2023 REU Project List

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Project 1: Steady-hand eye robot control for bilateral retinal surgery

PIs: Prof. Iulian Iordachita, Prof. Russell Taylor, Surgeons: Dr. Peter Gehlbach
Mentor: TBD

Project Description: Steady-hand eye robot (SHER) is a cooperatively control robot developed for assisting the surgeon during delicate maneuvers inside the eye. In "steady hand" control, both the surgeon and the robot hold the surgical instrument. The robot senses forces exerted by the surgeon on the tool and moves to comply. Since the motion is made by the robot, there is no hand tremor, the motion is very precise, and "virtual fixtures" may be implemented to enhance safety or otherwise improve the task. Potential applications include bilateral vein cannulation, subretinal injections, and membrane peeling.

Possible projects include:

- User studies comparing user performance with/without robotic assistance on suitable artificial phantoms.
- Optimization of SHER control and development of virtual fixtures for a specific surgical application
- Design of force-sensing instruments and instrument adapters for SHER
- Developing interfaces to surgical navigation software

Required Skills: The student should have a background in biomedical instrumentation and an interest in developing clinically usable instruments and devices for surgery. Specific skills will depend on the project chosen. Experience in at least one of robotics, mechanical engineering, and C/C++ programming is important. Similarly, experience in statistical methods for reducing experimental data would be desirable. For mechanical design, students should have significant experience with mechatronic design, CAD, 3D printing and other fabrication processes.

Project 2: Experimental Characterization of Psychophysical Metric of Stimulus Complexity for Animal Tracking Behavior

PI: Noah Cowan
Mentor: Yu Yang

Project Description: When a hummingbird feeds from a flower swaying in wind, it needs to sense how the flower moves back and forth to keep pace with the flower's movement. That is not a tough task in some scenarios; for instance, when flower follows a simple oscillatory trajectory, the hummingbird can track the flower almost perfectly. However, when the flower moves more randomly, the tracking performance of hummingbird gets worse. This example shows that the complexity of movement of the target greatly impacts an animal's tracking performance. In this project, we will investigate a similar animal model system, the weakly electric glass knifefish, Eigenmannia virescens. These fish naturally swim back and forth to track a moving refuge (a plastic tube) in much the same way that hummingbird moves back and forth to track a swaying flower. We will study how the fish brain categorizes stimulus complexity during refuge tracking. Intuitively, factors such as the number of frequencies in a signal, signal amplitude, relative frequency, and initial phases at each frequency could affect the signal complexity. However, the definition of "complexity" for the brain's automatic (subconscious) control system may be different from our signal designers' high-level, cognitive understanding. Thus, in this project, the REU student will seek to find, experimentally, what signals of refuge motion are hard to track (and therefore complex) vs. easy to track (and therefore predictable). The overall goal is to determine a signal "complexity measure" in a psychophysical sense, using ideas like entropy, Kolmogorov complexity, and sparsity as candidate metrics and understand how it impacts tracking performance in animals.

Role of REU Student: The REU student will run new experiments with the fish, analyze data in MATLAB, and write up the results for presentation. A reasonable goal will be co-authoring an abstract that will be presented at the annual meeting of the Society of Integrative and Comparative Biology.

Required Background & Skills: Knowledge of linear algebra and differential equations, and proficiency with MATLAB. No prior biological knowledge is required.

Preferred Background & Skills: A signals and systems or control systems course.

Project 3: Autonomous Robotic Soft Tissue Surgery

PI: Axel Krieger
Mentor: Jiawei Ge

Project Description: Autonomous robotic surgery systems have the potential to significantly improve efficiency, safety, and consistency over current tele-operated robotically assisted surgery (RAS) with systems such as the da Vinci robot (Intuitive Surgical). Elastic and plastic deformations occur constantly during soft tissue surgeries such as suturing and tumor resections. Accurately predicting tool and tissue deformations and compensating for them in surgical plans is paramount for accurately performing robotic surgeries and interventions. In this project, we will explore model and data-driven approaches to predict in real-time deformations and adjust surgical plans for suturing and tumor resections. The proposed research on deformation prediction will produce methodologies for understanding tissue behavior and how to compensate for deformations.

Role of REU Student: The REU student will help develop surgical planning and real-time control methods utilizing finite element modeling (FEM) to compensate and adjust for deformations. Here, we will compare surgical performance in suturing and

tumor resection applications between no deformation prediction, open loop, and closed loop prediction. This work will investigate how deformation prediction improves surgeries.

