Robotics and Computational Sensing

Laboratory for Computational Sensing and Robotics

The Laboratory for Computational Sensing and Robotics (LCSR) is an interdisciplinary academic center for robotics engineering, research, and development. LCSR was founded by the Whiting School of Engineering as the principal locus for robotics research at one of the world's premier research universities. LCSR is comprised of personnel from various academic departments including Computer Science, Mechanical Engineering, Biomedical Engineering, and Electrical and Computer Engineering at the Whiting School of Engineering, with affiliates in the JHU School of Medicine, the Bloomberg School of Public Health, the Zanvyl Krieger School of Arts and Sciences, the Kennedy Krieger Institute, and the JHU Applied Physics Laboratory. The Center fosters targeted research programs and collaboration with universities, corporations, and other research organizations worldwide. Located in Hackerman Hall at JHU’s Homewood campus in Baltimore, Maryland, this unique research center is one of the largest and most technologically advanced robotics research centers in the world.

Robotics research at Hopkins dates to the early 1960s when researchers at the Johns Hopkins University Applied Physics Laboratory (JHU APL) developed the “Hopkins Beast,” a wheeled mobile robot that could navigate hallways and automatically locate and connect to wall outlets to recharge its batteries autonomously. Robotics research at the Whiting School of Engineering (WSE) began in the mid-1990s. The establishment of the NSF Engineering Research Center for Computer-Integrated Surgical Systems and Technology (CISST ERC) in 1998 led to a significant expansion of the robotics program, with a strong emphasis on medical robotics. The Laboratory for Computational Sensing and Robotics (LCSR) was established in 2007 to provide infrastructure for a broad interdisciplinary program in robotics research. Johns Hopkins is widely regarded as one of the top robotics research sites in the world, and a leader in medical robotics. Currently, over a dozen WSE faculty members are closely affiliated with LCSR, along with faculty members from other JHU divisions who hold secondary appointments in WSE.

Minor in Robotics

The field of robotics integrates sensing, information processing, and movement to accomplish specific tasks in the physical world. As such, it encompasses several topics, including mechanics and dynamics, kinematics, sensing, signal processing, control systems, planning, and artificial intelligence. Applications of these concepts appear in many areas including medicine, manufacturing, space exploration, disaster recovery, ordinance disposal, deep-sea navigation, home care, and home automation.

The faculty of the Laboratory for Computational Sensing and Robotics (LCSR), in collaboration with the academic departments and centers of the Whiting School of Engineering, offers a robotics minor in order to provide a structure in which undergraduate students at Johns Hopkins University can advance their knowledge in robotics while receiving recognition on their transcript for this pursuit. The minor is not “owned” by any one department, but rather it is managed by the LCSR itself. Any student from any department within the university can work toward the minor.

Robotics is fundamentally integrative and multidisciplinary. Therefore, any candidate for the robotics minor must develop a set of core skills that cut across these disciplines, as well as obtain advanced supplementary skills.

Core Skills Include the Following

- Robot kinematics and dynamics (R)
- Systems theory, signal processing and control (S)
- Computation and sensing (C)

Supplementary advanced skills may be obtained in the following areas:

- Specialized applications, such as space, medicine, underwater, or haptics
- Advanced kinematics and dynamics
- Advanced systems theory
- Advanced computation, such as AI, machine learning, motion planning
- Advanced sensing such as computer vision

The full minor course listing (available at https://www.lcsr.jhu.edu/Robotics_Minor) specifies which courses fulfill these requirements. Note that ALL core areas must be covered, but that ANY advanced/supplementary courses can be chosen from the list. This allows students to strike a balance between breadth and depth.

Requirements

An undergraduate qualifies for the minor provided he or she has taken at least 18 credits (at the 300-level or above, with a C- or above) from an approved list of courses available at https://www.lcsr.jhu.edu/Robotics_Minor with the following requirements and restrictions:

- Between 6 and 12 credits chosen to cover the three core skills.
- At least 6 credits chosen from advanced supplementary skills.
- At least 3 credits of the 18 must be a laboratory course (at least 15 hours of laboratory time that includes working with physical hardware and/or real data);
- At most 3 credits of the 18 can be an independent research or individual study with a faculty member on the list of approved faculty advisors;
- At least 6 credits must be primarily listed in a department other than the student’s home department (it is acceptable if such a course is cross-listed in the student’s home department);
- At most one course up to 3 credits (including independent research or individual study) may be taken S/U, but all other courses must be taken for a letter grade.

Advising

- All students interested in the minor are required to make an appointment with Anita Sampath in the LCSR to be assigned to a minor advisor to receive guidance about the program.
  Phone: 410-516-6841
  Email: asampath@jhu.edu

When possible, you will be assigned an advisor in your department (though this is not required).
• Students who decide to pursue the minor should also review their academic transcript with their minor advisor to ensure they will be able to complete the requirements.
• Fill out and submit an Add Minor form (which can be obtained from the registrar’s office).
• Complete the Requirements Checkout tables in the CheckOut sheet, downloadable on this web page. You should meet with your minor advisor periodically (at least once per year), bringing a copy of this form for review.
• During your senior year, you must also note the Robotics Minor on your Application for Graduation.
• When all requirements have been completed, take the completed form to the Robotics Minor Program Coordinator for review and signature.

Undergraduates interested in completing the minor must be assigned a minor advisor. The advisor is responsible for helping the student choose courses and helps to ensure all requirements for the minor are met. The minor advisors are listed on the Robotics Minor website (https://www.lcsr.jhu.edu/Robotics_Minor).

Minor in Computer Integrated Surgery
The Whiting School of Engineering offers a minor in Computer Integrated Surgery (CIS) for full-time, undergraduate students at Johns Hopkins. The minor is particularly well suited for students interested in computer integrated surgery issues who are majoring in a variety of disciplines including biomedical engineering, computer science, computer engineering, electrical engineering, and mechanical engineering. The minor provides formal recognition of the depth and strength of a student’s knowledge of the concepts fundamental to CIS beyond the minimal requirements of his/her major.

In order to minor in CIS, a student will require a minor advisor from the Engineering Research Center in Computer Integrated Surgical Systems and Technology (CISSST ERC) in the Laboratory for Computational Sensing and Robotics. Current faculty members available as advisors include Professors Russell Taylor (CS), Greg Hager (CS), Jerry Prince (ECE), Ralph Etienne-Cummings (ECE), Louis Whitcomb (ME), Noah Cowan (ME), Peter Kazanzides (CS), Iulian Iordachita (ME), and Emad Boctor (Radiology).

To satisfy the requirements for the minor in CIS, a student must have a fundamental background in computer programming and computer science, sufficient mathematical background, and also take a minimum of six courses (with a total of at least 18 credits, earning at least a C- in each course) directly related to concepts relevant to CIS. These six CIS courses must include three core courses, which provide the student with the fundamental basis for CIS, and three upper-level courses (300-level or above) to allow the student to pursue an advanced CIS topic in depth.

