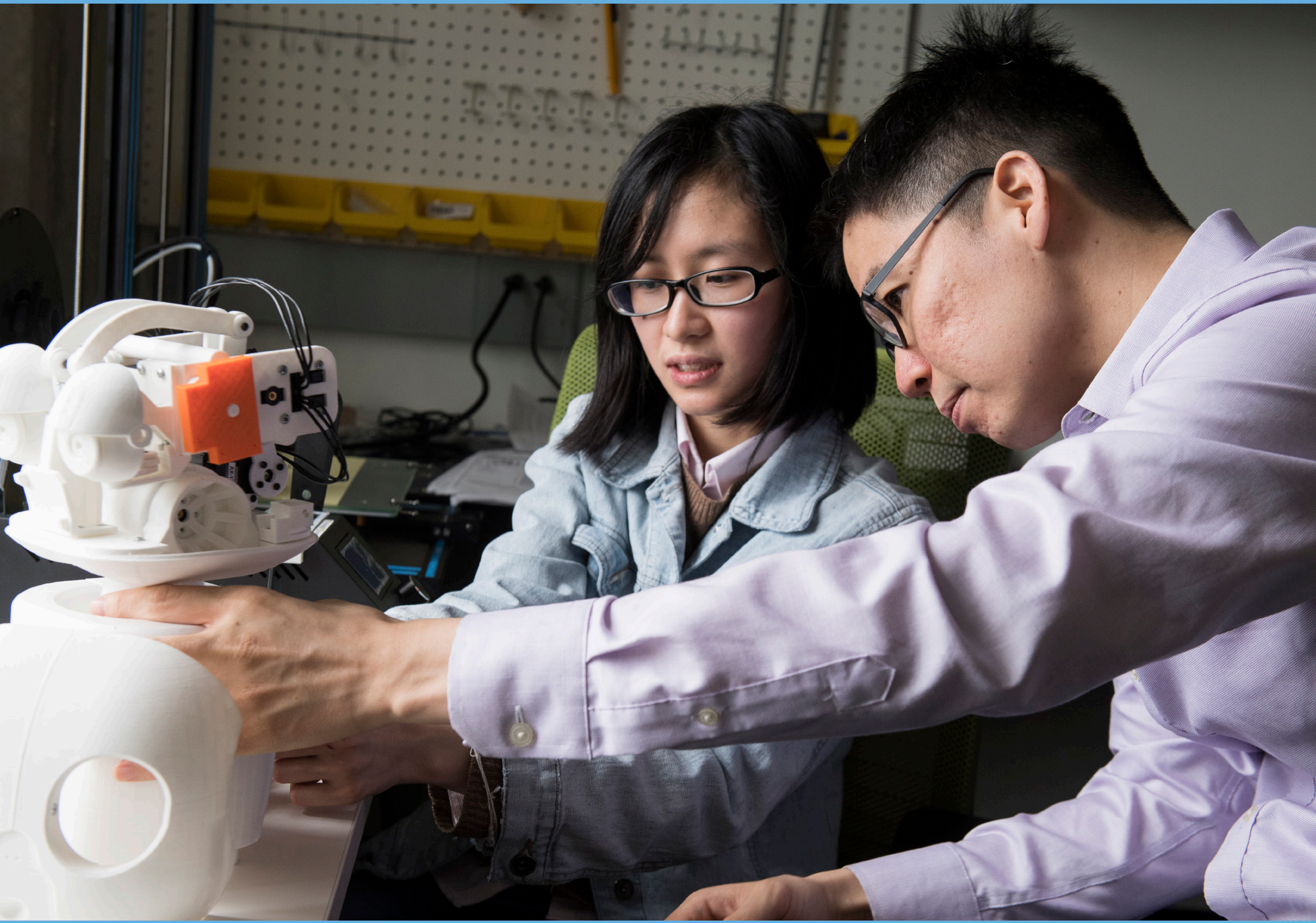
Laboratory for Computational Sensing & Robotics



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.

Laboratories

Medical UltraSound Imaging and Intervention Collaboration

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. In addition, the lab conducts research on advanced ultrasound techniques. These include ultrasound elastography imaging, 3D ultrasound reconstruction methods, parallel and GPU implementations, CT-US registration, tracked ultrasound, and segmentation, to name but a few. Our group is based on a collaboration among researchers from Johns Hopkins Medical School, Johns Hopkins Whiting School of Engineering, and partners from other academic institutions and industry.

Current Projects

Co-Robotic Ultrasound Tomography Framework for *In Vivo* Prostate Imaging

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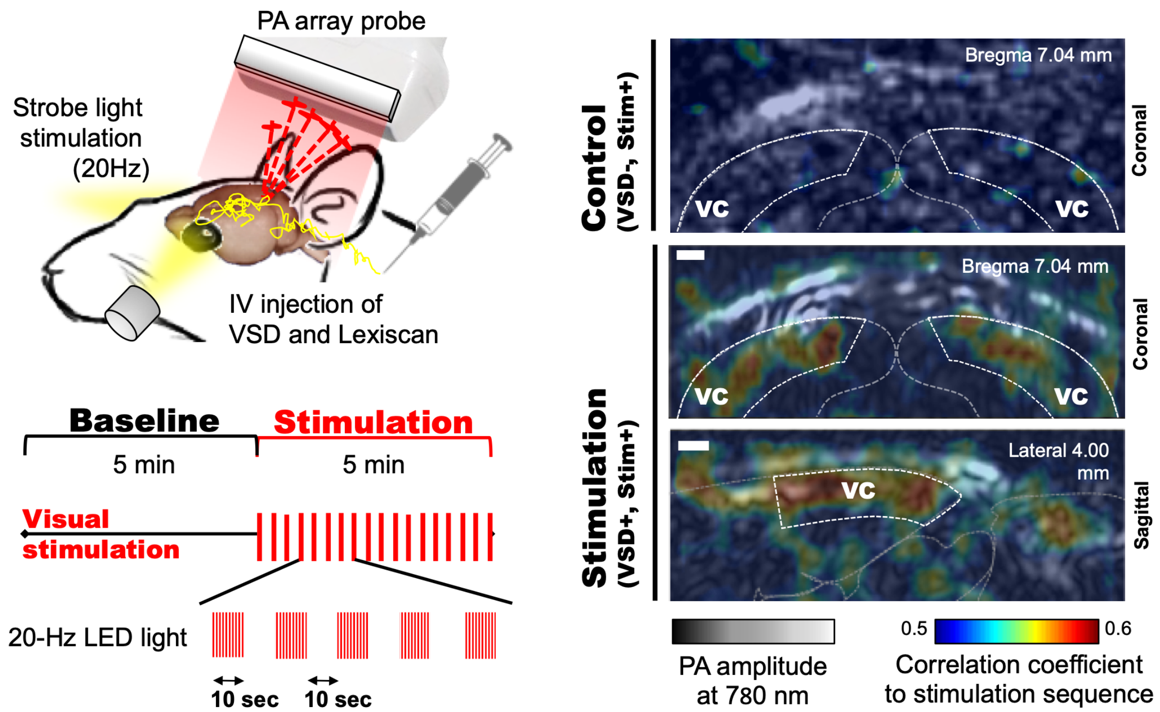
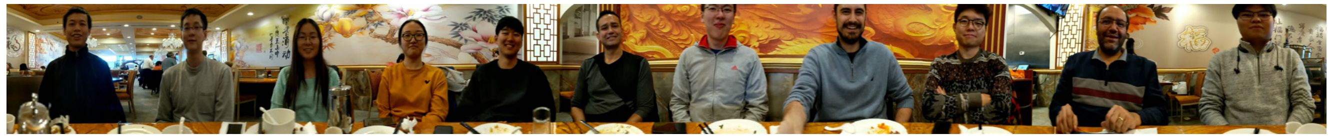
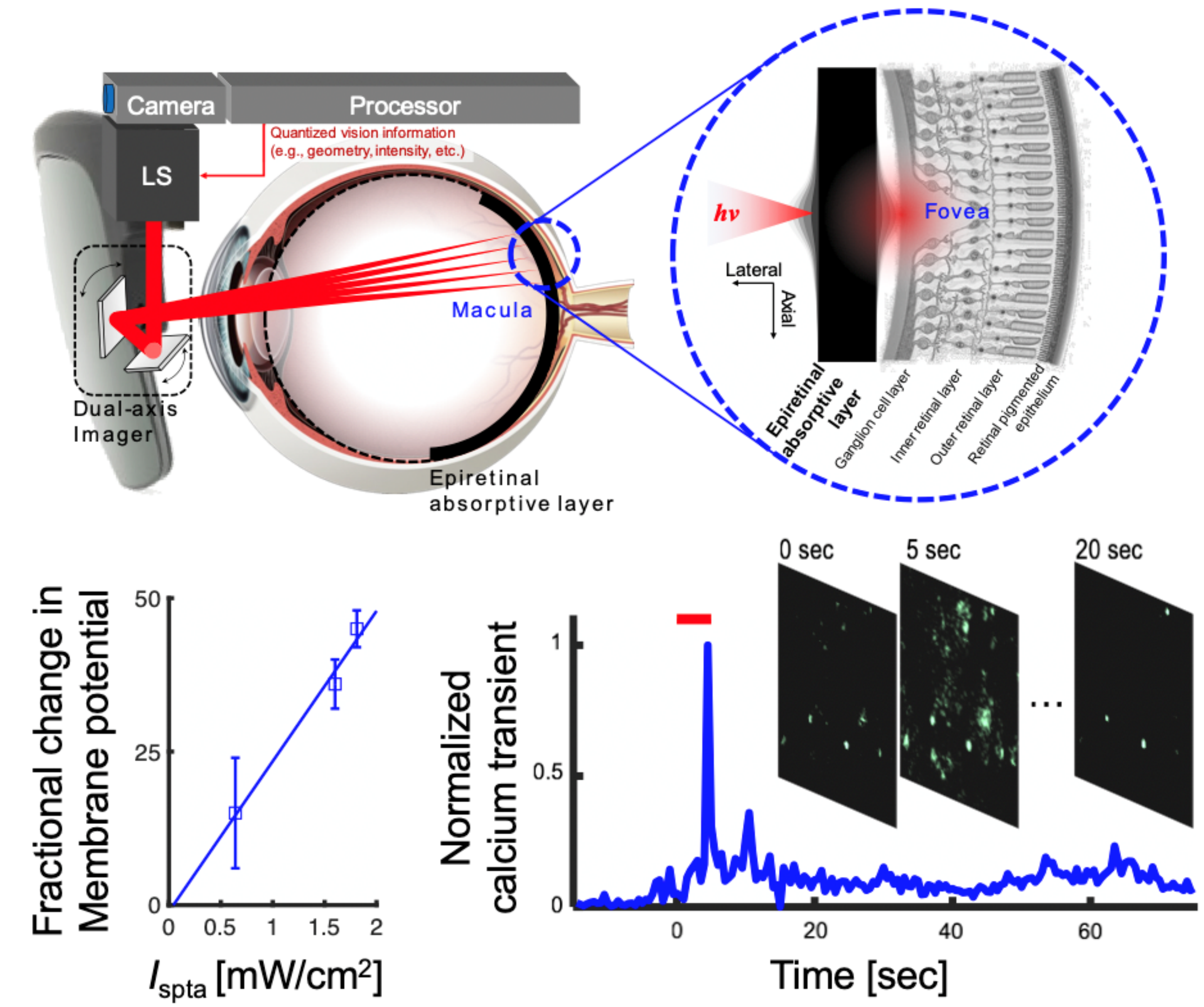


Novel retinal neuromodulation mechanism using photoacoustics. Prospective configuration of a bionic eye prosthesis and validation of calcium transient in *ex vivo* porcine retina.





Transcranial imaging of visual perception *in vivo*. The temporal correlation between fPA VSD response and stimulation sequence indicates exclusive contrast in primary visual cortex in rodent brain *in vivo*.

Advanced Medical Instrumentation and Robotics

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 medical robots and devices that will help clinicians deliver earlier diagnosis and less-invasive treatments more quickly and at a lower cost.

Current research efforts include developing MRI-compatible robots and devices for prostate cancer therapy and musculoskeletal and spinal interventions; surgical robots and medical instrumentation for microsurgery and minimally invasive surgery, and small animals research platforms for preclinical cancer research.

The AMIRo lab works closely with other research groups inside and outside of Johns Hopkins University and Hospital as well as local industries. Johns Hopkins-affiliated collaborators include: the CIIS, SMARTS, BIGSS, and ASCO at LCSR, POL at ECE and DROMRS at JHH. The outside collaborators include: SPL at BWH, AIM at WPI, Perk Lab at Queen's, SML at CMU, Acoustic MedSystems, and Xstrahl.

Recent Accomplishments and Publications

A. Ebrahimi, N. Patel, C. He, P. Gehlbach, M. Kobilarov, I. Iordachita. "Adaptive Control of Sclera Force and Insertion Depth for Safe Robot-Assisted Retinal Surgery," in Proc. *2019 IEEE International Conference on Robotics and Automation* (ICRA), May 2019, pp. 9073–9079. **Best Paper Award in Medical Robotics**.

M.G. Urias, N. Patel, C. He, A. Ebrahimi, J.W. Kim, I. Iordachita,P.L. Gehlbach, "Artificial intelligence, robotics and eye surgery: are we overfitted?" *International Journal of Retina and Vitreous*, vol.5, no.1, pp.1-4. Dec. 2019.

Z. Deng, X. Xu, T. Garzon-Muvdi, Y. Xia, E. Kim, Z. Belcaid, A. Luksik, R. Maxwell, J. Choi, H. Wang, J. Yu, I. Iordachita, M. Lim, J. Wong,K. Wang, "*In vivo* bioluminescence tomography center of mass-guided conformal irradiation," *International Journal of Radiation Oncology*, Biology, Physics, [Online], 15 Nov. 2019.

G. Li, N.A. Patel, J. Hagemeister, J. Yan, D. Wu, K. Sharma, K. Cleary,I. Iordachita, "Body-mounted robotic assistant for MRI-guided low back pain injection," *International Journal of Computer Assisted Radiology and Surgery*, pp.1-11, Oct. 2019.

F. Alambeigi, S.A. Pedram, J.L. Speyer, J. Rosen, I. Iordachita, R.H. Taylor, M. Armand, "SCADE: SimultaneoSensor Calibration and Deformation Estimation of FBG-equipped unmodeled continuum manipulators," *IEEE Transactions on Robotics*, 2019.

P. Huang, L. Su,, S. Chen, K. Cao, Q. Song, P. Kazanzides, I. Iordachita, M.A.L. Bell, J.W. Wong, D. Li, K. Ding, "2D ultrasound imaging based intra-fraction respiratory motion tracking for abdominal radiation therapy using machine learning," *Physics in Medicine & Biology*, [Online] 19 July 2019.

A. Beisenova, A. Issatayeva, I. Iordachita, W. Blanc, C. Molardi, D. Tosi, "Distributed fiber optics 3D shape sensing by means of high scattering NP-doped fibers simultaneous spatial multiplexing," *Optics Express*, vol. 27, no. 16, pp. 22074-22087. Aug. 2019.

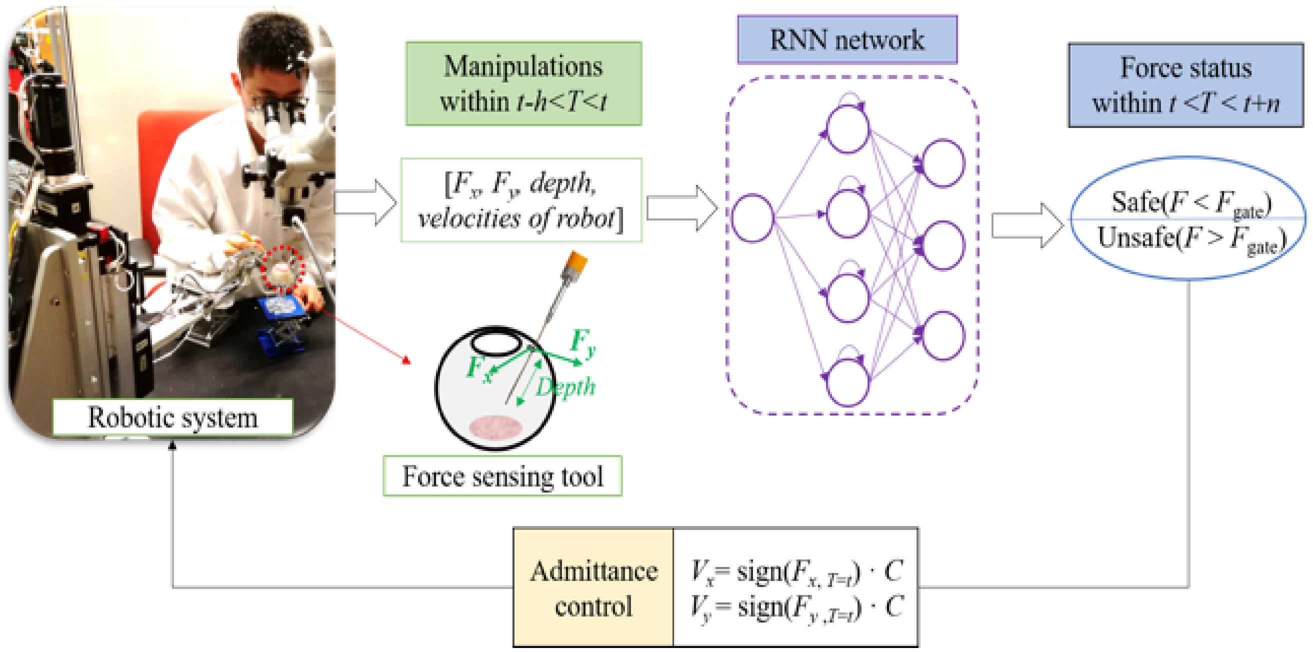
C. He, N. Patel, M. Shahbazi, Y. Yang, P. L. Gehlbach, M. Kobilarov, I. Iordachita, "Toward safe retinal microsurgery: development and evaluation of an RNN-based active interventional control framework." *IEEE Transactions on Bio-medical Engineering*, [Online] 01 July 2019.

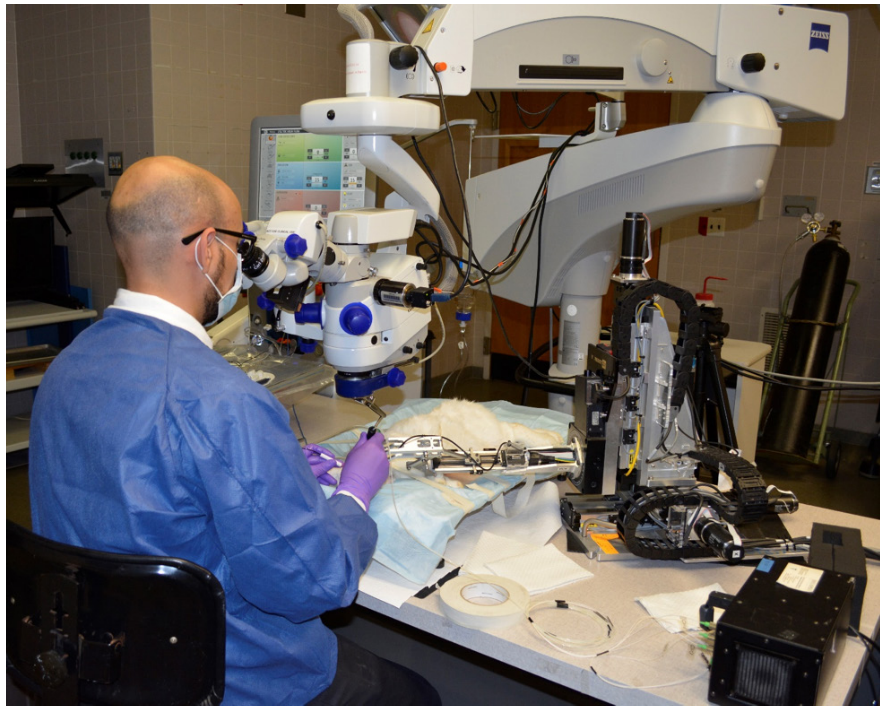
Current Projects

Enabling Technology for Safe Robot-assisted Surgical Micromanipulation

MRI Compatible Body-mounted Robot to Streamline Pediatric Shoulder Arthrography

MRI Compatible Robot for Improved Pain Injections in Adults and Children





Iulian Iordachita

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Terradynamics

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. Lab researchers are developing experimental tools and theoretical models to create terradynamics, a new field that describes the complex locomotor-terrain interactions and use terradynamics to better understand animal locomotion and to advance robot locomotion in complex terrains.

Recent Accomplishments and Publications

Published two articles in the Journal of Experimental Biology and published thirteen conference abstracts in 2018 and 2019.

Catalyst Award, Johns Hopkins University, 2019 (Chen Li)

Alumnus, Kavli Frontiers of Science, National Academy of Sciences, 2019 (Chen Li)

Mentee Honors

Best Student Paper Finalist, Society for Integrative & Comparative Biology Annual Conference, Division of Comparative Biomechanics, 2019 (Ratan Othayoth)

Robert George Gerstmyer Award, for outstanding undergraduate achievement, Department of Mechanical Engineering, Johns Hopkins University 2019 (Zhiyi Ren)

Travel Grant, Johns Hopkins University, Graduate Representative Organization, 2019 (Qihan Xuan)c

Outreach

Baltimore Polytechnic Institute Field Trip Lab Tour (30 attendees: most underrepresented minorities) 2019

Current Projects

Towards Terradynamics of Dynamic Legged Locomotion in Complex 3-D Terrains

The Terradynamics of Biological Movement in Complex Terrain

Neuromechanics of Legged Locomotion on Energy Landscapes of Complex Terrains

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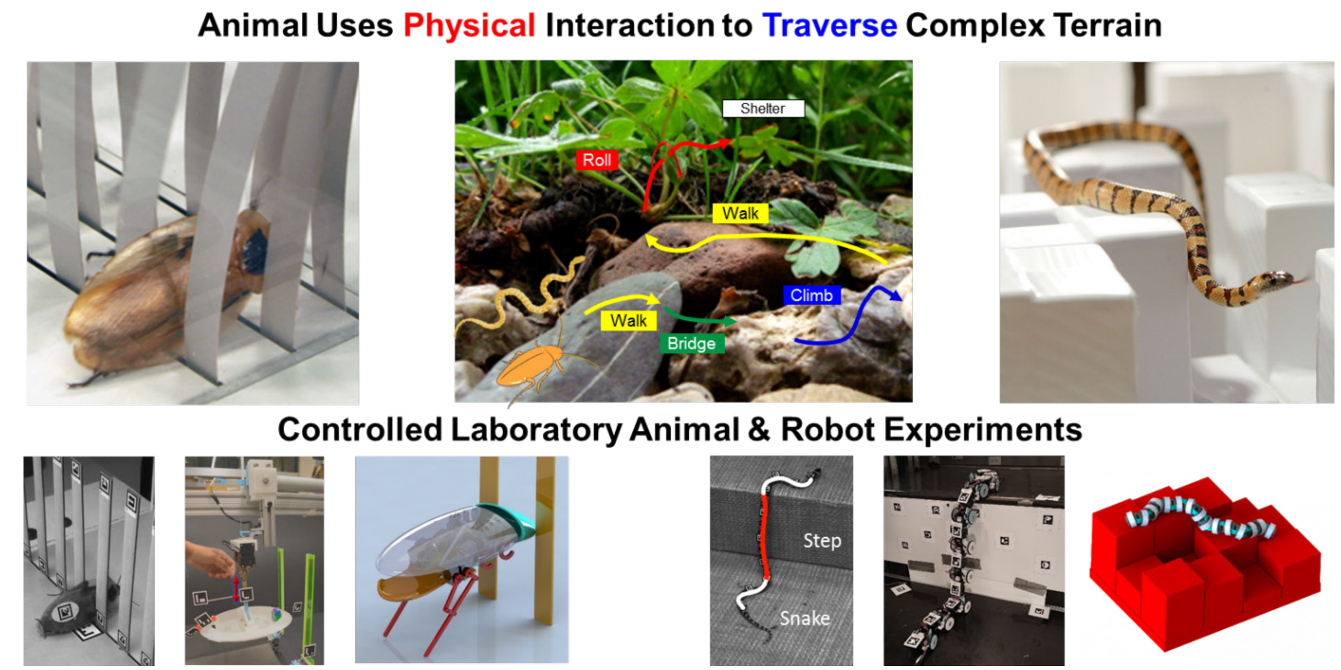

Sensing, Manipulation, and Real-Time Systems

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.

Recent Accomplishments and Publications

The SMARTS lab has developed and disseminated the open source da Vinci Research Kit (dVRK), supporting worldwide research in medical robotics.

H. Lin, C. Hui, Y. Wang, A. Deguet, P. Kazanzides, S. Au, “A reliable gravity compensation control strategy for dVRK robotic arms with nonlinear disturbance forces,” *IEEE Robotics and Automation Letters*, vol.4 (4), pp. 3892-3899, 2019.

L. Qian, A. Deguet, P. Kazanzides, “dVRK-XR: mixed reality extension for da Vinci research kit,” *Hamlyn Symposium on Medical Robotics*, pp. 93-94, 2019.

L. Qian, A. Deguet, Z. Wang, Y. Liu, P. Kazanzides, “Augmented reality assisted instrument insertion and tool manipulation for the first assistant in robotic surgery” *IEEE Intl. Conf. on Robotics and Automation* (ICRA), pp. 5173-5179, 2019.

W. Pryor, B. Vagvolgyi, W. Gallagher, A. Deguet, S. Leonard, L. Whitcomb, P. Kazanzides, “Experimental evaluation of teleoperation interfaces for cutting of satellite insulation,” *IEEE Intl. Conf. on Robotics and Automation* (ICRA), pp. 4775-4781, 2019.

M. Marinho, B. Adorno, K. Harada, K. Deie, A. Deguet, P. Kazanzides, R. Taylor, M. Mitsuishi, “A unified framework for the teleoperation of surgical robots in constrained workspaces,” *IEEE Intl. Conf. on Robotics and Automation* (ICRA), pp. 2721-2727, 2019.

G. Chrysilla, N. Eusman, A. Deguet, P. Kazanzides, “A compliance model to improve the accuracy of the da Vinci research kit (dVRK)” *Acta Polytechnica Hungarica, Special Issue on Platforms for Medical Robotics Research*, vol. 16 (8), pp. 49-60, 2019.

Current Projects

Augmented Reality Assistance for Minimally Invasive Surgery (ARAMIS)

Mixed Reality Head Mounted Display (HMD) for Neurosurgery

Telerobotic Satellite Servicing

Peter Kazanzides

Research Professor, Department of Computer Science

Director, Sensing, Manipulation, and Real-Time Systems Laboratory

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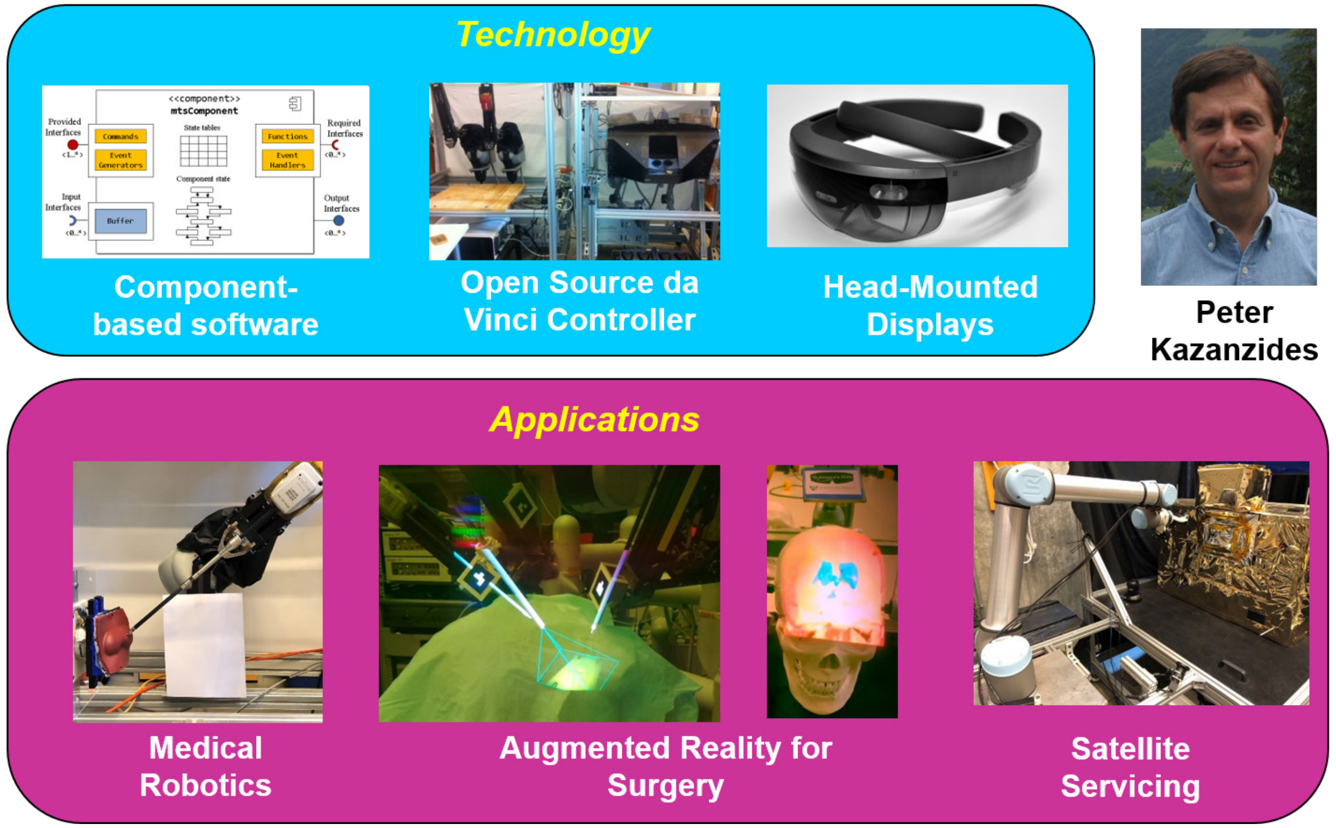
Sensing, Manipulation, and Real Time Systems (SMARTS) – https://smarts.lcsr.jhu.edu



Dynamical Systems and Control Laboratory

Louis Whitcomb

The DSCL 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. DSCL researchers 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. The lab's methodology is to address fundamental theoretical issues with concise mathematical analysis, and to experimentally validate our research results in actual working systems.

Recent Accomplishments and Publications

A. R. Spielvogel, L. L. Whitcomb. "A Stable Adaptive Observer for Hard-Iron and Soft-Iron Bias Calibration and Compensation for Two-Axis Magnetometers: Theory and Experimental Evaluation". IEEE Robotics and Automation Letters, vol. (5)2 pp.1295-1302, April 2020. http:/dx.doi.org/10.1109/LRA.2020.2967308

A. R. Spielvogel, L. L. Whitcomb. "Adaptive Bias and Attitude Observer on the Special Orthogonal Group for True-North Gyrocompass Systems: Theory and Preliminary Results." International Journal of Robotics Research, vol. 39(2–3) pp. 321–338, 2020. http://doi.org/10.1177/0278364919881689 Published online ahead of print Nov 5, 2019. http://doi.org/10.1177%2F0278364919881689. Invited Paper.

G. Troni, L. L. Whitcomb. "Field Sensor Bias Calibration with Angular-Rate Sensors: Theory and Experimental Evaluation with Application to Magnetometer Calibration." IEEE/ASME Transactions on Mechatronics, vol. 24(4) pp. 1698-1710, August 2019. http://dx.doi.org/10.1109/TMECH.2019.2920367 S.K. Kandala, E. Liapi, L.L. Whitcomb, A. Attaluri, R. Ivkov, "Temperature-controlled power modulation compensates for heterogeneous nanoparticle distributions: a computational optimization analysis for magnetic hyperthermia." International Journal of Hyperthermia, vol. 36(1), pp. 115-129. http://dx.doi.org/10.1080/02656736.2018.1538538. Awarded 2019 International Journal of Hyperthermia Editor's Award in Physics/Engineering.