Required Background & Skills:

- Basic or better object-oriented programming skills
- Familiarity with computer aided design and FEM
- Experience with conducting experiments

Preferred Background & Skills:

- Understanding of biomechanics for tissue interactions
- Robotics experience
- Experience with robot operating software (ROS)

Project 4: Haptic Feedback and Control for Upper-Limb Prosthetic Devices

PI: Prof. Jeremy D. Brown
Mentor: TBD

Project Description: Haptic (touch) feedback is essential for dexterous manipulation. Individuals with upper-limb loss who utilize myoelectric EMG-based prostheses do not receive haptic feedback when operating their device. Thus, myoelectric EMG-based prosthesis wearers are currently unable to feel many of the physical interactions between their prosthetic limb and the world around them. We have previously shown that prostheses with lower mechanical impedance allow for a high degree of naturalistic control, and that haptic force feedback of grip force provides more utility than vision in many tasks. This project seeks to build on these previous findings by investigating the entire sensorimotor control loop for upper-limb prostheses. The research objective of this project is to develop fundamental insights into amputee-prosthesis co-adaptation through novel control and feedback strategies.

Role of REU Student: With supportive mentorship, the REU student will lead the refinement and evaluation of our current mock upper-limb prosthesis experimental apparatus, which will be worn by non-amputee participants. He/she/they will then work closely with clinical partners to design, conduct, and analyze a human-subject experiment to evaluate specific aspects of the overarching research hypothesis.

Required Background & Skills: Experience with CAD, rapid prototyping, MATLAB/Simulink. Interest in working collaboratively with both engineers and clinicians.
Preferred Background & Skills: Mechatronic design experience and human-subject experiment experience, ROS, Python

Project 5: Bimanual Haptic Feedback for Robotic Surgery Training

PI: Prof. Jeremy D. Brown
Mentor: TBD

Project Description: Robotic minimally invasive surgery (RMIS) has transformed surgical practice over the last decade; teleoperated robots like Intuitive Surgical's da Vinci provide surgeons with vision and dexterity that are far better than traditional minimally invasive approaches. Current commercially available surgical robots, however, lack support for rich haptic (touch-based) feedback, prohibiting surgeons from directly feeling how hard they are pressing on tissue or pulling on sutures. Expert surgeons learn to compensate for this lack of haptic feedback by using vision to estimate the robot's interactions with surrounding tissue. Yet, moving from novice proficiency to that of an expert often takes a long time. We have previously demonstrated that tactile feedback of the force magnitude applied by the surgical instruments during training helps trainees produce less force with the robot, even after the feedback is removed. This project seeks to build on these previous findings by refining and evaluating haptic feedback in traditional and novel surgical robotic platforms. The research objective of this project is to test the hypothesis that haptic feedback accelerates the learning curve of trainees learning to perform robotic surgery. In addition, this project seeks to use haptic signals to objectively measure and eventually improve skill at robotic surgery.

Role of REU Student: With supportive mentorship, the REU student will lead the refinement and evaluation of our current haptic feedback system, which involves mechanical, electrical, and computational components. He or she will then work closely with clinical partners to select clinically appropriate training tasks and will design, conduct, and analyze a human-subject experiment to evaluate the system.

Required Background & Skills: Experience with CAD, rapid prototyping, MATLAB/Simulink, and Python. Interest in working collaboratively with both engineers and clinicians.
Preferred Background & Skills: Mechatronic design experience and human-subject experiment experience, and experience with ROS.

Project 6: User Performance in Human-in-the Loop Telerobotic Systems

PI: Prof. Jeremy D. Brown
Mentor: TBD

Project Description: Human-in-the-loop telerobotic systems (HiLTS) are robotic tools designed to extend and improve the dexterous capabilities of the human operator in virtual and remote environments. Dexterous manipulation, however, depends on how well the telerobot is incorporated into the operator's sensorimotor control scheme. Empirical evidence suggest haptic feedback can lead to improved dexterity. Unfortunately, the addition of haptic feedback, in particular kinesthetic feedback, can introduce dynamics between the leader and follower of the telerobot that can affect both stability and device performance. The overall goal of this project is to understand, from both a fundamental and applied perspective, how the application of haptic feedback affects operator performance in HiLTS. We have developed an electromechanical telerobotic testbed that will be used for fundamental haptic perception studies. The goal of this project is to develop a simulated virtual environment that will be used for haptic perception studies and carry out those investigations.