Required Fundamental Computer Science Courses

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.600.120</td>
<td>Intermediate Programming</td>
<td>4</td>
</tr>
<tr>
<td>EN.600.226</td>
<td>Data Structures</td>
<td>4</td>
</tr>
</tbody>
</table>

Or equivalent experience determined by your CIS minor advisor

Required Fundamental Mathematics Courses

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.106</td>
<td>Calculus I</td>
<td>4</td>
</tr>
<tr>
<td>or AS.110.108</td>
<td>Calculus I</td>
<td>4</td>
</tr>
</tbody>
</table>

Required Fundamental Computer Integrated Surgery Courses

• EN.600.445 Computer Integrated Surgery I
• A design course in CIS. Either EN.600.446 Computer Integrated Surgery II or a design course in biomedical engineering, electrical and computer engineering, or mechanical engineering with substantial CIS content approved by the student’s faculty advisor in the CIS minor.

One course in imaging, chosen from the following:

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
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</thead>
<tbody>
<tr>
<td>EN.600.361</td>
<td>Computer Vision (undergraduate version)</td>
<td>4</td>
</tr>
<tr>
<td>EN.600.461</td>
<td>Computer Vision (graduate version)</td>
<td>4</td>
</tr>
<tr>
<td>EN.520.414</td>
<td>Image Processing &amp; Analysis</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.432/</td>
<td>Medical Imaging Systems</td>
<td></td>
</tr>
<tr>
<td>EN.580.472</td>
<td></td>
<td></td>
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</tbody>
</table>

or

One course in robotics, chosen from the following:

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.530.420</td>
<td>Robot Sensors/Actuators</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.421</td>
<td>Mechatronics</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.646</td>
<td>Robot Devices, Kinematics, Dynamics, and Control</td>
<td>3</td>
</tr>
</tbody>
</table>

• Three advanced specialty courses chosen in consultation with the student’s faculty advisor in the CIS minor which define a topic relevant to CIS (such as CIS instrumentation, CIS imaging, or the mechanics of CIS). Note that these courses must be chosen together with the other three required CIS courses (EN.600.445 Computer Integrated Surgery I, the CIS design course and the CIS imaging course) to include at least one biomedical course and must be selected from the following courses or equivalent courses with significant CIS content, as determined by the CIS advisor:

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.600.461</td>
<td>Computer Vision</td>
<td>3</td>
</tr>
<tr>
<td>EN.520.414</td>
<td>Image Processing &amp; Analysis</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.646</td>
<td>Robot Devices, Kinematics, Dynamics, and Control</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.421</td>
<td>Mechatronics</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.472</td>
<td>Topics in Medical Imaging Systems</td>
<td>3</td>
</tr>
<tr>
<td>EN.580.471</td>
<td>Principles of Design of BME Instrumentation</td>
<td>4</td>
</tr>
<tr>
<td>EN.530.420</td>
<td>Robot Sensors/Actuators</td>
<td>4</td>
</tr>
</tbody>
</table>

Please visit http://www.lcsr.jhu.edu/Education/Undergraduate/CISminor for current course listing.
Robots M.S.E. Program
The Master of Science in Engineering in Robotics program provides a structure in which students from a wide variety of engineering, scientific, and mathematical backgrounds can advance their interdisciplinary knowledge in robotics at the Johns Hopkins University. Most students will complete the program in three or four full-time semesters.

Goals of robotics research and education are to conduct engineering and science teaching and research to develop next generation, intelligent devices, platforms, vehicles, and other products, and to create new understandings of the world, with emphasis on biological systems. These applications appear in many areas including medicine, manufacturing, space exploration, disaster recovery, ordnance disposal, deep-sea navigation, home care, and home automation.

Application Requirements for the M.S.E. in Robotics degree
- Bachelor’s degree in engineering, science, or math. (Or demonstrated knowledge or accomplishment in these fields.)
- Graduate application
- Statement of Purpose
- Transcripts: unofficial ones uploaded; officials ones sent to the following address:

  Johns Hopkins University  
  The Graduate Admissions Office  
  Full time Graduate Studies in Arts and Sciences  
  28 Shriver Hall  
  3400 North Charles Street  
  Baltimore, MD 21218
- Graduate Record Examination (GRE). Current JHU students may request that this requirement be waived. Such requests will be judged on a case-by-case basis.
- TOEFL or IELTS for international applicants.
- Three letters of reference

The Admissions Committee, in making its final decisions, will consider the combination of professional knowledge, academic excellence, letters of reference and the statement of purpose, as well as GRE, TOEFL, and IELTS scores of the applicants.

M.S.E. Program Prerequisites
Math and Physics Proficiency Prerequisites
Proficiency in undergraduate mathematics and physics is expected for all M.S.E. students in the robotics program. This will include the following:
- Multivariable integral and differential calculus
- Linear algebra
- Ordinary differential equations
- Physics - undergraduate calculus-based mechanics, electricity, and magnetism.
- Probability and statistics

This proficiency will be assumed in the prerequisites for the core courses.

Computing Proficiency Prerequisites
Proficiency in computer programming is expected for all M.S.E. students in the robotics program. This will include the following:
- Basic numerical methods using existing programming environments.
- The ability to write well-structured and documented programs in a standard programming language such as C++, Java, or MATLAB.

M.S.E. Degree Requirements
All incoming M.S.E. students will be assigned an M.S.E. Academic Advisor.

- Course Requirements:
  - Course Option: 10 credit-bearing courses that total at least 30 credit-hours.
  - Essay Option: 8 credit-bearing courses that total at least 24 credit-hours and a Master’s Essay supervised by a WSE faculty member who has been approved by the Robotics M.S.E. Curriculum Committee to serve as a faculty advisor.

At least 6 of these courses must be at the graduate level as defined by the offering department/center. All courses counted toward the M.S.E. degree requirements must be at the 300-level or above. Non-credit courses such as the weekly seminar courses offered by LCSR and Departments may not count toward this course requirement.

- Foundation Course Requirements: Two core courses, weekly seminar course, and systems/implementation requirement.
- Track Course Requirement: Four courses fulfilling one of the following track requirements:
  - Track in Medical Robotics and Computer Integrated Surgical Systems
  - Track in Perception and Cognitive Systems
  - Track in Automation Science and Engineering

Courses counted toward the track requirement may not be used to satisfy the elective requirement.

- Elective Course Requirement: Four courses, or two courses and a M.S.E. Essay, fulfilling the elective requirement as described in Section 2.7. Courses may be any engineering or quantitative (designated E or Q in the course catalog) course, subject to the degree requirement limitations, as approved by the student’s M.S.E. academic advisor. Courses counted toward the elective requirement may not be used to satisfy the track requirements.
- Academic Ethics: online tutorial required for all incoming M.S.E. students.
- Responsible Conduct of Research training course, (online); AS.360.625 Responsible Conduct of Research (in-person), for students who will be conducting research for pay or to complete degree requirements (http://eng.jhu.edu/wse/page/conduct-of-research-training).
- Course Grade Requirement: No more than two C grades can apply toward graduation requirements. One D or F grade or more than two grades in the range C- to C+ inclusive is grounds for dismissal from the program.
- Transfer Courses: Standard WSE policy and limitations on M.S.E. transfer credits apply (http://eng.jhu.edu/wse/page/masters-transfer). In addition, use of each transfer course toward satisfaction
of a specific Robotics M.S.E. degree requirement must be approved in writing by both the student’s faculty advisor and the Robotics M.S.E. Curriculum Committee.