B. Vagvolgyi, W. Pryor, R. Reedy, W. Niu, A. Deguet, L. L. Whitcomb, S. Leonard, and P. Kazanzides. "Scene Modeling and Augmented Virtuality Interface for Telerobotic Satellite Servicing", in IEEE Robotics and Automation Letters, vol. 3(4) pp. 4241-4248, 2018. http://dx.doi.org/10.1109/LRA.2018.2864358

Current Projects

Telerobotics for On-Orbit Servicing of Satellites

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

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

Precision Navigation of Low-Cost Underwater Robotic Vehicles for Ocean Science

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Autonomous Systems, Control, and Optimization

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 autonomy in mobile (ground and aerial) robots and small spacecraft, and computational tools for control and optimization of multi-body mechanical systems.

Recent Accomplishments and Publications

Demonstrated the successful development of theory, algorithms and software, and deployment on autonomous systems (self-driving cars, aerial drones, and underwater vehicles) operating in the real world.

M. Sheckells, M. Kobilarov, "Actor-critic PAC robust policy search," submitted to ICRA 2020. (pdf)

J. Kim, C. He, M. Urias, P. Gehlbach, G. D. Hager, I. Iordachita, M. Kobilarov, "Autonomously navigating a surgical tool inside the eye by learning from demonstration," submitted to ICRA RA-L 2020. (pdf)

G. Garimella, M. Sheckells, S. Kim, G. Baraban, M. Kobilarov, "A framework for reliable aerial manipulation," (preprint) (pdf)

G. Garimella, M. Sheckells, M. Kobilarov, "Nonlinear model predictive control of an aerial manipulator using a recurrent neural network model," 2018 (preprint) (pdf)

Current Projects

Robotic Environmental Sampling

Autonomous Aerial Manipulation

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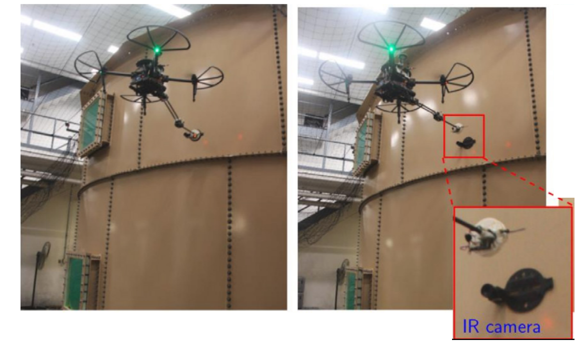
Autonomous Aerial Manipulation



JHU AirGripper performing sensor placement

JHU AirGripper performing package sorting

environmental sensor placement

vehicle for larger payloads

Robot and Protein Kinematics

Gregory Chirikjian

Researchers in the Robot and Protein Kinematics Laboratory investigate 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.

Recent Accomplishments and Publications

2019 ASME Machine Design Award

S. Ruan, K. L. Poblete, Y. Li, Q. Lin, Q. Ma, G. S. Chirikjian, "Efficient exact collision detection between ellipsoids and superquadrics via closed-form Minkowski sums," *The International Conference on Robotics and Automation* (ICRA), 2019.

S. Ruan, Q. Ma, K. L. Poblete, Y. Yan, G. S. Chirikjian, "Path planning for ellipsoidal robots and general obstacles via closed-form characterization of Minkowski operations," in *The 13th International Workshop on the Algorithmic Foundations of Robotics* (WAFR), 2018.

T.W. Mitchel, S. Ruan, Y. Gao, G.S. Chirikjian, "The globally optimal reparameterization algorithm: an alternative to fast dynamic time warping for action recognition in video sequences," in *International Conference on Control, Automation, Robotics and Vision* (ICARCV), 2018.

H. Wu, J. Mu, T. Da, M. Xu, R.H. Taylor, I. Iordachita, G.S. Chirikjian, "Multi-mosquito object detection and 2D pose estimation for automation of PfSPZ malaria vaccine production," in *IEEE 15th International Conference on Automation Science and Engineering* (CASE), Aug 2019.

Q. Ma, Z. Goh, S. Ruan, G.S. Chirikjian, "Probabilistic approaches to the AXB = Y CZ calibration problem in multi-robot systems," *Autonomous Robots*, pp. 1-24, 2018.

Current Projects

Conformational Probabilities: A Bridge Between Innate Knowledge and Action Recognition

Gregory Chirikjian
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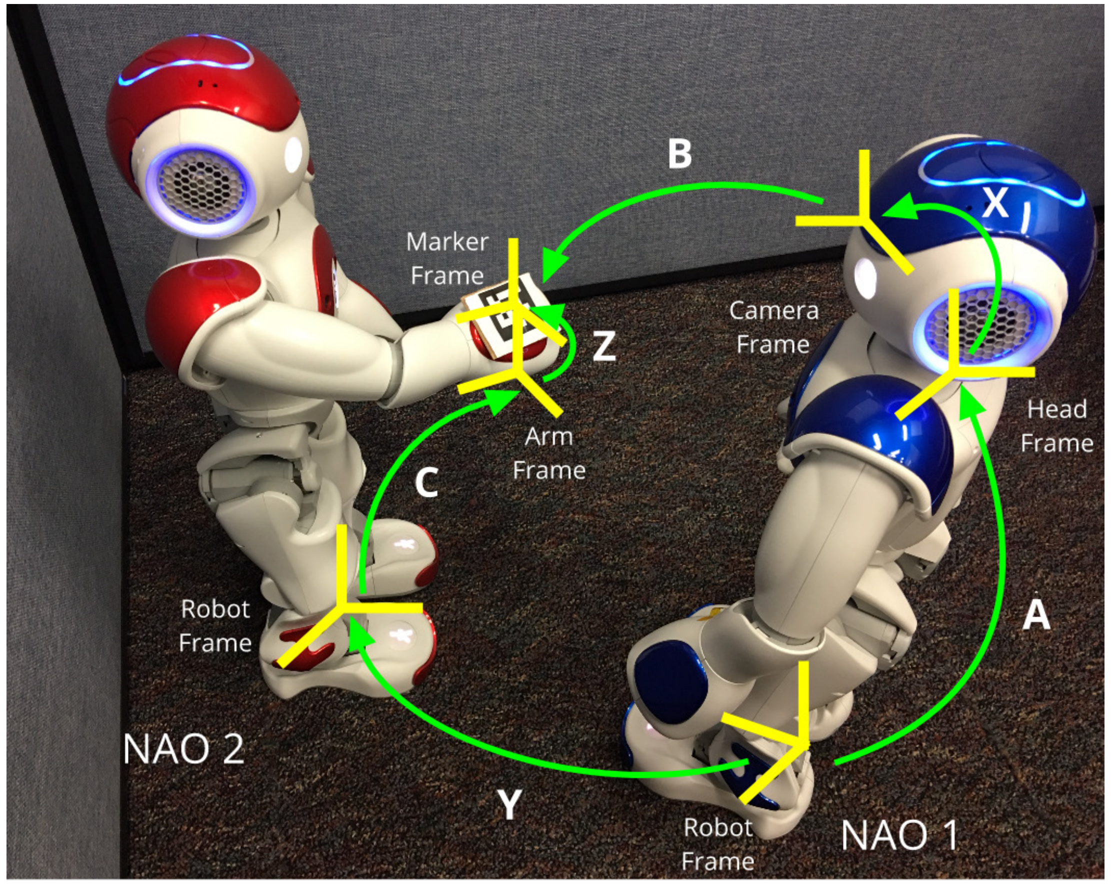

Computer Integrated Interventional Systems

Russell Taylor

The Computer-Integrated Interventional Systems (CiiS) Lab focuses on all aspects of medical robotics and computer-integrated interventional medicine, as well as related subject areas in medical image analysis, robotics, and human-machine cooperation. Our overall strategy aims to create a three-way-partnership between humans, technology, and information to fundamentally improve surgery and other medical procedures by making them safer, less invasive, and more effective.

Some recent research projects (many undertaken with other LCSR labs) 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, and a system for automatic dissection of mosquitoes for malaria vaccine production.

The CiiS lab collaborates closely with other labs within LCSR and the Malone Center for Engineering in Healthcare, with surgeons and others in the Johns Hopkins Engineering School and School of Medicine, and with research groups and institutions around the world.

Recent Accomplishments and Publications

The REMS head-and-neck microsurgery robot developed within CiiS by Kevin Olds is being commercialized by a startup company, Galen Robotics, which is also sponsoring research within LCSR.

Starting with its existence within the CISST ERC, The CiiS lab has produced over 475 peer reviewed journal and conference publications, and 58 patents. Within the past two years, the lab has produced 3 book chapters, 14 refereed conference papers, 24 journal papers, and 20 issued patents in the past two years. These have led to many "best paper" awards. A few selected recent publications are below.

S. Leonard, A. Sinha, A. Reiter, M. Ishii, G. L. Gallia, R. H. Taylor, and G. D. Hager, "Evaluation and stability analysis of video-based navigation system for functional endoscopic sinus surgery on in-vivo clinical data", *IEEE Trans Med Imaging*, vol. 37- 10, pp. 2185 - 2195, 2018. 10.1109/TMI.2018.2833868

X. Liu, A. Sinha, M. Ishii, G. D. Hager, A. Reiter, R. H. Taylor, M. Unberath, "Dense depth estimation in monocular endoscopy with self-supervised learning methods", *IEEE Transactions on Medical Imaging*, Epub ahead of print, 2019. 10.1109/TMI.2019.2950936

R. B. Grupp, R. A. Hegeman, R. J. Murphy, C. P. Alexander, Y. Otake, B. A. McArthur, M. Armand, R. H. Taylor, "Pose estimation of periacetabular osteotomy fragments with intraoperative X-Ray navigation", *IEEE Trans Biomed Eng.*, vol. 67- 2, pp. 441-452, Feb., 2020. Epub 8 March 2019 10.1109/TBME.2019.2915165

Z. Li, M. Shahbazi, N. Patel, O'Sullivan, Z. E., H., K. Vyas, P. Chalasani, P. Gehlbach, I. Iordachita, G. Z. Yang, R. H. Taylor, "A novel semi-autonomous control framework for retina confocal endomicroscopy scanning", in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems* (IROS), Macao, Nov., 2019. pp. 7083-7090.

A. L. Feng, C. R. Razavi, P. Lakshminarayanan, Z. Ashai, K. Olds, M. Balicki, Z. Gooi, A. T. Day, R. H. Taylor, and J. D. Richmon, "The robotic ENT microsurgery system: A novel robotic platform for microvascular surgery", *The Laryngoscope*, 127, pp. 2495-2500, November, 2017.

L. Akst, K. Olds, M. Balicki, P. Chalasani, and R. Taylor, "Robotic Microlaryngeal Phonosurgery: Testing of a "Steady-Hand Platform", *Laryngoscope*, vol. 128-, pp. 126-132, Jan., 2018. 10.1002/lary.26621, PMID: 28498632

Y. Sevimli, P. Wilkening, L. Feng, M. Balicki, K. Olds, T. Keady, R. H. Taylor, "Surgical workflow integration of the robotic ENT Microsurgical System", in *Hamlyn Symposium on Medical Robotics*, London, June 26-27, 2016. pp. 30-31.

H. Phalen, P. Vagdargi, M. Pozin, S. Chakravarty, G. S. Chirikjian, I. Iordachita, R. H. Taylor, "Mosquito pick-and-place: automating a key step in PfSPZ-based malaria vaccine production", in *IEEE Conference on Automation Science and Engineering* (CASE), Vancouver, BC, August 22-26, 2019. pp. 12-17.

Current Projects

Robot-assisted Confocal Endoscopic Imaging for Retinal Surgery

Automated Mosquito Salivary Gland Removal

Steady-Hand Robot for Head-and-Neck Surgery

Real-Time Stiffness Estimation Using Gaussian Processes

Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis

Dense Reconstruction of Sinus Anatomy from Endoscopic Video

Deformable Registration Using Statistical Shape Models

Complementary Situational Awareness for Intelligent Telerobotic Surgical Assistant Systems

Russell Taylor

Professor, Department of Computer Science

Director, Laboratory for Computational Sensing and Robotics

Director, Computer Integrated Interventional Systems Laboratory

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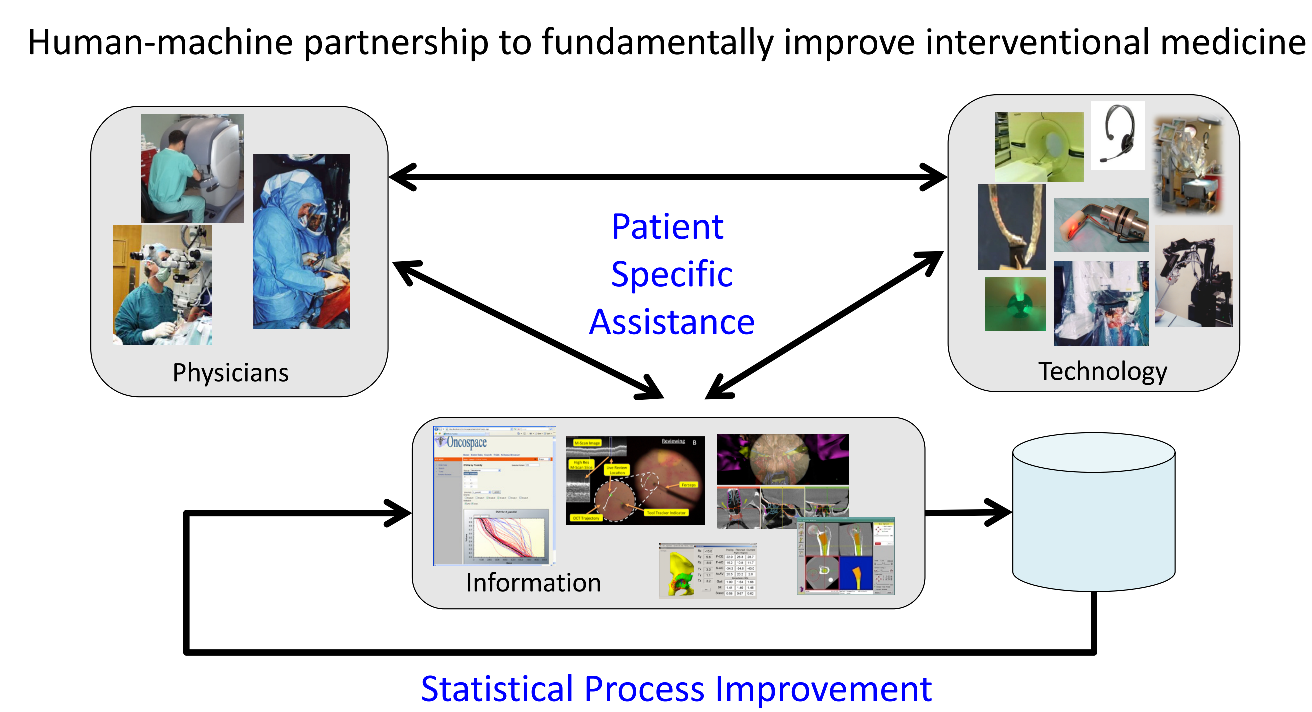

Computational Interaction and Robotics Laboratory

Gregory Hager

The Computational Interaction and Robotics Laboratory (CIRL) 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 human activities and skilled human manipulation, with a particular emphasis on surgery. Applications include automated skill evaluation, training, and human-robot collaborative task execution. Other work is aimed at machine learning to create systems that perform complex manipulation tasks.

CIRL also works in the area of medical imaging. Interactive computer-aided diagnostic systems based on images are also an area of interest. The CIRL lab has made advances in a number of areas including automated systems for surgical workflow analysis and surgical coaching, collaborative systems for manufacturing, perception and learning-based manipulation, and video-CT registration for surgical navigation.

Recent Accomplishments and Publications

F. Yu, GS Croso, T.S. Kim, Z. Song, F. Parker, G.D. Hager, A. Reiter, S. Vedula, H. Ali, S. Sikder,"Assessment of automated identification of phases in videos of cataract surgery using machine learning and deep learning techniques," *JAMA Network Open*, 2019.

C. Paxton, Y. Barnoy, K. Katyal, R. Arora, G.D. Hager, "Visual robot task planning. In *2019 International Conference on Robotics and Automation* (ICRA) (pp. 8832-8838). IEEE, May 2019

R. DiPietro, N. Ahmidi, A. Malpani, M. Waldram, G.I. Lee, M.R. Lee, S. Vedula, G.D. Hager, "Segmenting and classifying activities in robot-assisted surgery with recurrent neural networks," *International Journal of Computer Assisted Radiology and Surgery* (IJCARS), IPCAI 2019.

J. Jones, G.D. Hager, S Khudanpur, "Toward computer vision systems that understand real-world assembly processes," *Winter Conference on Applications of Computer Vision* (WACV), 2019.

T.S. Kim, M. Peven, W. Qiu, A. Yuille, G.D. Hager, "Synthesizing attributes with unreal engine for fine-grained activity analysis," *Winter Applications of Computer Vision Workshops* (WACVW), 2019.

Current Projects

The Language of Surgery

Machines with Imagination: Learning from Description through Synthesis and Analysis

Gregory Hager

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Director, Malone Center for Engineering in Healthcare

Director, Computational Interaction and Robotics Laboratory

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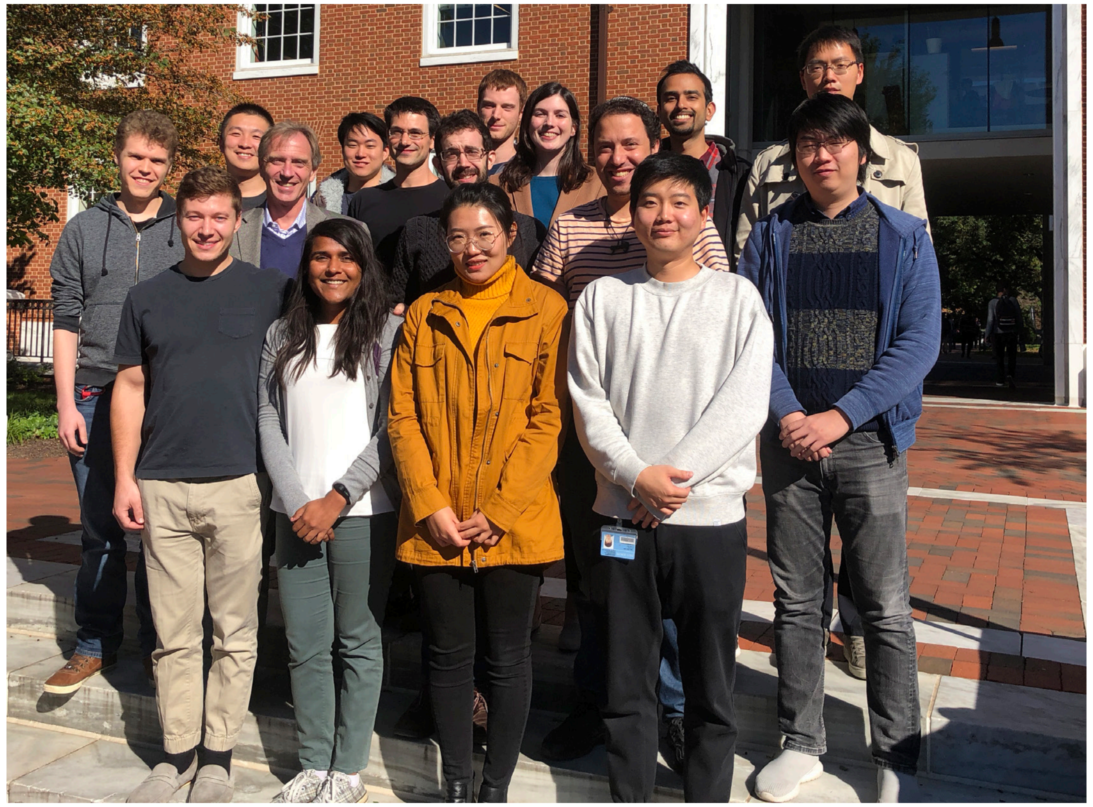

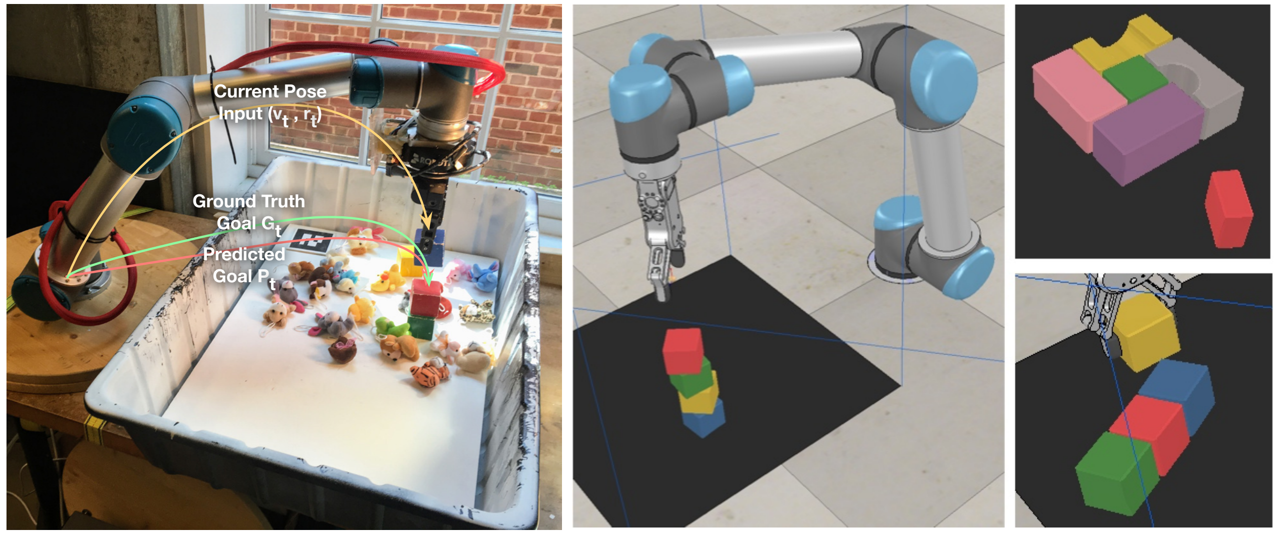

Locomotion In Mechanical and Biological Systems

Noah J. Cowan

The LIMBS laboratory strives to uncover principles of animal and robot sensory guidance. For animals, this is an analysis problem: the lab reverse engineers the biomechanical and neural control principles underlying animal movement. For robotics, this is a design problem: the lab incorporates biological inspiration and engineering insights to synthesize new approaches to robot control. The LIMBS lab, collaborating closely with neuroscientists, uses dynamical systems and control theory to discover how the brain and body work together to achieve agile movement.

Recent Accomplishments and Publications

In the past few years, LIMBS researchers have published their work in multiple flagship journals, including Nature, Scientific Reports, Current Biology, and IEEE Transactions on Automatic Control, and eLife.

Approximately $5 million dollars in active extramural funding during this time from agencies such as the National Institutes of Health, the National Science Foundation, and the Department of Defense.

A. M. Zimmet, A. J. Bastian, N. J. Cowan, "Cerebellar patients have intact feedback control that can be leveraged to improve reaching," *eLife*, In revision.

I. Uyanik, S. Sefati, S. A. Stamper, K. Cho, M. M. Ankarali, E. S. Fortune, N. J. Cowan, "Variability in locomotor dynamics reveals the critical role of feedback in task control," *eLife*, In press.

M. S. Madhav and N. J. Cowan, "The synergy between neuroscience and control theory: the nervous system as inspiration for hard control challenges," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 3, 2020.

R. W. Nickl, M. M. Ankarali, N. Cowan, "Complementary spatial and timing control in rhythmic arm movements," *Journal of Neurophysiology*, vol. 121, iss. 4, pp. 1543–1560, 2019.

I. Uyanik, S. A. Stamper, N. J. Cowan, E. S. Fortune, "Sensory cues modulate smooth pursuit and active sensing movements," *Frontiers in Behavioral Neuroscience*, vol. 13, iss. 59, 2019.

R. P. Jayakumar, M. S. Madhav, F. Savelli, H. T. Blair, N. Cowan, J. J. Knierim, "Recalibration of path integration in hippocampal place cells," *Nature*, vol. 566, iss. 745, p. 533–537, 2019.

S. Cutlip, J. Freudenberg, N. Cowan, B. R. Gillespie, "Haptic feedback and the internal model principle," in *IEEE World Haptics Conference*, 2019, pp. 568–573.

Current Projects

A User's Guide to System Identification for Sensorimotor Control

Programming Thermobiochemomechanical (TBCM) Multiplex Robot Gels

Noah J. Cowan
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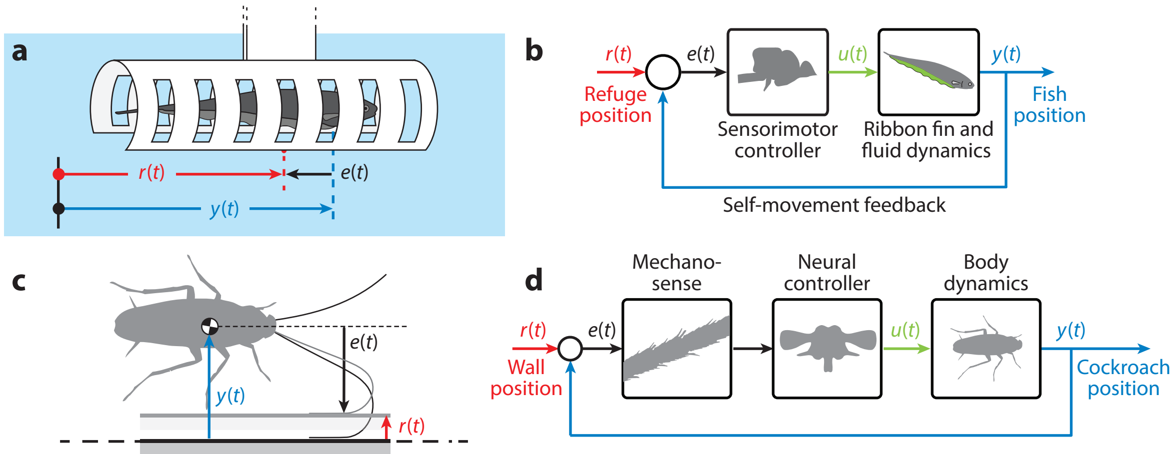

Figure 3

Illustration of top-down control systems modeling on two champion model systems. (a) Refuge tracking in *Eigenmannia virescens*. The fish moves back and forth [position = $y(t)$] to maintain a constant position with respect to a moving refuge [position = $r(t)$] (123). (b) Control-theoretic abstraction of the behavior. Through its sensory systems, the fish perceives the error signal, $e(t)$, between its own position and that of the refuge. The neural controller applies a control input, $u(t)$, to the biomechanical or environmental plant, which in turn produces the output, the fish's position $y(t)$ (52). (c) Wall following in *Periplaneta americana*. As it runs, the cockroach maintains a constant offset or error, $e(t)$, between its own position, $y(t)$, and the wall position, $r(t)$ (87). (d) The error signal is measured as deflection of the antennal mechanosensors (18) and processed by the neural controller (99) to generate a control signal to the body dynamics. The interaction of the body dynamics and the environment results in the output, the cockroach position $y(t)$. Figure adapted from Reference 7, with portions created by Eatai Roth and Eric Fortune.

Haptics and Medical Robotics

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. HAMR researchers 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, the lab uses techniques from human perception, human motor control, neuromechanics, and control theory.

Recent Accomplishments and Publications

M. Singhala, J.D. Brown. "A novel teleoperator testbed to understand the effects of master-slave dynamics on embodiment and kinesthetic perception." in *IEEE Haptics Symposium*, 2020. (Accepted—Works in Progress)

M. Singhala, J. Carducci, J.D. Brown. "Towards an understanding of how humans perceive stiffness during bimanual exploration". in *IEEE Haptics Symposium*, 2020. (Accepted—Works in Progress)

K. Shah, S. Ravichandar, J.D. Brown "Proposing a framework for evaluating haptic feedback as a modality for velocity guidance." in *IEEE Haptics Symposium*, 2020. (Accepted—Works in Progress)

Singhala M, Carducci J, Brown JD. Towards an understanding of how humans perceive stiffness during bimanual exploration. In: *IEEE Haptics Symposium* (Accepted—Works in Progress). ; 2020.

Shah K, Ravichandar S, Brown JD. Proposing a framework for evaluating haptic feedback as a modalityfor velocity guidance. In: *IEEE Haptics Symposium* (Accepted—Works in Progress). ; 2020.

M. Singhala, J.D. Brown, "Prefatory Study of the Effects of Exploration Dynamics on Stiffness Perception," in *IEEE Haptics Symposium* (Accepted), 2020.

E. Miller, I. Amanze, J.D. Brown, "A Wearable Anthropomorphically Driven Prosthesis with a Built-In Haptic Feedback System," in *IEEEE International Symposium on Medical Robotics* (Accepted), 2020.

G. Caccianiga, A. Mariani, E. De Momi, E.D. Brown, "Virtual Reality Training in Robot-Assisted Surgery: a Novel Experimental Setup for Skill Transfer Evaluation," in *12th Annual Hamlyn Symposium on Medical Robotics*, pp. 89-90, 2019.

N. Thomas, G. Ung, C. McGarvey, J.D. Brown, "Comparison of Vibrotactile and Joint-torque Feedback in a Myoelectric Upper-limb Prosthesis," *Journal of NeuroEngineering and Rehabilitation*, vol. 16(1), pp. 70, 2019.

Current Projects

Anthropomorphically Driven Upper-Extremity Prosthesis

Robot-Assisted Minimally Invasive Surgical Training

Haptic Feedback for Upper-Extremity Prostheses

User-Sensitive Haptic Displays

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Biomechanical– and Image–Guided Surgical Systems

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. BIGSS focuses on developing innovative computer-aided surgical guidance systems involving novel robots, advanced imaging, and real-time biomechanical assessments to improve surgical outcomes.

BIGSS researchers are developing and testing robotic workstations to assist in surgeries treating bone defects using continuum manipulators, and are performing intraoperative biomechanical analysis for use in craniofacial and orthopaedic surgery. The lab also develops and tests image-guided navigation systems for the treatment of hip dysplasia and single-stage cranioplasty.

Recent Accomplishments and Publications

S. Liu, W.L. Huang, A. Shin, C. Gordon, M. Armand. "A portable projection mapping device for medical augmented reality in single-stage cranioplasty." in *Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality* (*AR, VR, MR*) (International Society for Optics and Photonics) 2020. **2nd place student paper award**

S. Sefati, R. Hegeman, F. Alambeigi, I. Iordachita, M. Armand. "FBG-based position estimation of highly deformable continuum manipulators: model-dependent vs. data-driven approaches," in *IEEE International Symposium on Medical Robotics* (ISMR) **2019. Best Paper Award**

R. Grupp, et al. "Pose Estimation of Periacetabular Osteotomy Fragments With Intraoperative X-Ray Navigation." *IEEE Transactions on Biomedical Engineering*, vol. 67, no. 2, pp. 441-452, Feb. 2020. TBME Feature Paper.

A. Farvardin, E. Basafa, M. Bakhtiari Nejad, M. Armand. "Significance of Preoperative Planning for Cement-based Prophylactic Augmentation of Osteoporotic Hip." *A Computational Modeling Study Journal of Biomechanics*, vol. 94, pp. 75-81, 2019.

F. Alambeigi, M. Bakhtiari Nejad, S. Sefati, R. Hegeman, I. Iordachita, H. Khanuja, M. Armand. "On the Use of a Continuum Manipulator and a Bendable Medical Screw for Minimally Invasive Interventions in Orthopedic Surgery." *IEEE Transactions on Medical Robotics and Bionics*, vol. 1, pp. 14-21, 2019.

