**Project 1: Instruments and robots to sense and make use of physical interaction during locomotion in complex terrain**
**Mentor: Professor Chen Li**

**Project Description**: A main challenge that has prevented robots from moving as well as animals in complex terrain is our lack of understanding of how to sense and make use of *physical* interaction between animals and robots (locomotors) and the surrounding terrain (think about what if we wanted to fly an airplane but had no idea how to adjust its wings to generate sufficient lift and not too much drag!). Currently the primary approach of robot locomotion in 3-D terrains is to avoid obstacles (e.g., self-driving cars) simply relying on environment geometry. However, for small robots dynamically moving through many 3-D terrains such as forest floor or building rubble, it is impossible to always avoid obstacles. Instead, perceiving and making use of physical interaction between locomotors and environments becomes crucial. This project is part of our ongoing research to develop novel animal instruments (e.g., a backpack with sensors) and robots instrumented with sensors to systematically study locomotor-terrain contact forces and how they should make adjustments to make use of them in complex 3-D terrain.

**Role of the student**: The REU student will lead the development and systematic testing of these instruments and/or robots.

**Helpful skills**: Integrating multiple sensors and actuators, automation, feedback control, mechatronics, microcontroller, LabVIEW, MATLAB, C++, Robot Operating System, CAD design, 3D printing, machining, IMU / force sensors, circuit design, signal communication.

For more information, visit https://li.me.jhu.edu/.

**Project 2: Development of a New Remotely Operated Underwater Vehicle: Mechanical Development**
**Mentor: Professor Louis Whitcomb**

**Project Description:** This REU student project is to work with other undergraduate and graduate students to develop a new remotely operated underwater robotic vehicle (ROV) that will be used for research in navigation, dynamics, and control of underwater vehcles. Our goal is to develop a neutrally buoyant tethered vehicle capable of agile six degree-offreedom motion with six marine thrusters, and to develop new navigation and control system software using the open-source Robot Operating System (ROS). Role of REU Student: Mechanical design, fabrication, and testing.

**Background Skills:** Experience in CAD (solidworks preferred) and modern manufacturing methods – please submit work examples with application. C++ programming, Linux, and ROS programming experience desired but not required.

**Project 3: Photoacoustic-Guided Surgery**
**Mentor: Professor Muyinatu Bell**

**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 blood vessels behind tissues during minimally invasive surgeries, such as neurosurgery, spinal fusion surgery, and gynecological surgeries like hysterectomy.

**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 4: Photoacoustic-Based Visual Serving of Surgical Tool Tips**
**Mentor: Professor Muyinatu Bell**

**Project Description:** In intraoperative settings, the presence of acoustic clutter and refection artifacts from metallic surgical tools often reduces the effectiveness of ultrasound imaging and complicates the localization of surgical tool tips. This project explores an alternative approach to tool tracking and navigation in these challenging acoustic environments by augmenting ultrasound systems with a light source (to perform photoacoustic imaging) and a robot (to autonomously and robustly follow a surgical tool regardless of the tissue medium). The robotically controlled ultrasound probe will continuously visualize the location of the tool tip by segmenting and tracking photoacoustic signals generated from an optical fiber inside the tool.

**Role of REU Student:** System validation in the presence of multiple tissue types; hands-on experiments with an integrated robotic-photoacoustic imaging system; data analysis and interpretation

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

**Project 5: Deep Learning to Improve Ultrasound and Photoacoustic Image Quality**
**Mentor Professor Muyinatu Bell**

**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.

**Project 6: Project Title: Hole transporting materials development for quantum dot solar cells and photodetectors**
**Mentor: Professor Susanna Thon**

**Project Description:** Colloidal quantum dots are promising materials for technologies such as solar cells and infrared photodetectors, critical in applications including inexpensive sensing and energy-harvesting. Their performance to date is largely limited by poor hole (positive charge) collection. The aim of this project is to develop new hole-transporting materials for optoelectronic devices based on colloidal quantum dots including photodetectors, solar cells, and LEDs. The project will include chemical synthesis, device fabrication, and optical/electronic testing components.