Role of REU Student: With supportive mentorship, the REU student will lead the refinement and evaluation of our current haptic feedback system, which involves mechanical, electrical, and computational components. He or she will work alongside a graduate student mentor on the project and will be involved in the algorithm design of the virtual environment, experimental protocol design, human subjects experiment design, and data analysis.

Required Background & Skills: Experience with CAD, rapid prototyping, MATLAB/Simulink. Interest in working collaboratively.
Preferred Background & Skills: Mechatronic design experience and human-subject experiment experience.

Commented [JC1]: Is these skills for refining the hardware? Do we need to refine the hardware?

Project 7: Amphibious Fish and Robot Locomotion on Wet Deformable Substrate

PI: Chen Li
Mentor: Divya Ramesh

Project Description: Demands of amphibious robots are arising in applications such as environmental monitoring and search and rescue. However, few robots have succeeded in traversing complex amphibious environments with wet deformable substrates like mud common at the water-land interface. This is because little is understood about how to effectively interact with such substrates to generate forces appropriately. In addition, wet deformable substrate can go from very weak to very strong depending on how much water is mixed with solid particles, making locomotion control even more challenging.

This project will test amphibious fishes and fish-inspired robots on well controlled lab testbeds with mud of precisely-controlled, systematically variable strength and discover the principles of lift, thrust, drag, and suction force generation on mud that govern effective and failed locomotion on mud.

Role of REU Student: The REU student will develop experimental setups, perform experiments, and/or analyze data with the supervision of the PI and the mentor.

Required Background & Skills: Strong mechatronics skills, including CAD design, 3D printing, machining, microcontroller programming, servo motors/linear actuators, MATLAB, willingness and comfort to handle and care for vertebrate animals.

Preferred Background & Skills: Feedback control, circuit design, signal processing, knowledge on soft robotics, python.

Project 8: Predator-prey interaction in jumping spiders and their prey

PI: Chen Li
Mentor: Yaqing Wang

Project Description: Jumping spiders have superb vision for their small size, and it is known that they can identify and stalk dangerous prey from behind (for an example, see https://www.youtube.com/watch?v=UDtlvZGmHYk), but how they do so is poorly understood. Presumably they do so by formulating and weighing between various paths, and eventually choosing the safer path to attack. In other words, they should be capable of planning. Such intelligent behavior may seem commonplace for us. However, extensive literature supports the notion that only birds and mammals should have large enough brains to afford this ability. Here we will explore whether and why jumping spiders defy this "rule" and how they can achieve this with such a tiny brain. This project will study whether and how jumping spiders can choose between various paths to attack prey.

Role of REU Student: The REU student will develop experimental setups, perform animal experiments, and/or analyze data with the supervision of the PI and the mentor.

Alternatively, the REU student may carry out simulations if the lab already gathered sufficient animal data by Spring.

Required Background & Skills: Willingness and comfort to handle and care for invertebrate animals; strong mechatronics skills, including CAD design, 3D printing, machining, microcontroller programming, servo motors/linear actuators, MATLAB.

Alternatively, for simulation: strong mathematical foundation.

Preferred Background & Skills: Knowledge and familiarity with spiders and insects.

Alternatively, for simulation: Monte Carlo tree search, partially observable Markov Decision Planning.

Project 9: Software Framework for Research in Semi-Autonomous Teleoperation

PI: Peter Kazanzides, Russell Taylor
Mentor: Anton Deguet

Project Description:
We have developed an open source hardware and software framework to turn retired da Vinci surgical robots into research platforms (da Vinci Research Kit, dVRK) and have disseminated it to 39 institutions around the world. The goal of this project is to contribute to the advancement of this research infrastructure.

Role of REU Student:
The specific task will consider the student's background and interests, but may be one of the following: (1) 3D user interface software framework, (2) improved teleoperation (e.g., joint limits), (3) PSM to ECM registration, or (4) integration of alternative input devices and/or robots.