Current Projects

Continuum Robots, Tools, and Algorithms for Tissue Manipulation

X-ray Image-based Navigation for Periacetabular Osteotomy with Intraoperative Biomechanical Feedback

Mehran Armand

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Research Professor, Department of Mechanical Engineering

Member Principal Staff, Johns Hopkins University Applied Physics Laboratory

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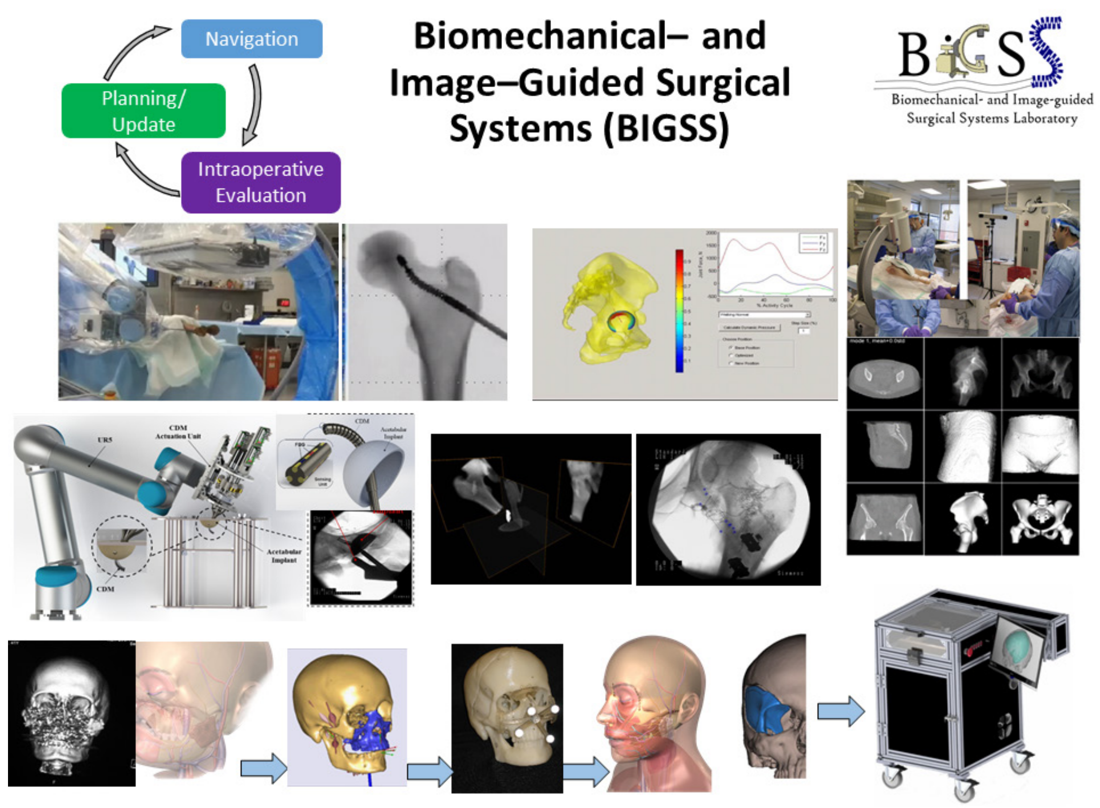

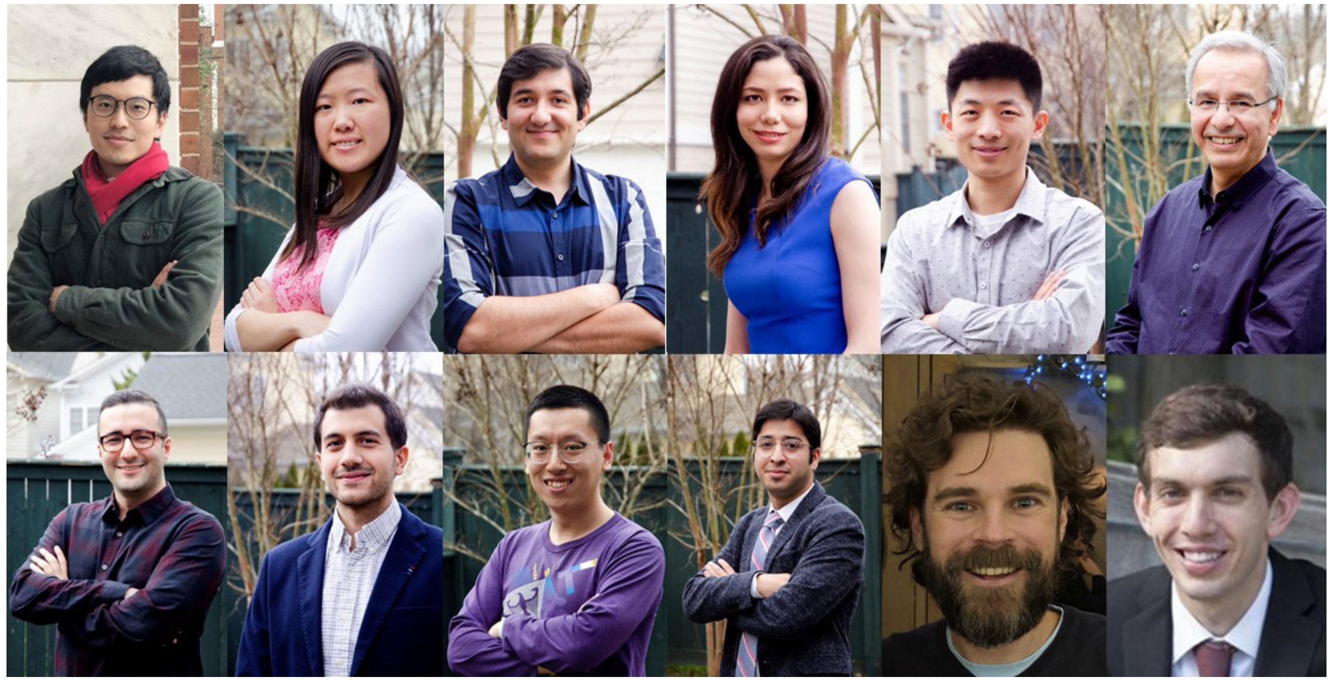

Computer Aided Medical Procedures

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, CAMP researchers work on novel robotized multi-modal imaging solutions. In order to satisfy challenging usability requirements, they 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.

Recent Accomplishments

J. Fotouhi , T. Song, A. Mehrfard, G. Taylor, Q. Wang, F. Xian, A. Martin-Gomez, B. Fuerst, M. Armand, M. Unberath, N. Navab, "Reflective-AR display: an interaction methodology for virtual-real alignment in medical robotics," *IEEE Robotics and Automation Letters* (RA-L) and International Conference on Robotics and Automation (ICRA) 2020.

J. Fotouhi, M. Unberath, T. Song, W. Gu, A. Johnson, G. Osgood, M. Armand, N. Navab, "Interactive Flying Frustums (IFFs): spatially aware surgical data visualization," *International Journal of Computer Assisted Radiology and Surgery*, vol. 14(6), pp. 913-22, June 2019.

J. Fotouhi, M. Unberath, T. Song, J. Hajek, S.C. Lee, B. Bier, A. Maier, G. Osgood, M. Armand, N. Navab, "Co-localized augmented human and X-ray observers in collaborative surgical ecosystem," *International Journal of Computer Assisted Radiology and Surgery*, vol.14(9):1553-63, Sept. 2019.

B.A. Koutenaei, J. Fotouhi, F. Alambeigi, E. Wilson, O. Guler, M. Oetgen, K. Cleary, N. Navab, "Radiation-free methods for navigated screw placement in slipped capital femoral epiphysis surgery," *International Journal of Computer Assisted Radiology and Surgery*, vol. 14(12):2199-210, Dec. 2019.

M. Unberath, J.N. Zaech, C. Gao, B. Bier, F. Goldmann, S.C. Lee, J. Fotouhi, R. Taylor, M. Armand, N. Navab, "Enabling machine learning in X-ray-based procedures via realistic simulation of image formation," *International journal of computer assisted radiology and surgery*, vol. 14(9):1517-28, Sept. 2019.

Current Projects

Interactive Flying Frustums

Reflective-AR Display

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Director, Computer Aided Medical Procedures Laboratory

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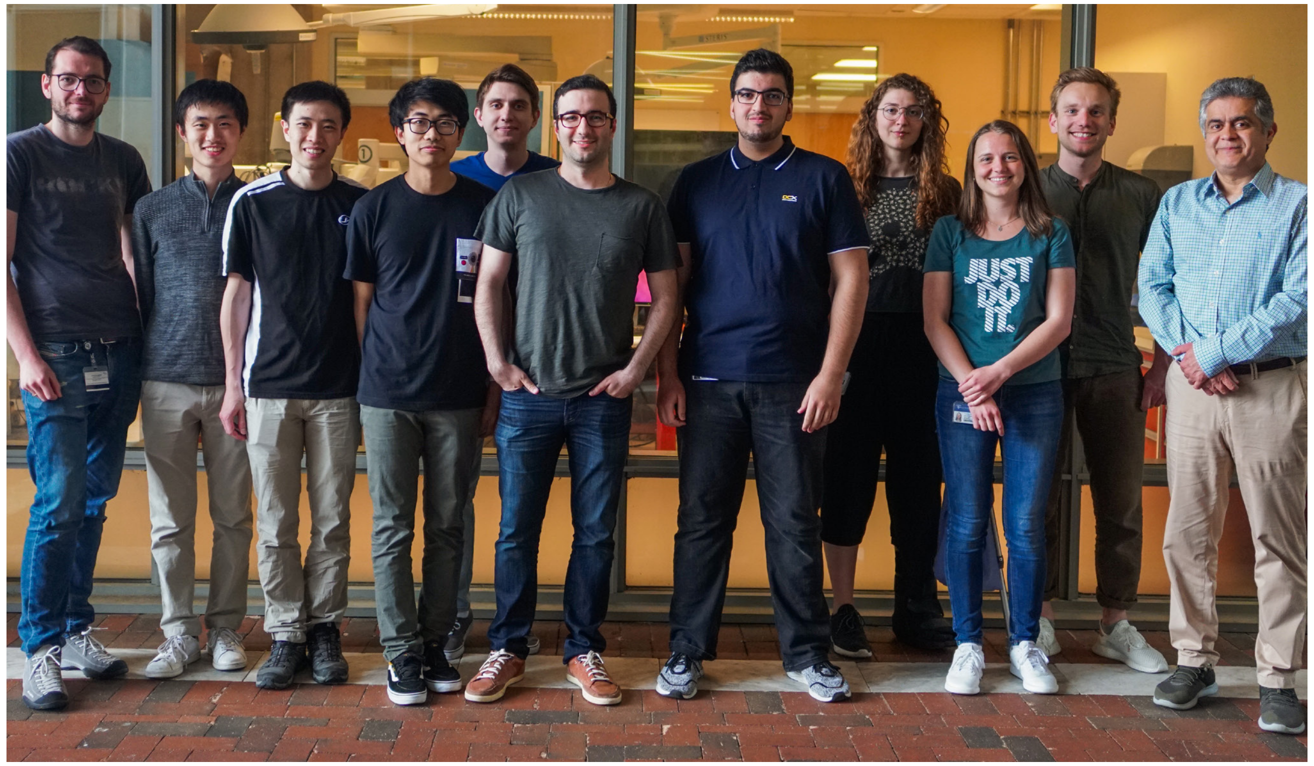
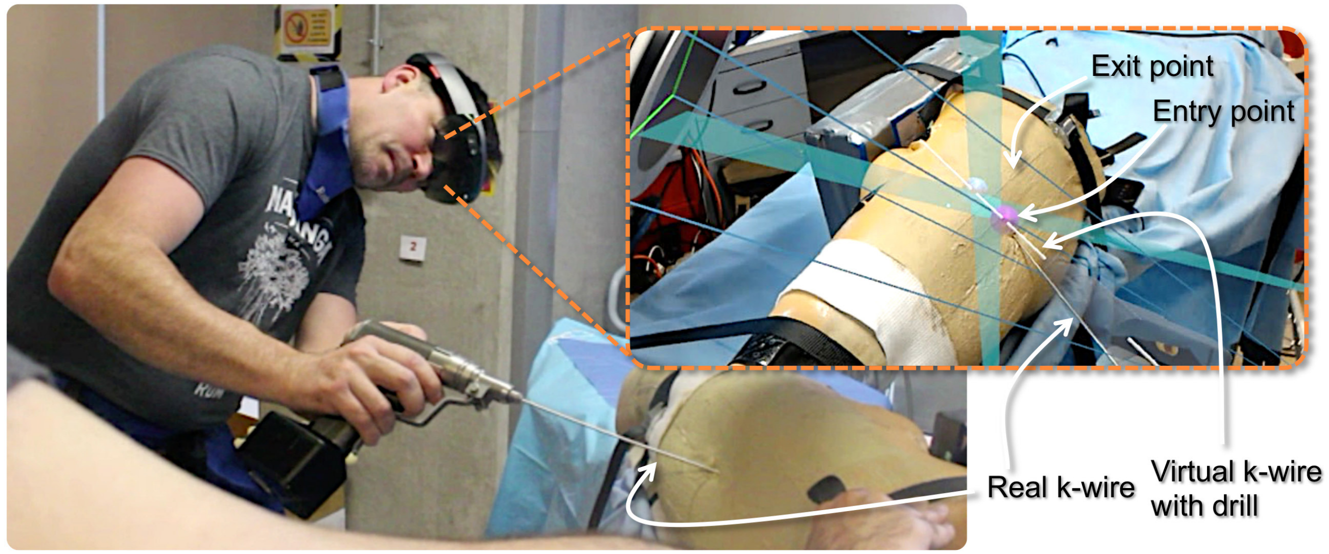
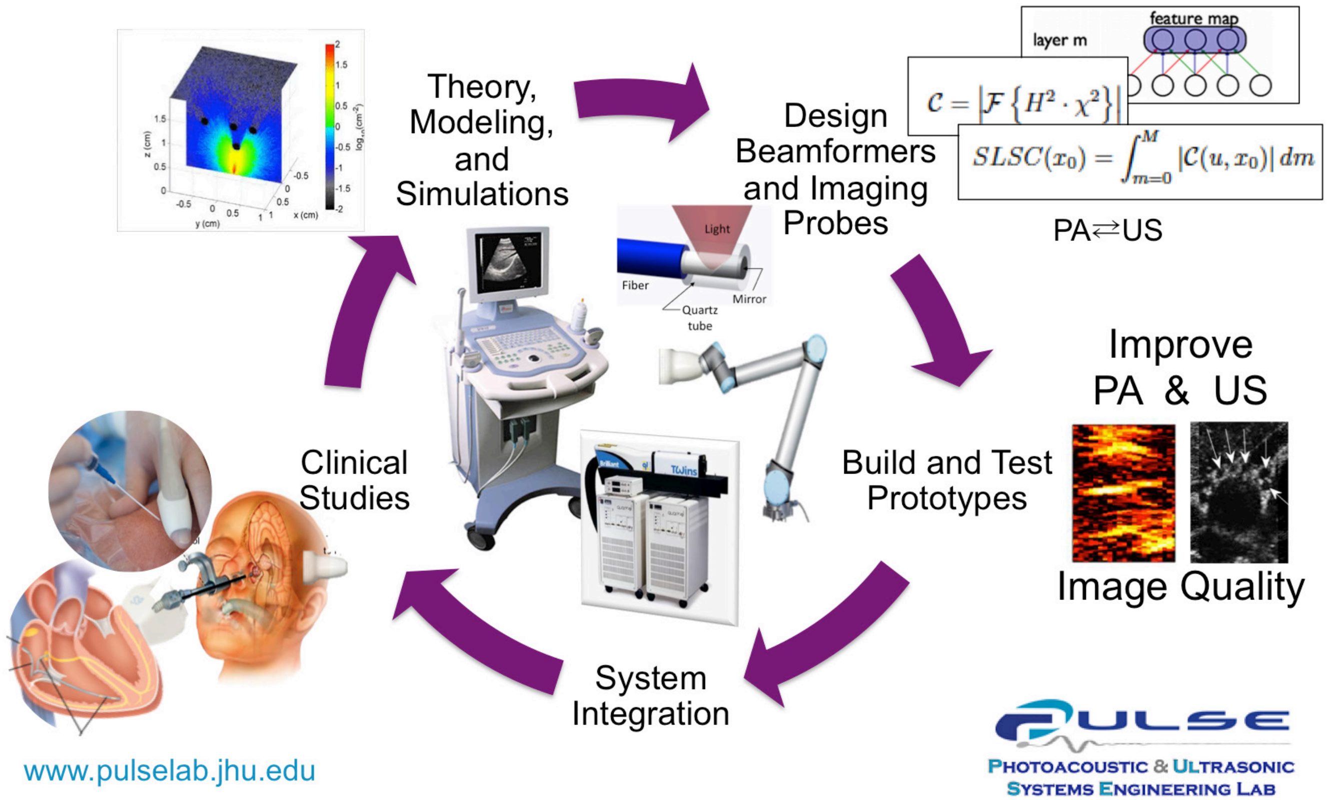




Photoacoustic and Ultrasonic Systems Engineering

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. The PULSE Lab's emphasis is diagnostic and surgical ultrasound and photoacoustic technologies, with applications in neurosurgery, cancer detection and treatment, and women's health. PULSE Lab technologies are designed to benefit patients through research-related clinical translation opportunities.

To achieve these goals, the PULSE Lab develops theories, models, and simulations to create advanced beamforming techniques that produce clearer ultrasonic and photoacoustic images. Complimenting this research are additional designs for light delivery systems for photoacoustic imaging and the incorporation of medical robots to improve ease-of-use for operators.

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 on both the Johns Hopkins University Homewood Campus and at the Johns Hopkins School of Medicine in East Baltimore.

Recent Accomplishments and Publications

Alycen Wiacek received the inaugural Whiting School of Engineering Research Trainee Award in 2019.

Kelley Kempski won an NSF Graduate Research Fellowship in 2019

Muyinatu Bell was named Maryland's Outstanding Young Engineer in 2019. She also received the Alfred P. Sloan Research Fellowship, the Allan C. Davis Medal from the Maryland Academy of Sciences, and the ORAU Ralph E. Powe Junior Faculty Enhancement Award in the same year. She was most recently selected to receive the inaugural IEEE UFFC Star Ambassador Lectureship Award from her IEEE professional society.

A. Wiacek, E. Oluyemi, K. Myers, L. Mullen, M.A.L. Bell, "Coherence-based beamforming increases the diagnostic certainty of distinguishing fluid from solid masses in breast ultrasound exams," *Ultrasound in Medicine and Biology* (accepted)

A. Rodriguez-Molares, O.M.H. Rindal, J. D'hooge, S. Måsøy, A. Austeng, M.A.L. Bell, H. Torp, "The generalized contrast-to-noise ratio: a formal definition for lesion detectability," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* (accepted)

M. Graham, F. Assis, D. Allman, A. Wiacek, E. González, M. Gubbi, J. Dong, H. Hou, S. Beck, J. Chrispin, M.A.L. Bell, "*In vivo* demonstration of photoacoustic image guidance and robotic visual servoing for cardiac catheter-based interventions," *IEEE Transactions on Medical Imaging* (accepted)

A. Wiacek, O.M.H. Rindal, E. Falomo, K. Myers, K. Fabrega-Foster, S. Harvey, M.A.L. Bell, "Robust short-lag spatial coherence imaging of breast ultrasound data: initial clinical results," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 66(3):527-540, 2019.

K. Kempski, A. Wiacek, M. Graham, E. González, B. Goodson, D. Allman, J. Palmer, H. Hou, S. Beck, J. He, M.A.L. Bell, "*In vivo* photoacoustic imaging of major blood vessels in the pancreas and liver during surgery," *Journal of Biomedical Optics*, 24(12):121905, 2019.

P. Huang, L. Su, S. Chen, K. Cao, Q. Song, P. Kazanzides, I. Iordachita, M.A.L. Bell, J. Wong, D. Li, K. Ding, "2D ultrasound imaging based intra-fraction respiratory motion tracking for abdominal radiation therapy using machine learning," *Physics in Medicine and Biology*, 64(18), 185006, 2019.

Current Projects

Photoacoustic-Guided Cardiac Catheter-Based Interventions

Photoacoustic-Guided Liver Surgery

Photoacoustic-Guided Cardiac Interventions

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Intuitive Computing

Chien-Ming Huang

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

Recent Accomplishments and Publications

G. Ajaykumar. C.-M. Huang., "User needs and design opportunities in enduser robot programming," *ACM/IEEE International Conference on Human-Robot Interaction Late-Breaking Report* (HRI'20 LBR), 2020.

Y. Wang, G. Ajaykumar, C.-M. Huang, "See what I see: enabling user-centric robotic assistance using first-person demonstrations," *ACM/IEEE International Conference on Human-Robot Interaction* (HRI'20), 2020.

K. Katyal, I.-J. Wang, G. Hager, C.-M. Huang, "Intent-aware human motion prediction using deep generative neural networks" in *Do Good Robotics Symposium*, 2019.

B. Paulhamus, E. Staley, C. Rivera, K. Katyal, C.-M. Huang, "Amplified control for robotic teleoperation," in *Do Good Robotics Symposium*, 2019.

Y. Gao, C.-M, Huang, "Robot programming by situated illustration," in *Do Good Robotics Symposium*, 2019.

A. Krishnaraj, "Designing social robots for early detection of mental health conditions," Master of Science in Engineering in Robotics (Robotics MSE) thesis, Johns Hopkins Univ., Baltimore, MD, 2019.

A. Ramachandran, C.-M. Huang, B. Scassellati, "Toward effective robot-child tutoring: intrinsic motivation, behavioral intervention, and learning outcomes," in *ACM Transactions on Interactive Intelligent Systems*, 2019.

Y. Gao, C.-M. Huang, "PATI: a Projection-based Augmented Table-top Interface for robot programming," *ACM International Conference on Intelligent User Interface* (IUI'19), 2019.

Current Projects

Human-Robot Co-Navigation

Human-Machine Teaming for Medical Decision Making

Accessible Robot Programing

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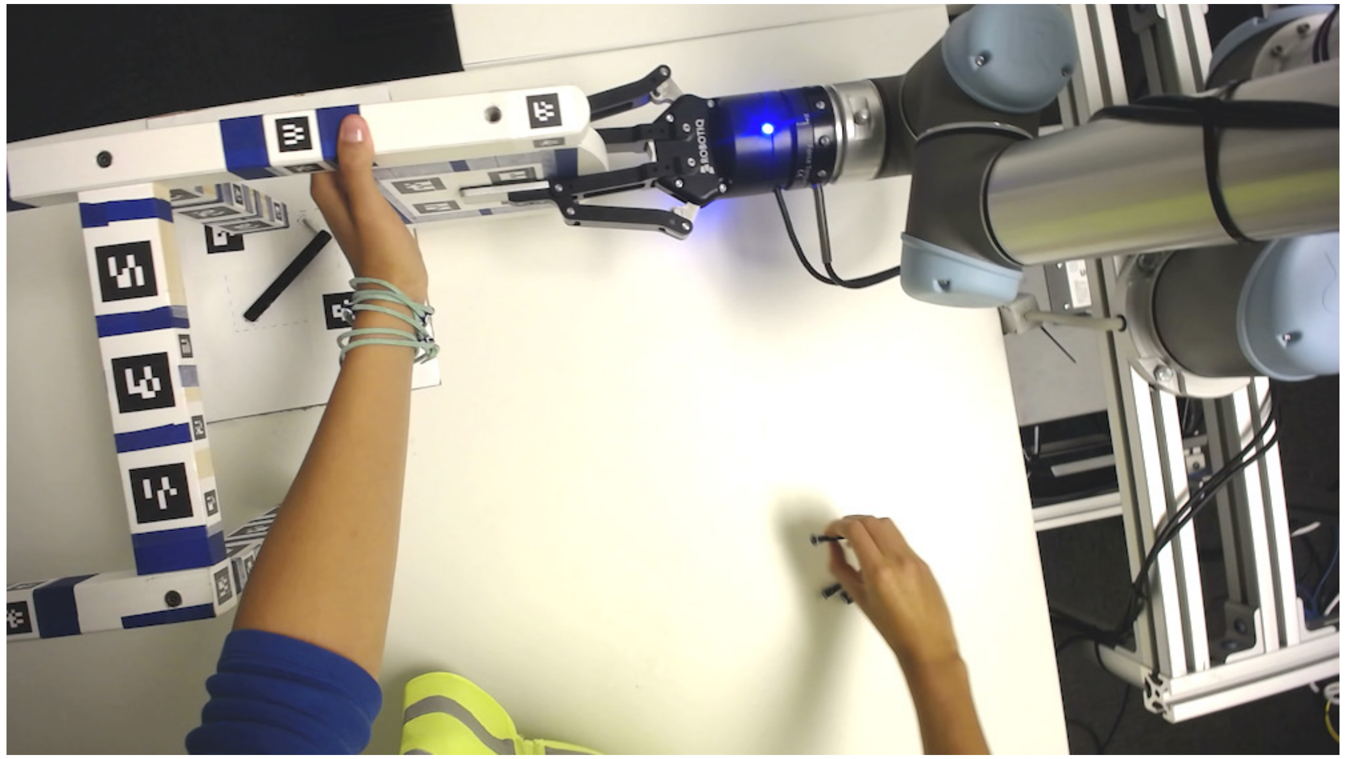

Advanced Robotics and Computationally Augmented Environments

Mathias Unberath

A new lab that opened in 2019, the Advanced Robotics and Computationally AugmenteD Environments (ARCADE) Laboratory focuses on computer vision, machine learning, augmented reality, and the application thereof to medical imaging, surgical robotics, and clinician-centric assistance systems. The ARCADE lab collaborates closely with care providers to understand clinical workflow, identify opportunities and constraints, and facilitate translation.

Recent Accomplishments and Publications

Our recent innovations designed to improve image guidance in fluoroscopy-guided interventions were distinguished with several international awards.

Our marker-free calibration paradigm that enables effective 3D visualization of intra-operative radiographs in dynamic augmented reality environments was Runner Up for the IJCARS Best Paper Award. Further, our research on anatomical landmark detection in pelvic X-ray received the MICCAI Young Scientist Award and the IJCARS Best Paper Award.

Bier, B., Goldmann, F., Zaech, J.N., Fotouhi, J., Hegeman, R., Grupp, R., Armand, M., Osgood, G., Navab, N., Maier, A. and Unberath, M., 2019. Learning to detect anatomical landmarks of the pelvis in X-rays from arbitrary views. *International journal of computer assisted radiology and surgery*, 14(9), pp.1463-1473.

Fotouhi, J., Unberath, M., Song, T., Hajek, J., Lee, S.C., Bier, B., Maier, A., Osgood, G., Armand, M. and Navab, N., 2019. Co-localized augmented human and X-ray observers in collaborative surgical ecosystem. *International journal of computer assisted radiology and surgery*, 14(9), pp.1553-1563.

Liu, X., Sinha, A., Ishii, M., Hager, G.D., Reiter, A., Taylor, R.H. and Unberath, M., 2019. Dense Depth Estimation in Monocular Endoscopy with Self-supervised Learning Methods. *IEEE transactions on medical imaging*.

Vercauteren, T., Unberath, M., Padoy, N. and Navab, N., 2019. CAI4CAI: The Rise of Contextual Artificial Intelligence in Computer-Assisted Interventions. *Proceedings of the IEEE*, *108*(1), pp.198-214.

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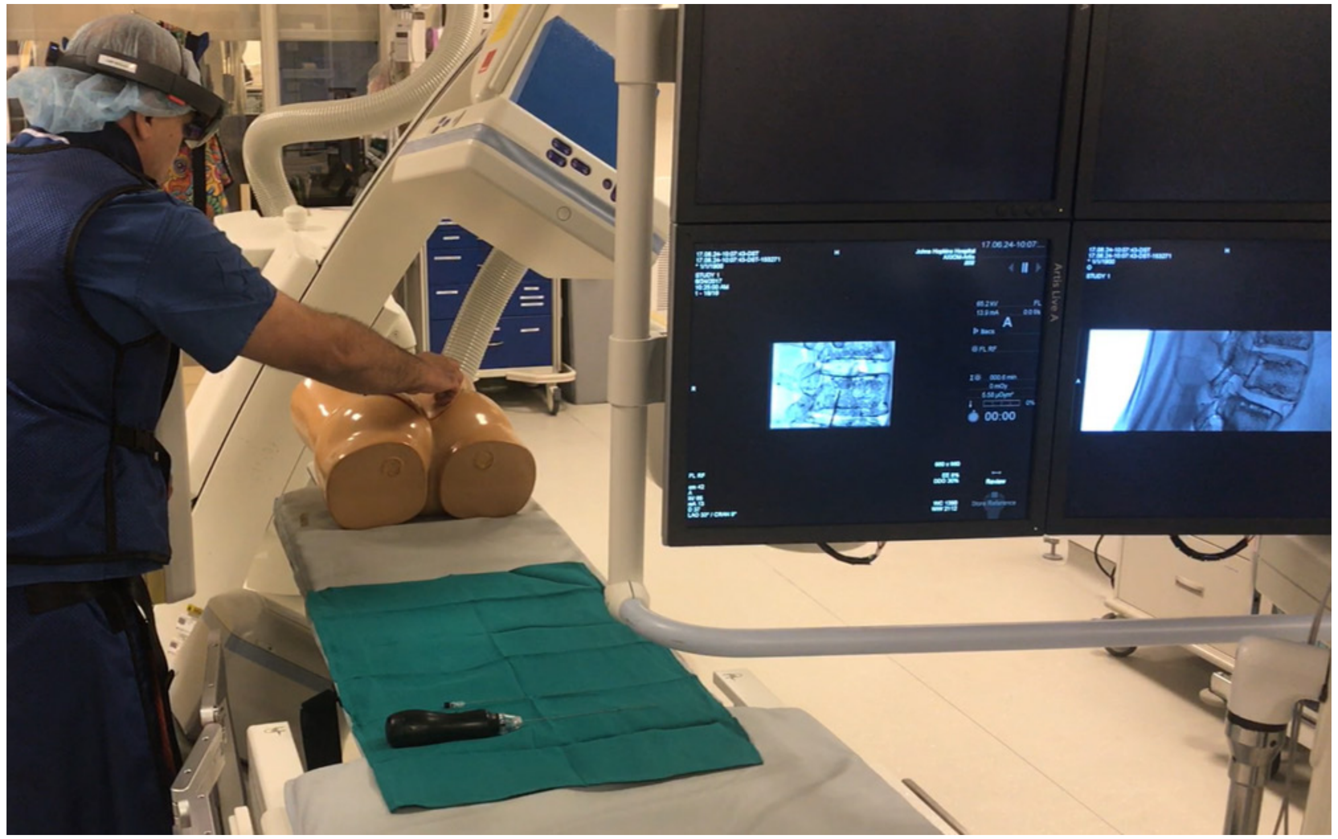

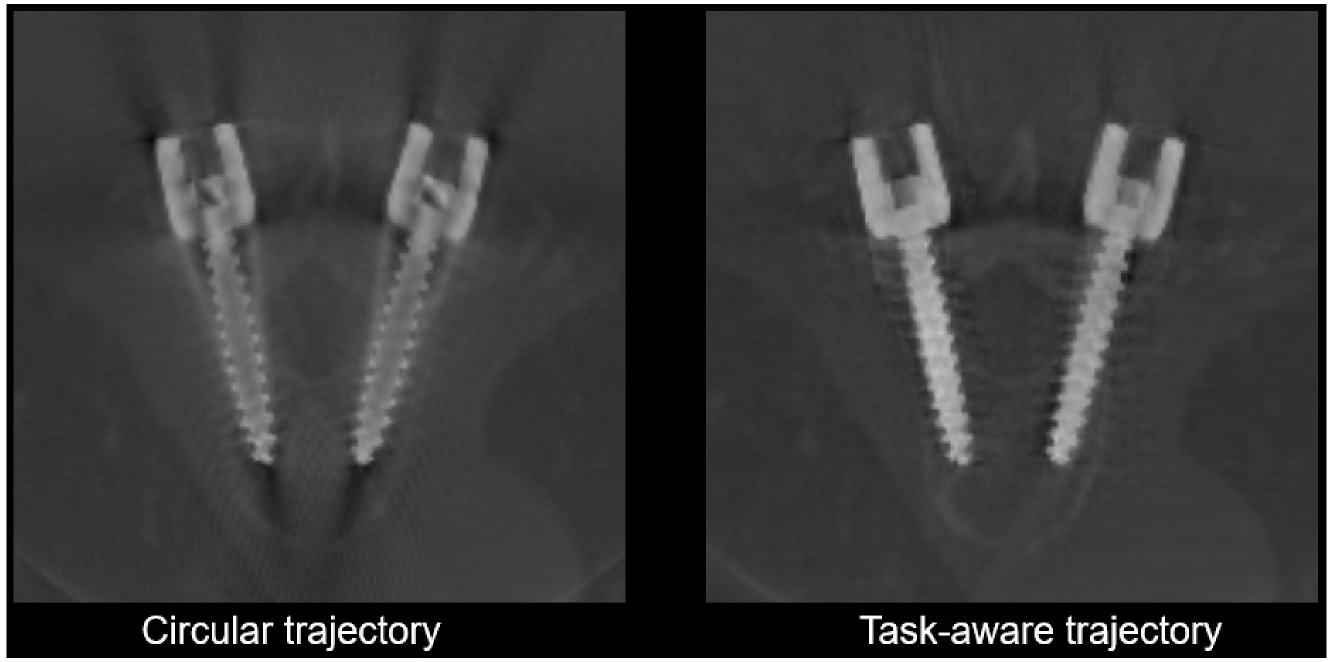

Medical Robotics and Equipment

Axel Krieger

Our work in the Medical Robotics and Equipment (MRE) [mys·tery] lab focuses on both basic research and translational research in the development of novel tools, imaging, and robot control techniques for medical robotics. Specifically, we investigate methodologies that increase the intelligence and autonomy of a device and improve image guidance of medical robots to perform previously impossible tasks, improve efficiency, and improve patient outcomes.