- **Double Counting**: Standard WSE policy and limitations on double counting apply (http://eng.jhu.edu/wse/page/graduate-double-counting).

- **Duration**: Students must complete degree within 5 years from matriculation in the M.S.E. program. University-approved leave of absence does not count toward this limit.

- **Graduate Research Courses**: No more than one 1-semester graduate research course (e.g., EN.530.600 MSE Graduate Research) may be counted toward degree requirements.

- **WSE Engineering for Professionals (EP) Courses** may count toward the M.S.E. degree elective requirements if they are approved in writing by the student’s faculty advisor.

- **Residency Requirement**: Minimum residency of two full-time academic terms at WSE.

## M.S.E. Degree Core Courses

Two first-year graduate level courses form the core of the Robotics M.S.E. program. Although these courses can be taken in either order, it is expected that EN.600.436 Algorithms for Sensor-Based Robotics will usually be taken first, followed by EN.530.646 Robot Devices, Kinematics, Dynamics, and Control.

### EN.600.436 Algorithms for Sensor-Based Robotics

**Prerequisites:**
- Basic data structures and programming; calculus; linear algebra; basic probability and statistics

**Content:**
- Basics of geometric modeling and perception of environment and task space
- Configuration Space
- Uncertainty characterization
- Motion and sensing planning in the presence of uncertainty
- Sensor fusion
- Simultaneous localization and mapping (SLAM)
- Software and control architectures for robotics
- Basics of human-machine cooperative systems, teleoperation, shared autonomy, and task automation
- Virtual fixtures

### EN.530.646 Robot Devices, Kinematics, Dynamics, and Control

**Prerequisites:**

**Content:** Graduate-level introduction to the mechanics of robotic systems with emphasis on the mathematical tools for kinematics and dynamics of robot arms and mobile robots. Topics include the geometry and mathematical representation of rigid body motion, forward and inverse kinematics of articulated mechanical arms, trajectory generation, manipulator dynamics, actuation, and design issues, manipulator control, and additional special topics.

- Multivariable integral and differential calculus
- Classical physics
- Linear algebra
- Ordinary differential equations
- Programming: Knowledge of the Matlab programming language including data input/output, 1-D and 2-D arrays, and user-defined function calls. Students with experience with these language elements in other programming languages (C, C++, FORTRAN, Pascal, Java, etc.) should be able to self-tutor themselves in the Matlab language as part of the programming exercises.

## Seminar Course Requirement

Students are required to register for the following non-credit weekly robotics research seminar course every term in which they are in full-time residency:

EN.500.745 Seminar in Computational Sensing and Robotics

## Systems/Implementation Requirement

- **Students must demonstrate the ability to undertake substantial implementation projects requiring independent design and decision making.**
- **Students will be required to take one course with a project involving substantial interaction with or development of actual hardware (sensors, mechanisms, etc.) and one course requiring a substantial software implementation effort.**

Course projects may have both elements but two courses are still required and the student’s individual focus in group projects must have one in each area.

- A student’s M.S.E. Essay can, if approved by their advisor, count toward one of the two required systems/implementation project courses.
- Courses that include class projects that are often well suited to satisfying these system/implementation requirement include:

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
<th>Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.530.421</td>
<td>Mechatronics</td>
<td>3</td>
</tr>
<tr>
<td>EN.600.446</td>
<td>Computer Integrated Surgery II</td>
<td>3</td>
</tr>
<tr>
<td>EN.600.461</td>
<td>Computer Vision</td>
<td>3</td>
</tr>
<tr>
<td>EN.530.676</td>
<td>Locomotion in Mechanical and Biological Systems</td>
<td>3</td>
</tr>
</tbody>
</table>

The approval of course projects to satisfy the systems/implementation course requirements must be approved by the student’s faculty advisor. The course names, project names, and project dates must be identified in the Robotics M.S.E. Checkout Sheet.

## M.S.E. Degree Track Requirements

(4 Courses)

Tracks consist of course sequences that provide the student with strength in a specific area. The required and recommended courses for tracks are listed below. Other courses may be substituted only with written approval of both the student’s academic advisor and the Robotics M.S.E. curriculum committee.

## Track in Medical Robotics and Computer Integrated Surgical Systems

**Required for the track:**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
<th>Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.600.445</td>
<td>Computer Integrated Surgery I</td>
<td>4</td>
</tr>
<tr>
<td>EN.600.446</td>
<td>Computer Integrated Surgery II</td>
<td>3</td>
</tr>
<tr>
<td>Two of the following:</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
Track in Perception and Cognitive Systems

Required for the track:

- EN.600.461 Computer Vision 3
- EN.600.435 Artificial Intelligence 3

Two of the following Courses: 6-8

- EN.530.420 Robot Sensors/Actuators
- EN.530.421 Mechatronics
- EN.550.437 Statistical Learning With Applications
- EN.530.660 Computational Analysis of Stochastic Processes
- EN.530.647 Adaptive Systems
- EN.530.649 System Identification
- EN.600.681 Advanced Topics in Computer Vision
- EN.600.676 Locomotion in Mechanical and Biological Systems
- EN.600.475 Machine Learning
- EN.600.660 FFT in Graphics & Vision
- EN.600.681 Advanced Topics in Computer Vision
- EN.600.775 Data Intensive Computing & Machine Learning Seminar

AS.080.810/.811 Readings/Systems Neuro I

Track in Automation Science and Engineering

Required for the track:

- EN.530.414 Computer-Aided Design 3
- EN.530.454 Manufacturing Engineering 3

Two of the following Courses: 6-8

- EN.530.457 Topics in Operations Research: Supply Chains: Models and Analyses
- EN.550.661 Foundations of Optimization
- EN.550.662 Optimization Algorithms
- EN.530.420 Robot Sensors/Actuators
- EN.530.660 Computational Analysis of Stochastic Processes
- EN.530.649 System Identification
- EN.530.421 Mechatronics
- EN.600.461 Computer Vision
- EN.530.495 Microfabrication Laboratory
- EN.530.653 Advanced Systems Modeling
- EN.530.648 Group Theory in Engineering Design

Other courses may be substituted with both the approval of the student's academic advisor and the approval of the Robotics M.S.E. curriculum committee. A form for approval of such a substitution is available from the academic coordinator.

