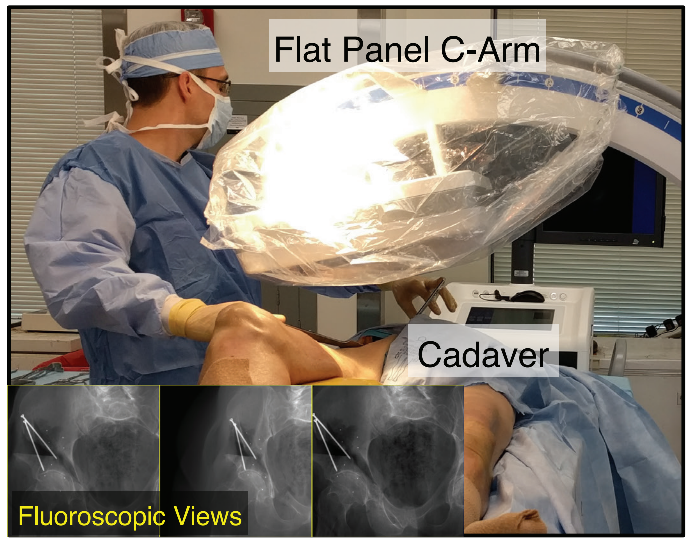
Our surgeon collaborator, Dr. Masaru Ishii, believes that this capability will be especially useful in training surgical residents.

Second Generation Research System

This slide shows a second generation non-clinical research prototype of the Galen system that was exhibited to selected surgeons at the American Academy of Otolaryngology – Head and Neck Surgery (AAO-HNSF) annual meeting in Chicago, Sept 10-13, 2017.

Robots and Computer
Assisted Surgical Technology

Fiducial-Free Pose Estimation of Periacetabular Osteotomy Fragments with Intraoperative X-ray Navigation



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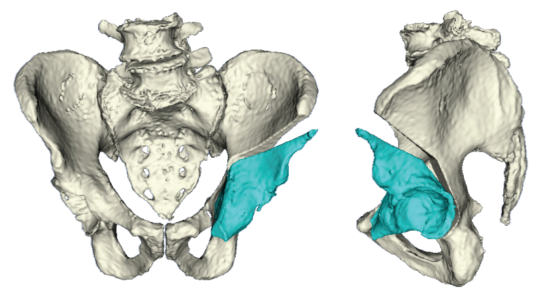


$$\underset{\theta_1,\ldots,\theta_N \in SE(3)}{\arg\min} \sum_{m=1}^{M} \mathcal{S}\left(I_m, \sum_{n=1}^{N} \mathcal{P}_m\left(I_{CT};\theta_n\right)\right)$$

Report the 3D Pose of the Relocated Acetabular Fragment using 2D/3D Registration

Accomplishment: We have developed processing to use X-Ray navigation for pose estimation of periacetabular fragments without fiducials. Previous pelvic osteotomy navigation systems have used optical tracking devices or relied on external fiducial objects. In our approach, the fragment pose is recovered through a series of 2D/3D registrations, and was evaluated through simulation studies and 3 cadaveric surgeries. Since the exact osteotomy locations are not known prior to the surgery, the true 3D model of the fragment must be estimated intraoperatively. Using 2D contours of the osteotomies and a registration of the full pelvis shape, 3D cutting planes are computed and used to approximate the fragment shape. In simulation, the fragment pose estimates were within 2°/2 mm of ground truth for 99.7%, 46.3%, and 96.8% of registration trials, when using the exact fragment shape, a mismatched shape, and an intraoperatively estimated shape, respectively. Cadaver experiments confirmed this trend, with average fragment rotation errors of 1.4°, 3.8°, and 2.0°, when using a hand segmented fragment shape, an arbitrary preoperatively planned shape, and the intraoperatively estimated shape. These results are significant, because the manual interpretation of 2D X-Ray images is challenging, and limits the accurate rotation estimates to the Anterior-Posterior axis. Our processing is able to estimate a full rigid pose with respect to all anatomical axes. Moreover, our method imposes no additional requirement on the incision used, or any additional external objects beyond a portable fluoroscopic C-Arm.