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Director, Medical Robotics and Equipment Laboratory
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Recent Accomplishments

2019 Best Paper Award IEEE 19th International Conference on Bioinformatics and Bioengineering (BIBE), Athens, Greece.

2019 University of Maryland Invention of the Year Finalist for Confidence Based Robot Control

2018 University of Maryland Pi Tau Sigma Excellence in Teaching Award

2016 Popular Science, The 12 Most Important Health Innovations of The Year for Smart Tissue Autonomous Robot (STAR): Most Dexterous Robot

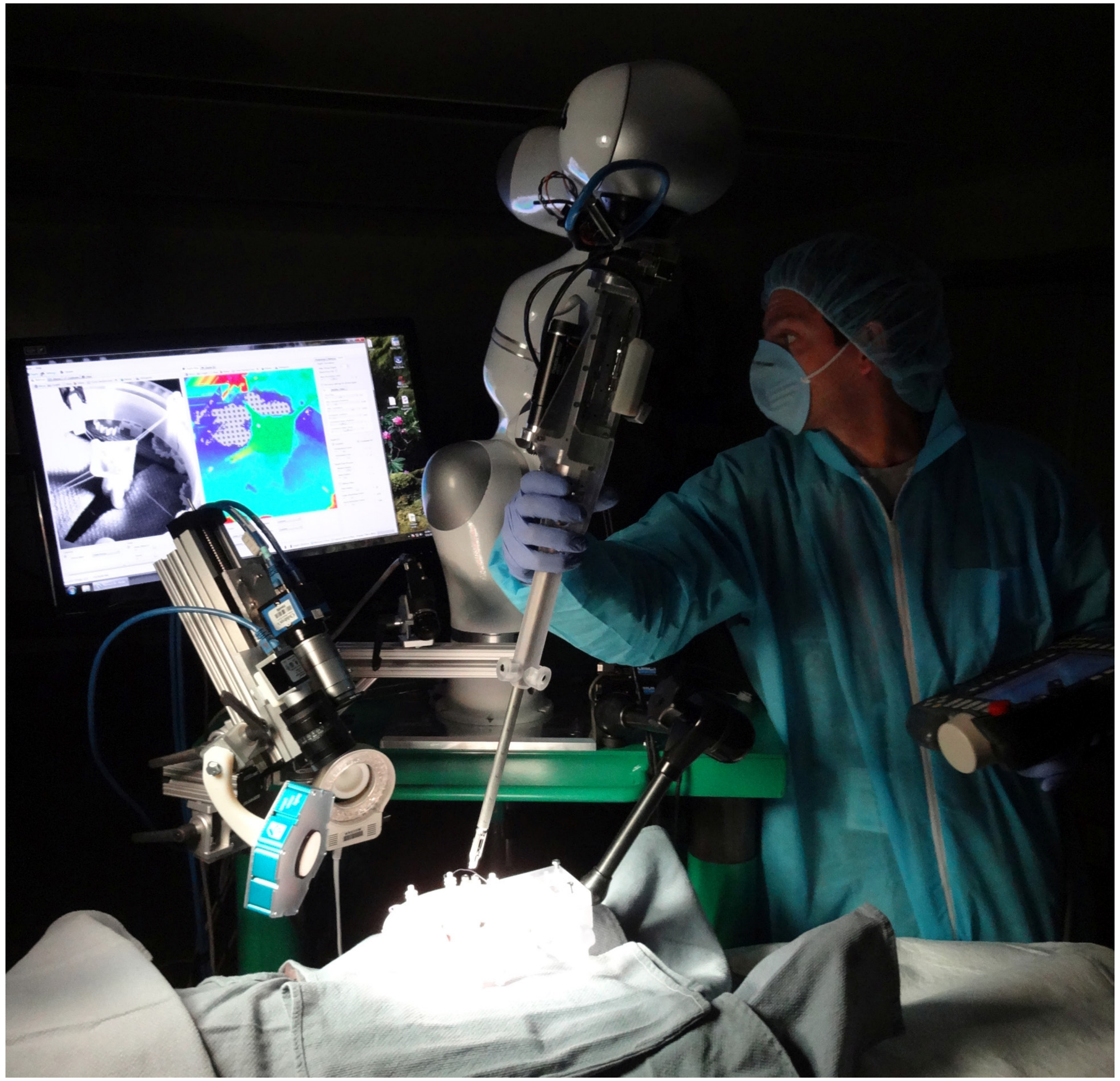
Recent Publications

Loke, Yue-Hin, Byeol Kim, Paige Mass, Justin D. Opfermann, Narutoshi Hibino, Axel Krieger, and Laura Olivieri. Role of Surgeon Intuition and Computer-Aided Design in Fontan Optimization: A Computational Fluid Dynamic Simulation Study. The Journal of Thoracic and Cardiovascular Surgery, 2020.

Guo S, Sarfaraz NR, Gensheimer WG, Krieger A, Kang JU. Demonstration of Optical Coherence Tomography Guided Big Bubble Technique for Deep Anterior Lamellar Keratoplasty DALK). Sensors (Basel). 2020 Jan 12;20(2). PMID: 31940877.

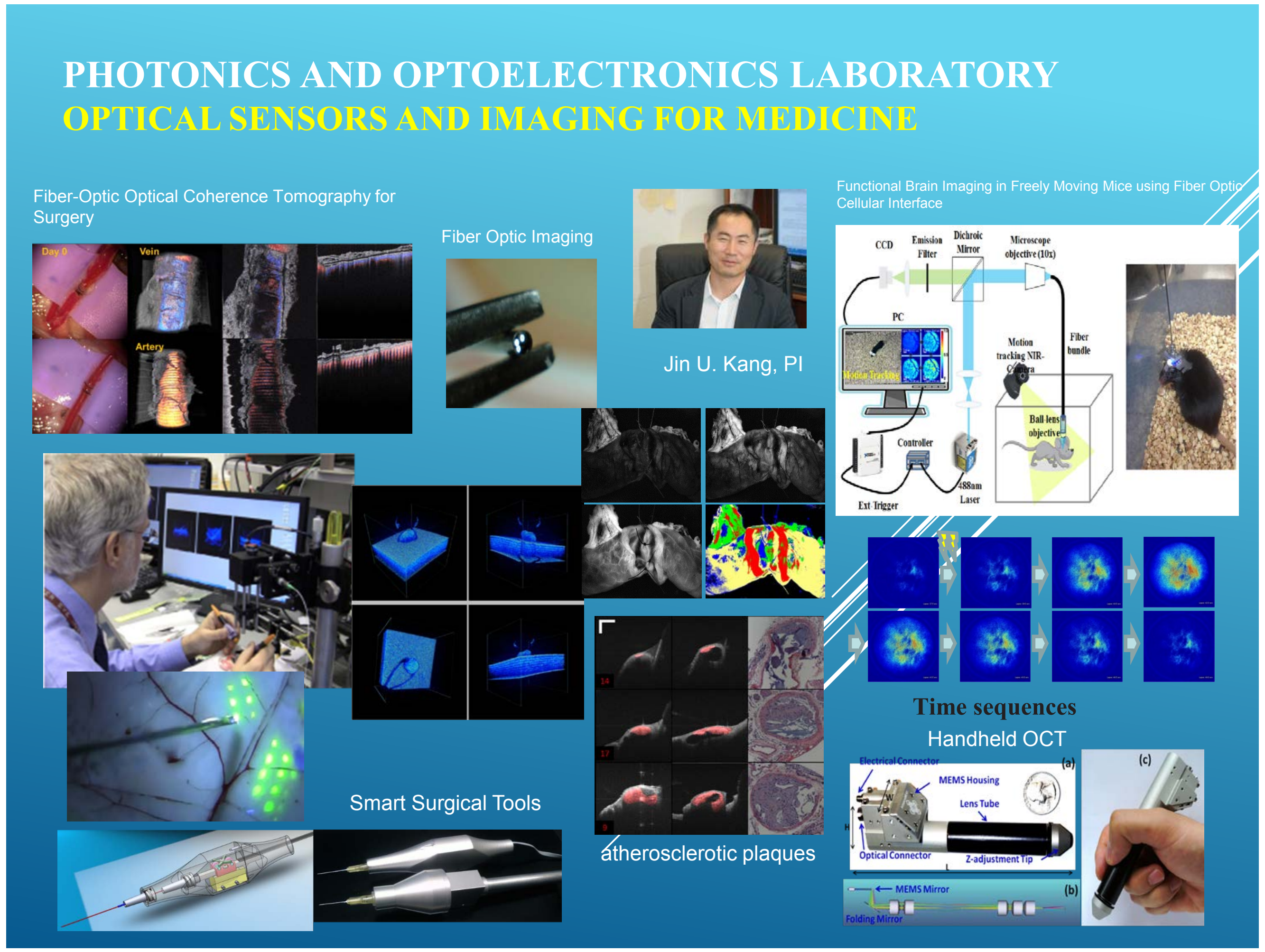
Yeung E, Inoue T, Matsushita H, Opfermann J, Mass P, Aslan S, Johnson J, Nelson K, Kim B, Olivieri L, Krieger A, Hibino N. *In vivo* implantation of 3-dimensional printed customized branched tissue engineered vascular graft in a porcine model. J Thorac Cardiovasc Surg. 2019 Oct 9.

H. Saeidi, J. Ge, M. Kam, J. D. Opfermann, S. Leonard, A. Joshi, and A. Krieger. Supervised Autonomous Electrosurgery via Biocompatible Near-Infrared Tissue Tracking Techniques, in IEEE Transactions on Medical Robotics and Bionics, vol. 1, no. 4, pp. 228-236, Nov. 2019.



Photonics and Optoelectronics

Jin U. Kang



The Photonics and Optoelectronics (PO) Laboratory conducts experimental and theoretical investigations in the area of photonics and optoelectronics with an emphasis on developing, novel fiber optic imaging and sensor systems, novel fiber laser systems, and ultrafast fiber optic and optoelectronic devices. These developments have applications in the areas of medicine, communications, and the space sciences.

The PO lab is currently developing optical coherence tomography (OCT) techniques for medical imaging and sensing; these systems have enabled the development of microsurgical and robotic tools that allow safer, more precise surgical outcomes. The lab was the first to develop and demonstrate real-time 4D OCT systems that allow real-time 3D video monitoring of surgical sites during operations.

The lab works closely with the NASA, FDA, ARL, NIST, NRL as well as local industries and other research groups in and outside the Johns Hopkins University.

Recent Accomplishments and Publications

Dr. Kang recently launched a JHU Fast Forward startup company, LIV (Live Imaging Vision) Med Tech Inc., to commercialize OCT image-guided robotic tools.

S. Lee, S. Wei, S. Guo, J. Kim, B. Kim, G. Kim, J.. Kang, “Selective retina therapy monitoring by speckle variance optical coherence tomography for dosimetry control,” *Journal of Biomedical Optics*, accepted for publication, Jan. 2020.

S. Guo, N.R. Sarfaraz, W.G. Gensheimer, A. Krieger, J.U. Kang, “Demonstration of optical coherence tomography guided big bubble technique for deep anterior lamellar keratoplasty (DALK),” *Sensors*, vol. 20, 428, 2020.

S. Guo, S. Wei, S. Lee, M. Sheu, S. Kang and J. U. Kang, "Intraoperative speckle variance optical coherence tomography for tissue temperature monitoring during cutaneous laser therapy," *IEEE Journal of Translational Engineering in Health and Medicine*, vol. 7, pp. 1-8, 2019.

S. Wei, S. Guo, J. Kang, "Analysis and evaluation of BC-mode OCT image visualization for microsurgery guidance," *Biomedical Optics Express*, vol. 10, pp. 5268-5290, 2019.

D. Heiferman, M. Heiferman, B. Africk, L. Ghadiali, E. Price, S. Pappu, J. Serrone, J. Kang, V. Prabhu, “Optical coherence tomography and its relevance to neurosurgical practice,” *Contemporary Neurosurgery*, vol. 41(11), July 30 2019.

J. Kang, H. Zhang, S. Kadam, J. Fedorko, H. Valentine, A. Malla, P. Yan, M. Harraz, J. Kang, A. Rahmim, A. Gjedde, L. Loew, D. Wong, E. Boctor, “Transcranial recording of electrophysiological neural activity in the rodent brain *in vivo* using functional photoacoustic imaging of near-infrared voltage-sensitive dye”, *Frontiers in Neuroscience*, May 2019.

S. Lee, C. Lee, R. Verkade, G.W. Cheon, J.U. Kang, “Common-path all-fiber optical coherence tomography probe based on high-index elliptical epoxy-lensed fiber,” *Optical Engineering*, vol. 58 (2), 026116.

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Brain, Learning, Animation, and Movement

John Krakauer and Adrian Haith

The Brain Learning, Animation, and Movement (BLAM) lab studies human movement, how people learn new movement skills, and how our capacity to move is affected by neurological diseases—in particular, stroke. The lab studies this through a combination of behavioral experiments and computational modeling, along with neuroimaging and brain stimulation.

A key feature of the BLAM lab's research is the relationship between cognition and motor control, which has led to projects examining cognitive control, decision making, habit formation and their relation to motor skill. The lab also studies the neurobiology of limb and hand control, how this is affected by stroke, and how it recovers over the months following a stroke.

Recent Accomplishments and Publications

Published a comprehensive, 50-page review of motor skill learning in Comprehensive Physiology.

Developed a novel device for measuring fine finger forces in 3-dimenions, simultaneously in all four fingers and the thumb, enabling us to assess hand dexterity in unprecedented detail.

Completed a thorough longitudinal study of stroke recovery (SMARTS) examining hand and arm control, along with neuroimaging and neurophysiology to precisely measure the process of recovery from stroke.

R. Kundert, J.Goldsmith, J. Veerbeek, J. Krakauer, A. Luft, "What the proportional recovery rule is (and is not): methodological and statistical considerations," 2019 Neurorehabilitation & Neural Repair, Sept. 15 2019.

D. Huberdeau, J. Krakauer, A. Haith. "Practice induces a qualitative change in the memory representation for visuomotor learning," Journal of Neurophysiology, Aug. 7 2019.

M. Branscheidt, N. Ejaz, J. Xu, M. Widmer, M. Harran, Juan. Cortés, T. Kitago, P. Celnik, C. Hernandez-Castillo, J. Diedrichsen, A. Luft, J. Krakauer, "No evidence for motor recovery-related cortical reorganization after stroke using resting-state fMRI" bioRxiv, June 26 2019.

G. Kwakkel, E. van Wegen, J. Burridge, C. Winstein, L. van Dokkum, M. Murphy, and J.. Krakauer, "Standardized measurement of quality of upper limb movement after stroke: consensus-based core recommendations from the Second Stroke Recovery and Rehabilitation Roundtable (2019) on behalf of the ADVISORY group," International Journal of Stroke, June 12 2019.

T. Scott, A. Albert, A. Hadjiosif, J. Jang, A. Zimnik, M. Churchland, J. Krakauer, R. Shadmehr, "Holding the arm still through integration of cortical commands," bioRxiv, June 1 2019.

H. Schambra, J. Xu, M. Branscheidt, M. Lindquist, J. Uddin, L. Steiner, B. Hertler, N. Kim, J. Berard, M. Harran, J. Cortes, T. Kitago, A. Luft, J. Krakauer, P. Celnik, "Differential post-stroke motor recovery in an arm versus hand muscle in the absence of motor evoked potentials," Neurorehabilitation and Neural Repair, June 6 2019.

Current Projects

Perception and Cognitive Systems

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Computational Cognition, Vision, and Learning

Alan Yuille

The main goal of the CCVL (Computational Cognition, Vision, and Learning) research group is to develop mathematical models of vision and cognition. These models are intended primarily for designing artificial (computer) vision systems. Learning is required for extracting knowledge from data. Practical applications include vision for the disabled. These models also serve as computational models of biological vision which can be tested by behavioral methods and, in collaborative projects, with invasive, and non-invasive neuroscience techniques. We also study how humans and animals perform cognitive tasks such as learning and reasoning. In addition, we also use machine learning for interpreting medical images and studying brain function. CCVL collaborates with many other groups at JHU including others in LCSR (Prf. G. Hager), Cognitive Science, the Mind/Brain Institute, and the Department of Radiology.

Recent research projects include: (i) early detection of pancreatic cancer from Computer Tomography Images, (ii) attacks on deep network algorithms, (iii) defenses of deep network algorithms, (iv) improving the performance of deep networks using attacked images, (v) designing virtual worlds for testing machine learning algorithms, (vi) training vision algorithms using virtual data to improve performance on real work images (for tasks which are hard to annotate.

Recent Accomplishments and Publications

The FELIX project, in collaboration with the Department of Radiology, on automated detection of Pancreatic Cancer was featured by NPR.

CCVL was founded in January 2016. Since them it has produced about 130 peer reviewed journals and conference papers, with roughly 70 in the last two years. All the publications can be found at https://ccvl.jhu.edu/publication/

L.C. Chen, G. Papandreou, I. Kokkinos, K. Murphy, A.L. Yuille, “DeepLab,” IEEE Transactions on Pattern Analysis and Machine Intelligence 40(4), pp. 834-848. 2017.

L.C. Chen, Y. Yang, J. Wang, W. Xu, A.L. Yuille, “Attention to scale,” Conference on Computer Vison and Pattern Recognition, 2016.

C. Liu, B. Zoph, M., Neumann, J. Shlens, W. Hua, J. Li, F.F. Li, A. Yuille, J. Huang, K. Murphy, “Progressive Neural Architecture Search,” European Conference on Computer Vision, 2018.

J. Mao, J. Huang, A. Toshev, O. Camburu, A.L. Yuille, K Murphy, “Generation and Comprehension of Unambiguous Object Descriptor,” Conference on Computer Vision and Pattern Recognition, 2016.

X. Chu, W. Yang, W. Ouyang, C. Ma, A.L. Yuille, X. Wang, “Multi-context Attention for Human Pose Estimation,” Conference on Computer Vision and Pattern Recognition, 2017.

C. Xie, J. Wang, Z. Zhang, Y. Zhou, L. Xie, A. Yuille, “Adversarial Examples for Semantic Segmentation and Object Detection.” International Conference on Computer Vision, 2017.

Current Project

Felix Project: Early Detection of Pancreatic Tumors

Alan Yuille
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Director, Computational Cognition, Vision, and Learning
ayuille1@jhu.edu

Areas of Impact

Bio-Robotics	Human-Machine Collaborative Systems	Medical Robots and Computer Integrated Interventional Systems	Modeling, Dynamics, Navigation, and Control	Perception and Cognitive Systems	Robotics in Extreme Environments

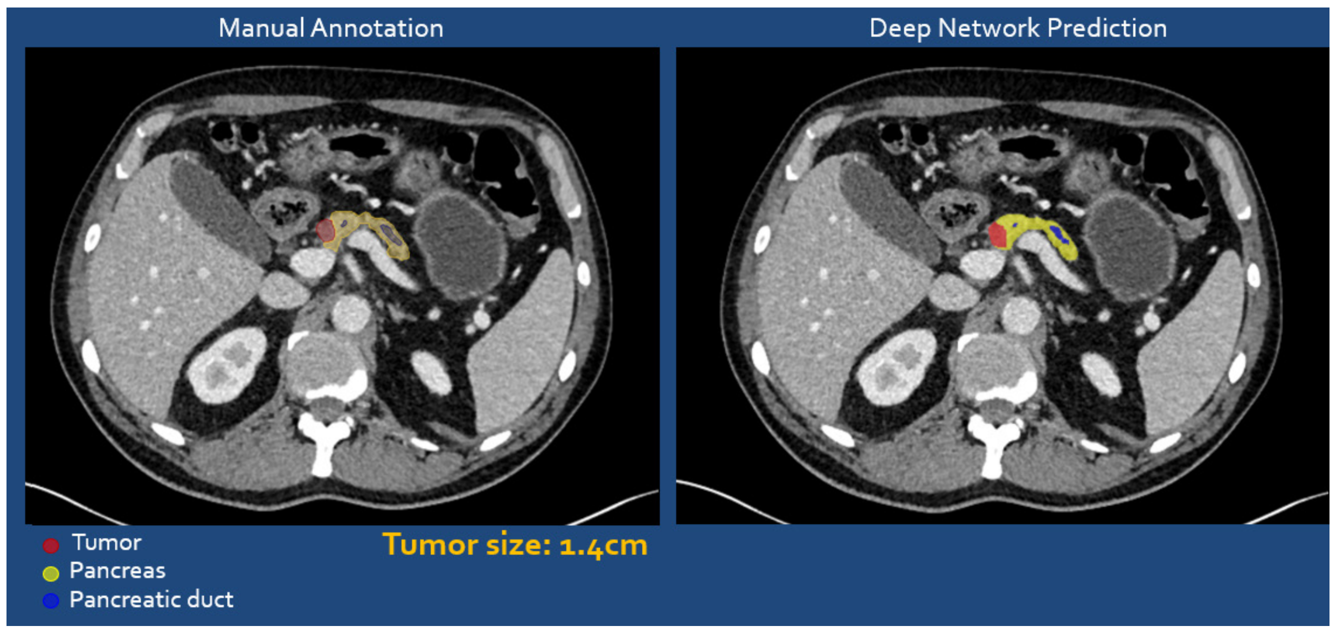
Color key for research areas

Projects

Felix Project: Early Detection of Pancreatic Tumors

PI: Alan Yuille

Perception and Cognitive Systems



Key Personnel: E. Fishman, B. Vogelstein, A. Yuille

Funding: Lustgarten Foundation

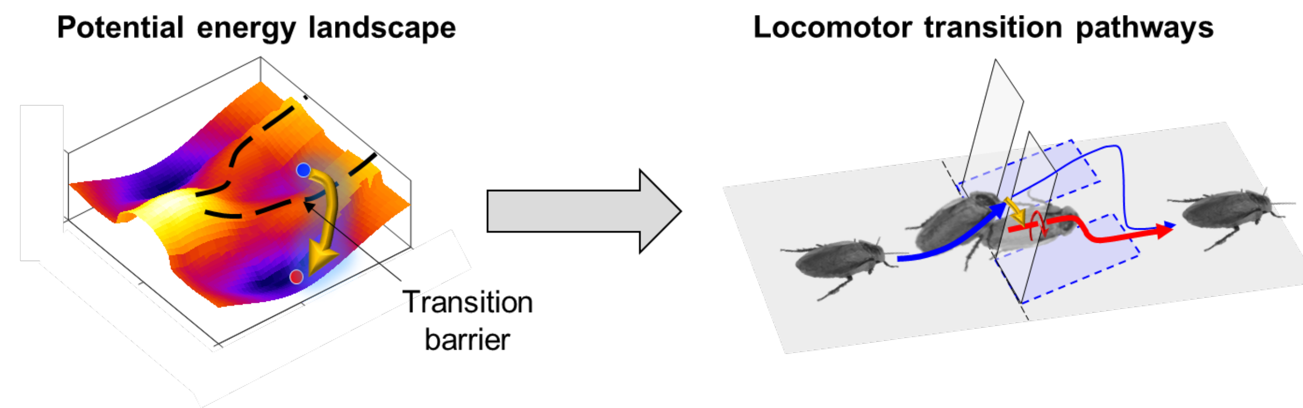
Find out more: https://www.hopkinsmedicine.org/news/publications/hopkins_medicine_magazine/features/spring-summer-2019/this-is-our-manhattan-project

Accomplishments and Status: Pancreatic cancer is an extremely deadly disease unless it is detected early enough to enable treatment. In collaboration with the Department of Radiology and Radiological Science at the Johns Hopkins School of Medicine, we create a dataset of computer tomography (CT) images with the pancreas and pancreatic tumors annotated. We train Deep Networks on this dataset and show they are highly effective at detecting the pancreas and small tumors inside it.

Towards Terradynamics of Dynamic Legged Locomotion in Complex 3D Terrains

PI: Chen Li

Perception and Cognitive Systems



Key Personnel: Ratan Othayoth, Qihan Xuan, Chen Li

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

Funding: Army Research Office Young Investigator Program

Accomplishments and Status: The goal is to test the hypothesis that legged animals use their natural body oscillations to move in complex terrain.

Journal papers published: *Li C**, Wöhrl T, Lam HK, Full RJ (2019), Cockroaches use diverse strategies to self-right on the ground, *Journal of Experimental Biology*, 222, jeb186080

Gart SW, Yan C, Othayoth R, Ren Z, ***Li C** (2018). Dynamic traversal of large gaps by insects and legged robots reveals a template, *Bioinspiration & Biomimetics*, 13, 026006

Gart SW, *Li C (2018). Body-terrain interaction affects large bump traversal of insects and legged robots, *Bioinspiration & Biomimetics*, 13, 026005

Journal papers submitted: Xuan Q, ***Li C**, Coordinated appendages help accumulate energy to overcome barrier in leg-assisted, winged ground self-righting, *IEEE Robotics and Automation Letters*, submitted

Othayoth R, Thoms G, ***Li C**, An energy landscape of locomotor transitions in complex terrain, *Proceedings of the National Academy of Sciences*, in revision

Han Y, Wang Y, Hsu C-C, de la Tijera Obert R, Francois E, ***Li C**, Shape-modulated obstacle attraction and repulsion during dynamic locomotion, *International Journal of Robotics Research*, in review

The Terradynamics of Biological Movement in Complex Terrain

PI: Chen Li

Bio-Robotics

Modeling, Dynamics, Navigation, and Control

Robotics in Extreme Environments

Funding: Burroughs Welcome Fund Career Award at the Scientific Interface

Key Personnel: Qiyuan Fu, Sean Gart, Tommy Mitchel, Chen Li

Accomplishments and Status: This project tests the biological hypothesis that terrestrial animals use terradynamic shapes to move in complex terrain (analogous to aero- and hydrodynamic shapes like airfoil and streamlined body).

Journal papers published: Fu Q, *Li C (2020), Robotic modeling of snake traversing large, smooth obstacles reveals stability benefits of body compliance, *Royal Society Open Science*, 7, 191192

***Li C**, Wöhrl T, Lam HK, Full RJ (2019), Cockroaches use diverse strategies to self-right on the ground, *Journal of Experimental Biology*, 222, jeb186080

Gart SW, Yan C, Othayoth R, Ren Z, *Li C (2018). Dynamic traversal of large gaps by insects and legged robots reveals a template, *Bioinspiration & Biomimetics*, 13, 026006

Gart SW, *Li C (2018). Body-terrain interaction affects large bump traversal of insects and legged robots, *Bioinspiration & Biomimetics*, 13, 026005

*Li C, Kessens CC, Fearing RS, Full RJ (2017). Mechanical principles of dynamic terrestrial self-righting using wings, *Advanced Robotics*, 31, 881-900 (Invited Paper; *Advanced Robotics* Best Paper Award, 4 awards out of 96)

Conference papers published: *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 awards out of 840)

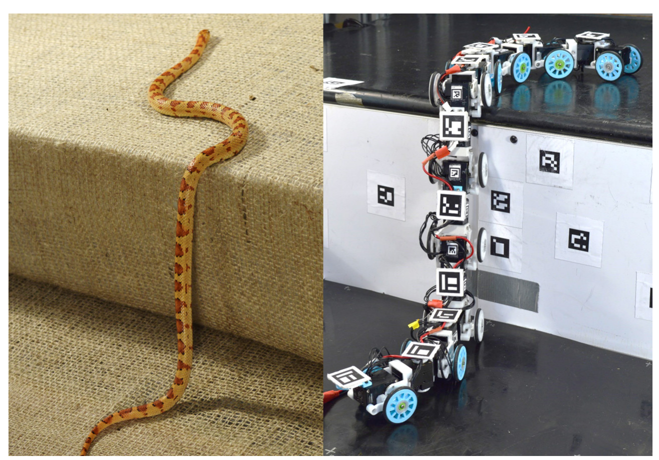
Journal papers submitted: Xuan Q, *Li C, Coordinated appendages help accumulate energy to overcome barrier in leg-assisted, winged ground self-righting, *IEEE Robotics and Automation Letters*, submitted

Othayoth R, Thoms G, *Li C, An energy landscape of locomotor transitions in complex terrain, *Proceedings of the National Academy of Sciences*, in revision

Han Y, Wang Y, Hsu C-C, de la Tijera Obert R, Francois E, *Li C, Shape-modulated obstacle attraction and repulsion during dynamic locomotion, *International Journal of Robotics Research*, in review

†Mitchel TW, †Fu Q, Kim JS, Chirikjian GS, *Li C, Continuous body 3D reconstruction of limbless animals using elastic rod modeling and backbone optimization, *Journal of Experimental Biology*, in review

Fu Q, Gart SW, Mitchel TW, Kim JS, Chirikjian GS, *Li C, Body undulation and compliance help snakes and snake robots traverse stably traverse large, smooth obstacles, *Integrative & Comparative Biology*, in review (Invited Paper)



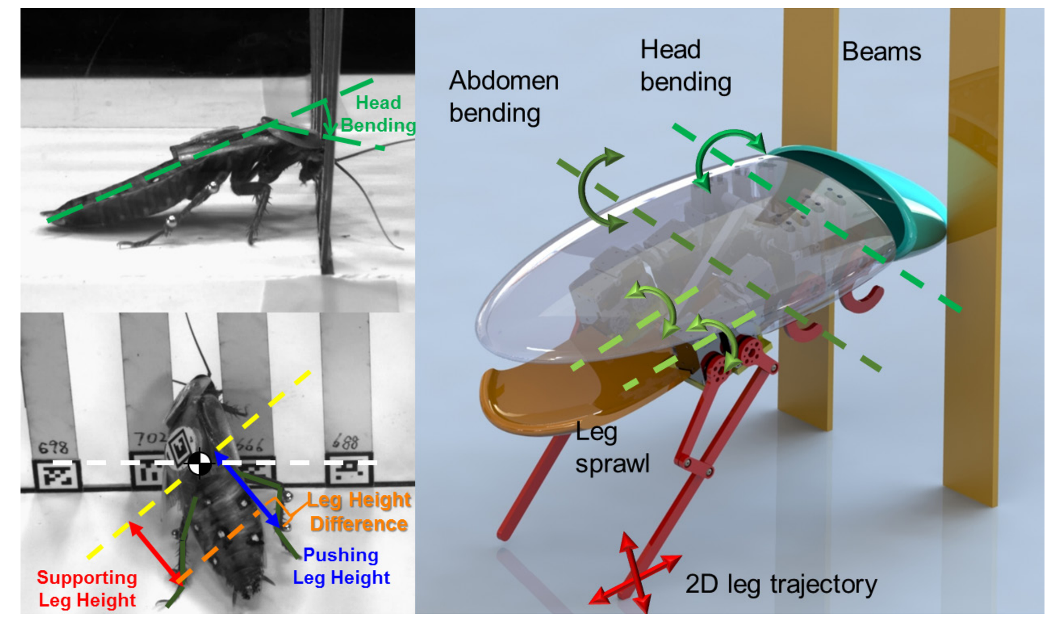
Neuromechanics of Legged Locomotion on Energy Landscapes of Complex Terrains

PI: Chen Li

Bio-Robotics

Modeling, Dynamics, Navigation, and Control

Robotics in Extreme Environments



Key Personnel: Yaqing Wang, Ratan Othayoth, Divya Ramesh, Chen Li

Funding: Arnold and Mabel Beckman Foundation

Accomplishments and Status: This project studies the neuromechanics of how animals actively sense and make adjustments to move in complex terrain by developing new instruments to measure sensor input and motor output.