M.S.E. Degree Electives Courses
(4 Courses or 2 Courses + M.S.E. Essay)

Any engineering or quantitative (designated E or Q in the course catalog) course, subject to the degree requirement limitations, as approved by the student’s M.S.E. academic advisor. Includes but is not limited to the following:

- EN.520.432 Medical Imaging Systems 3
- EN.520.427 Product Design Lab 3
- EN.520.433 Medical Image Analysis 3
- EN.520.483 Bio-Photonics Laboratory 3
- EN.520.491 CAD Design of Digital VLSI Systems I (Seniors/Grads) 3
- EN.520.761 Large Scale Analog Compt 3
- EN.530.414 Computer-Aided Design 3
- EN.530.420 Robot Sensors/Actuators 4
- EN.530.421 Mechatronics 3
- EN.530.424 Dynamics of Robots and Spacecraft 3
- EN.530.454 Manufacturing Engineering 3
- EN.530.495 Microfabrication Laboratory 4
- EN.530.616 Introduction to Linear Systems 3
- EN.530.647 Adaptive Systems 3
- EN.530.648 Group Theory in Engineering Design 3
- EN.530.649 System Identification 3
- EN.530.653 Advanced Systems Modeling 3
- EN.530.660 Computational Analysis of Stochastic Processes 3
- EN.530.676 Locomotion in Mechanical and Biological Systems 3
- EN.550.437 Statistical Learning With Applications 3
- EN.550.457 Topics in Operations Research: Supply Chains: Models and Analyses 3
- EN.550.661 Foundations of Optimization 3
- EN.550.662 Optimization Algorithms 3
- EN.600.445 Artificial Intelligence 3
- EN.600.445 & EN.600.446 Computer Integrated Surgery I and Computer Integrated Surgery II 7
- EN.600.461 Computer Vision 3
- EN.600.475 Machine Learning 3
- EN.600.464 Computer Integrated Surgery II 3
- EN.600.660 FFT in Graphics & Vision 3
- EN.600.681 Advanced Topics in Computer Vision 3
- EN.600.775 Data Intensive Computing & Machine Learning Seminar 3

AS.080.810 & AS.080.811 Readings/Systems Neuro I and Systems Neuro II 0

Courses

AS.080.810. Readings/Systems Neuro I.

This is a graduate-level seminar series on current literature in systems neuroscience. It also serves as a discussion group/journal club for students and faculty at the Krieger Mind/Brain Institute, and is open to the wider systems/cognitive neuroscience community at Homewood and other Hopkins campuses. Each week, a student or faculty member will present a recent article selected in consultation with the course directors. The selected readings will focus on the neural mechanisms of perception, attention, motor behavior, learning and memory. Pass/Fail only. Permission required for undergraduate students.

Instructor(s): E. Niebur; V. Stuphorn.
AS.080.811. Readings/System Neuro II.
Graduate students only or permission required. The combined journal club functions as a graduate-level seminar series on the current literature in systems neuroscience. It will also serve as a discussion group for systems neuroscience post-docs and faculty from the Homewood and Medical School campuses. All participants interested in systems/cognitive neuroscience are welcome. Each week, a student or faculty member will present a recent article selected in consultation with the course directors. The selected readings will focus on the neural mechanisms of perception, attention, motor behavior, learning and memory, as studied using physiological, psychophysical, computational and imaging techniques. Discussions and open exchanges of opinions are strongly encouraged.
Instructor(s): E. Niebur; V. Stuphorn.

AS.110.106. Calculus I. 4 Credits.
Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, introduction to differential equations, functions of several variables, linear systems, applications for systems of linear differential equations, probability distributions. Many applications to the biological and social sciences will be discussed.
Instructor(s): R. Brown
Area: Quantitative and Mathematical Sciences.

AS.110.107. Calculus II (For Biological and Social Science). 4 Credits.
Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, introduction to differential equations, functions of several variables, linear systems, and applications for systems of linear differential equations, probability distributions.
Instructor(s): V. Pingali
Area: Quantitative and Mathematical Sciences.

AS.110.108. Calculus I. 4 Credits.
Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, polar coordinates, parametric equations, Taylor's theorem and applications, infinite sequences and series.
Instructor(s): B. Smithling
Area: Quantitative and Mathematical Sciences.

AS.110.109. Calculus II (For Physical Sciences and Engineering). 4 Credits.
Differential and integral calculus. Includes analytic geometry, functions, limits, integrals and derivatives, polar coordinates, parametric equations, Taylor's theorem and applications, infinite sequences and series. Some applications to the physical sciences and engineering will be discussed, and the courses are designed to meet the needs of students in these disciplines.
Instructor(s): M. Arap
Area: Quantitative and Mathematical Sciences.

AS.110.202. Calculus III. 4 Credits.
Calculus of functions of more than one variable: partial derivatives, and applications; multiple integrals, line and surface integrals; Green’s Theorem, Stokes’ Theorem, and Gauss’ Divergence Theorem.
Prerequisites: Grade of C- or better in AS.110.107 OR AS.110.109 OR AS.110.113, or a 5 on the AB exam.
Instructor(s): J. Lind
Area: Quantitative and Mathematical Sciences.

AS.110.211. Honors Multivariable Calculus. 4 Credits.
This course includes the material in AS.110.202 with some additional applications and theory. Recommended for mathematically able students majoring in physical science, engineering, or especially mathematics. AS.110.211-AS.110.212 used to be an integrated yearlong course, but now the two are independent courses and can be taken in either order.
Prerequisites: Pre/Co-Requisite: 110.201 or 110.212
Instructor(s): C. McTague; R. Brown
Area: Quantitative and Mathematical Sciences.

AS.110.212. Honors Linear Algebra. 4 Credits.
This course includes the material in AS.110.201 with some additional applications and theory. Recommended for mathematically able students majoring in physical science, engineering, or mathematics.
AS.110.211-AS.110.212 used to be an integrated yearlong course, but now the two are independent courses and can be taken in either order. This course satisfies a requirement for the math major that its non-honors sibling does not.
Prerequisites: Grade of B+ or better in AS.110.107 or AS.110.109 or AS.110.113, or a 5 on the AP BC exam.
Instructor(s): S. Zucker
Area: Quantitative and Mathematical Sciences.

EN.500.410. Surgery For Engineers. 3 Credits.
Perm Req’d. Students must apply for this course - contact Cynthia Ramey at cramay@jhu.edu
Instructor(s): M. Marohn; R. Kumar
Area: Engineering, Natural Sciences.

EN.500.745. Seminar in Computational Sensing and Robotics.
Seminar series in robotics. Topics include: Medical robotics, including computer-integrated surgical systems and image-guided intervention. Sensor based robotics, including computer vision and biomedical image analysis. Algorithmic robotics, robot control and machine learning. Autonomous robotics for monitoring, exploration and manipulation with applications in home, environmental (land, sea, space), and defense areas. Biorobotics and neuromechanics, including devices, algorithms and approaches to robotics inspired by principles in biomechanics and neuroscience. Human-machine systems, including haptic and visual feedback, human perception, cognition and decision making, and human-machine collaborative systems. Cross-listed Mechanical Engineering, Computer Science, Electrical and Computer Engineering, and Biomedical Engineering.
Instructor(s): Staff.