Status: Additional cadaver surgeries have been conducted to continue validation of the approach. With the eventual goal of clinical trials, more emphasis has been placed on refining the system interface and intraoperative workflow.

Funding: NIH/NIBIB grants R21EB020113, R01EB006839, JHU APL Graduate Student Fellowship

Current Key Personnel: (JHU) Robert Grupp, Russell Taylor; (JHU,APL) Rachel Hegeman, Mehran Armand, (UT Austin) Benjamin McArthur

Earlier Collaborators: (JHU,APL) Ryan Murphy, (NAIST) Yoshito Otake

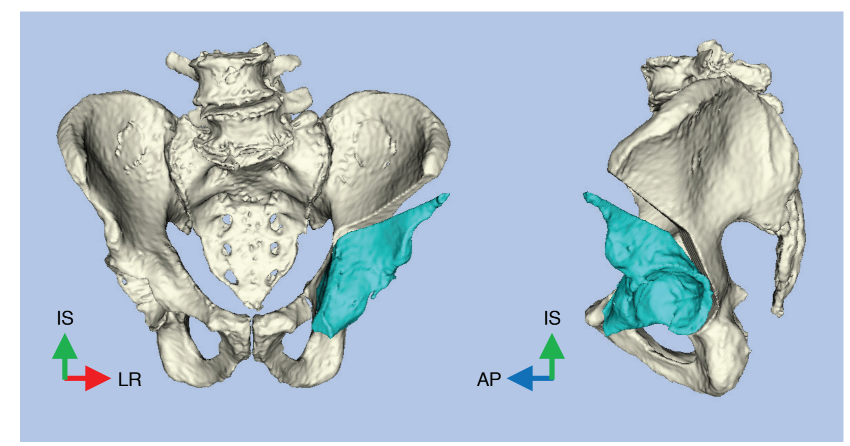
To find out more: http://bigss.lcsr.jhu.edu

Patents and Disclosures: N/A

Papers:

Pose Estimation of Periacetabular Osteotomy Fragments with Intraoperative X-Ray Navigation. R. Grupp, R. Murphy, Y. Otake, B. McArthur, M. Armand, R. Taylor. IEEE Transactions on Biomedical Engineering. *Under Review.*

The Robotic ENT Microsurgery System (REMS)

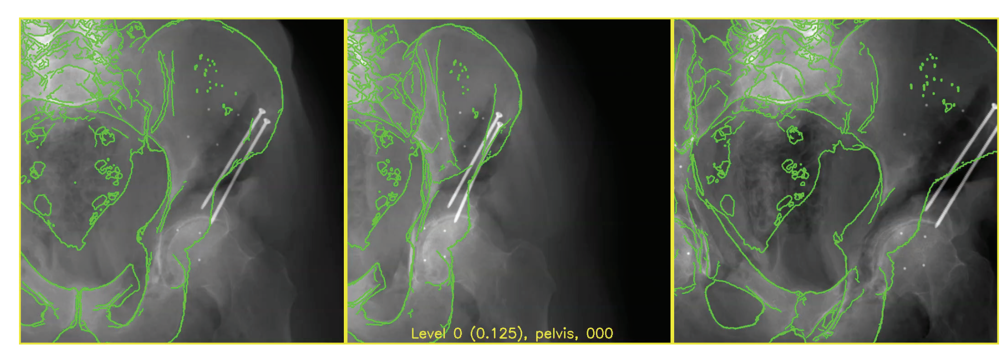


Total Rotation: 20.5°
Anterior/Posterior Rotation: 3.7°
Left/Right Rotation: 16.3°
Inferior/Superior Rotation: 12.5°