Publications: Fu Q, ***Li C** (2020), Robotic modeling of snake traversing large, smooth obstacles reveals stability benefits of body compliance, *Royal Society Open Science*, 7, 191192

Xuan Q, ***Li C**, Coordinated appendages help accumulate energy to overcome barrier in leg-assisted, winged ground self-righting, *IEEE Robotics and Automation Letters*, submitted

Othayoth R, Thoms G, ***Li C**, An energy landscape of locomotor transitions in complex terrain, *Proceedings of the National Academy of Sciences*, in revision

Han Y, Wang Y, Hsu C-C, de la Tijera Obert R, Francois E, ***Li C**, Shape-modulated obstacle attraction and repulsion during dynamic locomotion, *International Journal of Robotics Research*, in review

†Mitchel TW, †Fu Q, Kim JS, Chirikjian GS, ***Li C**, Continuous body 3D reconstruction of limbless animals using elastic rod modeling and backbone optimization, *Journal of Experimental Biology*, in review

Fu Q, Gart SW, Mitchel TW, Kim JS, Chirikjian GS, ***Li C**, Body undulation and compliance help snakes and snake robots traverse stably traverse large, smooth obstacles, *Integrative & Comparative Biology*, in review (Invited Paper)

Human-Robot Co-Navigation

PI: Chien-Ming Huang

Human-Machine Collaborative Systems

Key Personnel: Kapil Katyall-Jeng Wang

Funding: JHU IAA seed fund

Accomplishments and Status: As we build and transition into the autonomous future, it is critical to place people at the center of our disruptive innovations. Therefore, this research aims to design, develop, and evaluate human-centered assured autonomy; we focus this project particularly on socially aware robot navigation in human environments. While abundant research has explored techniques for enabling mobile robots to navigate in human environments, most efforts have been on avoiding collisions with dynamic (e.g., people) and static (e.g., environmental constraints) obstacles and treated pedestrians as individual entities neglecting social grouping and their interactions. However, to maximize utility and ensure a wide acceptance and trust of intelligent mobile robots in assisting human work, we need to probe beyond simple obstacle avoidance and consider the more complicated aspects of social norms and interpersonal interactions in naturalistic human environments. This research particularly addresses the aspects of technology and ecosystem in assured autonomy.

Through three research thrusts, the team will investigate (1) dynamic social groups in human environments; (2) socially aware robot navigation; and (3) the longer-term effects of deploying mobile robots in naturalistic human environments. The successful integration of autonomous mobile robots into human spaces has the opportunity to revolutionize the future of human work. Our collaborative efforts in human-centered assured autonomy will help guide this revolution and contribute to the creation of a productive human-robot ecosystem. This project expects to generate tangible products, including (a) scholarly publications; (b) an open-source software testbed for simulating human social groups and navigation; (c) a physical testbed for studying social navigation; (d) a field deployment of human-robot co-navigation; and (e) guidelines for designing autonomous mobile robots and smart environments for near-term effective human-robot interaction.

Human-Machine Teaming for Medical Decision Making

PI: Chien-Ming Huang

Human-Machine Collaborative Systems

PI: Chien-Ming Huang

Key Personnel: Suchi Saria

Funding: NSF

Find out more: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1840088&HistoricalAwards=false

Accomplishments and Status: Algorithmic advances in artificial intelligence are transforming human work in diverse areas including transportation, finance, national security, and medicine. Machine intelligence presents opportunities to increase human work productivity and the quality of jobs through augmenting human capabilities. Effective teaming between humans and intelligent machines similar to effective human-human teamwork has the potential to yield significant near-term gains. This project explores the challenges of human-machine teaming in medical decision making. Health care is one of the most difficult challenges that the United States is facing. The U.S. spends $3 trillion dollars in health care each year, while medical error is the third leading cause of death. Human-machine cognitive teaming creates a new model of patient care in which providers team with intelligent cognitive assistants to enhance quality of care under time pressure, taxing workloads, and uncertainties in medical conditions. This project explores the potential for effective human-machine teaming to mitigate such challenging problems in health care.

Specifically, this project seeks to understand (1) whether human-machine teaming can benefit medical decision making and decision making in other related high stakes domains; (2) the guiding principles for designing effective human-machine teams; (3) barriers that currently exist for building such teams; (4) novel solutions needed to address barriers in order to develop highly performant teams; and (5) the economic and societal impacts of the planned approach for human-machine teaming. Understanding effective human-machine teaming, including the broader implications in the workspace and in human workflows, will contribute to positive transformation of human work. In particular, it is anticipated that the outcomes of this project will result in improvements in hospital utilization and reduction of medical errors. The project integrates multiple disciplinary perspectives, including computer science, medical expertise, health policy, and decision making. The impacts of the research will extend to multiple hospitals in the Baltimore region. Furthermore, the project will engage local high school students in summer research experiences, and the outcomes of the research will be integrated into undergraduate curricula.

Accessible Robot Programming

PI: Chien-Ming Huang

Human-Machine Collaborative Systems

Perception and Cognitive Systems

Funding: JHU internal funding

Accomplishments and Status: The goal of accessible robot programming is to empower everyday people who may not have technical training or backgrounds to be able to author robotic assistance to meet their needs and contextual constraints.

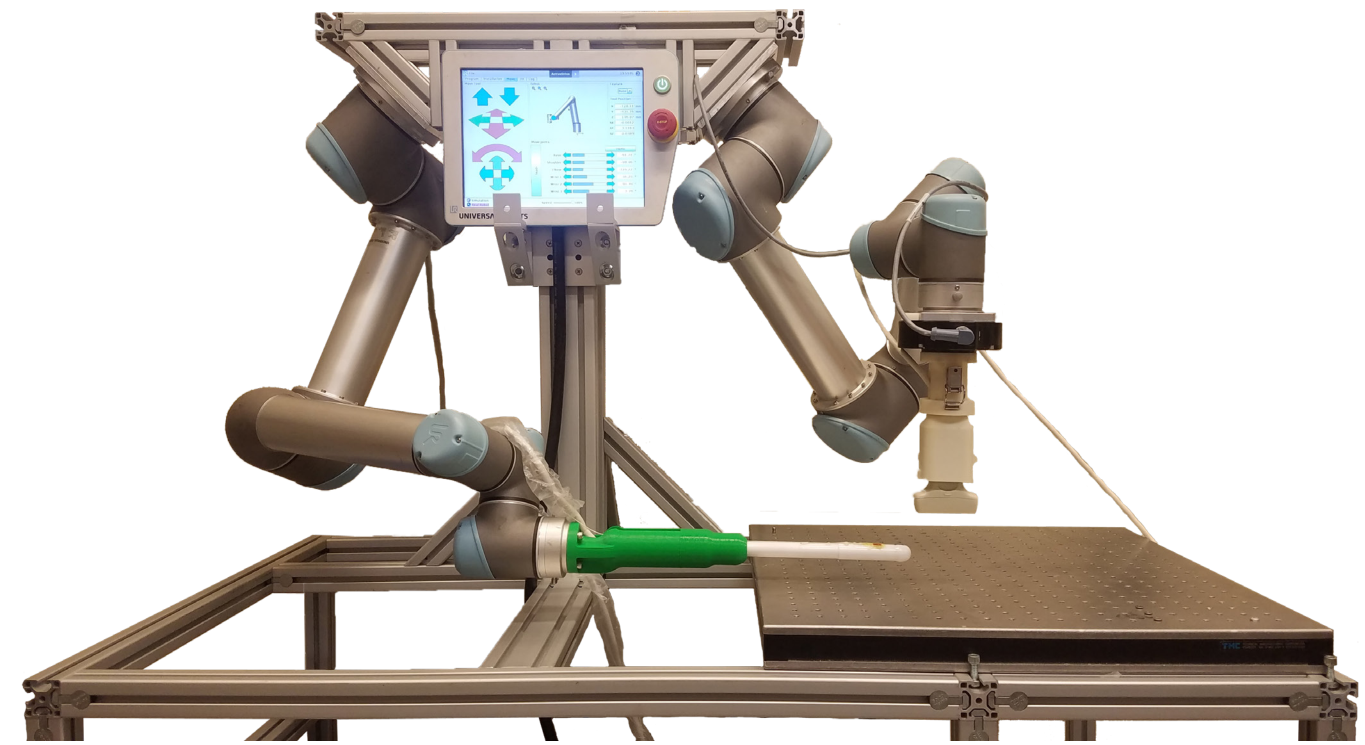
Collaborative robots are envisioned to assist people in an increasing range of domains, from manufacturing to home care; however, due to the variable nature of these fields, such robots will inevitably face unfamiliar situations and unforeseen task requirements, and must be able to interact with users who possess diverse skill sets, backgrounds, and needs. Presently, robust, autonomous solutions for appropriately handling these vast possibilities and uncertainties are unattainable. End-user robot programming offers an alternative approach that lets end users provide task specifications and author robot skills to meet their own specific contextual constraints and custom task needs. Contextual information— such as task objects, environmental landmarks, and user preferences— is essential in realizing desirable, flexible, and reliable robot programs. However, most robot programming systems at present do not afford intuitive ways of specifying contextual information. This project explores new approaches to providing a robot system with contextual information about the user, task, and environment, and how these methods can help improve task performance and user experience.

Co-Robotic Ultrasound Tomography Framework for *In Vivo* Prostate Imaging

PI: Emad Boctor

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Kevin Gilboy, Yixuan Wu, Russell Taylor, Emad Boctor

Accomplishments and Status: Our goal is to develop a co-robotic framework for controlled ultrasound slice acquisition of the *in vivo* prostate. Slices are to be acquired via transmission ultrasound between robotically held, collinear Tx and Rx probes flanking the anatomy to be imaged: one located abdominally, and one located transrectally for prostate imaging. These slices will then serve as input to a limited-angle tomography reconstruction algorithm previously developed by our lab to generate a quantitative measurement of the prostate's acoustic properties.

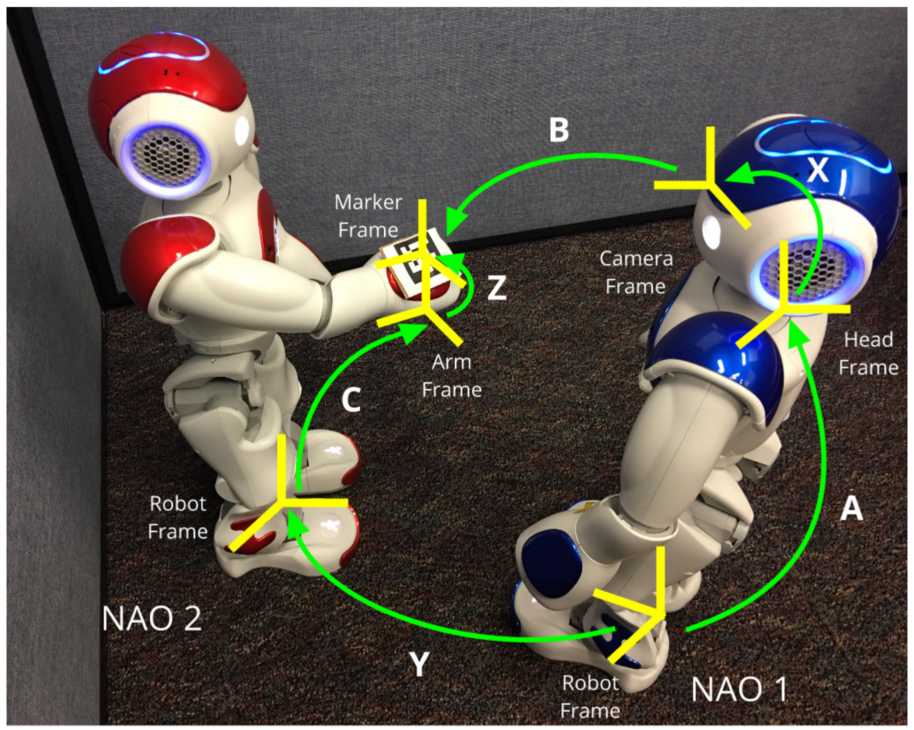
The robot control framework that keeps the abdominal probe held against the skin and aligned with the hand-maneuvered transrectal (TRUS) probe has been developed. Over the coming weeks, our team will use the robotic system to acquire ultrasound slices of a pelvic phantom that has varying speed-of-sound within the prostate and perform tomographic reconstruction to measure the system's overall effectiveness in tissue characterization.

Conformational Probabilities: A Bridge Between Innate Knowledge and Action Recognition

PI: Gregory Chirikjian

Human-Machine Collaborative Systems

Modeling, Dynamics, Navigation, and Control



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

Funding: ONR Award

Accomplishments and Status:

Goals: 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.

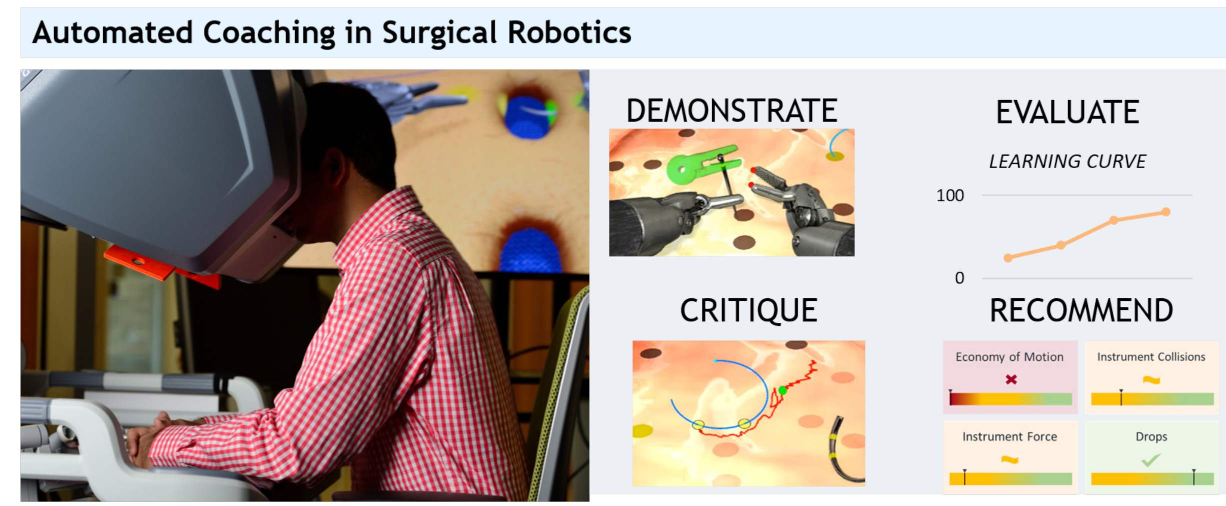
The mapping between observed actions to classes in the quotient space has been formalized. This framework will be developed further and will be demonstrated on a robotic testbed (displayed in figure) which is currently under development.

The Language of Surgery Project

PI: Gregory Hager

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: *Whiting School of Engineering*: Gregory Hager, Anand Malpani, Swaroop Vedula, Narges Ahmidi

School of Medicine: Masaru Ishii, Shameema Sikder, Gina Adrales, Grace Chen

Past Collaborators: Sanjeev Khudanpur, Rene Vidal, David Yuh, Steve Hsiao

Funding: Current and past sources supporting research in this project include:
NSF
NIH
Intuitive Surgical, Inc.
Wilmer Eye Institute Pooled Professors Fund
Johns Hopkins Science of Learning Institute

Find out more: https://cirl.lcsr.jhu.edu/research/language-of-surgery-update

Accomplishments and Status: The core research objectives for the Language of Surgery Project enable the following applications: automated recognition of surgical context including activity; objective assessment of surgical skill in the operating room and in simulation; automated targeted feedback for individualized learning; and human machine collaboration including automated coaching in surgical robotics. The eventual outcome of these applications is to improve the safety and effectiveness of surgical care, and the efficiency of surgical training.

The Language of Surgery Project is focused upon methods to represent and model complex surgical performance data to support applications that improve surgical care and education. Since its inception in 2006, the Language of Surgery Project has fostered several interdisciplinary collaborations across the University, including various divisions in the School of Medicine and departments in the Whiting School of Engineering.

Machines with Imagination: Learning from Description through Synthesis and Analysis

PI: Gregory Hager

Perception and Cognitive Systems

Key Personnel: *Computational Interaction and Robotics Laboratory*: Gregory Hager, Tae Soo Kim, Michael Peven, Jin Bai

Computational Cognition, Vision and Learning: Alan L. Yuille, Weichao Qiu, Yi Zhang, Zihao Xiao

Past Collaborators: Austin Reiter, Haider Ali, Chi Li, Balazs Vagvolgyi, Chenxu Luo

Funding: Supported by the Intelligence Advanced Research Projects Activity (IARPA) via Department of Interior/Interior Business Center (DOI/IBC)

Find out more: https://cirl.lcsr.jhu.edu/deep-intermodal-video-analytics-diva-project

Accomplishments and Status: The "DIVA" (Deep Intermodal Video Analytics) project is focused on developing an analysis-by-synthesis framework which takes advantage of state-of-the-art advancements both in graphical rendering engines as well as machine learning to create an intelligent system that can learn to recognize complex activities from descriptions. The core research objectives of the DIVA project span over multiple disciplines in the field of computer vision and machine learning, including fine-grained activity recognition applied towards smarter video surveillance, 3D object pose estimation under severe visual conditions, and development of techniques for machine learning with data synthesis systems.

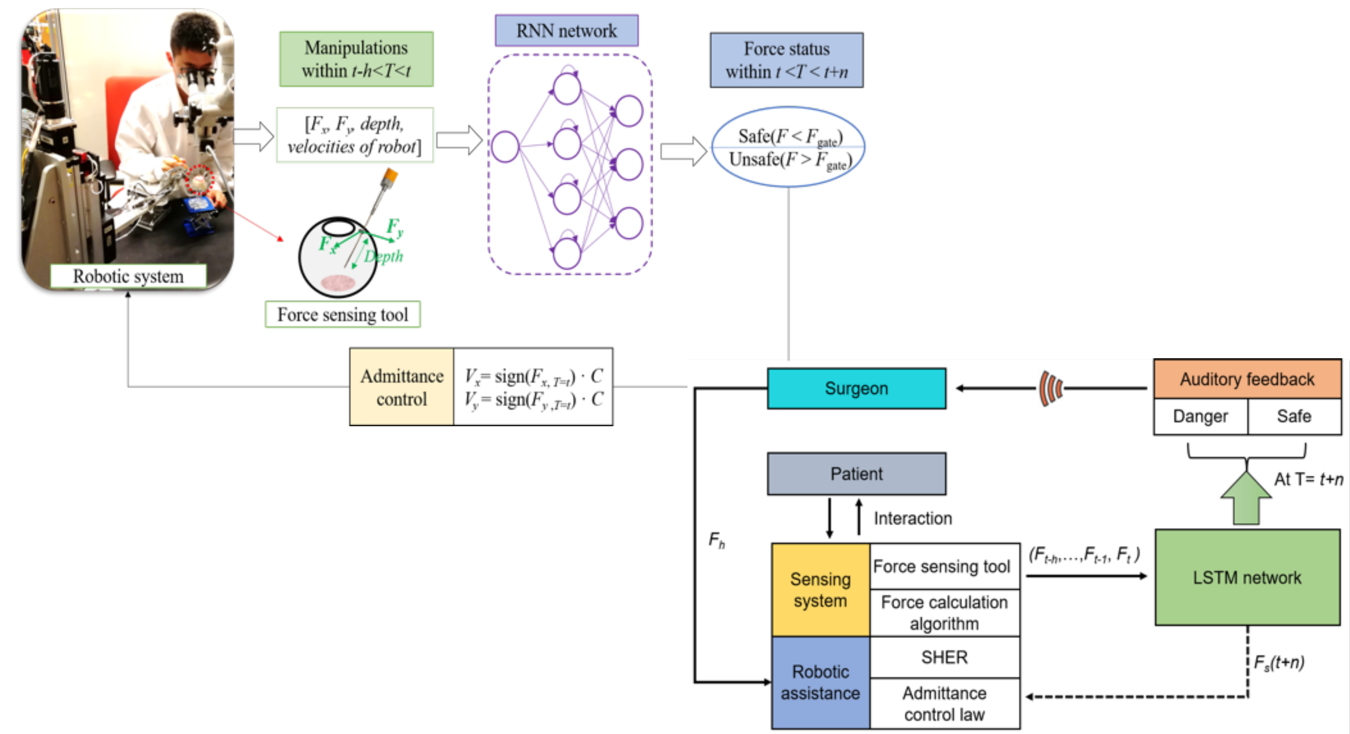
The DIVA (Deep Intermodal Video Analytics) project has fostered active collaborations with other institutions in the DIVA IARPA program as well as the wider research community, yielding a visual data synthesis system capable of generating highly structured visual data at scale as well as a strong publication record in computer vision and machine learning.

Enabling Technology for Safe Robot-Assisted Surgical Micromanipulation

PI: Iulian Iordachita

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Iordachita I., Kobilarov M., Gehlbach P., Taylor R., Patel N., Urias M., Ebrahimi A., He C., Kim B., Yang E., Wu J.

Funding: NIH and JHU internal funds

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

Accomplishments and Status: We have focused on development of robot control algorithms that provide the surgeon with information about tool position and forces measured at the tool-sclerotomy insertion site.

In one approach, we implemented an active control strategy for the robot to prevent iatrogenic injury at the sclera by enabling the robotic system to actively interrupt the surgeon's possible unsafe operations in advance. We proposed a recurrent neural network (RNN) with a long-short term memory unit to monitor the surgical procedure and to predict unsafe scleral force events. We applied an admittance control to actuate the robot to reduce the predicted scleral force before it actually occurs.

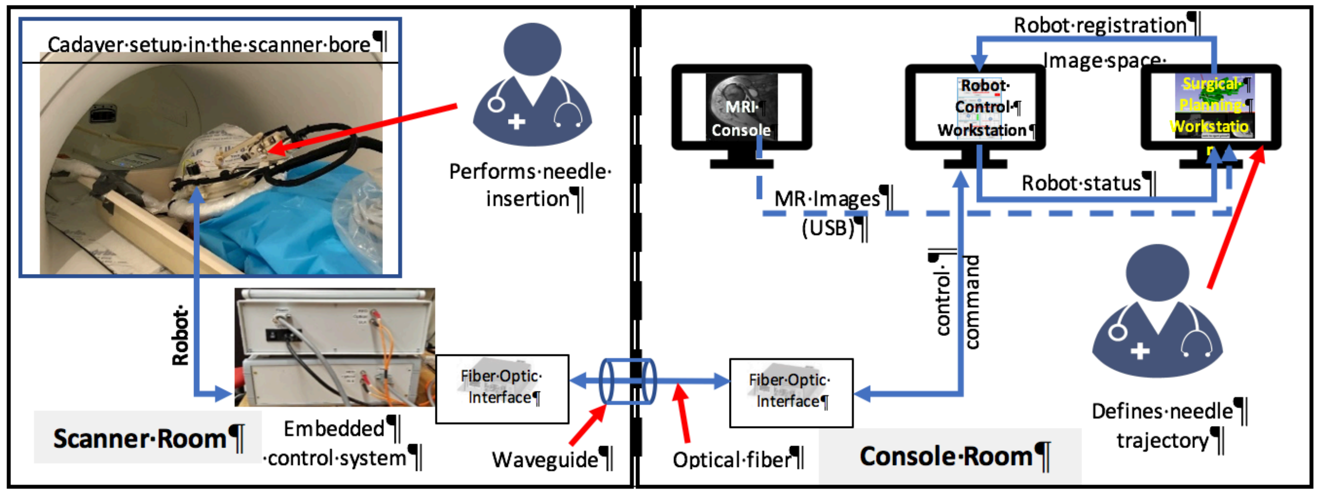
The method was evaluated in an artificial eye phantom by performing a "vessel following" mock retinal surgery operation. In a different approach, we used an adaptive control method for 3-dimensional control of sclera force components, and tool insertion depth, and then implemented the method on the velocity-controlled robot. The control method enabled the robot to perform autonomous adjustments to the sclera force and/or insertion depth of the tool tip, to force them to follow pre-defined desired and safe trajectories when they exceed safe bounds. The results demonstrate the feasibility of safe robot-assisted micromanipulation, based on sclera force/position feedback in phantoms.

Presently, we're focusing on refining control strategy for safe sclera and tool-tip force-based manipulation and conducting *in vivo* animal experiments (rabbits) for system evaluation.

MRI Compatible Body-Mounted Robot to Streamline Pediatric Shoulder Arthrography

PI: Iulian Iordachita

Medical Robots and Computer Integrated Interventional Systems



PI: Iulian Iordachita

Key Personnel: (CNMC) Monfaredi R., Sharma K., Cleary K., (JHU) Iordachita I., Patel N., Li G., Kim G.H., Yan J.

Funding: NIH, Children's National Health System, Sheikh Zayed Institute for Pediatric Surgical Innovation, and JHU internal funds

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

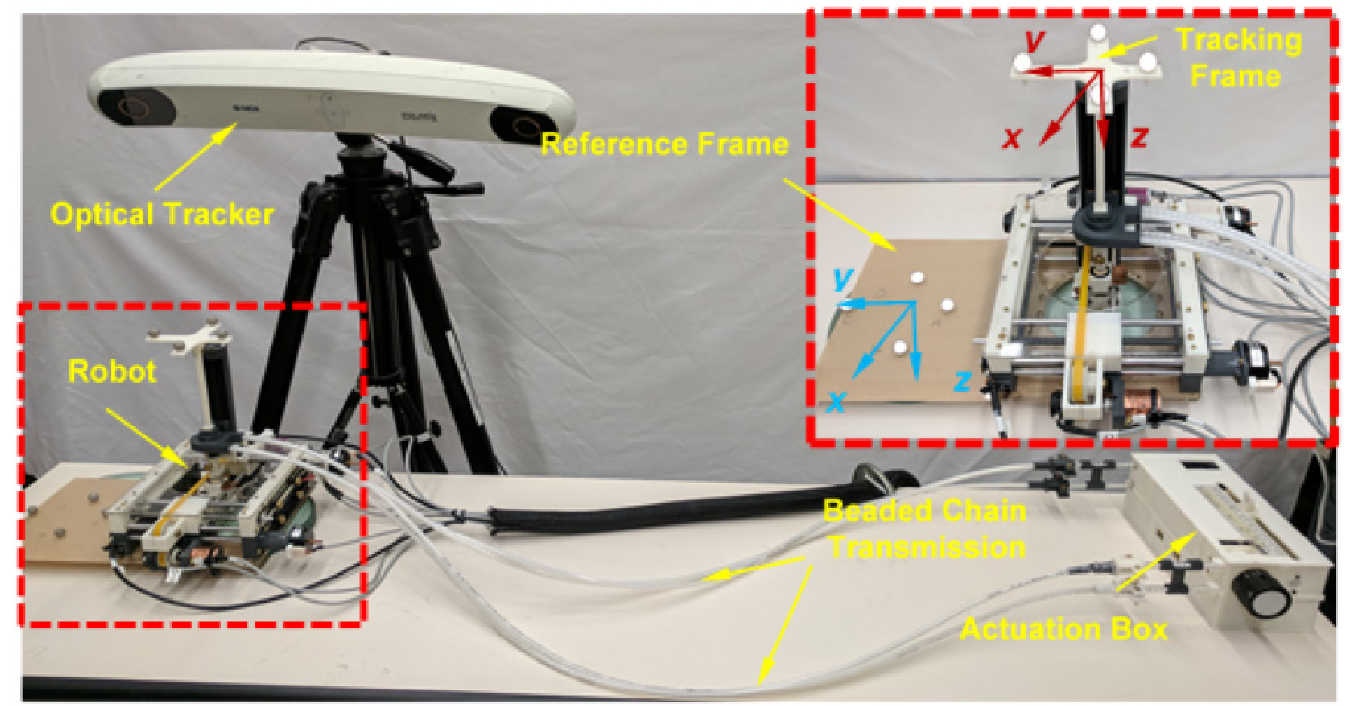
Accomplishments and Status: The goal is to develop and test a new patient-mounted MRI-compatible shoulder arthrography robot for needle guidance in pediatric interventional procedures. The robot is designed to be lightweight and compact, while providing desired needle tip accuracy for the targeting procedure. To prepare this system for clinical trials, we addressed issues related to clinical workflow such as homing of the robot inside the bore and maintaining sterile environment. We have designed the robot mechanism such that the sterile field remains protected without any mechanical disassembly. The robot is controlled by an embedded controller and a GUI based application providing both joint space as well as task-space control. The robot control GUI is designed such that the clinician can observe all the desired robot status information such as current robot pose versus its desired pose, while the technical operator have access to the necessary sensor information such as encoder counts and limit switch status.

Our clinical grade prototype is under evaluation in cadaver experiments, and we are currently developing a 3D slicer-based user interface to control the robot.

MRI Compatible Robot for Improved Pain Injections in Adults and Children

PI: Iulian Iordachita

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: (CNMC) Monfaredi R., Sharma K., Cleary K., (JHU) Iordachita I., Fritz J., Patel N., Li G., Wu D., Yan J., Wang Y.

Funding: NIH, Children's National Health System, Sheikh Zayed Institute for Pediatric Surgical Innovation, and JHU internal funds

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

Accomplishments and Status: The goal of this Bioengineering Research Grant is to develop and evaluate a patient-mounted MRI-compatible robot that allows for highly accurate needle placement while completely eliminating radiation exposure. The robot will serve as an enabling platform technology that can be applied to any needle-based MRI-guided interventions that require a high level of precision. In this project, we will develop and evaluate a body-mounted MRI-compatible robot for perineural injections used to treat pain in adult and pediatric patients. The robot will be strapped over the area of interest and will precisely orient a needle guide for injection inside the MRI scanner bore. The robot will include active needle driving to enable real-time imaging of the path and needle tip as the needle is advanced via remote control.

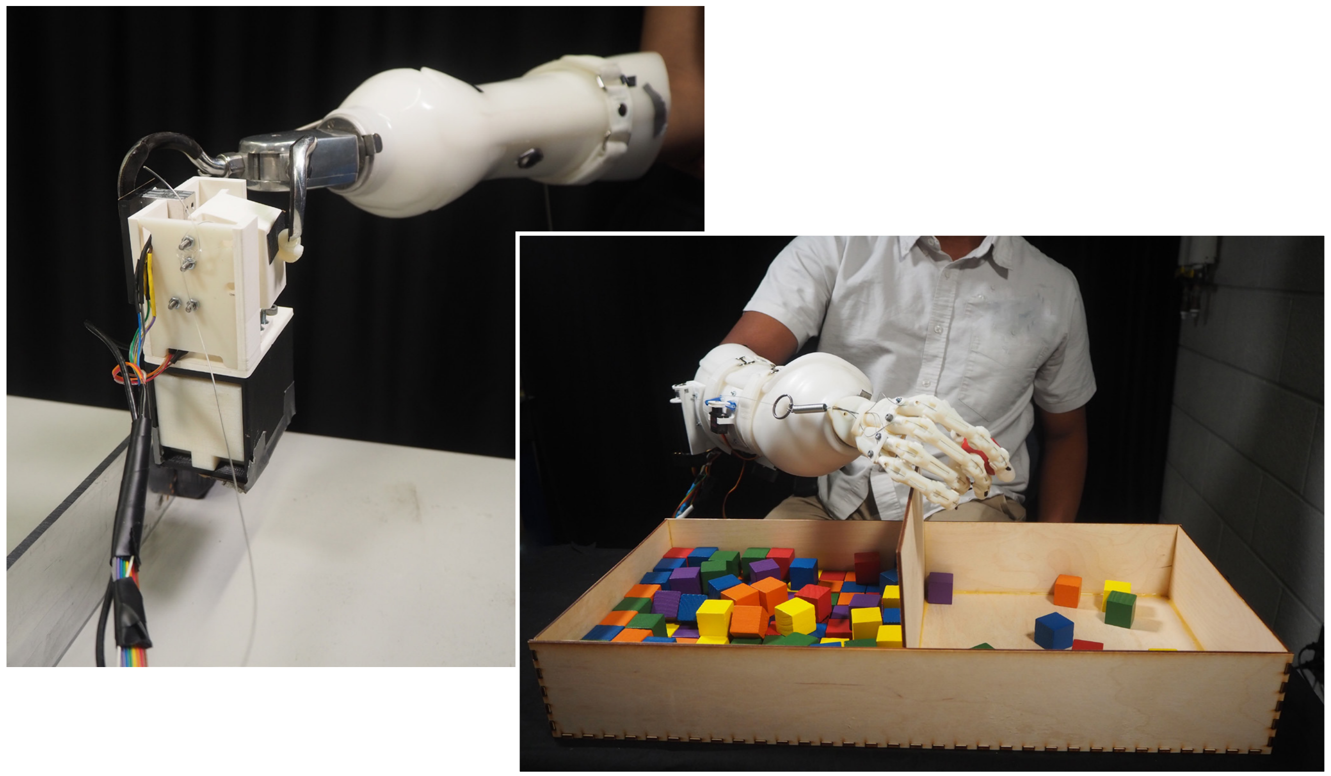
Currently we have developed and tested a4-DOF needle positioning and orientation robot and a 2DOF needle driver. We're developing a 3D Slicer-based user interface to control the robot, and have conducted the first cadaver experiment to evaluate the system in OR

Haptic Feedback for Upper-Extremity Prostheses

PI: Jeremy D. Brown

Bio-robotics

Human-Machine Collaborative Systems



Key Personnel: Neha Thomas, Garrett Ung, Colette McGarvey

Funding: JHU start-up

Accomplishments and Status: We have developed a prosthesis testbed that allows for evaluation of various haptic feedback modalities. We have conducted an experiment that compares vibrotactile feedback and joint-torque feedback and found that participants performed better with both feedback modalities compared to the current clinical standard of no haptic feedback. These findings were published in the following manuscript.