Required Background & Skills:
Programming skills in C/C++ or Python

Preferred Background & Skills:
Programming skills in C/C++ and Python, and experience with ROS

Project 10: Robotic System for Mosquito Dissection

PIs: Professor Russell Taylor and Professor Iulian Iordachita
Mentor: TBD

Project Description:
We have an ongoing collaboration with Sanaria, Inc. to develop a robotic system for extracting salivary glands from *anopheles* mosquitoes, as part of a manufacturing process for a clinically effective malaria vaccine that is being developed by Sanaria. This project combines computer vision, real time programming, robotics, and novel mechanical design aspects. The specific task(s) will depend on the student(s) background, but may include: 1) real time computer vision; 2) machine learning for vision; 3) real time robot programming; 4) mechanical design; 5) system testing and evaluation. Depending on the project and progress, there will be opportunities to participate in academic publication and possible further patenting.

Preferred Background Skills:
For software, robot programming, or vision projects, the student(s) should have experience with Python. In addition, experience with vision and/or deep learning will be needed for vision-oriented projects. For mechanical design, students should have significant experience with mechatronic design, CAD, 3D printing and other fabrication processes. Experience with computer interfaces and low-level control (e.g., with Arduino-type subsystems) may also be useful.

Project 11: Instrumentation and steady-hand control for new robot for head-and-neck surgery

PIs: Prof. Russell Taylor, Surgeons: Dr. Francis Creighton, Dr. Deepa Galaiya
Mentor: TBD

Project Description:
We have an active collaboration with Galen Robotics, which is commercializing a "steady hand" robot developed in our laboratory for head-and-neck microsurgery. In "steady hand" control, both the surgeon and the robot hold the surgical instrument. The robot senses forces exerted by the surgeon on the tool and moves to comply. Since the motion is actually made by the robot, there is no hand tremor, the motion is very precise, and "virtual fixtures" may be implemented to enhance safety or otherwise improve the task. Potential applications include endoscopic sinus surgery, skull-base neurosurgery, laryngeal surgery, otologic surgery, and open microsurgery. While the company is developing the clinical version of the robot, we have active on-going research to develop novel applications for the system, using a pre-clinical prototype.

Possible projects include:

- Development of "phantoms" (anatomic models) for evaluation of the robot in realistic surgical applications.
- User studies comparing surgeon performance with/without robotic assistance on suitable artificial phantoms.
- Optimization of steady-hand control and development of virtual fixtures for a specific surgical application
- Design of instrument adapters for the robot
- Developing interfaces to surgical navigation software

Required Skills:
The student should have a background in biomedical instrumentation and an interest in developing clinically usable instruments and devices for surgery. Specific skills will depend on the project chosen. Experience in at least one of robotics, mechanical engineering, and C/C++ programming is important. Similarly, experience in statistical methods for reducing experimental data would be desirable.

Project 12: Control of tool-to-tissue interaction forces in a cooperatively controlled surgical robot

PIs: Prof. Russell Taylor, Surgeons: Dr. Francis Creighton, Dr. Deepa Galaiya
Mentor: TBD

Description:
We have an active collaboration with Galen Robotics, which is commercializing a "steady hand" robot developed in our laboratory for head-and-neck microsurgery. In "steady hand" control, both the

surgeon and the robot hold the surgical instrument. The robot senses forces exerted by the surgeon on the tool and moves to comply. Since the motion is actually made by the robot, there is no hand tremor, the motion is very precise, and "virtual fixtures" may be implemented to enhance safety or otherwise improve the task. Potential applications include endoscopic sinus surgery, skull-base neurosurgery, laryngeal surgery, otologic surgery, spine surgery, and open microsurgery. While the company is developing the clinical version of the robot, we have active on-going research to develop novel applications for the system, using a pre-clinical prototype.

Many of the contemplated applications for this robot, especially in the lateral skull base and spine, can require delicate control to tool-to-tissue interaction forces. We have developed a force-sensing surgical drill for use with the robot that enables the system to sense these forces while separating the sensed force values from the hand forces exerted by the surgeon on the drill body.

Possible projects include:

- Mechanical/mechatronic projects:
    - Development of improved designs for the drill holder providing for improved ergonomics or sensing.
    - Development of drill-mounted surgeon interaction inputs (e.g., buttons, sliders, etc.) to enhance the control options available to the surgeon while using the robot.
- Control enhancements to enhance the surgeon's ability to control tool-to-tissue interaction forces.
- User studies comparing surgeon performance with/without robotic assistance on suitable artificial phantoms.

Required Skills:
Specific skills will depend on the project chosen. Experience in at least one of robotics, mechanical engineering, and C/C++ programming is important. Similarly, experience in statistical methods for reducing experimental data would be desirable.