Specimen #1, Left Side

Solve With 2D/3D Multiple Object Registration

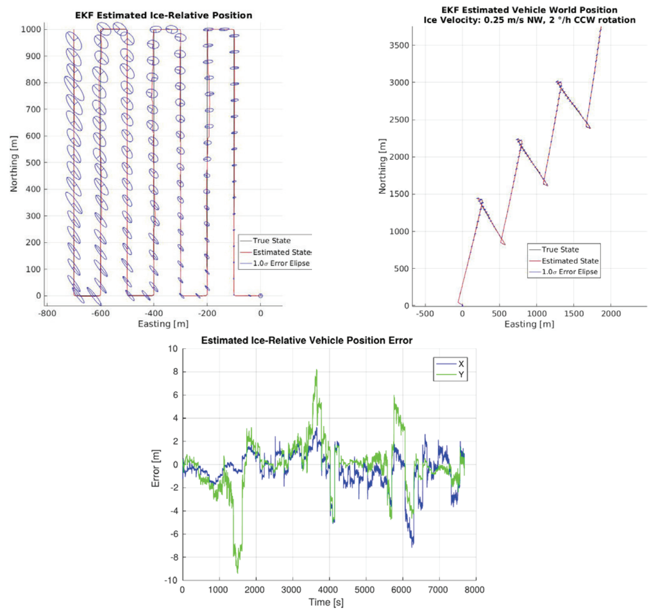
$$\underset{\theta_1,\ldots,\theta_N \in SE(3)}{\arg\min} \sum_{m=1}^{M} \mathcal{S}\left(I_m, \sum_{n=1}^{N} \mathcal{P}_m\left(I_{CT};\theta_n\right)\right)$$



Specimen #1, Left Side

Ice-Relative Underwater Vehicle Navigation Beneath Moving Sea Ice

- Extended Kalman Filter (EKF)-based navigation system using upward-looking doppler velocity sonar
- Simulations indicate system is robust against ice rotation and translation with commercially available GPS deployed atop ice



Navigation of Nereid Under-Ice underwater vehicle in ice-covered Polar seas

Simulation results indicate ice-deployed commercial GPS sufficient for high-accuracy under-ice navigation

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Accomplishment: We addresses the problem of precision ice-relative navigation of underwater robotic vehicles in the upper water-column under moving sea ice in the Polar ice-pack—a GPS-denied undersea environment in which conventional bottom-lock Doppler sonar navigation is generally not possible due to excessive water depth below the vehicle.

Status: We have developed an approach to under-ice navigation in which

- multiple GPS transceivers are deployed on the moving ice floe to instrument the geodetic position, orientation, and velocity of the floe,
- the surface ship is equipped with a precision GPS receiver, a true-North seeking gyrocompass, and two acoustic modems providing precise acoustic ranging and telemetry to the underwater vehicle(s),
- the underwater vehicle(s) are equipped with upward-looking Doppler sonars, precision pressure depth sensors, and true-North seeking gyrocompasses.

We address the ice-relative navigation problem in a state estimation framework, where states are comprised of the linear and angular positions and velocities of the vehicle, ship, and ice.

Simulation results suggest commercially available GPS units for ice floe instrumentation are sufficient to allow high-precision ice-relative navigation

Funding: NSF IIS-13064216

Current Key Personnel: Louis L. Whitcomb, Laughlin Barker, Christopher, McFarland, Michael Jakuba, Stefano Suman

To find out more: https://dscl.lcsr.jhu.edu

References:

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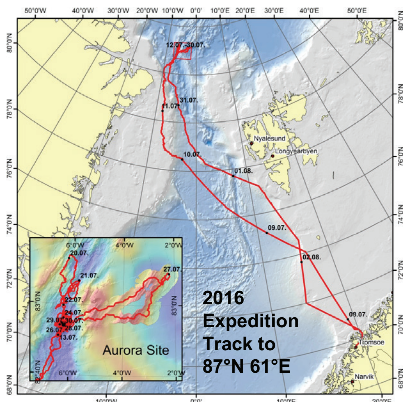
- A. D. Bowen et al., "Design of Nereid-UI: A remotely operated underwater vehicle for oceanographic access under ice," 2014 Oceans - St. John's, St. John's, NL, 2014, pp. 1-6. doi: 10.1109/OCEANS.2014.7003125 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7003125&isnumber=7002974

Development of Nereid Under-Ice (NUI): An Underwater Robot for Oceanographic Exploration Under Polar Ice