We have investigated the utility of haptic feedback in reducing mental workload in prosthesis operation and have found that the addition of vibrotactile feedback of grip force significantly reduces cognitive effort compared to the current clinical standard prosthesis with no haptic feedback. These findings are currently under review in the IEEE Transactions on Human-Machine Systems.

Publications: Thomas N, Ung G, McGarvey C, Brown JD. Comparison of vibrotactile and joint-torque feedback in a myoelectric upper-limb prosthesis. *Journal of NeuroEngineering and Rehabilitation*. 2019;16(1):70. doi:10.1186/s12984-019-0545-5

Key Personnel: Ethan Miller, Ihemriorochi Amanze

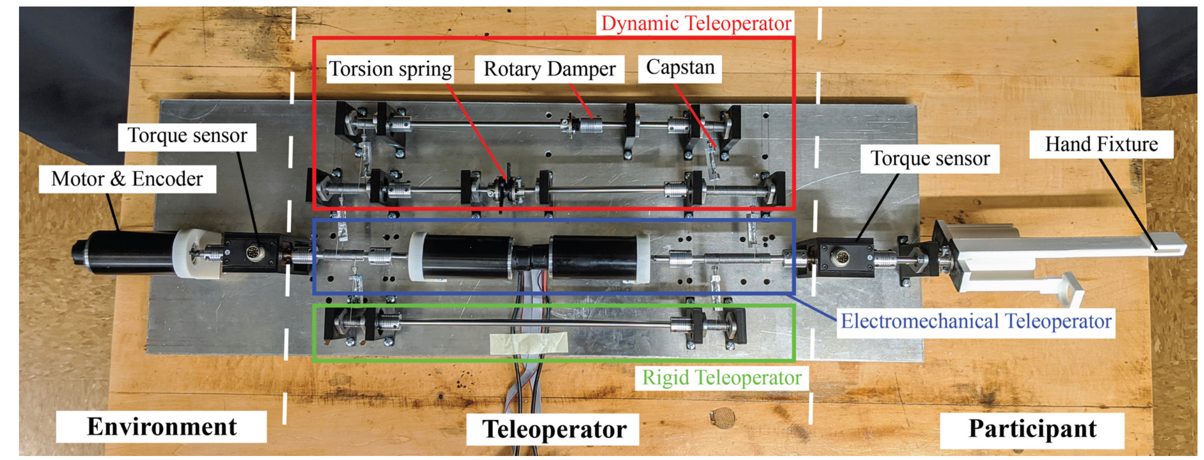
Funding: JHU start-up

Accomplishments and Status: We developed an anthropomorphically driven upper-extremity prosthesis that uses antagonist tendon actuation for bidirectional control of hand opening and closing. The device also features an integrated haptic feedback system that provides wearers with realtime information regarding the tension in the tendon actuators. A study has been conducted to investigate two different control schemes for the device, and the finding have been accepted for publication in the *2020 IEEE International Symposium on Medical Robotics*.

User-Sensitive Haptic Displays

PI: Jeremy D. Brown

Human-Machine Collaborative Systems



Key Personnel: Mohit Singhala

Funding: NSF

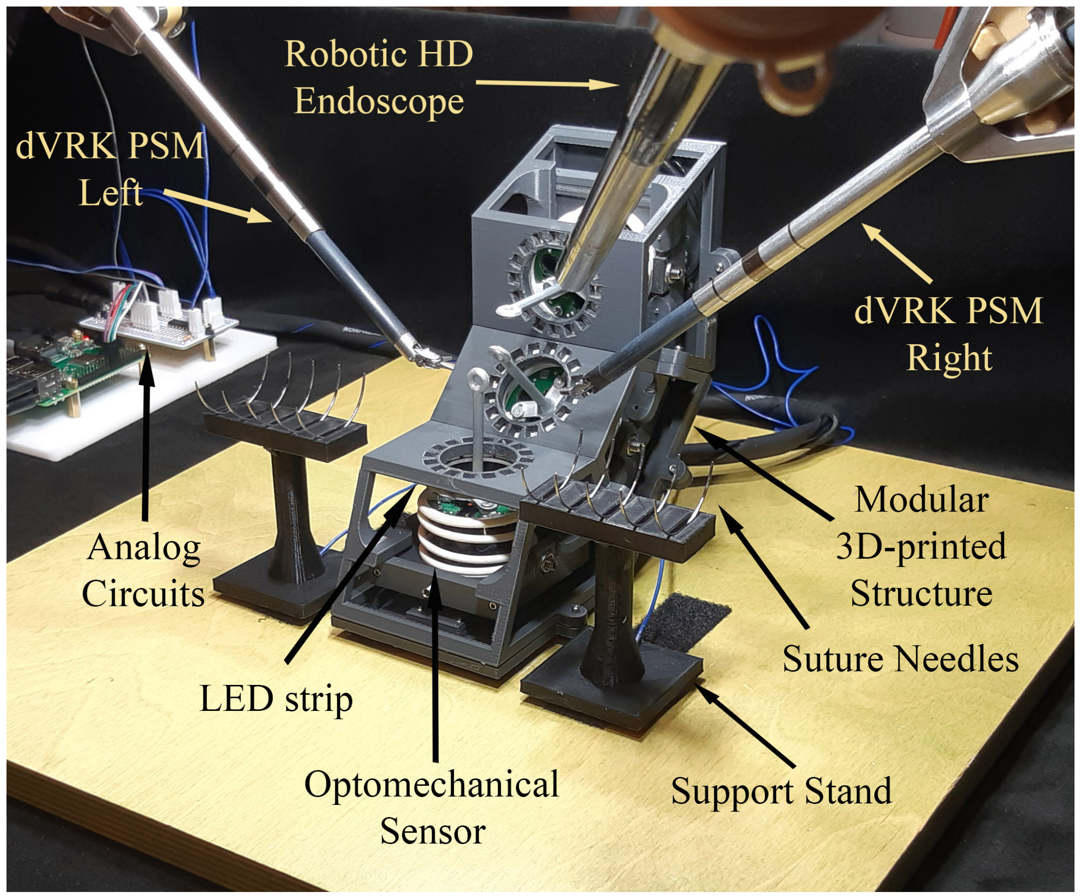
Accomplishments and Status: We have investigated the role of limb velocity on haptic perception and discovered that although trends exist on an individual level, they do not generalize across the population. These findings were accepted for publication in the 2020 IEEE Haptics Symposium. We have also begun the development of a teleoperator testbed that allows for investigations into the effect of master/slave dynamics on haptic perception.

Robot-Assisted Minimally Invasive Surgical Training

PI: Jeremy D. Brown

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Guido Caccianiga, Gabriela Cantarero

Funding: JHU internal funds

Accomplishments and Status: We have developed identical virtual reality and inanimate surgical training platforms for robot-assisted minimally invasive surgery (RAMIS) in order to compare both approaches for RAMIS training.

We have conducted a user to compare skill development and skill transfer for each of these platforms. Our findings suggest that skill development and skill transfer are more robust with inanimate training. These findings are currently under review in the *IEEE Transactions on Medical Robotics and Bionics*.

Publications: Caccianiga G, Mariani A, De Momi E, Brown JD. Virtual Reality Training in Robot-Assisted Surgery: a Novel Experimental Setup for Skill Transfer Evaluation. In: *12th Annual Hamlyn Symposium on Medical Robotics*; 2019:89-90.

Adaptation and De Novo Learning Exhibit Qualitatively Different Learning Signatures

PI: John Krakauer

Perception and Cognitive Systems

Figure 1

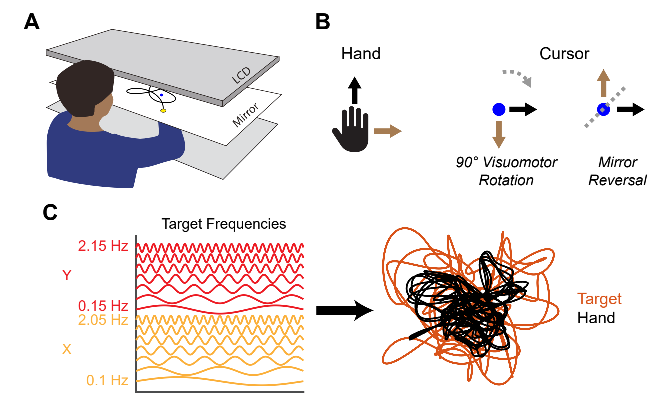
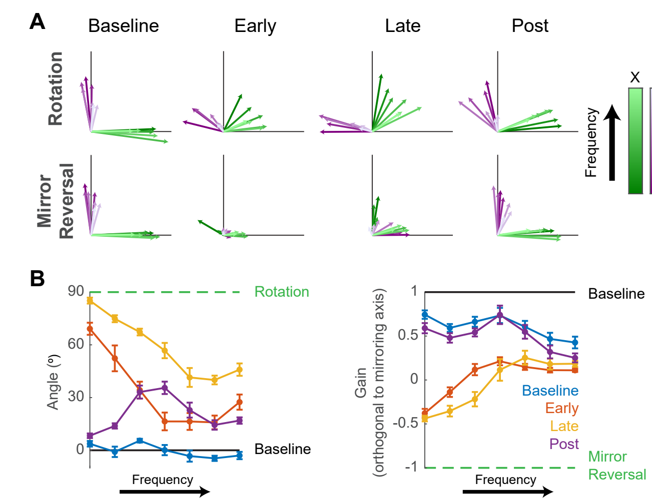


Figure 2



Key Personnel: Christopher Yang, John Krakauer, Noah Cowan, Adrian Haith

Funding: Link Foundation

Accomplishments and Status: We ascertained differences in how humans learn to adapt existing motor controllers (adaptation) versus creating new motor controllers (de novo learning). We found that controllers created de novo (assayed with mirror-reversal task) have more control limitations in comparison to adapted controllers (assayed with visuomotor rotation task).

Publication in preparation.

Other Main Author: Adrian Haith, assistant professor, neurology, ahoaith1@jhu.edu

Figure 1. Experimental design. A) Participants controlled an on-screen cursor using their right hand in order to track a target moving in a continuous, pseudorandom trajectory. B) Participants learned to control the cursor under one of two hand-to-cursor mappings: 1) rotation of cursor visual feedback by 90˚ (adaptation), and 2) reversal of visual feedback about an oblique 45˚ axis (mirror-reversal). We sought to understand whether these two mappings were learned using qualitatively different learning mechanisms. C) The target followed a sum-of-sinusoids trajectory, moving at different frequencies in the x- and y-axes. The separation of frequencies on the two axes allowed us to assay how participants learned each cursor mapping (i.e., movement at a particular frequency should flip from one axis to the other during learning). System identification was performed to separately identify control properties of movements in each axis.

Figure 2. Compensation for the cursor mappings during learning. A) The direction and amplitude of movement gain at each frequency of target movement. Movement gains were assessed at baseline, early learning, and late learning. They were also assessed post-learning (reverting to normal, veridical cursor control) in order to ascertain how learning each perturbation manifested as an aftereffect. Low frequencies are illustrated as darker colors and high frequencies as lighter colors. By late learning, the rotation group successfully compensated at all frequencies of movement and expressed a rotational aftereffect post-learning. In contrast, the mirror-reversal group only was capable of compensating at low frequencies and did not express an aftereffect. B) Movement angle was estimated for the rotation group (left) and movement gain orthogonal to the mirror axis was estimated for the mirror-reversal group (right). Our results suggest that rotation and mirror reversal are learned via qualitatively different mechanisms (based on aftereffects) and learning a mirror-reversal is fundamentally more difficult than learning a rotation.

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

PI: Louis L. Whitcomb

- Modeling, Dynamics, Navigation, and Control
- Robotics in Extreme Environments
- Human-Machine Collaborative Systems

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

Funding: NSF Office of Polar Programs, James Family Foundation, George Fredrick Jewett Foundation East, Woods Hole Oceanographic Institution, NASA Astrobiology Program, 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).

To find out more: https://www.whoi.edu/what-we-do/explore/underwater-vehicles/nereid-under-ice

Accomplishments and Status: The Nereid Under-Ice (NUI) vehicle is 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 83°N 6°W from icebreaker F/S Polarstern. Katlein et al. presents under-ice light transmission data from some of NUI's first science operations.

NUI is operational and has completed major Arctic expeditions about to 83°N 6°W in 2018, and to 87°N 61°E in 2016.

Publications: Michael V. Jakuba, Christopher R. German, Andrew D. Bowen, Louis L. Whitcomb, Kevin Hand, Andrew Branch, Steve Chien, Christopher McFarland. Teleoperation and Robotics under Ice: Implications for Extra-Planetary Exploration, 2018 IEEE Aerospace Conference.

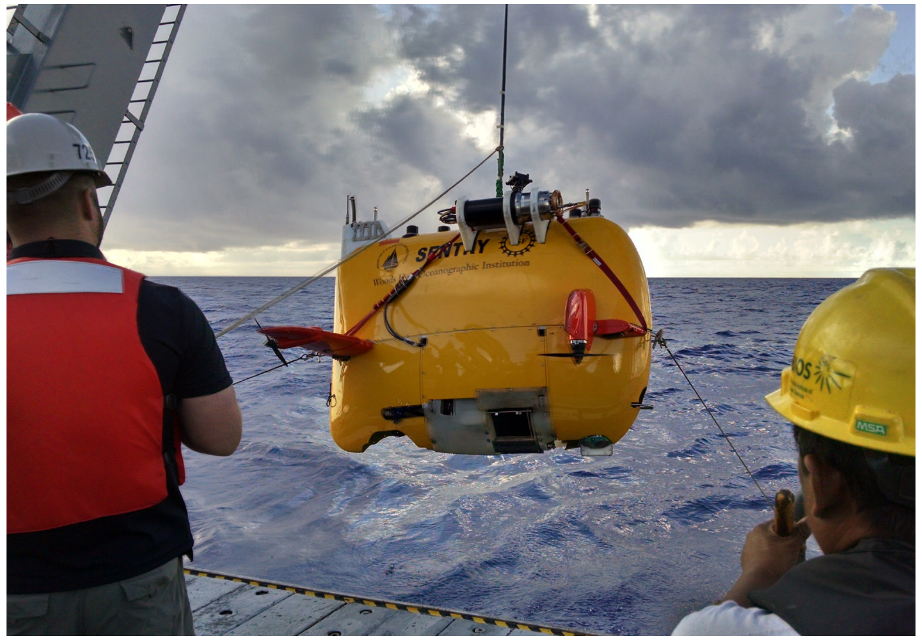
C. Katlein, S. Arndt, M. Nicolaus, D. K. Perovich, M. V. Jakuba, S. Suman, S. Elliot, Louis L. Whitcomb, C. J. McFarland, R. Gerdes, A. Boetius, and C. R. German. Influence of ice thickness and surface properties on light transmission through Arctic sea ice. *J. Geophys. Res. Oceans*, 120:1–13, Sept. 2015. doi:10.1002/2015JC010914.

C. J. McFarland, M. V. Jakuba, S. Suman, J. C. Kinsey and L. L. Whitcomb, "Toward ice-relative navigation of underwater robotic vehicles under moving sea ice: Experimental evaluation in the Arctic sea," 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, 2015, pp. 1527-1534. doi: 10.1109/ICRA.2015.7139392 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7139392&isnumber=7138973

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

PI: Louis L. Whitcomb

- Modeling, Dynamics, Navigation, and Control,
- Perception and Cognitive Systems
- Robotics in Extreme Environments



Key Personnel: Louis Whitcomb, Andrew Spielvogel, Rachel Hegeman

Funding: NSF

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

Accomplishments and Status: 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.

Our prototype instrument has been developed and tested on the lab bench. Our in-water laboratory tests are underway. The at-sea full-scale oceanographic testing was completed in 2018 and 2019.

Publications: A. R. Spielvogel and L. L. Whitcomb, "Adaptive Bias and Attitude Observer on the Special Orthogonal Group for True-North Gyrocompass Systems: Theory and Preliminary Results," *International Journal of Robotics Research*. Invited Paper. Published online ahead of print Nov 5, 2019.

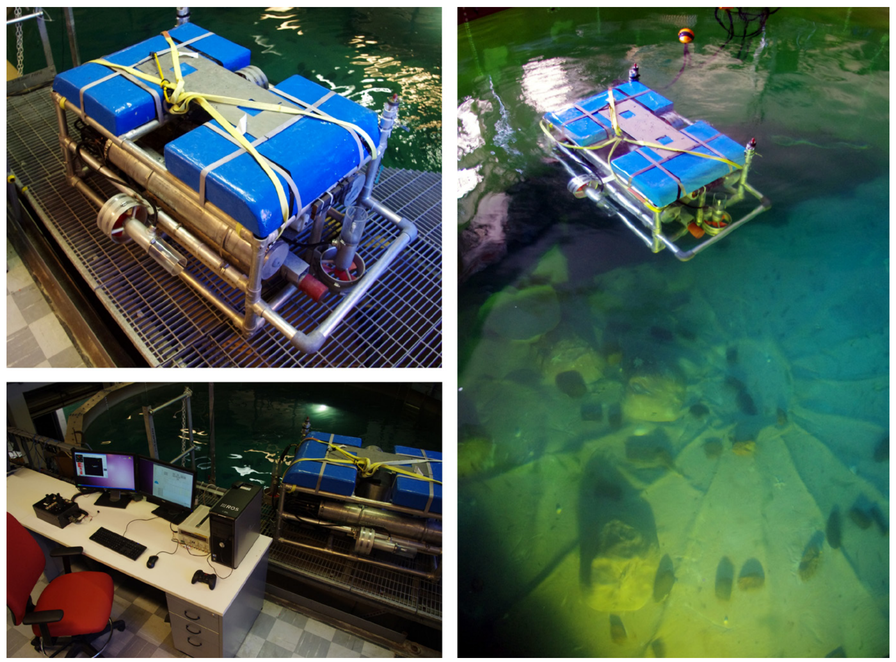
Precision Navigation of Low-Cost Underwater Robotic Vehicles for Ocean Science

PI: Louis L. Whitcomb

Modeling, Dynamics, Navigation, and Control

Perception and Cognitive Systems

Robotics in Extreme Environments



Key Personnel: Louis L. Whitcomb, Zachary Harris, Andres Spielvogel, Abhimanyu Shah, Giangarlo Troni

Funding: NSF

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

Accomplishments and Status: 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.

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.

Publications: Z. J. Harris and L. L. Whitcomb, "Preliminary Study of Cooperative Navigation of Underwater Vehicles without a DVL Utilizing Range and Range-Rate Observations," Invited Book Chapter, in *Cooperative Localization and Navigation*: Theory, Research and Practice (#K376186), Chao Gao and Guorong Zhao, Editors. CRC Press (Taylor & Francis Group), June 2019.

G. Troni and L. L. Whitcomb. "Field Sensor Bias Calibration with Angular-Rate Sensors: Theory and Experimental Evaluation with Application to Magnetometer Calibration," *IEEE/ASME Transactions on Mechatronics*. 24 (4):1698–1710, August, 2019.

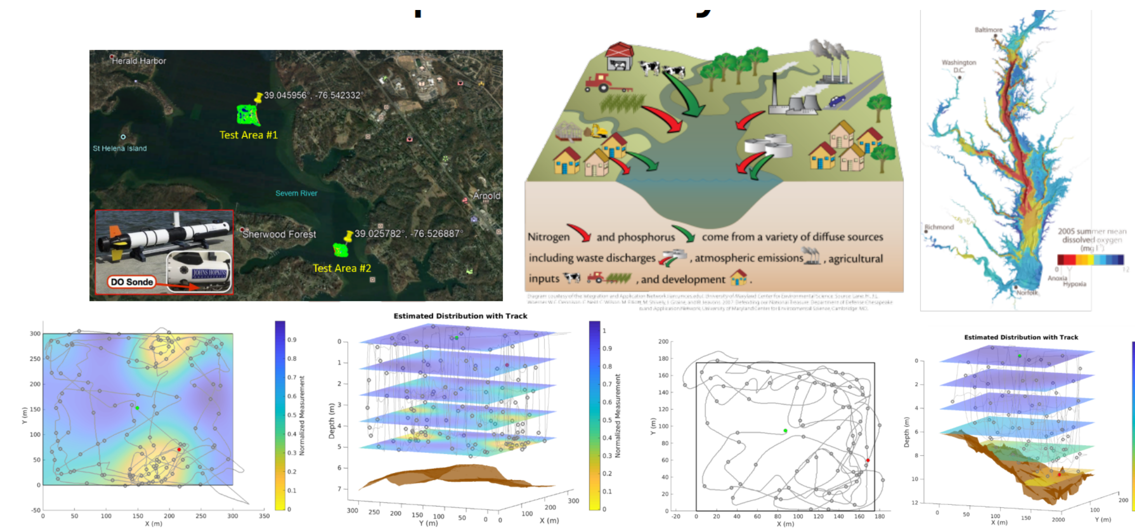
Robotic Environmental Sampling

PI: Marin Kobilarov

Modeling, Dynamics, Navigation, and Control,

Robotics in Extreme Environments

Hypoxia detection in the Chesapeake Bay



- real-time water quality sensing: dissolved oxygen and nitrates
- information-maximizing intelligent sampling
- autonomous navigation to next-best sample location

Key Personnel: Paul Stankiewicz, William Tan, William Ball, Marin Kobilarov

Funding: USDA NIFA

To find out more: asco.lcsr.jhu.edu

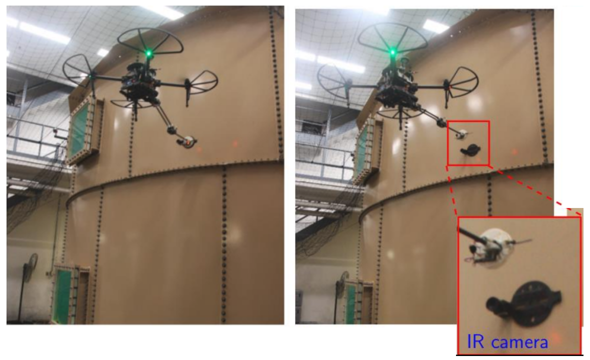
Accomplishments and Status: Demonstrated adaptive sampling with underwater vehicles to build informative models of dissolved oxygen in the Chesapeake Bay. As a result, the development and spread of hypoxia (oxygen depletion) could be identified and tracked more accurately than current methods with fixed stations or ship-based sampling.

Autonomous Aerial Manipulation

PI: Marin Kobilarov

Modeling, Dynamics, Navigation, and Control

Robotics in Extreme Environments



JHU AirGripper performing sensor placement

JHU AirGripper performing package sorting

environmental sensor placement

vehicle for larger payloads

Key Personnel: Gowtham Garimella, Matthew Sheckells, Gabe Baraban, Marin Kobilarov

Funding: NSF

To find out more: asco.lcsr.jhu.edu

Accomplishments and Status: Developed drones equipped with manipulators and demonstrated autonomous aerial grasping applied to:

1) package delivery in a mock-up warehouse setting

2) sensor placement on vertical structures for infrastructure inspection.

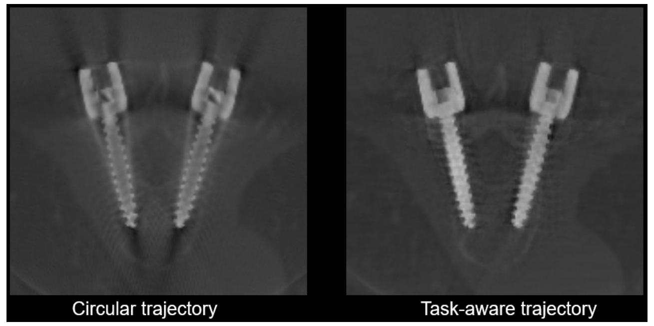
Task-Aware and Autonomous C-Arm Imaging

PI: Mathias Unberath

Human-Machine Collaborative Systems

Perception and Cognitive Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Mathias Unberath, Mehran Armand, Greg Osgood, Jan-Nico Zäch (now ETH Zurich), Andreas Maier (FAU Erlangen)

Funding: NSF

Accomplishments and Status: C-arm X-ray systems are the workhorse modality for numerous percutaneous procedures across diverse clinical disciplines, enabling over 17 million interventions during 2006 and in the United States alone. This number is projected to further increase, creating a global market of $3 billion for C-arm X-ray systems by 2023.

Use of these systems interventionally, however, requires highly trained surgeons and C-arm technologists since the software back-end driving these systems is still task-agnostic. The modality has no notion of anatomy, procedural progress, or desired information, effectively degrading even most modern C-arm systems to "medical grade cameras". Surgeons and technologists must actively steer the C-arm to achieve and reproduce radiographs from multiple, well-defined viewpoints to infer procedural progress. This high responsibility is associated with excessive radiation dose to patient and staff, high procedure times, repeat attempts, and—in the worst case—adverse outcome.

A task-aware robotic C-arm system that autonomously acquires and interprets fluoroscopic images best suited for decision making on a patient-specific basis can significantly reduce radiation dose and procedure time, and thus improve outcomes by decreasing the risk for morbidity and mortality. The major obstacle hindering the introduction of autonomous, task-aware imaging modalities is the development of appropriate machine intelligence, the innovation of which becomes possible through novel approaches by ourselves and colleagues that enable machine learning for X-ray-based interventions.

Our first application of such a task-aware and autonomous C-arm system targets cone-beam CT (CBCT) reconstruction for intra-operative verification of metal implant positioning. Metal artifacts in CT arise from a mismatch between physics of image formation and idealized assumptions during tomographic reconstruction.

These artifacts are particularly strong around metal implants, inhibiting widespread adoption of 3D CBCT despite clear opportunity for intra-operative verification of implant positioning, e.g. in spinal fusion surgery. On synthetic and real data, we demonstrate that much of the artifact can be avoided by acquiring better data for reconstruction in a task-aware and patient-specific manner and describe the first step towards the envisioned task-aware CBCT protocol. The traditional short-scan CBCT trajectory is planar, with little room for scene-specific adjustment. We extend this trajectory by autonomously adjusting out-of-plane angulation. This enables C-arm source trajectories that are scene-specific in that they avoid acquiring "poor images", characterized by beam hardening, photon starvation, and noise. The recommendation of ideal out-of-plane angulation is performed on-the-fly using a deep convolutional neural network that regresses a detectability-rank derived from imaging physics.

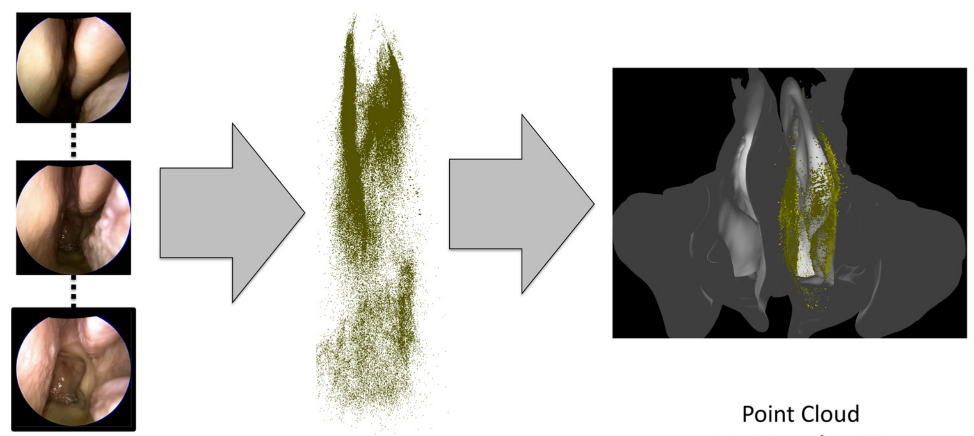
Publications: ''Task-aware and Anatomy-specific Cone-beam Computed Tomography", *US Provisional Application* Serial No. 62/896,352

3D Reconstruction of Sinus Anatomy from Monocular Endoscopic Video Using Self-Supervised Learning

PI: Mathias Unberath/Russell Taylor

Perception and Cognitive Systems

Medical Robots and Computer Integrated Interventional Systems



Video Sequence

Dense Point Cloud

Point Cloud Registered to 3D Mesh Model of Sinus

Key Personnel: Mathias Unberath, Russell Taylor, Greg Hager, Masaru Ishii, Ayushi Sinha (now Philips), Xingtong Liu

To find out more: https://github.com/lppllppl920/EndoscopyDepthEstimation-Pytorch

Accomplishments and Status: Minimally invasive procedures in the head and neck typically employ surgical navigation systems to provide surgeons with additional anatomical and positional information to avoid critical structures. Computer vision-based navigation systems that rely on the intra-operative endoscopic video stream and do not introduce additional hardware are both easy to integrate into clinical workflow and cost-effective, but require registration of pre-operative data, such as CT scans, to the intra-operative videos. For 3D-to-3D registration algorithms, estimating an accurate and dense intra-operative 3D reconstruction is necessary to ensure acceptable performance of the system.

Obtaining such reconstructions is not trivial, due to problems such as textureless surface, specular reflectance, lack of photometric constancy across frames, and tissue deformation. Several methods have been explored for 3D reconstruction in endoscopy. Multi-view stereo methods, such as Structure from Motion (SfM) and Simultaneous Localization and Mapping (SLAM), are able to reconstruct 3D structure and estimate camera poses in feature-rich scenes. However, the paucity of features in endoscopic images can cause these methods to produce sparse and unevenly distributed reconstructions, which may lead to inaccurate registration.

We research learning-based approaches to 1) identify corresponding points across multiple frames of endoscopic video sequences, 2) use this information to derive sparse reconstructions and relative camera motion that enable the training of deep convolutional neural networks for monocular depth estimation, and 3) fuse monocular depth estimates via the relative camera poses into a volumetric 3D reconstruction of sinus endoscopy with large anatomical coverage. This approach results in sub-millimeter registration errors between endoscopic video and pre-operative CT scans.