Project 13: Development of "digital twin" simulation models to provide complementary situational awareness for surgical robots

PIs: Prof. Russell Taylor, Dr. Adnan Munawar, Prof. Mathias Unberath, Surgeons: Dr. Francis Creighton, Dr. Masaru Ishii
Mentor: TBD

Description:
A key long-term research goal within our laboratory is development of "surgical assistant" systems creating a three-way partnership between human surgeons, technology (robots, sensors, etc.) and information to improve patient care. Within this framework, we wish to develop modes of "shared autonomy" in which a surgical robot can actively assist in executing surgical maneuvers. To do this, both the surgeon and the computer controlling the system must have a shared understanding of the surgical

task, patient anatomy, and the progress of the surgery. Our strategy for implementing this complementary situational awareness rests heavily on developing and maintaining real-time "digital twin" simulation models of the patient and surgical procedure, in which actions of the robot and sensed information from computer vision and other sensors is used to update the model. Similarly, the simulation model can be used to help the controller to interpret and execute surgeon commands to the system. Currently, we have initial implementations for key components of this architecture, but fully implementing our vision will involve multiple research projects.

Possible projects include:

- Real-time computer vision to recognize and update models of patient anatomy and tool-to-tissue interactions
- Online updating of robot-to-model and model-to-patient registration
- Augmented reality display of relevant information from the simulation model to the surgeon
- Improvements to the underlying simulation framework
- User studies involving surgeons with an existing robot and physical phantoms

Required Skills:
Specific skills will depend on the project chosen. Experience in C/C++ programming is important. Many of the specific projects will require computer vision, computer graphics, or experience with simulation systems. Similarly, experience in statistical methods for reducing experimental data would be very desirable for user studies.

Project 14: Photoacoustic Molecular Imaging for Breast Cancer Detection

PI: Professor Muyinatu Bell

Mentor: TBD

Project Description:

Photoacoustic imaging is an emerging technique that uses pulsed lasers to excite selected tissue and create an acoustic wave that is detected by ultrasound technology. This project explores the use of photoacoustic imaging to detect molecular structures during breast biopsies and other minimally invasive procedures.

Role of REU Student:

Literature searches; phantom design and construction; perform experiments with *ex vivo* tissue; data analysis and interpretation; preparation of a photoacoustic imaging system for clinical studies; interact and interface with clinical partners at the Johns Hopkins Hospital

Preferred Background & Skills:

Ability to perform laboratory experiments and analyze results; programming experience in MATLAB; experience with ultrasound imaging, lasers, optics, and/or programming experience in C/C++ or Python would be helpful, but not required.

Project 15: Photoacoustic Laser Safety

PI: Professor Muyinatu Bell
Mentor: TBD

Project Description:

Currently, laser safety limits are only defined for skin and eyes, which provides overly conservative limits for other tissues, particularly when considering the significant differences in optical and thermal properties between liver and skin tissues. Preliminary results from the PULSE Lab indicate that exceeding currently defined limits for skin does not damage internal tissues, which is promising for photoacoustic imaging of internal organs in intraoperative settings. This project aims to redefine laser safety limits for specific internal organs.

Role of REU Student:

Simulation of tissue heating for multiple tissue types; hands-on experiments; data analysis and interpretation

Preferred Background & Skills:

Ability to perform simulations, laboratory experiments, and data analysis; programming experience in MATLAB and COMSOL; experience with ultrasound imaging, lasers, and/or optics, would be helpful, but not required.

Project 16: Deep Learning to Improve Ultrasound and Photoacoustic Image Quality

PI: Professor Muyinatu Bell
Mentor: TBD

Project Description:

Deep learning methods are capable of performing sophisticated tasks when applied to a myriad of artificial intelligent research fields. This project builds on our pioneering expertise to explore novel approaches that replace the inherently flawed beamforming step during ultrasound and photoacoustic image formation by applying deep learning directly to raw channel data. In ultrasound and photoacoustic imaging, the beamforming process is typically the first line of software defense against poor quality images.

Role of REU Student:

Implement simulations of acoustic wave propagation to create a sufficient training data set; train and test multiple network architectures; data analysis and interpretation

Preferred Background & Skills:

Programming experience in MATLAB and C/C++; experience with Keras and/or TensorFlow; familiarity with computer vision and basic deep learning techniques; experience with ultrasound imaging and would be helpful, but not required.