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Accomplishment: The Nereid Under-Ice (NUI) vehicleis a lightly tethered hybrid AUV/ROV (HROV) developed by Woods Hole Oceanographic Institution and collaborator Louis Whitcomb at the Johns Hopkins University. Designed to be operated under fixed or moving ice, NUI is capable of standoff distances up to 20 km from the deployment vessel, and is equipped with a navigation suite including LBL and OWTT acoustic packages, a FOG IMU, and a Doppler velocity log. McFarland et al. describe the ice-relative navigation algorithm as implemented during July 2014 operations at 83ºN 6ºW from icebreaker F/S Polarstern. Katlein et al. present under-ice light transmission data from some of NUI's first science operations

Status: NUI is operational and has completed major Arctic expeditions about the F/S Polarstern: PS86 Expedition to 83°N 6°W in 2016, and PS 101 Expedition to 87°N 61°E in 2016.

Funding:

Vehicle Development Support:
- NSF Office of Polar Programs ANT-1126311
- James Family Foundation
- George Fredrick Jewett Foundation East
- Woods Hole Oceanographic Institution

Field Trial Support:
- 2016: NASA Astrobiology Program
- 2014: NOAA OER
- Chief Scientist Dr. Antje Boetius, Alfred Wegener Institute for Polar and Marine Research, and the Officers, Crew, and Scientific Research Teams of PS 86 Expedition (2014) and P S101 Expedition (2016)

Current Key Personnel: Michael V. Jakuba, Christopher R. German, Andrew D. Bowen, Louis L. Whitcomb

Collaborators: Antje Boetius, Christian Katlein, Stefanie Arndt, Mar Fernandez Mendez, Benjamin Lange, Marcel Nicolaus, Frank Wenzhofer, Larry Mayer, Kevin Hand, Andrew Branch, Steve Chien, Christopher McFarland

To find out more:
- http://dscl.lcsr.jhu.edu
- http://www.whoi.edu/main/nereid-under-ice

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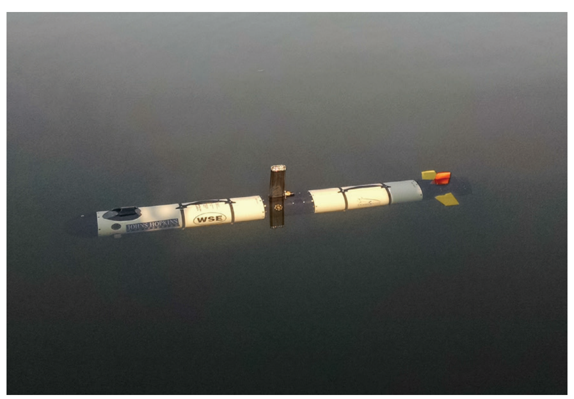
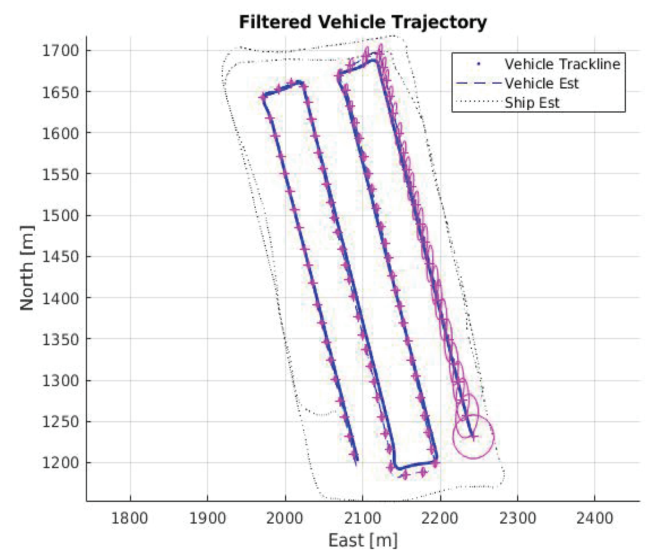
Fast, Cheap, and In Control: Precision Navigation of Low-Cost Underwater Robotic Vehicles for Ocean Science

- Precision Navigation of small and low-cost underwater vehicles not equipped with Doppler velocity sonar
- Simultaneous acoustic communication and navigation using acoustic range and range-rate measurements
- Nonlinear, second-order vehicle dynamic model in an Extended Kalman Filter