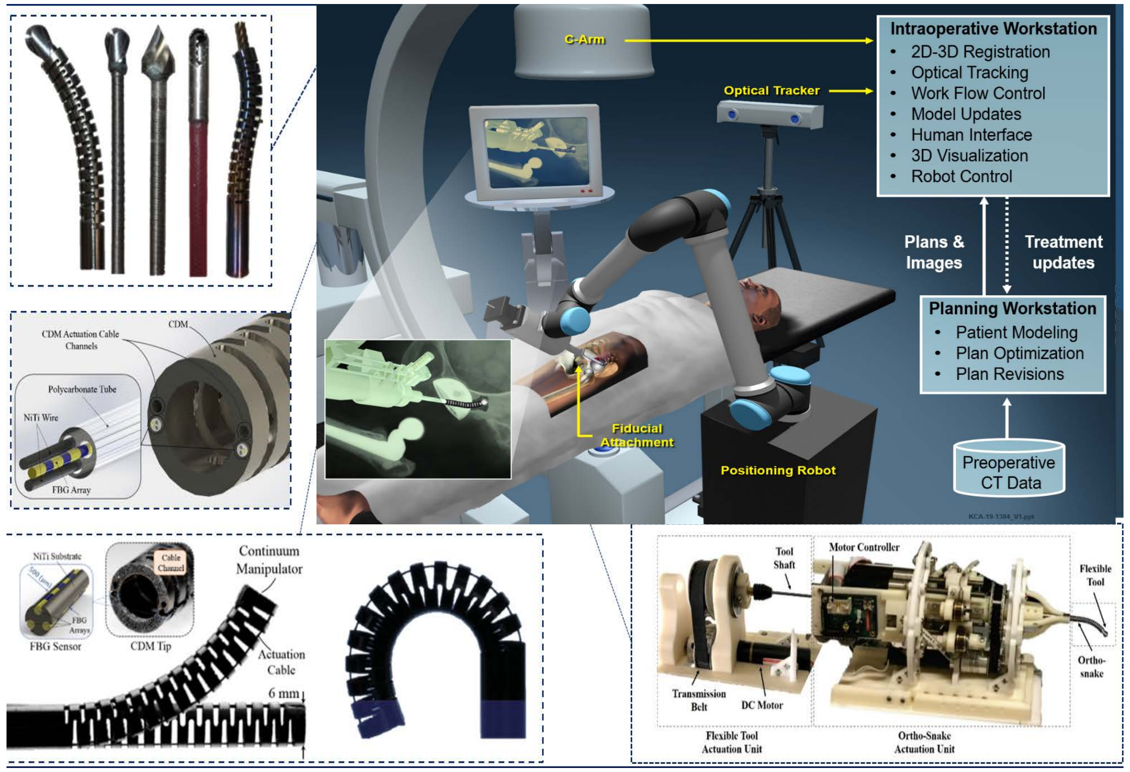
See Also: Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis

Continuum Robots, Tools, and Algorithms for Tissue Manipulation

PI: Mehran Armand

Medical Robots and Computer Integrated Interventional Systems

Continuum Manipulators and Tools for Minimally-Invasive Surgery



Key Personnel: Mehran Armand, Russell Taylor, Peter Kazanzidas, Mathias Unberath, Iulian Iordochita, Shahriar Sefati, Cong Gao, Rachel Hageman, Mahsan Bakhtiar Nejad

Funding: NIH/NIBIB

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

Accomplishments and Status: We have developed a robot-assisted workstation including snake-like manipulators with shape-sensing ability for treatment of osteolysis behind the acetabular cup during hip revision surgery. We successfully performed cadaver studies demonstrating the system feasibility.

We are currently extending the application to the treatment of osteonecrosis of the hip by performing curved drilling and applying novel bendable screws.

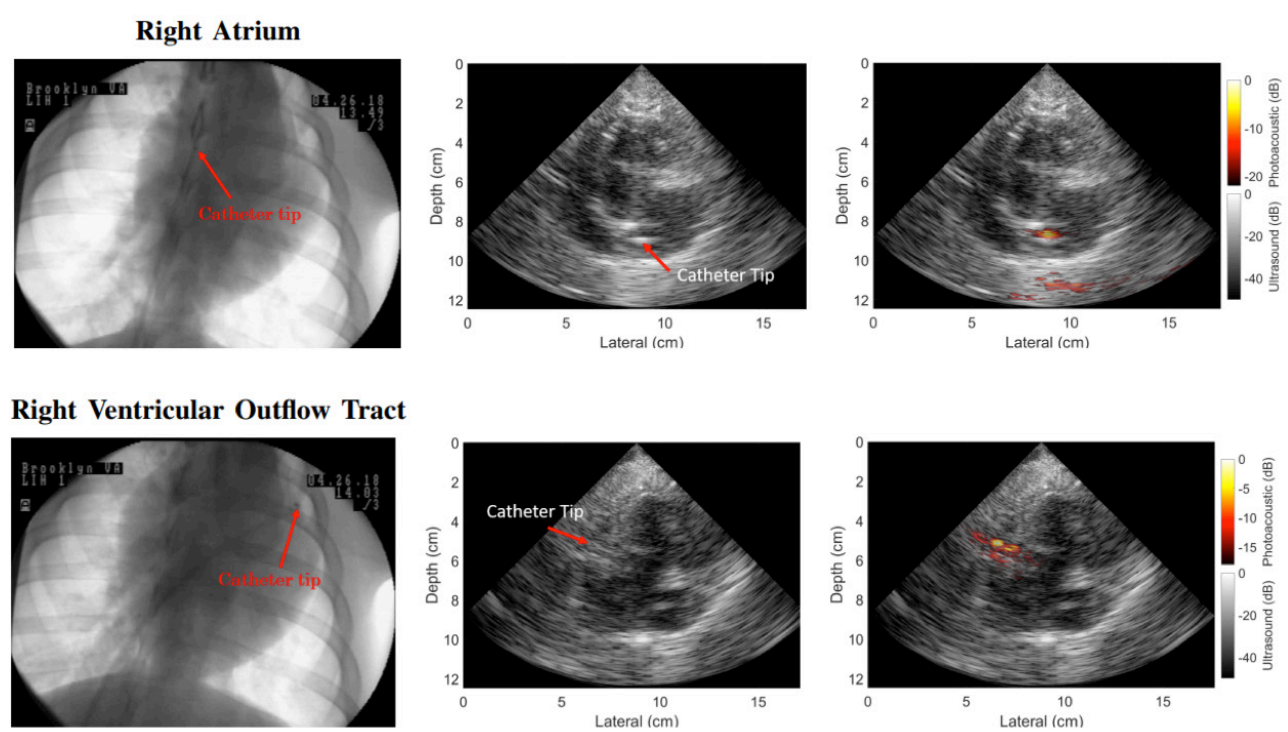
See Also: X-ray Image-based Navigation for Periacetabular Osteotomy with Intraoperative Biomechanical Feedback

Photoacoustic-Guided Cardiac Catheter-Based Interventions

PI: Muyinatu Bell

Perception and Cognitive Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Michelle Graham, Fabrizio Assis, Derek Allman, Alycen Wiacek, Eduardo González, Mardava Gubbi, Jinxin Dong, Huayu Hou, Sarah Beck, Jonathan Chrispin, Muyinatu A. Lediju Bell

Funding: NSF CAREER Award

Find out more: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8825818

Accomplishments and Status: First known *in vivo* demonstration of cardiac photoacoustic imaging, including an *in vivo* example that pairs robotic assistance with photoacoustic image guidance to find and constantly visualize cardiac catheter tips during manual insertion from peripheral veins to the heart (with the ultimate goal of replacing fluoroscopy). We also show the first-known photoacoustic images of cardiac catheter tips within an *in vivo* heart.

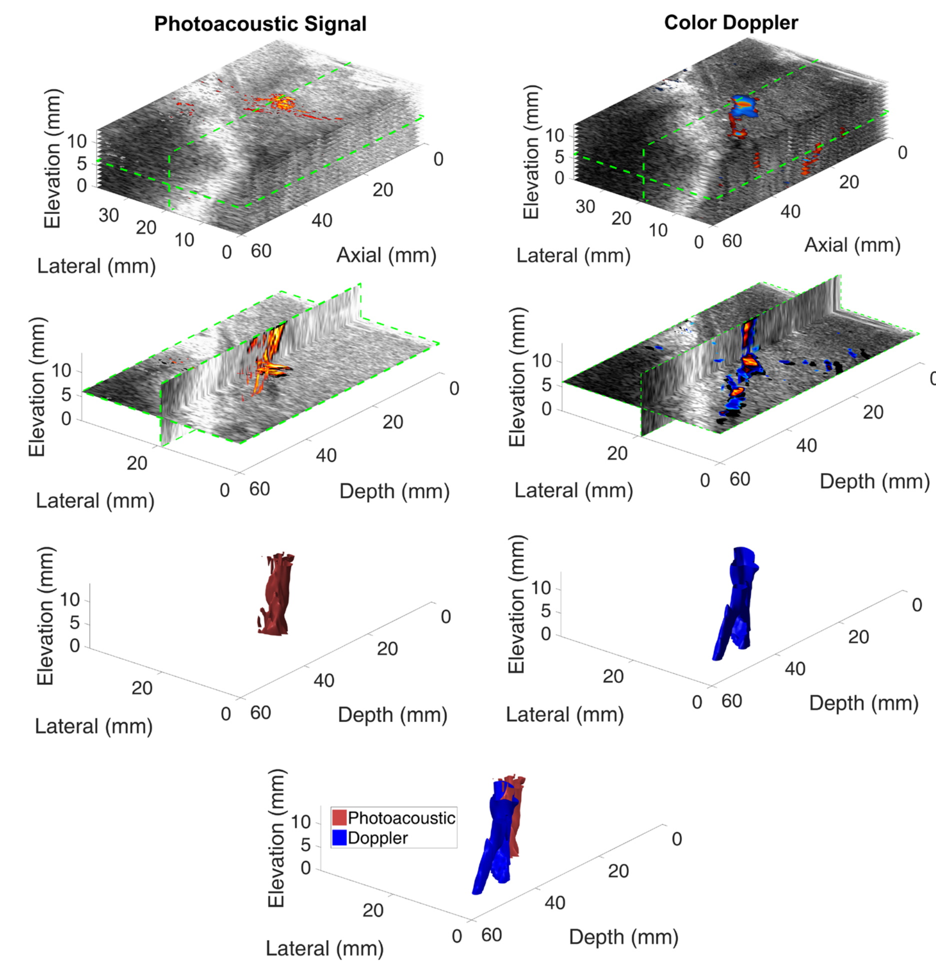
Catheter tips were visualized at depths as large as 9 cm from the chest wall with photoacoustic imaging in cases where ultrasound imaging failed (due to the similar echogenicity of catheter tips and nearby cardiac tissue). Results show promise toward reducing the use of fluoroscopy during cardiac catheter-based interventions, which is desirable because fluoroscopy exposes both patients and operators to harmful ionizing radiation.

Publications: *IEEE Transactions on Medical Imaging*. Citation: Graham M, Assis F, Allman D, Wiacek A, González E, Gubbi M, Dong J, Hou H, Beck S, Chrispin J, Bell MAL, "*In vivo* demonstration of photoacoustic image guidance and robotic visual servoing for cardiac catheter-based interventions," *IEEE Transactions on Medical Imaging* (accepted)

Photoacoustic-Guided Liver Surgery

PI: Muyinatu Bell

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Kelly Kempski, Alycen Wiacek, Michelle Graham, Eduardo González, Bria Goodson, Derek Allman, Jasmin Palmer, Huayu Hou, Sarah Beck, Jin He, Muyinatu Bell

Funding: NSF CAREER Award, REU Supplement and the NSF Computational Sensing and Medical Robotics Research Experience for Undergraduates program at Johns Hopkins University

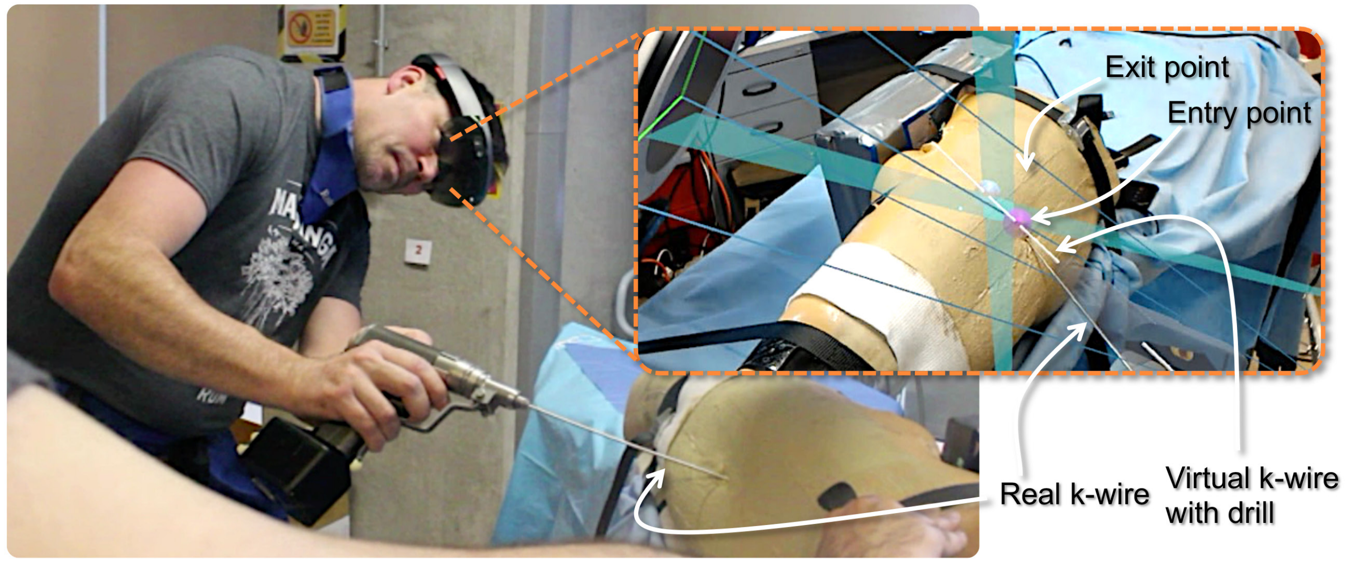
Accomplishments and Status: This work is the first to demonstrate *in vivo* blood vessel visualization with photoacoustic imaging, with possible applications to a range of liver surgeries. The 3D structure of major blood vessels was additionally visualized with robotic assistance.

Publications: Kempski K, Wiacek A, Graham M, González E, Goodson B, Allman D, Palmer J, Hou H, Beck S, He J, Bell MAL, *In vivo* photoacoustic imaging of major blood vessels in the pancreas and liver during surgery, *Journal of Biomedical Optics*, 24(12):121905, 2019

Interactive Flying Frustums

PI: Nassir Navab

- Human-Machine Collaborative Systems
- Perception and Cognitive Systems
- Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Nassir Navab, Greg Osgood, Javad Fotouhi, Mehran Armand, Alex Johnson, Mathias Unberath, Tianyu Song

Funding: JHU internal

Find out more: medicalaugmentedreality.org

Accomplishments and Status: Presented at the international conference of Information Processing in Computer-Assisted Interventions (IPCAI) 2019.

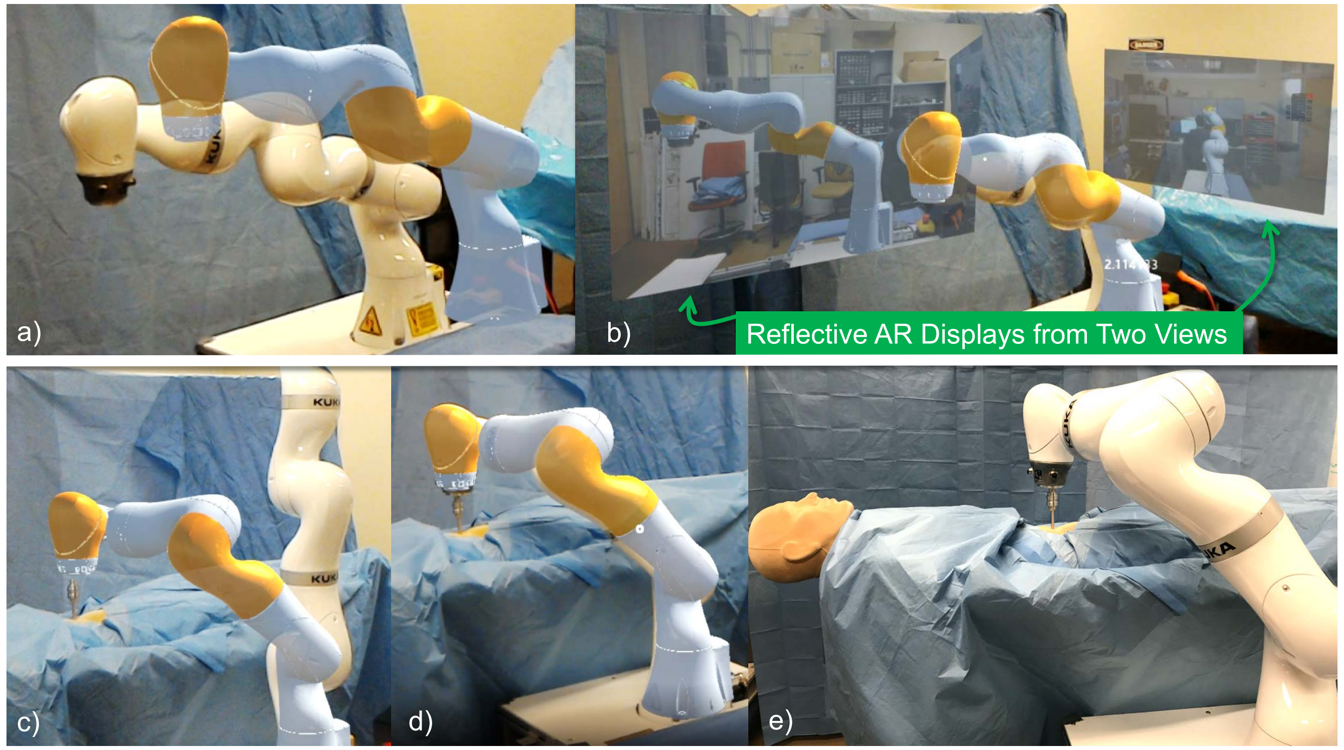
Redefined the workflow and user interaction in image-guided surgery based on Augmented Reality and the novel concept of flying frustums (IEEE TMI submission in preparation).

Full pre-clinical user study in collaboration with Greg Osgood and Alex Johnson from Johns Hopkins School of Medicine.

Reflective-AR Display

PI: Nassir Navab

- Human-Machine Collaborative Systems
- Perception and Cognitive Systems
- Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Nassir Navab, Javad Fotouhi, Mehran Armand, Mathias Unberath, Bernhard Fuerst, Tianyu Song, and Arian Mehrfard

Funding: Johns & Johnson / Verb Surgical

Find out more: https://camp.lcsr.jhu.edu/camps-article-accepted-at-ra-l-and-icra-2020

Accomplishments and Status: *IEEE Robotics and Automation Letters* (RA-L) and ICRA 2020

Bringing the new paradigm of presenting additional sensor data as augmented perspective views (reflective AR).

Validated through user-studies via Microsoft HoloLens and the KUKA robot.

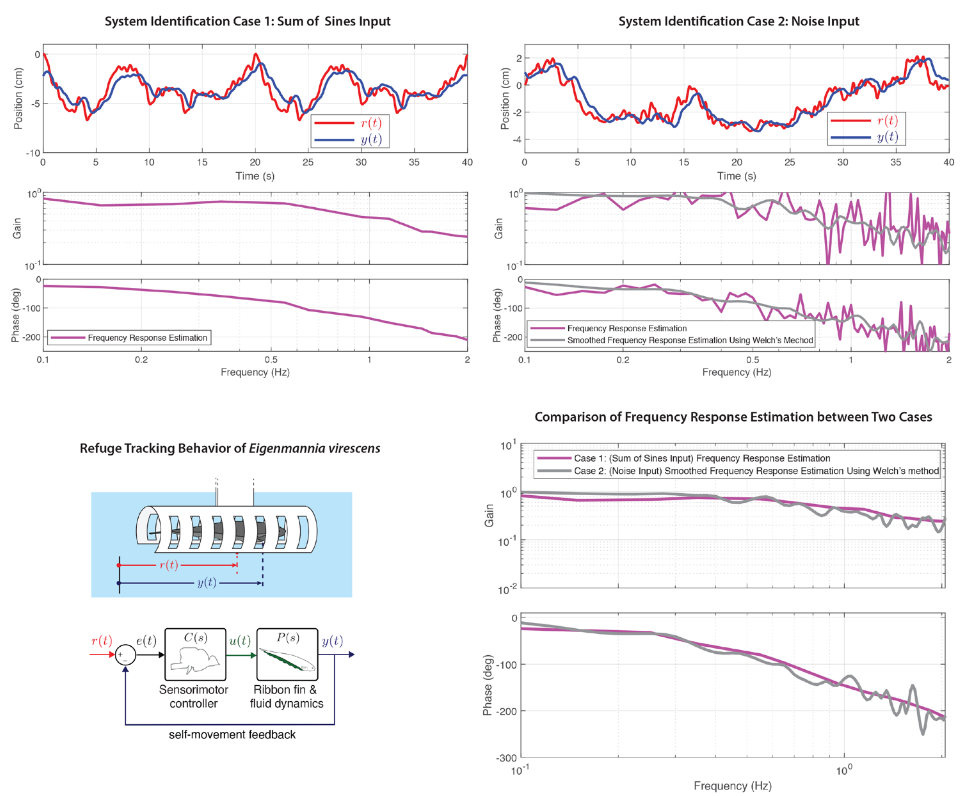
A User's Guide to System Identification for Sensorimotor Control

PI: Noah J. Cowan

Bio-Robotics

Modeling, Dynamics, Navigation, and Control,

Perception and Cognitive Systems



Key Personnel: Yu Yang, Yuqing (Eva) Pan, Ismail Uyanik, Noah J Cowan

Funding: NSF Award

Find out more: http://vps40083.inmotionhosting.com/~sicb/meetings/2020/schedule/abstractdetails.php?id=1626

Accomplishments and Status: Mathematical models are widely used to study animal behaviors. But for high-level tasks like sensorimotor processing, dynamics cannot be easily predicted using "first principles" models. In these cases, data-driven system identification techniques are essential. We have developed a set of best practices for system identification that can be applied across behaviors and animal taxa, including humans.

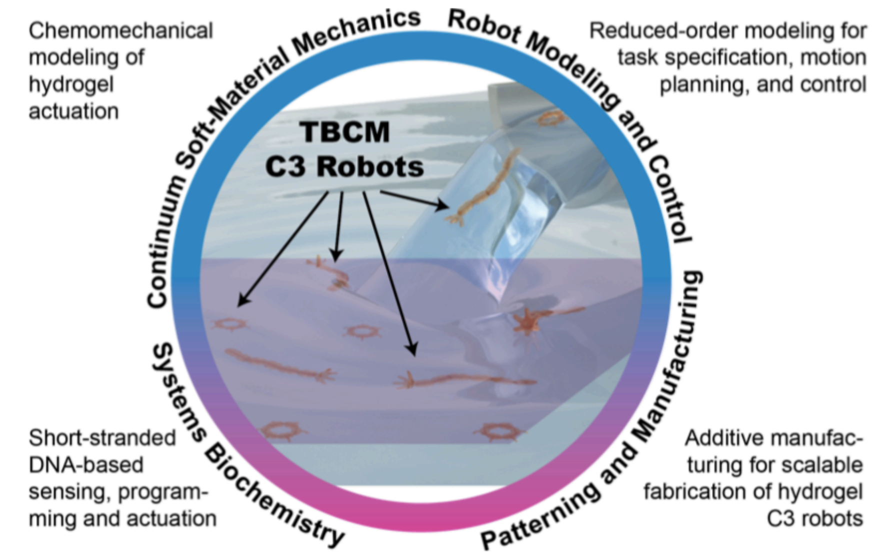
We have performed linear and nonlinear system identification of closed-loop sensorimotor behavior from cockroaches, to fish, to humans. For sensorimotor control systems like reaching to a target, we have developed a set of best practices, by comparing the performance of several approaches to system identification. The results we present here focus on system identification of refuge tracking responses in the weakly electric glass knifefish, *Eigenmannia virescens*, because it is a champion animal model for sensorimotor control, but the recommendations apply across taxa, including humans.

Programming Thermobiochemomechanical (TBCM) Multiplex Robot Gels

PI: Noah J. Cowan

Bio-Robotics

Modeling, Dynamics, Navigation, and Control



PI: Noah J. Cowan

Key Personnel: Siming Deng, Kuan-lin Chen, Ruohong Shi, Aishwarya Pantula, Jinwoo Choi, David Gracias, Thao (Vicky) Nguyen, Rebecca Schulman, Noah J Cowan

Funding: NSF Award

Find out more: http://vps40083.inmotionhosting.com/~sicb/meetings/2020/schedule/abstractdetails.php?id=1626

Accomplishments and Status: The combination of stimulus-responsive and non-responsive gels make possible the ability to direct controlled shape changes within structures, including elongation, bending and twisting. Systematically interconnecting these actively controlled components leads to small scale robotic systems that can be controlled to locomote on substrates in aqueous environments. Using geometric mechanics, we designed a simple robot-gait that is being tested in a gel simulation using finite element analysis, and is leading to new robotic designs that are currently being fabricated by our JHU collaborators. Our work consolidates stimulus-responsive structures with design evaluation tools examined in previous studies and provides insight to future robot-gait design rules.

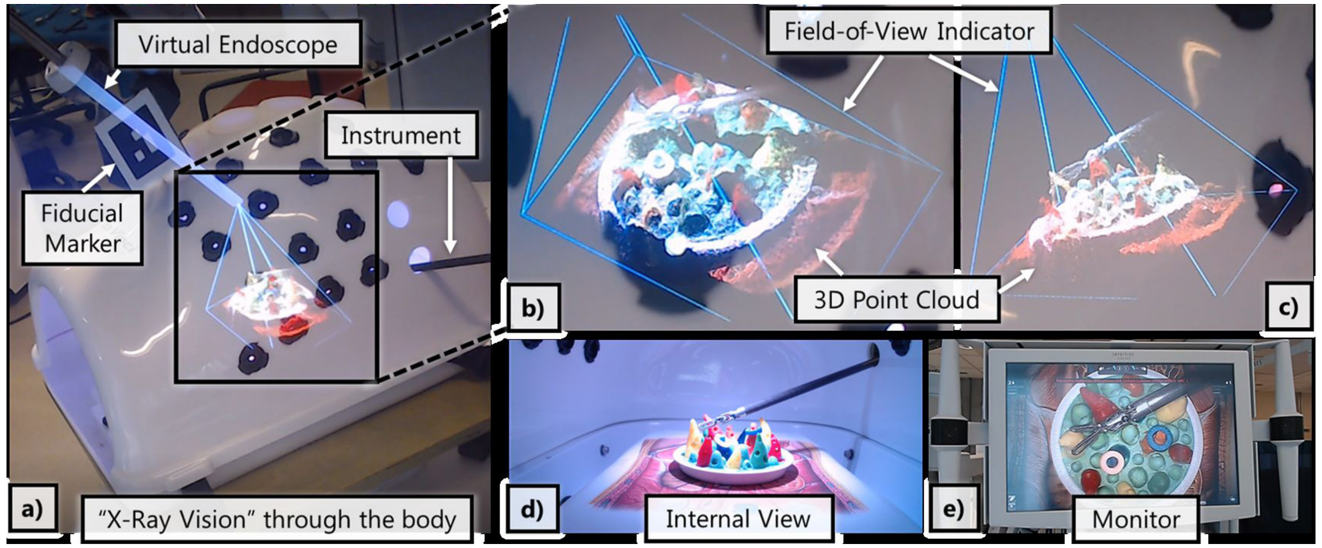
During the course of the first year, we surveyed the literature on differential geometry and motion planning tools. These tools enable the evaluation of robot designs by optimizing the best gait within a given design. We recently designed and built an automated experiment rig for gel imaging so that our theoretical models can be tested experimentally. Future work will include alternatively optimizing robot-gait designs within certain constraints in simulation, realization of simulation results, and optimization for real robots.

Augmented Reality Assistance for Minimally Invasive Surgery (ARAMIS)

PI: Peter Kazanzides

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Long Qian, Xiran Zhang, Anton Deguet, Peter Kazanzides

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

Accomplishments and Status: ARAMIS provides real-time "X-ray see-through vision" of a patient's internal anatomy to the surgeon, via a head-mounted display (HMD), in minimally invasive laparoscopic surgery. The system creates a real-time 3D point based on the disparity map from a stereo endoscope and projects the endoscope video onto this point cloud, enabling it to be viewed from the user's perspective.

A user study shows improved hand-eye coordination and similar completion time for peg transfer with the guidance of ARAMIS, as compared to conventional visualization on an external monitor.

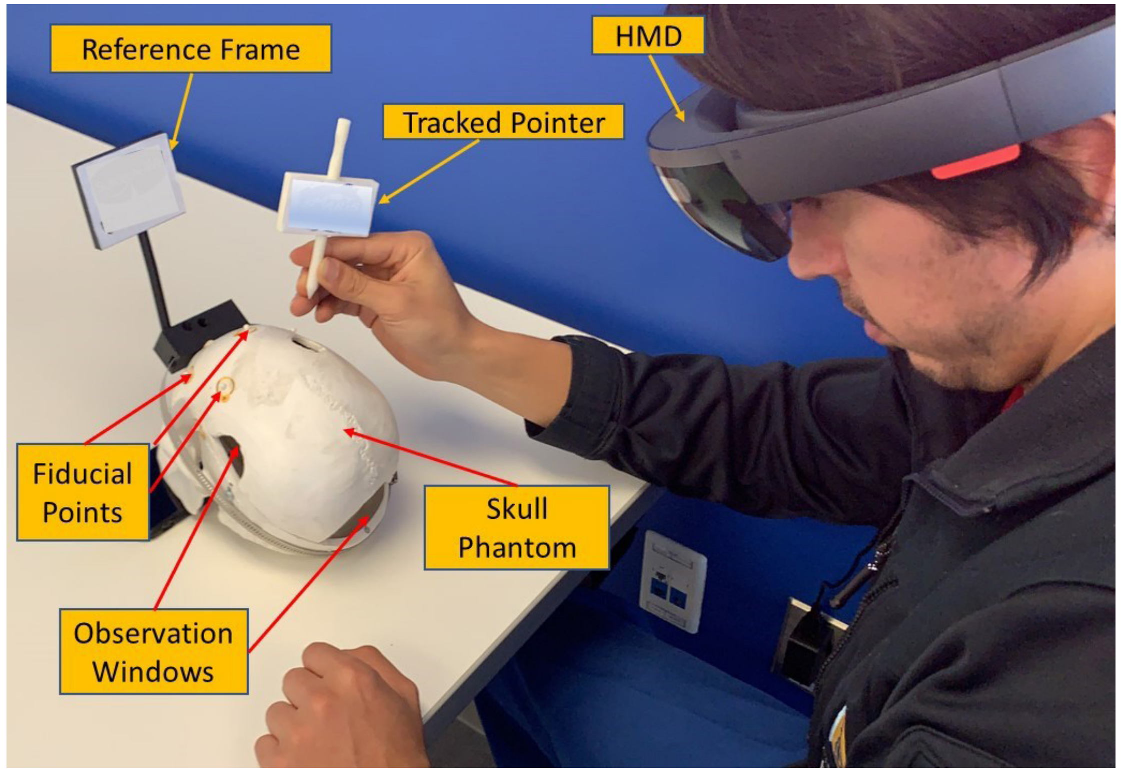
Publications: L. Qian, X. Zhang, A. Deguet, P. Kazanzides, "ARAMIS: Augmented Reality Assistance for Minimally Invasive Surgery using a Head-Mounted Display," *Medical Image Computing and Computer-Assisted Intervention (MICCAI)*, pp. 74-82, Oct. 2019.

Mixed Reality Head Mounted Display (HMD) for Neurosurgery

PI: Peter Kazanzides

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: Ehsan Azimi, Peter Kazanzides, Chien-Ming Huang, Camilo Molina, Judy Huang, Ruby Liu, Nikhil Dave, Zhiyuan Niu, Nicholas Greene

Funding: Link Foundation Fellowship

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

Accomplishments and Status: Developed a portable navigation system, based on Microsoft HoloLens, to provide mixed reality guidance for ventriculostomy, a neurosurgical procedure where a catheter is inserted into the brain ventricles to drain cerebrospinal fluid (CSF). Because this procedure is typically performed at the bedside, the conventional technique does not benefit from image guidance and about one third of insertions miss the target.