EN.520.353. Control Systems. 3 Credits.
Modeling, analysis, and an introduction to design for feedback control systems. Topics include state equation and transfer function representations, stability, performance measures, root locus methods, and frequency response methods (Nyquist, Bode).
Instructor(s): D. Tarraf
Area: Engineering, Quantitative and Mathematical Sciences.
EN.520.414. Image Processing & Analysis. 3 Credits.
The course covers fundamental methods for the processing and analysis of images and describes standard and modern techniques for the understanding of images by humans and computers. Topics include elements of visual perception, sampling and quantization, image transforms, image enhancement, color image processing, image restoration, image segmentation, and multiresolution image representation. Laboratory exercises demonstrate key aspects of the course.
Prerequisites: EN.520.214.
Instructor(s): J. Goutsias
Area: Engineering.

EN.520.415. Image Process & Analysis II. 3 Credits.
This course covers fundamental methods for the processing and analysis of images and describes standard and modern techniques for the understanding of images by morphological image processing and analysis, image representation and description, image recognition and interpretation.
Prerequisites: EN.520.414
Instructor(s): J. Goutsias
Area: Engineering.

EN.520.427. Product Design Lab. 3 Credits.
This project-based course is designed to help students learn how to turn their ideas into commercial products. In the first half of the course, emphasis will be placed on the product development process: student teams will gradually build up a complete "contract book" including a mission statement, competitive analysis, patent review, product specifications, system schematics, economic analysis, development schedule, etc. In the second half of the course, each team will be expected to implement its design and demonstrate a prototype of their product's core functionality. At the end of the semester, a final written report will be submitted in the form of a utility patent. Students are encouraged to take this course in conjunction with Electronic Design Lab (ECE 520.448) in the Spring semester and leverage the groundwork developed here to enable production of a fully functional and marketable prototype by the end of the academic year.
Instructor(s): P. Pouliquen
Area: Engineering.

EN.520.432. Medical Imaging Systems. 3 Credits.
An introduction to the physics, instrumentation, and signal processing methods used in general radiography, X-ray computed tomography, ultrasound imaging, magnetic resonance imaging, and nuclear medicine. The primary focus is on the methods required to reconstruct images within each modality, with emphasis on the resolution, contrast, and signal-to-noise ratio of the resulting images. Co-listed as EN.580.472
Instructor(s): J. Prince
Area: Engineering.

EN.520.433. Medical Image Analysis. 3 Credits.
This course covers the principles and algorithms used in the processing and analysis of medical images. Topics include interpolation, registration, enhancement, feature extraction, classification, segmentation, quantification, shape analysis, motion estimation, and visualization. Analysis of both anatomical and functional images will be studied and images from the most common medical imaging modalities will be used. Projects and assignments will provide students experience working with actual medical imaging data.
Prerequisites: EN.520.432 OR EN.580.472 OR EN.550.310 OR EN.550.311
Instructor(s): J. Prince
Area: Engineering.

EN.520.435. Digital Signal Processing. 4 Credits.
Methods for processing discrete-time signals. Topics include signal and system representations, z-transforms, sampling, discrete Fourier transforms, fast Fourier transforms, digital filters.
Prerequisites: EN.520.214.
Instructor(s): H. Weinert
Area: Engineering.

EN.520.454. Control Systems Design. 3 Credits.
Classical and modern control systems design methods. Topics include formulation of design specifications, classical design of compensators, state variable and observer based feedback. Computers are used extensively for design, and laboratory experiments are included.
Prerequisites: EN.520.353 AND AS.110.201
Area: Engineering, Natural Sciences.

EN.520.448. Electronics Design Lab. 3 Credits.
An advanced laboratory course in which teams of students design, build, test and document application specific information processing microsystems. Semester long projects range from sensors/actuators, mixed signal electronics, embedded microcomputers, algorithms and robotics systems design. Demonstration and documentation of projects are important aspects of the evaluation process. Recommended: EN.600.333, EN.600.334, EN.520.349, EN.520.372, EN.520.490 or EN.520.491.
Prerequisites: EN.520.345 or equivalent Recommended: EN.600.333, EN.600.334, 520.216, 520.349, 520.372, 520.490 or 520.491.
Instructor(s): P. Pouliquen.

EN.520.454. Control Systems Design. 3 Credits.
Classical and modern control systems design methods. Topics include formulation of design specifications, classical design of compensators, state variable and observer based feedback. Computers are used extensively for design, and laboratory experiments are included.
Prerequisites: EN.520.353 AND AS.110.201
Area: Engineering, Natural Sciences.

EN.520.483. Bio-Photonics Laboratory. 3 Credits.
This laboratory course involves designing a set of basic optical experiments to characterize and understand the optical properties of biological materials. The course is designed to introduce students to the basic optical techniques used in medicine, biology, chemistry and material sciences.
Instructor(s): J. Kang.

EN.520.491. CAD Design of Digital VLSI Systems I (Seniors/Grads). 3 Credits.
Seniors and Graduate Students Only
Instructor(s): P. Pouliquen
Area: Engineering.
EN.520.608. Image Reconstruction & Restoration.
This course covers the principles and methods used to reconstruct images from remotely sensed data and to restore images from blurred and noisy observations. General variational and stochastic regularization methods for ill-posed inverse problems will be covered. Those specific methods used in imaging problems, where the amount of data is typically huge, are presented in detail. Synthetic aperture radar and X-ray computed tomography will serve as motivating examples throughout the course, and specific details for reconstruction and restoration within these applications are covered. Recommended Course Background: EN.520.651.