**Role of the Undergraduate Student:**
The undergraduate researcher will be in charge of doing capacitance-voltage and photocurrent transient measurements on a variety of new hole transporting materials to measure their doping densities and mobilities. Additionally, the undergraduate researcher will assist graduate students with colloidal materials synthesis and device fabrication to build the new materials and test structures.

**Preferred Background Skills:**
Familiarity with Matlab is preferred. Basic data analysis, laser operation, and electronic testing experience will be useful. Some experience or comfort level with wet chemistry techniques is desirable but not required. All lab skills will be taught as-needed.

**Project 7: Haptic Feedback and Control for Upper-Limb Prosthetic Devices**
**Mentor: Professor Jeremy D. Brown**

**Description:** Individuals with an upper-limb amputation generally have a choice between two types of prostheses: body-powered and externally-powered. Body powered prostheses use motion in the body to generate motion of the prosthetic gripper by means of a cable and harness system that connects the body to the device. In this way, body-powered prostheses feature inherent haptic feedback: what is felt in the gripper gets transmitted through the cable to the harness. Externally-powered prostheses come in many forms, however, most utilize electromyography (EMG) for controlling the prosthetic gripper. Since this control input is electrical, there is no mechanical connection between the body and the prosthetic gripper. Thus, myoelectric EMG-based prostheses do not feature haptic feedback and amputees who wear them 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 an object recognition task. 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 test the hypothesis that sensory feedback and control requirements for upper-limb prosthesis function will be task specific.

**Role of the student:** With supportive mentorship, the REU student will lead the refinement and evaluation of our current mock upper-limb prosthesis experimental apparatus, which involves mechanical, electrical, and computational components. He or she 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.

**Background skills:** Experience with CAD, Matlab, and/or C++ would be beneficial. Interest in working collaboratively with both engineering and clinical researchers. Mechatronic design experience and human-subject experiment experience would be helpful but are not required. 9.

**Project 8: Bimanual Haptic Feedback for Robotic Surgery Training**
**Mentor: Professor Jeremy D. Brown**

**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 a bimanual haptic feedback system that produces a squeezing sensation on the trainee's two wrists in proportion to the forces they produce with the left and right surgical robotic instruments. The research objective of this project is to test the hypothesis that this bimanual haptic feedback will accelerate 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 the 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.

**Background skills:** Experience with CAD, Matlab, and/or Python would be beneficial. Interest in machine learning and in working collaboratively with both engineering and clinical researchers. Mechatronic design experience and human-subject experiment experience would be helpful but are not required.

**Project 9: Subspace Clustering**
**Mentor: Professor Rene Vidal**

**Description:** Consider the task of separating different moving objects in a video (e.g., driving cars and walking people in a video clip of a street). While humans can easily solve this task, it is challenging for a computer, which sees only ordered 0's and 1's. Fortunately, this problem has a specific property that allows a computer to tackle this challenge: For all the points of the same moving object, the vectors built from their trajectories lie in a common subspace. Thus, this problem boils down to a math problem of separating different subspaces in the ambient space.

**Project Goals:** Given a set of data points that are drawn from multiple subspaces with unknown membership, we want to simultaneously cluster the data into appropriate subspaces and find subspaces fitting each group of points. This problem is known as *subspace clustering*, which has applications in, beside the motion segmentation mentioned above, image segmentation, face clustering, hybrid system identification, etc. The Vision Lab has worked extensively on this topic and has developed geometric approaches such as the Generalized Principle Component Analysis, and spectral clustering approaches such as the Sparse Subspace Clustering. The goal of the project is to further improve the algorithms for subspace clustering. Possible research directions include:

- To develop scalable algorithms that are able to deal with data that has millions of entries.
- To develop algorithms that can effectively deal with class-imbalanced data and improve clustering accuracy.
- To develop algorithms that are able to deal with missing entries in the data, e.g., incomplete trajectories in the motion segmentation applications.
- To develop algorithms than can effectively deal with data points that are drawn from high relative dimensional subspaces. Specifically, the approach will be based on the novel framework called Dual Principal Component Analysis developed by the Vision Lab.
- To extend current subspace clustering algorithms so that they can account for nonlinear structures in data. In particular, one of the approaches is to jointly learn a feature representation using deep neural networks and apply subspace clustering.