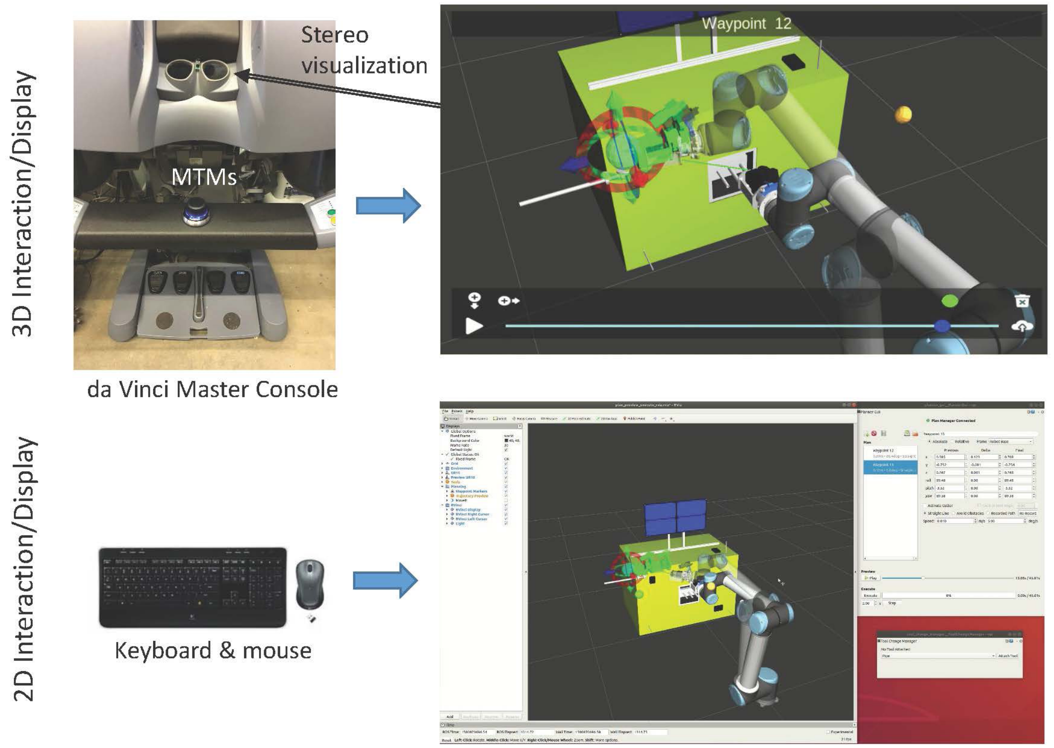
The system has been developed and is currently being evaluated by neurosurgeons. One of our next steps is to conduct a clinical trial.

Publications: E. Azimi, R. Liu, C. Molina, J. Huang, P. Kazanzides, "Interactive Navigation System in Mixed-Reality for Neurosurgery", *IEEE Virtual Reality* (VR), March 2020.

Telerobotic Satellite Servicing

PI: Peter Kazanzides

- Human-Machine Collaborative Systems
- Modeling, Dynamics, Navigation, and Control
- Perception and Cognitive Systems
- Robotics in Extreme Environments



Key Personnel: Peter Kazanzides, Louis Whitcomb, Simon Leonard, Balazs Vagvolgyi, Anton Deguet, Will Pryor, Amama Mahmood, Ehsan Azimi, Rishibrata Biswas, Sam Kamran, Adarsh Malapaka

Funding: NASA

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

Accomplishments and Status: Research in support of NASA's Restore-L mission to demonstrate telerobotic refueling of a satellite on orbit, subject to multi-second ground-to-orbit communication delays.

Accomplishments this year include: (1) the Worksite Registration Tool (WRT) software to create a 3D model of the space environment from a robotic camera survey, (2) an interactive planning capability that enables operators to plan, preview, and then execute robotic motions, while avoiding collisions, and (3) a computer vision method to measure and control tool engagement during thermal blanket cutting.

The Worksite Registration Tool (WRT) software was transferred to NASA and is being considered for integration into the ground system for the Restore-L mission. Performing experiments at JHU to evaluate the interactive planning software and the tool engagement measurement software.

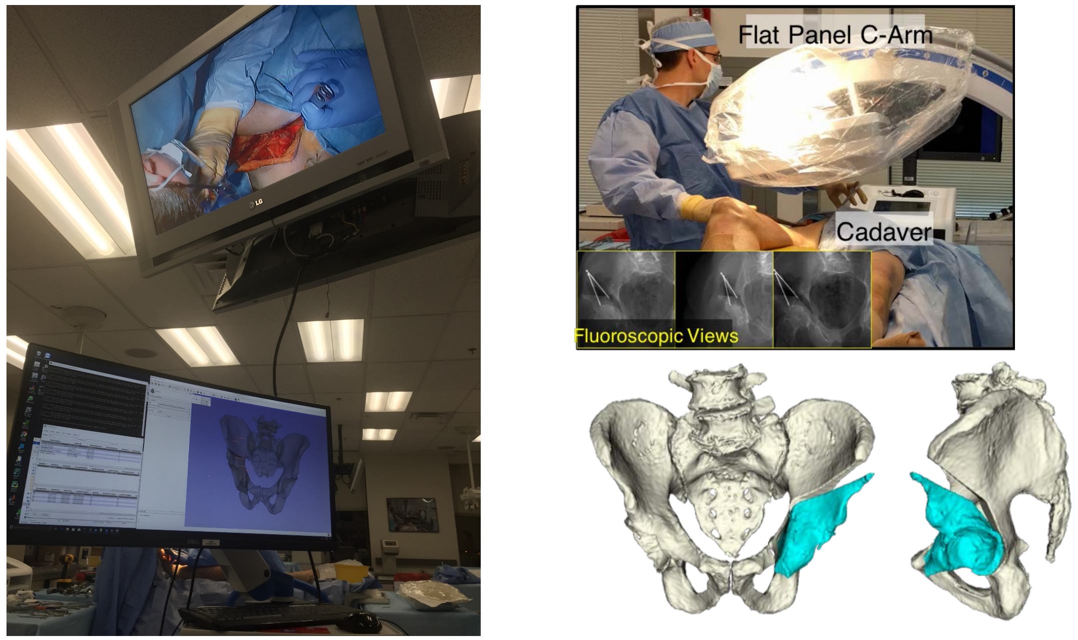
Publications: W. Pryor, B.P. Vagvolgyi, W.J. Gallagher, A. Deguet, S. Leonard, L.L. Whitcomb, P. Kazanzides, "Experimental evaluation of teleoperation interfaces for cutting of satellite insulation", *IEEE Intl. Conf. on Robotics and Automation* (ICRA), pp. 4775-4781, May 2019.

X-ray Image-based Navigation for Periacetabular Osteotomy with Intraoperative Biomechanical Feedback

PI: Russell Taylor/Mehran Armand

- Medical Robots and Computer Integrated Interventional Systems

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



Key Personnel: Mehran Armand, Russell Taylor, Robert Grupp, Mahsan Bakkhtiar Nejad

Funding: NIH/NIBIB, JHU/APL graduate student scholarship

Find out more: https://bigss.lcsr.jhu.edu and https://ciis.lcsr.jhu.edu

Accomplishments and Status: We have developed processing to use intraoperative 2D X-ray imaging for anatomical pose estimation of intact and fractured bone structures. Our approach differs from existing systems by not requiring the use of optical tracking devices or external fiducial objects.

The navigation system tested with cadaver experiments. Optimal screw placement simulated.

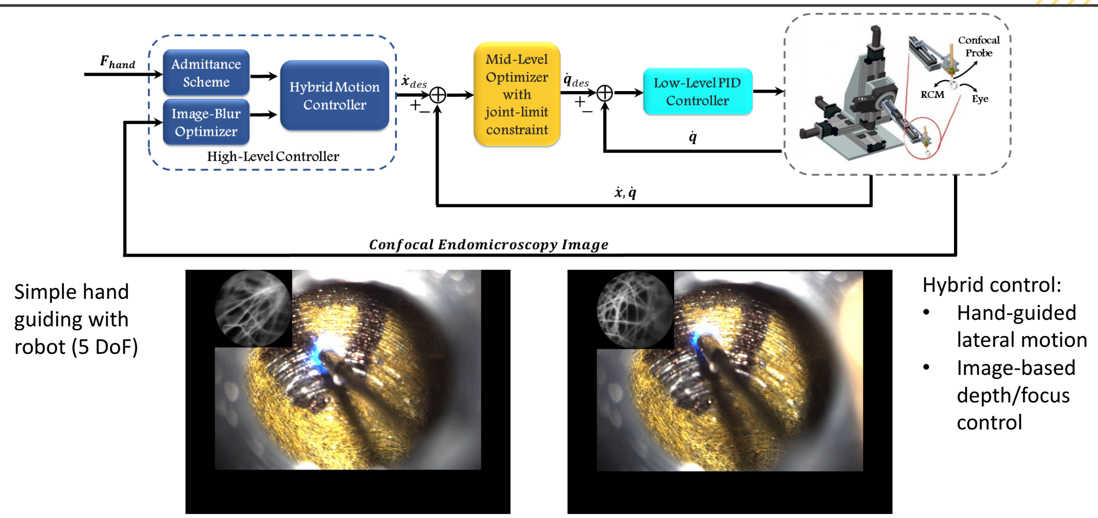
See Also: Continuum Robots, Tools, and Algorithms for Tissue Manipulation

Robot-Assisted Confocal Endoscopic Imaging for Retinal Surgery

PI: Russell Taylor

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Z. Li, M. Shahbazi, M. Patel, P. Chalasani, E. O'Sullivan, H. Zhang, K. Vyas, A. Deguet, P. Gehlbach, I. Iordachita, G. Z. Yang, R. H. Taylor, "A Comparison of Cooperative vs. Teleoperated Robot-Assisted Frameworks for Confocal Endomicroscopy Scanning of the Retina", *IROS 2019*.

Key Personnel: Zhaoshuo Li, Mahya Shahbazi, Preetham Chalasani, Niravkumar Patel, Peter L. Gehlbach, Iulian Iordachita, Russell H. Taylor, Hanlyn Centre for Medical Robotics: Eimear O' Sullivan, Haojie Zhang, Khushi Vyas, Guang-Zhong Yang

Funding: This work was funded in part by: NSF NRI Grants, Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship #516873; Johns Hopkins internal funds; Robotic Endobronchial Optical Tomography (REBOT), Micro-robotics for Surgery; and NIH

Find out more: https://ciis.lcsr.jhu.edu

Accomplishments and Status: We have developed a novel semi-autonomous control framework enabling probe-based confocal laser endomicroscopy (pCLE) scan of retinal tissue. This method combines real-time image-based autonomous control of the probe-to-tissue distance with virtual fixtures to assist lateral scanning of the probe across the retinal surface. It was implemented using the dVRK software framework developed at JHU and demonstrated on using the JHU "eye robots" developed here for retinal microsurgery.

This was a joint project with the Hamlyn Centre for Medical Robotics.

Publications:

Z. Li, M. Shahbazi, N. Patel, E. O. Sullivan, P. Chalasani, H. Zhang, K. Vyas, A. Deuget, P. L. Gehlbach, I. Iordachita, G.-Z. Yang, and R. H. Taylor, "An Image-Based Control Framework for Teleoperated Semi-Autonomous Retina Endomicroscopy Scanning", in *Int. Symposium of Medical Robotics* (ISMR), Atlanta, Georgia, April 4-5, 2019.

Z. Li, M. Shahbazi, N. Patel, E. O. Sullivan, H. Zhang, K. Vyas, P. Chalasani, P. L. Gehlbach, I. Iordachita, G.-Z. Yang, and R. H. Taylor, "A Novel Semi-Autonomous Control Framework for Retina Confocal Endomicroscopy Scanning", in *International Conference on Intelligent Robots and Systems* (IROS), Macao, Nov. 4-8, 2019.

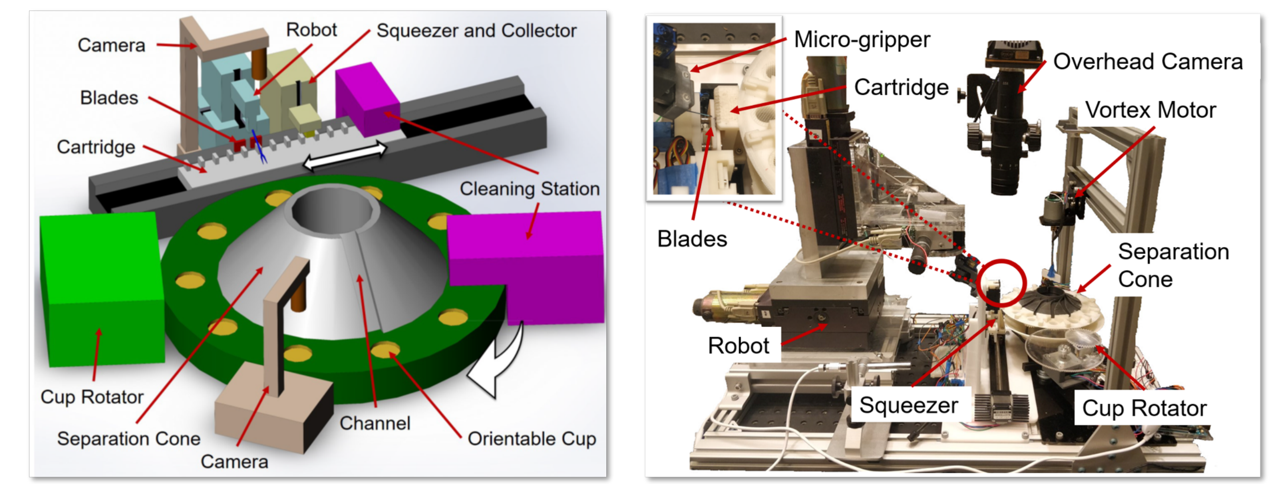
See Also: Complementary Situational Awareness for Intelligent Telerobotic Surgical Assistant Systems

Automated Mosquito Salivary Gland Removal

PI: Russell Taylor

Human-Machine Collaborative Systems

Prototype Automated Mosquito Dissection System



Conceptual Drawing | Current System Prototype

Key Personnel: *Current WSE*: Russell Taylor, Iulian Iordachita, Greg Chirikjian, Balazs Vagvolgyi, Simon Leonard, Mariah Schrum, Amanda Canezin, Henry Phalen, Alan Lai, Akash Chaurasia, Matthew Fernandez, Wanzi Li, Jialan Ma, Disha Mishra, Disha Sarawgi, Andrew Shaughnessy, Hongtao Wu, Mengdi Xu, Shengnan Lu, Michael Pozin, Jin Seob Kim, Nicholas Lamaison, Can Kocabalkani, Prasad Vagdargi

Sanaria: Stephen Hoffman, Sumana Chakravarty, Kim Lee Sim

Funding: NIH SBIR grants and NSF Graduate Research Fellowship.

Patents and Disclosures: US Patent Application 0355951

US Patent Application 62888160

Find out more: https://ciis.lcsr.jhu.edu

Accomplishments and Status: In collaboration with Sanaria, Inc., we have developed novel apparatus to assist in the extraction of salivary glands from mosquitoes, in order to address a significant barrier for large-scale production of a malaria vaccine developed by Sanaria. In an undergraduate project, we 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. Subsequently, we have been working with Sanaria on develop a fully automated mosquito dissection system, using key insights drawn from our manual system.

Sanaria is pursuing further development of the manual production fixtures for good-manufacturing-practice (GMP) while we are working with Sanaria on the automated system.

Publications: M. Schrum, A. Canezin, S. Chakravarty, M. Laskowski, S. Comert, Y. Sevimli, G. S. Chirikjian, Stephen L. Hoffman, and R. H. Taylor, "An Efficient Production Process for Extracting Salivary Glands from Mosquitoes", *arXIV*, 2019, http://arxiv.org/abs/1903.02532.

H. Phalen, P. Vagdargi, M. Pozin, S. Chakravarty, G. S. Chirikjian, I. Iordachita, and R. H. Taylor, "Mosquito Pick-and-Place: Automating a Key Step in PfSPZ-based Malaria Vaccine Production", in *IEEE Conference on Automation Science and Engineering* (CASE), Vancouver, BC, August 22-26, 2019. pp. 12-17.

Steady-Hand Robot for Head-and-Neck Surgery

PI: Russell Taylor

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems

Key Personnel: *Current WSE*: Russell Taylor, Iulian Iordachita, Zhaoshuo Li, Can Kocabalkanli, Kevin Gilboy, Alan Lai, Seena Vafaee

JHU SOM: Kevin Olds, Chris Razavi, Francis Creighton, Deepa Galaiya, Lee Akst, Masaru Ishii, Jeremy Richmon, Matt Stewart, Wade Chien, Henry Brem

Galen Robotics: Bruce Lichorowic, Dave Saunders, Florin Neacsu , Dave Levi, Olivia Puelo, Rui Yin

Past (partial list): Lihang Feng, Preetham Chalasani, Marcin Balicki, Kevin Olds, Paul Wilkening, Yunus Sevimli, Paul Wilkening, Thomas Keady, Mariah Schrum, Joe Peine

Funding: JHU internal funds, JHU Cohen Fund, Maryland Innovation Initiative, contract with Galen Robotics

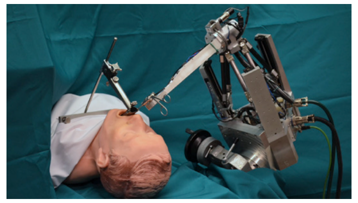
Patents and Disclosures: United States Patent 8,911,429 B2; United States Patent 9,554,865; United States Patent 9,873,198 B2; Israel Patent 232310; Japan Patent 6366506; United States Patent 10,166,080

Accomplishments and Status: 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.

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 start-up company making a clinical/commercial version. Advanced R&D work continues in LCSR under a master agreement with Galen Robotics, Inc.

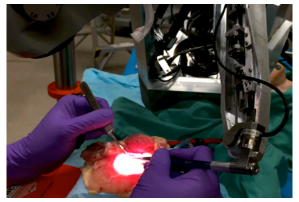
Under a license agreement between Galen Robotics, Inc. and the Johns Hopkins University, several of the key personnel are entitled to royalty distributions on technology described in this article. Also, Taylor is a paid consultant to and owns equity in Galen Robotics, Inc. This arrangement has been reviewed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

Initial prototype



Cadaver laryngeal surgery with initial prototype

Cadaver sinus surgery with initial prototype



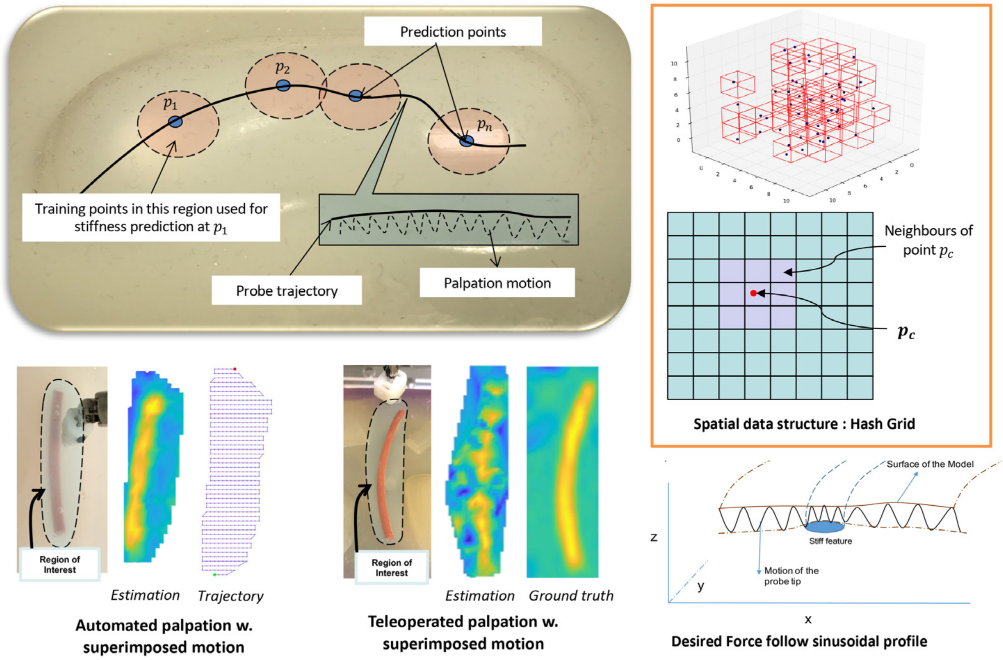
Microsurgery Anastomosis with initial prototype

Galen Prototype System

Real-Time Stiffness Estimation Using Gaussian Processes

PI: Russell Taylor

Perception and Cognitive Systems



Key Personnel: *JHU*: Russell Taylor, Preetham Chalasani, Peter Kazanzides, Anton Deguet, Marin Kobilarov, Mahya Shahbazi, Long Wang, Zihan Chen, Zhaoshuo Li

CMU: Howie Choset, Rangaprasad Arun Srivatsan, Nicolas Zevallos, Hadi Salman;

Vanderbilt: Nabil Simaan, Long Wang, Rashid Yasin, Colette Abah

Funding: NSF NRI grants

Find out more: https://ciis.lcsr.jhu.edu

(video) https://tinyurl.com/rbn2o34

Accomplishments and Status: One key capability developed as part of our Complementary Situational Awareness project 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.

Publications: 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.

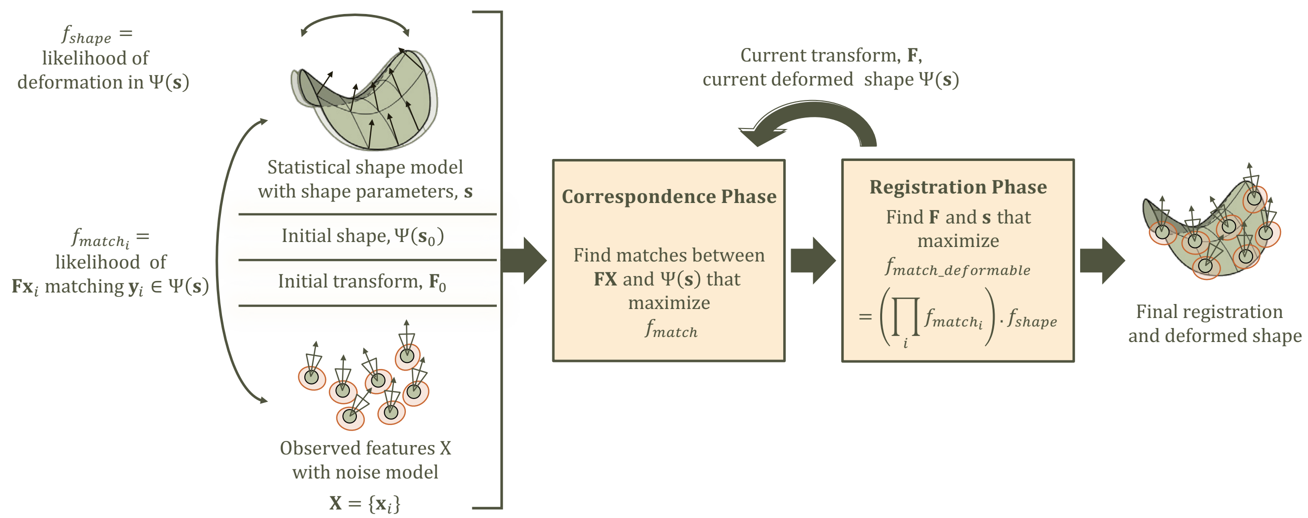
P. Chalasani, L. Wang, R. Yasin, N. Simaan, and R. H. Taylor, "Preliminary Evaluation of an Online Estimation Method for Organ Geometry and Tissue Stiffness", *IEEE Robotics and Automation Letters*, vol. 3-, pp. 1816–1823, 2018. 10.1109/LRA.2018.2801481

See Also: Complementary Situational Awareness for Intelligent Telerobotic Surgical Assistant Systems

Deformable Registration Using Statistical Shape Models

PI: Russell Taylor

Perception and Cognitive Systems



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

Funding: NIH

Accomplishments and Status: 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.

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. This work has also been used in registration of both CT-derived and statistical models of sinus anatomy to endoscopic video.

Publications: S. Billings and R. Taylor, "Generalized Iterative Most-Likely Oriented Point (G-IMLOP) Registration", *Int. J. Computer Assisted Radiology and Surgery*, vol. 8–10, pp. 1213-1226, 2015. DOI 10.1007/s11548-015-1221-2

A. Sinha, S. Leonard, A. Reiter, M. Ishii, R. H. Taylor, and G. D. Hager, "Automatic segmentation and statistical shape modeling of the paranasal sinuses to estimate natural variations", in *Proc. SPIE 9784, Medical Imaging 2016: Image Processing*, San Diego, Feb. 27, 2016. pp. 97840D.1-8.

A. Sinha, S. D. Billings, A. Reiter, X. Liu, M. Ishii, G. D. Hager, and R. H. Taylor, "The deformable most-likely-point paradigm", *Medical Image Analysis*, vol. 55-, pp. 148-164, July, 2019.

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

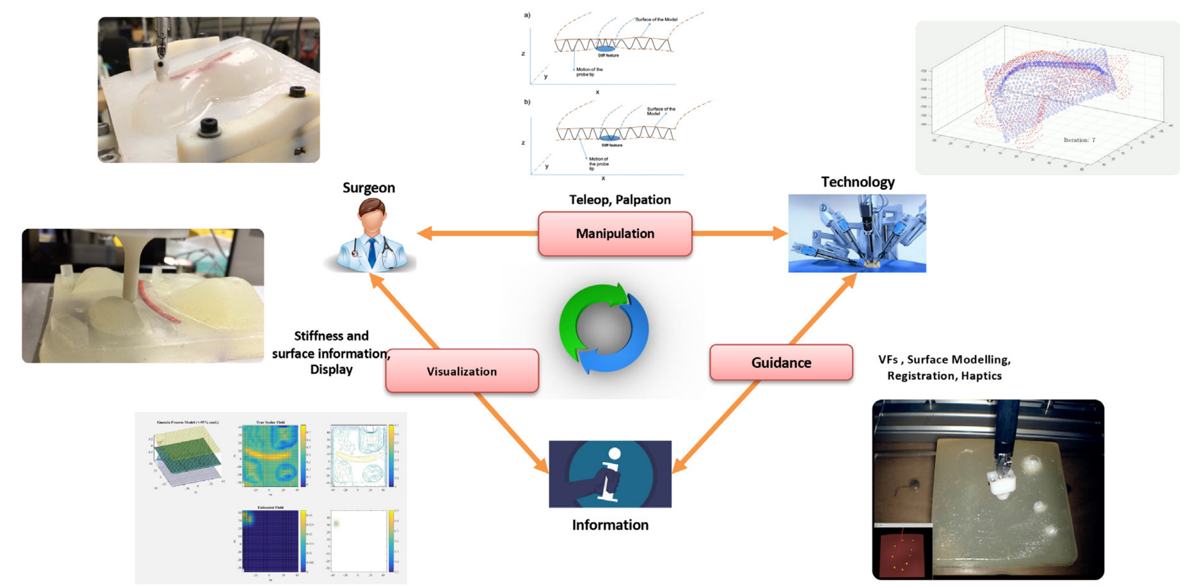
A. Sinha, Deformable registration using shape statistics with applications in sinus surgery, PhD thesis in Computer Science, Johns Hopkins University, Baltimore, May 2018.

Complementary Situational Awareness for Intelligent Telerobotic Surgical Assistant Systems

PI: Russell Taylor

Medical Robots and Computer Integrated Interventional Systems

Human-Machine Collaborative Systems



Key Personnel: Z. Chen, A. Malpani, P. Chalasani, A. Deguet, S. S. Vedula, P. Kazanzides, R.H. Taylor, L. Wang, R. Yasin, N. Simaan

Find out more: http://nri-csa.vuse.vanderbilt.edu/joomla

https://ciis.lcsr.jhu.edu

(video) https://tinyurl.com/rbn2o34

Accomplishments and Status: The main goal of this 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.

This project has been completed.

Publications: Z. Chen, A. Malpani, P. Chalasani, A. Deguet, S. S. Vedula, P. Kazanzides, and R. H. Taylor, "Virtual fixture assistance for needle passing and knot tying", in *IEEE International Conference on Intelligent Robots and Systems*. vol. 2016-Novem: IEEE, 2016, pp. 2343-2350,

P. Chalasani, "Complementary Situational Awareness For Intelligent Telerobotic Surgical Assistant Systems," Ph.D. thesis in Computer Science, Johns Hopkins University, Baltimore, October 2018.

P. Chalasani, L. Wang, R. Yasin, N. Simaan, and R. H. Taylor, "Preliminary Evaluation of an Online Estimation Method for Organ Geometry and Tissue Stiffness," *IEEE Robotics and Automation Letters*, vol. 3-, pp. 1816–1823, 2018. 10.1109/LRA.2018.2801481

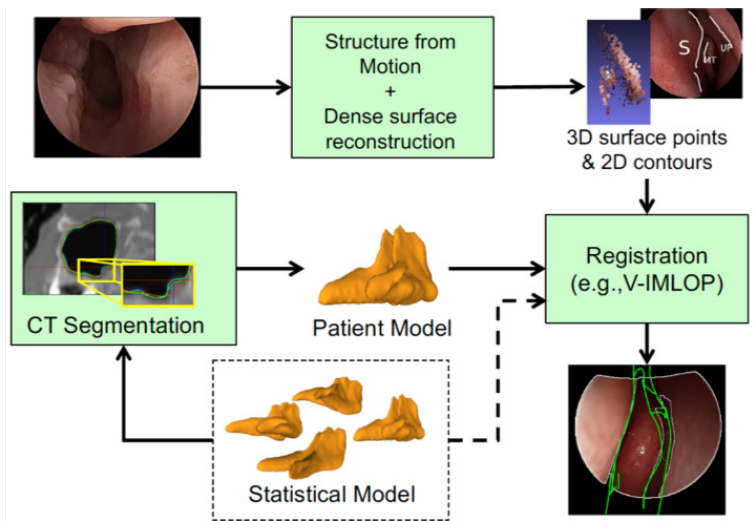
See Also: Robot-Assisted Confocal Endoscopic Imaging for Retinal Surgery

Enhanced Navigation for Endoscopic Sinus Surgery through Video Analysis

PI: Gregory D. Hager/Russell Taylor

Human-Machine Collaborative Systems

Medical Robots and Computer Integrated Interventional Systems



Key Personnel: A. Sinha, X. Liu, B. Vágvölgyi, S. Leonard, S. Billings, A. Reiter, S. Vedula, M. Ishii, M. Unbareth, R.H. Taylor, G. D. Hager

Funding: Galen Robotics, Johns Hopkins University internal funds

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

Accomplishments and Status: We have developed methods for reconstructing the shape of surfaces in the sinus cavity directly from untracked endoscopic video sequences and then registering them to patient CT or to statistical models of anatomy. This enables surgical navigation without external tracking devices and also enables combining anatomic labels and other information with real time video displays to assist the surgeon.

Publications: S. D. Billings, A. Sinha, A. Reiter, S. Leonard, M. Ishii, G. D. Hager, and R. H. Taylor, "Anatomically Constrained Video-CT Registration via the V-IMLOP Algorithm", in *Medical Image Computing and Computer Assisted Interventions* (MICCAI), Athens, October 18–20, 2016. pp. 133-141.

S. Leonard, A. Sinha, A. Reiter, M. Ishii, G. L. Gallia, R. H. Taylor, and G. D. Hager, "Evaluation and Stability Analysis of Video-Based Navigation System for Functional Endoscopic Sinus Surgery on In-Vivo Clinical Data", *IEEE Trans Med Imaging*, vol. 37- 10, pp. 2185–2195, 2018. 10.1109/TMI.2018.2833868

A. Sinha, X. Liu, A. Reiter, M. Ishii, G. Hager, and R. H. Taylor, "Endoscopic Navigation in the Absence of CT Imaging", in *Medical Image Computing and Computer Assisted Interventions* (MICCAI), Grenada, Spain, Sept. 16-20, 2018. pp. 64-71.

A. Sinha, S. D. Billings, A. Reiter, X. Liu, M. Ishii, G. D. Hager, and R. H. Taylor, "The deformable most-likely-point paradigm", *Medical Image Analysis*, vol. 55-, pp. 148-164, July, 2019.

A. Sinha, M. Ishii, G. D. Hager, and R. H. Taylor, "Endoscopic navigation in the clinic: registration in the absence of preoperative imaging", *Int J CARS*, vol. 14-, pp. 1495-1506, 2019. 10.1007/s11548-019-02005-0.

See Also: 3D Reconstruction of Sinus Anatomy from Monocular Endoscopic Video using Self-supervised Learning

2020

Bio-Robotics	Human-Machine Collaborative Systems	Medical Robots and Computer Integrated Interventional Systems	Modeling, Dynamics, Navigation, and Control	Perception and Cognitive Systems	Robotics in Extreme Environments

LABORATORY FOR
Computational
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