EN.520.761. Large Scale Analog Compt.
Instructor(s): A. Andreou; R. Etienne Cummings.
EN.530.343. Design and Analysis of Dynamical Systems. 4 Credits.
Modeling and analysis of damped and undamped, forced and free vibrations in single and multiple degree-of-freedom linear dynamical systems. Introduction to stability and control of linear dynamical systems.
Prerequisites: Prereq: (110.108 and 110.109 and (110.202 or 110.211) and ((550.291) or (110.201 and 110.302) or (110.201 and 110.306)), and C- or better or concurrent enrollment in 530.202 or 560.202. MechE Majors must also have taken 530.241
Instructor(s): S. Marra
Area: Engineering.
EN.530.414. Computer-Aided Design. 3 Credits.
The course outlines a modern design platform for 3D modeling, analysis, simulation, and manufacturing of mechanical systems using the "Pro/E" package by PTC. The package includes the following components: • Pro/ENGINEER: is the kernel of the design process, spanning the entire product development, from creative concept through detailed product definition to serviceability. • Pro/MECHANICA: is the main analysis and simulation component for kinematic, dynamic, structural, thermal and durability performance. • Pro/NC: is a numeric-control manufacturing package. This component provides NC programming capabilities and tool libraries. It creates programs for a large variety of CNC machine tools.
Instructor(s): D. Stoianovici
Area: Engineering.
EN.530.420. Robot Sensors/Actuators. 4 Credits.
Introduction to modeling and use of actuators and sensors in mechatronic design. Topics include electric motors, solenoids, micro-actuators, position sensors, and proximity sensors. Mechanical Engineering and Engineering Mechanics majors only.
Prerequisites: (171.101 and 171.102 or 530.103 and 530.104), and 110.108 and 110.109, and (110.202 or 110.211), and (EN.550.291 or AS.110.302) and (EN.530.241 or EN.520.345)
Instructor(s): D. Kraemer
Area: Engineering.
EN.530.421. Mechatronics. 3 Credits.
Students from various engineering disciplines are divided into groups of two to three students. These groups each develop a microprocessor-controlled electromechanical device, such as a mobile robot. The devices compete against each other in a final design competition. Topics for competition vary from year to year. Class instruction includes fundamentals of mechanism kinematics, creativity in the design process, an overview of motors and sensors, and interfacing and programming microprocessors.
Prerequisites: EN.530.420 or permission of instructor
Instructor(s): G. Chirikjian
Area: Engineering.
EN.530.424. Dynamics of Robots and Spacecraft. 3 Credits.
An introduction to Lagrangian mechanics with application to robot and spacecraft dynamics and control. Topics include rigid body kinematics, efficient formulation of equations of motion, stability theory, and Hamilton’s principle.
Area: Engineering.
EN.530.420. Robot Sensors/Actuators. 4 Credits.
Introduction to modeling and use of actuators and sensors in mechatronic design. Topics include electric motors, solenoids, micro-actuators, position sensors, and proximity sensors. Mechanical Engineering and Engineering Mechanics majors only.
Prerequisites: (171.101 and 171.102 or 530.103 and 530.104), and 110.108 and 110.109, and (110.202 or 110.211), and (EN.550.291 or AS.110.302) and (EN.530.241 or EN.520.345)
Instructor(s): D. Kraemer
Area: Engineering.
EN.530.454. Manufacturing Engineering. 3 Credits.
An introduction to the various manufacturing processes used to produce metal and nonmetal components. Topics include casting, forming and shaping, and the various processes for material removal including computer-controlled machining. Simple joining processes and surface preparation are discussed. Economic and production aspects are considered throughout. Open only to seniors in Mechanical Engineering and Engineering Mechanics and other majors at all levels.
Instructor(s): Y. Ronzhes
Area: Engineering.
EN.530.495. Microfabrication Laboratory. 4 Credits.
This laboratory course is an introduction to the principles of microfabrication for microelectronics, sensors, MEMS, and other synthetic microsystems that have applications in medicine and biology. Course comprised of laboratory work and accompanying lectures that cover silicon oxidation, aluminum evaporation, photoresist deposition, photolithography, plating, etching, packaging, design and analysis CAD tools, and foundry services. Seniors only or Permission Required.
Instructor(s): A. Andreou; J. Wang
Area: Engineering, Natural Sciences.
EN.530.616. Introduction to Linear Systems.
This course examines linear, discrete- and continuous-time, and multi-input-output systems in control and related areas. Least squares and matrix perturbation problems are considered. Topics covered include state-space models, stability, controllability, observability, transfer function matrices, realization theory, feedback compensators, state feedback, optimal regulation, observers, observer-based compensators, measures of control performance, and robustness issues using singular values of transfer functions. ME EN.530.616 can be used to fulfill the requirement of BME EN.580.616 or ECE EN.520.601.
Instructor(s): N. Cowan.
EN.530.646. Robot Devices, Kinematics, Dynamics, and Control.
Graduate-level introduction to the mechanics of robotic systems with emphasis on the mathematical tools for kinematics and dynamics of robot arms and mobile robots. Topics include the geometry and mathematical representation of rigid body motion, forward and inverse kinematics of articulated mechanical arms, trajectory generation, manipulator dynamics, actuation, and design issues, manipulator control, and additional special topics. Recommended course background: multivariable integral and differential calculus, classical physics, linear algebra, ordinary differential equations. Programming: Knowledge of the Matlab programming language including data input/output, 1-D and 2-D arrays, and user-defined function calls. Students with experience with these language elements in other programming languages (C, C++, Python, Java, etc.) should be able to self-tutor themselves in the Matlab language as part of the programming exercises.
Instructor(s): L. Whitcomb.

This course is a survey of group theory with an emphasis on applications in mechanical design research. In particular, the representation theory of finite groups, compact Lie groups, and certain noncompact unimodular groups is reviewed, and Fourier analysis on these groups is applied as a tool in design problems. The concentration is on applications in CAD, discrete and computational geometry, and robotics. Specific applications include modern interpolation, deformation of solid models, and pattern matching.
Instructor(s): G. Chirikjian.

EN.530.653. Advanced Systems Modeling.
This course covers the following topics at an advanced level: Newton’s laws and kinematics of systems of particles and rigid bodies; Lagrange’s equations for single- and multi-degree-of-freedom systems composed of point masses; normal mode analysis and forced linear systems with damping, the matrix exponential and stability theory for linear systems; nonlinear equations of motion: structure, passivity, PD control, noise models and stochastic equations of motion; manipulator dynamics: Newton-Euler formulation, Langrange, Kane’s formulation of dynamics, computing torques with O(n) recursive manipulator dynamics: Luh-Walker-Paul, Hollerbach, O(n) dynamic simulation: Rodrigues-jain-Kreutz, Saha, Fixman. There is also an individual course project that each student must do which related the topics of this course to his or her research.
Instructor(s): G. Chirikjian.

EN.530.660. Computational Analysis of Stochastic Processes.
This class will cover stochastic processes (including both discrete and continuous time, and including both discrete and continuous state), leading to a rigorous treatment of stochastic differential equations and filtering, emphasizing computation. The class will draw from examples relevant to engineering, such as the Kalman filter. The course will comprehensively, but rapidly review all needed material in probability and statistics.
Prerequisites: 580.616 or 530.616 Linear Dynamical Systems.

EN.530.661. Applied Mathematics for Engineering.
This course presents a broad survey of the basic mathematical methods used in the solution of ordinary and partial differential equations: linear algebra, vector calculus, power series, Fourier series, separation of variables, integral transforms.
Instructor(s): M. Hilpert.

EN.530.676. Locomotion in Mechanical and Biological Systems.
Advanced graduate course on the mechanics of locomotion in animals and machines, and neural control of locomotion. Terrestrial, aquatic, and aerial locomotion modes are considered. Topics include dynamical systems theory, linear and nonlinear differential equations, Poincaré and Floquet theory, and system identification techniques. Recommended Course Background: graduate course in robotics, controls, or dynamical systems theory, and a basic understanding of probability theory; or permission of instructor.
Instructor(s): N. Cowan.