JHU Iver3
Autonomous Underwater Vehicle



Precision underwater vehicle using dynamic model and no Doppler velocity sonar

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Accomplishment: A novel class of small low-cost unmanned underwater vehicles (UUVs) is beginning to perform oceanographic, environmental assessment, and national security missions that are faster and less expensive than previous methods such as large high-cost UUVs, human-piloted vehicles, and human divers. A significant limitation of small low-cost UUVs is their low-cost navigation systems which presently limit them to missions requiring comparatively low-precision navigation. This project developed new methods for high-accuracy navigation with low-cost sensors to provide dramatically improved navigation accuracy for low-cost UUVs.

Status: We have (1) employed Doppler sonar velocity measurement and low-cost low-power inertial measurement units to estimate attitude; (2) developed nonlinear model-based state estimators employing a full nonlinear model of the vehicle's second-order plant dynamics; and (3) developed underwater acoustic modem networks to provide simultaneous acoustic communication and acoustic range and range-rate data, and employ these data for improved underwater vehicle navigation.

Funding: NSF IIS-13064216

Current Key Personnel: Louis L. Whitcomb, Zachary Harris, Laughlin Barker, Giancarlo Troni, Christopher McFarland

To find out more: https://dscl.lcsr.jhu.edu

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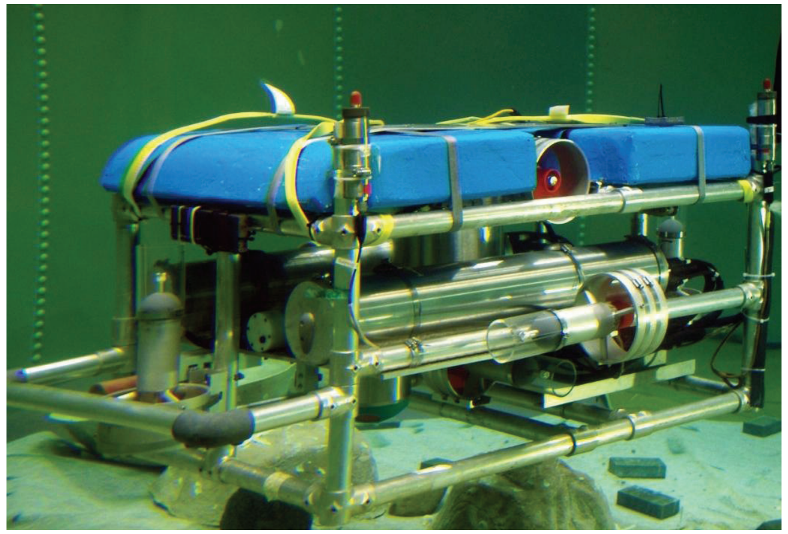
Development of a Low-Cost True-North Seeking Fiber Optic Gyrocompass for Precision Underwater Robot Navigation



- Attitude estimation directly on the group SO(3)
- Use full non-linear dynamics instead of linearizing and using an Extended Kalman Filter (EKF)
- Adaptive IMU sensor bias estimation

In-water testing of the novel gyrocompass system with the JHU ROV underwater vehicle

Accomplishment: This project seeks to develop a high-accuracy comparatively low-cost, compact, and low-power true-North seeking attitude (heading, pitch, and roll) sensor, and to incorporate this new instrument into a tightly integrated precision Doppler navigation system for UUVs. The goal is to develop a comparatively low-cost and high-accuracy navigation system to enable small low-cost UUVs to perform science missions requiring high-precision navigation (e.g. high precision hydrographic survey, time-series acoustic and optical survey for environmental assessment) that are presently considered impractical or infeasible with low-cost UUVs.

Status: Development of novel adaptive algorithms for true-North attitude estimation with low-cost fiber-optic IMUs is nearing completion. Prototype instrument developed and tested on the lab bench. In water laboratory tests underway. At-sea full-scale oceanographic testing in 2018.