**Internship Goals:** As part of the project, the intern will work alongside PhD students and develop novel algorithms for subspace clustering. The intern will implement code for these algorithms as well as test them on several databases. The intern will learn necessary background knowledge in machine learning, computer vision, compressed sensing, optimization, and will read research papers on subspace clustering. Moreover, the intern will implement novel algorithms in MATLAB/Python using different datasets. The intern will present his or her work to other graduate students and professors and will potentially be able to publish the research in computer vision conferences and journals. As part of the group, the intern will experience first-hand a rigorous and rewarding research environment.

**Background Skills:** Strong background in linear algebra and experience in MATLAB/Python coding is a plus.

**Project 10: Understanding Deep Neural Network Training**
**Mentor: Professor Rene Vidal**

**Description:** Deep learning based methods have replaced traditional machine learning algorithms as the state-of-the-art in nearly every problem domain. However, our understanding of why these methods are so successful is still very limited. Why is it that bigger networks always seem to generalize better? How is stochastic gradient descent able to converge to networks with zero loss, despite the dramatic non-convexity of the learning problem? What explains the success of certain design innovations over others, e.g. rectified linear activation and batch normalization? An important goal of ongoing research in the field is to begin to address some of these puzzles.

**Project Goals:** The deep learning optimization problem is highly non-convex: there exist many equivalent locally-optimal weight parameters, separated in the optimization landscape by ridges of poor parameters. This makes the process of finding good network weights a challenging combinatorial problem in principle. Interestingly however, deep network training works remarkably well in practice.

Recent theoretical work shows that if a deep network is allowed to vary in size, and the network activation is enforced to be positively homogeneous--a condition which the popular rectified linear activation satisfies--then the non-convex learning problem admits a tight convex relaxation. This suggests that for this kind of deep network, the optimization landscape, although non-convex, has nice structure enabling efficient optimization. In this project, we will investigate this hypothesis experimentally and theoretically, by studying the deep learning optimization landscapes for different network architectures, activation functions, and forms of regularization.

**Internship Goals:** As part of the project, the intern will work alongside PhD students to develop empirical and theoretical approaches to probe the high-dimensional deep learning optimization landscape. The intern will learn necessary background knowledge in machine learning and optimization to contribute to this research. The intern will gain experience implementing small and medium-scale deep networks using popular deep learning frameworks and evaluating their behavior. The intern will present his or her work to other graduate students and professors and will potentially be able to publish the research in machine learning conferences and journals. As part of the group, the intern will experience first-hand a rigorous and rewarding research environment.

**Background Skills:** A strong background in linear algebra, optimization, and experience in MATLAB/Python coding is strongly encouraged.

**Project 11: Activity Recognition**
**Mentor: Professor Rene Vidal**

**Description:** The human visual system is exquisitely sensitive to an enormous range of human movements. We can differentiate between simple motions (left leg up vs. right hand down), actions (walking vs. running) and activities (making a sandwich vs. making a pancake). Recently, significant progress has been made in automatically recognizing human activities in videos. Such advances have been made possible by the discovery of powerful video descriptors and the development of advanced classification techniques. With the advent of deep learning, performance in simple tasks, such as action classification, has been further improved. However, performance in recently released large-scale video datasets depicting a variety of complex human activities in untrimmed videos is well below human performance for most activity recognition methods, since scaling to thousands of videos and hundreds of action classes as well as recognizing actions in real, unstructured environments is particularly challenging.

**Project Goals:** The goal of this project is to develop algorithms for recognizing human actions in unstructured and dynamically changing environments. We are especially interested in designing activity recognition algorithms for two applications. One of them is the rehabilitation of young children with mobility disorders. We would like to design algorithms to analyze data collected from a network of cameras during physical therapy sessions, localize the baby and recognize the actions (e.g. crawl, walk, sit and stand) performed at each time-step. A second ongoing project is related to analyzing surveillance data, where the goal is to detect actions in space and time. This project involves more complex actions, which can involve more than one actor (e.g. two or more people or vehicles) and multiple objects.