EN.550.291. Lin Alg & Diff Equations. 4 Credits.
An introduction to the basic concepts of linear algebra, matrix theory, and differential equations that are used widely in modern engineering and science. Intended for engineering and science majors whose program does not permit taking both AS.110.201 and AS.110.302.
Prerequisites: ( AS.110.106 OR AS.110.108 ) AND ( AS.110.107 OR AS.110.109 )
Instructor(s): B. Castello
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.437. Statistical Learning With Applications. 3 Credits.
Statistical modeling and inference, inductive learning and information theory together provide a cohesive framework for machine perception, which amounts to building a data-description machine converting physical measurements (images, molecular counts, etc.) to interpretations or descriptions. Recurring themes include quantifying uncertainty, estimating generalization error, Occam’s razor, the bias/variance dilemma and small-sample learning. Various problems in computational vision and computational biology will be analyzed in this context, including visual tracking, object recognition, cancer diagnosis, neural decoding and learning molecular networks.
Instructor(s): D. Geman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.457. Topics in Operations Research: Supply Chains: Models and Analyses. 3 Credits.
Sports provide interesting topics for a variety of mathematical analyses (optimization, statistical, etc.) The course will discuss a number of these applications.
Prerequisites: EN.550.361 and general mathematical maturity
Instructor(s): A. Goldman
Area: Engineering, Quantitative and Mathematical Sciences.

EN.550.493. Mathematical Image Analysis. 3 Credits.
Prerequisites: ( AS.110.202 or AS.110.211 ) AND ( AS.110.201 or EN.550.291 )
Instructor(s): E. Younes
Area: Engineering, Quantitative and Mathematical Sciences.
Design and analysis of mainstream algorithms for solving optimal control, statistical/machine learning, financial engineering, compressed sensing, robust principal component analysis, sparse optimization, and structural engineering problems. Algorithms may include: sequential quadratic programming methods, interior-point methods, stochastic gradient descent algorithm, dual averaging algorithm, limited memory quasi-Newton methods, fast iterative shrinkage-thresholding algorithm, Pegasos, alternating linearization augmented Lagrangian methods, the support vector machine, Bender’s Algorithm, and the method of moving asymptotes. However, other algorithms may be covered depending on the interests of the students. The goals of the course include (i) understanding the algorithms, why they work, and when they should be used; (ii) recognizing the strengths and weaknesses of each algorithm; and (iii) motivating/discussing open research questions.
Instructor(s): D. Robinson.

EN.580.471. Principles of Design of BME Instrumentation. 4 Credits.
This core design course will cover lectures and hands-on labs. The material covered will include fundamentals of biomedical sensors and instrumentation, FDA regulations, designing with electronics, biopotentials and ECG amplifier design, recording from heart, muscle, brain, etc., diagnostic and therapeutic devices (including pacemakers and defibrillators), applications in prosthetics and rehabilitation, and safety. The course includes extensive laboratory work involving circuits, electronics, sensor design and interface, and building complete biomedical instrumentation. The students will also carry out design challenge projects, individually or in teams (examples include “smart cane for blind,” “computer interface for quadriplegic”). Students satisfying the design requirement must also register for EN.580.571. Lab Fee: $150. Recommended Course Background: EN.520.345
Instructor(s): N. Thakor
Area: Engineering, Natural Sciences.

EN.580.472. Topics in Medical Imaging Systems. 3 Credits.
An introduction to the physics, instrumentation, and signal processing methods used in general radiography, X-ray computed tomography, ultrasound imaging, magnetic resonance imaging, and nuclear medicine. The primary focus is on the methods required to reconstruct images within each modality, with emphasis on the resolution, contrast, and signal-to-noise ratio of the resulting images. Cross-listed with Neuroscience and Electrical and Computer Engineering (EN.520.432).
Instructor(s): J. Prince
Area: Engineering.

EN.580.681. Advanced Topics in Computer Vision.
(Formerly 580.464) State-of-the-art methods in dynamic vision, with an emphasis on segmentation, reconstruction, and recognition of static and dynamic scenes. Topics include reconstruction of static scenes (tracking and correspondence, multiple view geometry, self-calibration), reconstruction of dynamic scenes (2-D and 3-D motion sementation, nonrigid motion analysis), recognition of visual dynamics (dynamic textures, face and hand gestures, human gaits, crowd motion analysis), as well as geometric and statistical methods for clustering and unsupervised learning, such as K-means, Expectation Maximization, and Generalized Principal Component Analysis. Applications in robotics and biomedical imaging are also included.
Prerequisites: Prereq: AS.110.202, EN.600.461 or instructor permission.

This class will cover machine learning techniques for modeling and segmentation of multivariate mixed data. Topics will include subspace learning (PCA, Probabilistic PCA, Robust PCA, Sparse representation, Rank minimization), manifold learning (Kernel PCA, LLE, Isomap), subspace clustering (K-subspaces, Mixtures of PPCAs, Generalized PCA, Sparse subspace clustering), and manifold clustering (LLMC). These methods will be applied to several problems in computer vision, biomedical imaging, neuroscience, and computational biology.
Instructor(s): R. Vidal.

EN.600.226. Data Structures. 4 Credits.
This course covers the design and implementation of data structures including collections, sequences, trees, and graphs. Other topics include sorting, searching, and hashing. Course work involves both written homework and Java programming assignments. Recommended Course Background: EN.600.107 or EN.600.120 or equivalent.
Instructor(s): P. Froehlich
Area: Engineering, Quantitative and Mathematical Sciences.

EN.600.361. Computer Vision. 3 Credits.
This course gives an overview of fundamental methods in computer vision from a computational perspective. Methods studied include: camera systems and their modeling; computation of 3-D geometry from binocular stereo, motion, and photometric stereo; and object recognition. Edge detection and color perception are covered as well. Elements of machine vision and biological vision are also included. [Applications] (https://cirl.lcsr.jhu.edu/Vision_Syllabus)
Prerequisites: EN.600.226
Instructor(s): R. Vidal
Area: Engineering, Quantitative and Mathematical Sciences.

EN.600.435. Artificial Intelligence. 3 Credits.
Students may receive credit for EN.600.335 or EN.600.435, not both. Graduate level version of EN.600.335 [Applications]. Prerequisite: EN.600.226, EN.550.171; Recommended: linear algebra, prob/stat.
Instructor(s): B. Mitchell
Area: Engineering.

EN.600.436. Algorithms for Sensor-Based Robotics. 3 Credits.
This course surveys the development of robotic systems for navigating in an environment from an algorithmic perspective. It will cover basic kinematics, configuration space concepts, motion planning, and localization and mapping. It will describe these concepts in the context of the ROS software system, and will present examples relevant to mobile platforms, manipulation, robotics surgery, and human-machine systems. [Analysis] Formerly EN.600.336. Students may receive credit for only one of EN.600.336, EN.600.436 and EN.600.636.
Prerequisites: EN.600.226 and Linear Algebra and Probability, Students may receive credit for only one of EN.600.336, EN.600.436 and EN.600.636.
Instructor(s): G. Hager
Area: Engineering.
This course focuses on computer-based techniques, systems, and applications exploiting quantitative information from medical images and sensors to assist clinicians in all phases of treatment from diagnosis to preoperative planning, execution, and follow-up. It emphasizes the relationship between problem definition, computer-based technology, and clinical application and includes a number of guest lectures given by surgeons and other experts on requirements and opportunities in particular clinical areas. Recommended Course Background: EN.600.120, EN.600.226, and AS.110.201 or permission of instructor. Recommended: EN.600.457, EN.600.461, image processing. Instructor(s): R. Taylor Area: Engineering.