Funding: NSF 1435818

Current Key Personnel: Louis Whitcomb, Andrew Spielvogel, Andy Cohen, Katherine Mao, Florian Pontani, Louis Whitcomb

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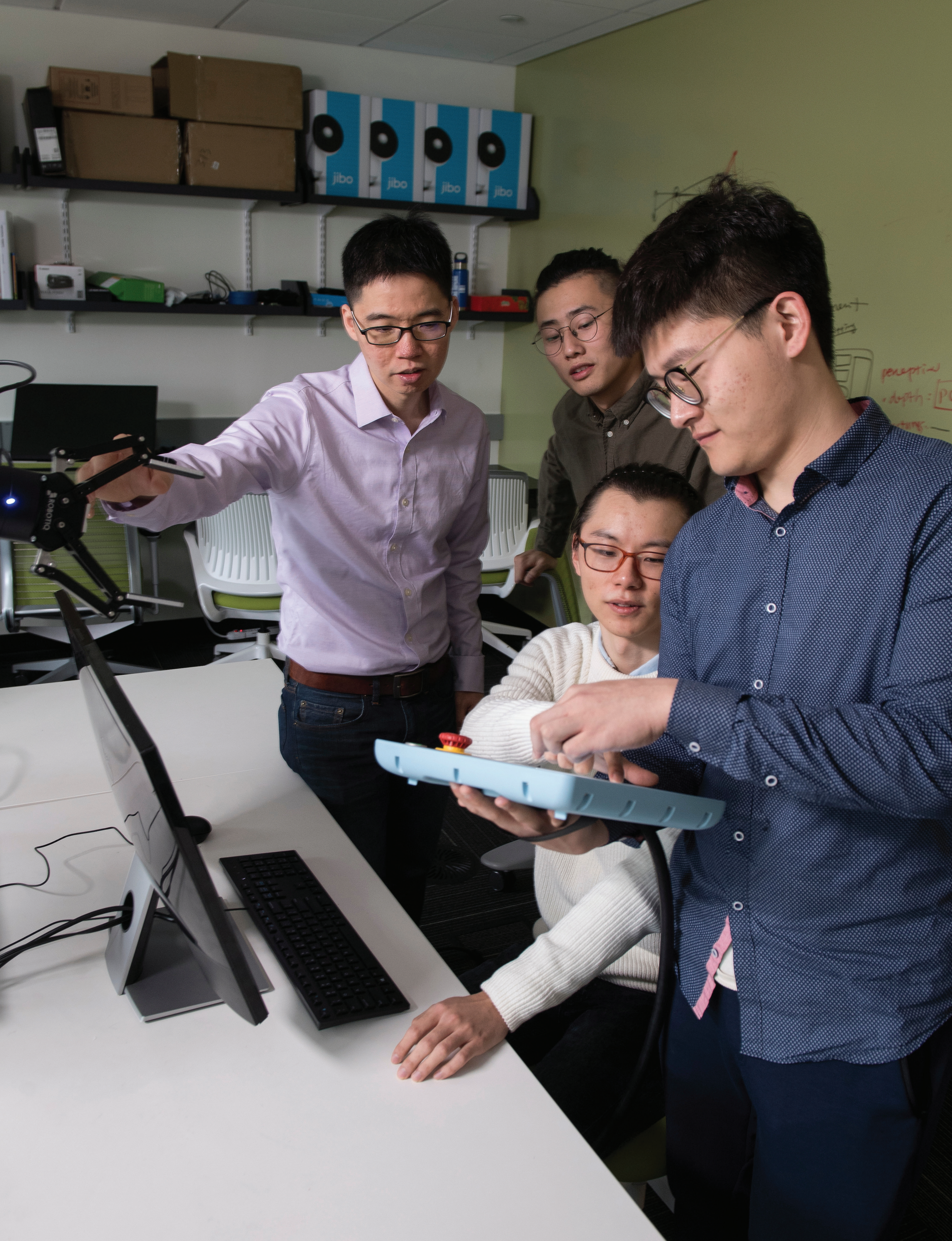
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Color key for research areas

Bio-Robotics	Human-Machine Collaborative Systems	Modeling, Dynamics, Navigation, and Control	Perception and Cognitive Systems	Robotics in Extreme Environments	Robots and Computer Assisted Surgical Technology

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