**Internship Goals:** As part of the project, the intern will work alongside PhD students and develop novel algorithms for activity recognition tasks, such as fine-grained temporal activity segmentation and recognition and/or action detection/localization. The intern will implement code for these algorithms as well as test them on several benchmark datasets. The intern will read research papers on activity recognition and time-series modeling, and will learn new techniques to solve the above problems. Moreover, the intern will implement novel algorithms in Python (MATLAB/C++) and become familiar with several computer vision and machine learning concepts.

The intern will present his or her work to other graduate students and professors and will potentially be able to publish the research in computer vision conferences and journals. As part of the group, the intern will experience first-hand a rigorous and rewarding research environment.

**Background Skills:** Experience in programming in programming (Python/MATLAB/C++) and familiarity with computer vision and basic machine learning techniques (such as Support Vector Machines, Conditional Random Fields, Hidden Markov Models and Neural Networks) is a plus.

**12: Accelerated Non-Convex Optimization**
**Mentor: Professor Rene Vidal**

**Project Description:** Optimization is at the core of almost every problem in machine learning and statistics. Modern applications require minimizing high dimensional functions for problems that may have polynomial complexity on the number of data points, imposing severe limits on the scalability of standard methods, such as gradient descent or other first order methods. In the 1980's Nesterov proposed a method to accelerate gradient descent which provably attains the fastest convergence possible under general assumptions, and since then this technique has been applied to several other first order algorithms. Nevertheless, the mechanism behind acceleration is still considered not well understood. Our group has recently obtained several promising results in connection to continuous dynamical systems, providing a unified perspective on acceleration methods. Moreover, from such connections, new algorithms were obtained.

**Project Goals:** We want to understand known and some of the new accelerated algorithms obtained in connection to continuous dynamical systems in convex and possibly nonconvex settings. These methods will be applied to some problems of interest in machine learning such as subspace clustering, matrix factorization, matrix completion, or others. We aim at making solution methods to these problems faster and more scalable.

**Internship Goals:** The intern will work alongside PhD students and Postdocs, having the opportunity to learn modern research methods in optimization for machine learning and dynamical systems, besides background material in machine learning, subspace clustering, and matrix completion. The intern will implement code for accelerated optimization algorithms in Python, and run them against real datasets. The intern will present his or her work to other graduate students and professors and will potentially be able to publish the research in conferences and journals. As part of the group, the intern will experience first-hand a rigorous and rewarding research environment. A strong background in undergraduate mathematics and working experience in Python or MATLAB are required.

**13. Cerebellum Parcellation and Data Analysis**
**Mentors: Dr. Jerry Prince, Shuo Han**

**Description:** The aim of this project is to run a cerebellum parcellation algorithm—a convolutional neural network—on multiple cohorts. The project will establish estimates of volumes for various regions of the cerebellum during the normal aging process and in Alzheimer's disease. The project is an opportunity to learn about the anatomy of core portion of the human brain while being engaged in a cutting edge research project.

**Role of the REU Student:** The REU student will learn how to manage a large dataset and its processed results. The student will carry out basic statistics on the results.

**Preferred Skills:** Matlab, Python, and basic image processing.

**14. Feature Computation Methods in OCT Angiography**
**Mentors: Dr. Jerry Prince, Yufan He**
**Description:** Retinal optical coherence tomography (OCT) is proving to be an important tool in the diagnosis and management of neurological diseases. OCT angiography (OCTA), a new tool based on the same underlying technology, is proving to be a rich source of data on the condition of the vessels in the retina.

**Role of the REU Student:** The REU student will investigate new features that can be computed from OCTA data and will analyze the reliability of these computed features.

**Preferred Skills:** Basic image processing and Matlab.

**15. Software Framework for Research in Semi-Autonomous Teleoperation**
**Mentors: Dr. Peter Kazanzides and Dr. Russell Taylor**

**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 this to more than 30 institutions around the world. The goal of this project is contribute to the advancement of this research infrastructure. The specific task will take into account the student's background and interests, but is expected be one of the following: (1) 3D user interface software framework, (2) constrained optimization control framework, (3) Simulink Real-Time interface to the robot controller, (4) integration of alternative input devices and/or robots, or (5) development of dynamic models and simulators.

**Preferred Background Skills:** Student should have experience with at least one of the following programming environments: C/C++, Python, ROS, Matlab/Simulink.