EN.600.446. Computer Integrated Surgery II. 3 Credits.
This weekly lecture/seminar course addresses similar material to EN.600.445, but covers selected topics in greater depth. In addition to material covered in lectures/seminars by the instructor and other faculty, students are expected to read and provide critical analysis/presentations of selected papers in recitation sessions. Students taking this course are required to undertake and report on a significant term project under the supervision of the instructor and clinical end users. Typically, this project is an extension of the term project from EN.600.445, although it does not have to be. Grades are based both on the project and on classroom recitations. Students wishing to attend the weekly lectures as a 1-credit seminar should sign up for EN.600.452. Students may also take this course as EN.600.464. The only difference between EN.600.446 and EN.600.464 is the level of project undertaken. Typically, EN.600.464 projects require a greater degree of mathematical, image processing, or modeling background. Prospective students should consult with the instructor as to which course number is appropriate. [Applications] Students may receive credit for EN.600.446 or EN.600.646, but not both. Prerequisites: Prereq for EN.600.446: EN.600.445 or permission Instructor(s): R. Taylor Area: Engineering.

EN.600.461. Computer Vision. 3 Credits.
Graduate version of EN.600.361. Students may receive credit for EN.600.361 or EN.600.461, but not both. Recommended Course Background: EN.600.226 & linear algebra Instructor(s): R. Vidal Area: Engineering, Quantitative and Mathematical Sciences.

EN.600.475. Machine Learning. 3 Credits.
This course takes an application driven approach to current topics in machine learning. The course covers supervised learning (classification/structured prediction/regression/ranking), unsupervised learning (dimensionality reduction, bayesian modeling, clustering) and semi-supervised learning. Additional topics may include reinforcement learning and learning theory. The course will also consider challenges resulting from learning applications, such as transfer learning, multitask learning and large datasets. We will cover popular algorithms (naive Bayes, SVM, perceptron, HMM, winnow, LDA, k-means, maximum entropy) and will focus on how statistical learning algorithms are applied to real world applications. Students in the course will implement several learning algorithms and develop a learning system for a final project. [Applications] Recommended Course Background: multivariate calculus. Instructor(s): M. Dredze Area: Engineering.

Graduate level version of EN.600.436 (see description above). Formerly EN.600.436. Students may receive credit for only one of EN.600.336, EN.600.436 or EN.600.636. Recommended Course Background: EN.600.226, AS.110.106, and Prob/Stat. Prerequisites: Students may receive credit for only one of EN.600.336, EN.600.436 and EN.600.636. Instructor(s): G. Hager.

EN.600.646. Computer Integrated Surgery II. 3 Credits.
Students may receive credit for EN.600.446 or EN.600.646, but not both. Advanced version of EN.600.446. [Applications] Prerequisites: EN.600.445 OR PERMISSION OF INSTRUCTOR Instructor(s): R. Taylor.

EN.600.660. FFT in Graphics & Vision.
In this course, we will study the Fourier Transform from the perspective of representation theory. We will begin by considering the standard transform defined by the commutative group of rotations in 2D and translations in two- and three-dimensions, and will proceed to the Fourier Transform of the non-commutative group of 3D rotations. Subjects covered will include correlation of images, shape matching, computation of invariances, and symmetry detection. Recommended Course Background: AS.110.201 and comfort with mathematical derivations. Instructor(s): M. Kazhdan.

EN.600.681. Advanced Topics in Computer Vision.
Prerequisites: Prereq: 600.461 & linear algebra or permission. Area: Engineering.

EN.600.735. Seminar in Machine Learning.
This seminar course will look at research in machine learning. topics will be selected from those of mutual interest between students and the instructor. Sample topics include reinforcement learning, kernel methods, experimental methods in machine learning, computational learning theory, lazy learning, evolutionary computation, and neural networks. Students are expected to select papers and lead discussion. Instructor(s): J. Sheppard.

For current faculty and contact information go to https://www.lcsr.jhu.edu/Faculty

Faculty

Professors
Gregory Chirikjian

Ralph Etienne-Cummings
Professor (Electrical and Computer Engineering): Neuromorphic Computational Sensing and Integrated Microsystems; Courses: CAD Design of Digital VLSI Systems, Electronics Design Laboratory, Product Design Laboratory, Large Scale Analog Computation.

Gregory Hager
Professor (Computer Science): Computer Vision, Human-Machine Systems, Medical Applications; Courses: Computer Vision, Artificial Intelligence, Algorithms for sensor-based robotics.

Jerry Prince
Professor (Electrical and Computer Engineering): Medical Imaging and Computer Vision; Courses: Medical Imaging Systems.
Dan Stoianovici
Robotics Faculty with Secondary Appointments in the Whiting School of Engineering: Professor (Urology, Mechanical Engineering, Neurosurgery): Medical Robotics; Mechanical Design; Courses: Computer Aided Design.

Russell Taylor
Professor (Computer Science): Medical Robotics and Computer-Integrated Interventional Systems, Medical Imaging and Modeling; Courses: Computer Integrated Surgery I & II.

Louis Whitcomb

Associate Professors
Mehran Armand
Robotics Faculty with Secondary Appointments in the Whiting School of Engineering: Associate Research Professor (Applied Physics Laboratory): Medical Robotics and Computer-Integrated Interventional Systems; Biomechanics; Courses: Kinematics and Dynamics of Robots, Robot Control.

Noah Cowan
Associate Professor (Mechanical Engineering): Robotics, Dynamics, Controls, Locomotion, System Identification.

Rene Vidal
Associate Professor (Biomedical Engineering): Biomedical Imaging, Computer Vision and Machine Intelligence; Courses: Introduction to Linear Systems, Advanced Topics in Computer Vision, Advanced Topic in Machine Learning.

Assistant Professors
Emad Boctor
Robotics Faculty with Secondary Appointments in the Whiting School of Engineering: Assistant Professor (Radiology): Interventional Ultrasound.

Dennice Gayme
Assistant Professor (Mechanical Engineering): Dynamics and control of nonlinear, networked and spatially distributed systems. Applications include: the electric power grid, wall turbulence and wind farms. Courses: Nonlinear Dynamical Systems, Energy Systems Analysis.

Suchi Saria
Assistant Professor (Computer Science): Computational healthcare; machine learning; probabilistic graphical models; human-centric dynamical systems.

Assistant Research Professor
Iulian Iordachita
Assistant Research Professor (Mechanical Engineering): Medical Robotics; Mechanical Design; Sens

Marin Kobilarov
Assistant Professor (Mechanical Engineering): Computational Dynamical Systems, Robot Control and Motion Planning; Courses: Nonlinear control and planning in robotics.

Associate Research Professor
Peter Kazanzides