ROBOTICS AND COMPUTATIONAL SENSING

https://www.lcsr.jhu.edu/Main_Page

The Laboratory for Computational Sensing and Robotics (LCSR) is one of the most technologically advanced robotics research centers worldwide, and is an international leader in the areas of medical robotics, autonomous systems, and bio-inspiration. Within Johns Hopkins, a premiere research university, the LCSR is a hub for innovative and interdisciplinary robotics engineering, research, and development. The LCSR brings a core group of scholars and students from the Whiting School of Engineering together with researchers from the Johns Hopkins School of Medicine, the Bloomberg School of Public Health, the Krieger School of Arts and Sciences, the Johns Hopkins University Applied Physics Laboratory and the Kennedy Krieger Institute to focus on the common purpose of creating knowledge and fostering innovation.

Undergraduate Programs

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.

Please visit http://lcsr.jhu.edu/computer-integrated-surgery-minor/ for current course listings and full minor policies.

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 specialized applications, such as space, medicine, or marine systems; or in one of the three core areas listed above.

The full minor course listing, provided below and available at https://lcsr.jhu.edu/robotics-minor/, specifies which courses fulfill these requirements. Please always check the website for the most up-to-date listing of courses. 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

Undergraduates qualify for the minor provided they have taken at least 18 credits (at the 300-level or above, with a C- or above) from an approved list of courses available below and at https://lcsr.jhu.edu/robotics-minor/ with the following requirements and restrictions:

- Between 6 and 12 credits chosen to cover the three core skills (R, S, C).
- At least 6 credits chosen from advanced supplementary skills (Sup).
- At least 3 credits of the 18 must be a laboratory course (Lab) (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 advisers.

- 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.

Graduate levels of the same course may be substituted for the undergraduate levels listed below without additional permissions.

<table>
<thead>
<tr>
<th>Course Number/Title</th>
<th>Lab</th>
<th>R</th>
<th>S</th>
<th>C</th>
<th>Sup</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.520.353 Control Systems</td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>EN.520.412 Machine Learning for Signal Processing</td>
<td></td>
<td></td>
<td>X</td>
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<tr>
<td>EN.520.414 Image Processing &amp; Analysis</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>EN.520.415 Image Process &amp; Analysis II</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>EN.520.417 Computation for Engineers</td>
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<td>X</td>
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<tr>
<td>EN.520.424 FPGA Synthesis Lab</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>EN.520.432 Medical Imaging Systems</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>EN.520.433 Medical Image Analysis</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>EN.520.435 Digital Signal Processing</td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>EN.520.448 Electronics Design Lab</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN.520.454 Control Systems Design X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>EN.520.601 Linear Systems Theory</td>
<td></td>
<td>X</td>
<td></td>
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<tr>
<td>EN.520.612 Machine Learning for Signal Processing</td>
<td>X</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EN.530.343 Design and Analysis of Dynamical Systems</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN.530.420 Robot Sensors/Actuators X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>EN.530.421 Mechatronics X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
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<tr>
<td>EN.530.424 Dynamics of Robots and Spacecraft X</td>
<td>X</td>
<td>X</td>
<td></td>
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</tr>
<tr>
<td>EN.530.446 Robot Devices, Kinematics, Dynamics, and Control X</td>
<td>X</td>
<td>X</td>
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</tbody>
</table>
### Advising

- All students interested in the minor are required to make an appointment with Alison Morrow in LCSR to be assigned a minor adviser to receive guidance about the program. Email: Alison.morrow@jhu.edu
- When possible, you will be assigned an adviser in your department (though this is not required).
- Students who decide to pursue the minor should also review their academic transcript with their minor adviser 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).
- 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 Alison Morrow for review and signature.

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

The minor is managed by faculty of the LCSR in collaboration with academic departments and centers of the Whiting School of Engineering. If you have suggestions / questions regarding the minor, please direct them to Prof. Louis Whitcomb at llw@jhu.edu.

### 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 adviser from the Engineering Research Center in Computer Integrated Surgical Systems and Technology (CISST ERC) in the Laboratory for Computational Sensing and Robotics. Current faculty members available as advisers include Professors Russell Taylor (CS), Greg Hager (CS), Jerry Prince (ECE), Ralph Etienne-Cummings (ECE), Louis Whitcomb (ME), Noah Cowan (ME), Marin Kobilarov (ME), Peter Kazanzides (CS), Iulian Iordachita (ME), and Emad Docter (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 the concepts relevant to CIS. These six CIS courses must include two fundamental CIS core courses, which provide the student with the fundamental basis for CIS, and four approved upper-level courses (300-level or above) to allow the student to pursue an advanced CIS topic in depth. The additional four upper-level courses must include at least one course designated as an "imaging" course or one course designated as a "robotics" course, as discussed below.

### Required Fundamental Mathematics Courses

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.530.470</td>
<td>Space Vehicle Dynamics &amp; Control</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.475</td>
<td>Locomotion I: Mechanics</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.476</td>
<td>Locomotion in Mechanical and Biological Systems</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.486</td>
<td>Mechanics of Locomotion</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.603</td>
<td>Applied Optimal Control</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.645</td>
<td>Kinematics</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.678</td>
<td>Nonlinear Control and Planning in Robotics</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.682</td>
<td>Haptic Applications</td>
<td>X</td>
</tr>
<tr>
<td>EN.530.707</td>
<td>Robot System</td>
<td>X</td>
</tr>
<tr>
<td>EN.550.493</td>
<td>Mathematical Image Analysis</td>
<td>X</td>
</tr>
<tr>
<td>EN.580.471</td>
<td>Principles of Design of BME Instrumentation</td>
<td>X</td>
</tr>
<tr>
<td>EN.580.472</td>
<td>Medical Imaging Systems</td>
<td>X</td>
</tr>
<tr>
<td>EN.580.571</td>
<td>Honors Instrumentation</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.455</td>
<td>Computer Integrated Surgery I</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.456</td>
<td>Computer Integrated Surgery II</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.461</td>
<td>Computer Vision</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.463</td>
<td>Algorithms for Sensor-Based Robotics</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.464</td>
<td>Artificial Intelligence</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.475</td>
<td>Machine Learning: Data to Models</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.476</td>
<td>Machine Learning: Data to Models</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.491</td>
<td>Human-Robot Interaction</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.682</td>
<td>Machine Learning: Deep Learning</td>
<td>X</td>
</tr>
<tr>
<td>EN.601.760</td>
<td>FFT in Graphics &amp; Vision</td>
<td>X</td>
</tr>
</tbody>
</table>

### Required Fundamental Computer Science Courses

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN.601.226</td>
<td>Data Structures</td>
<td>4</td>
</tr>
<tr>
<td>EN.500.112</td>
<td>Gateway Computing: JAVA</td>
<td>3</td>
</tr>
</tbody>
</table>

Or equivalent experience determined by your CIS minor adviser.

### Required Fundamental Mathematics Courses

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS.110.108</td>
<td>Calculus I</td>
<td>4</td>
</tr>
<tr>
<td>AS.110.109</td>
<td>Calculus II (For Physical Sciences and Engineering)</td>
<td>4</td>
</tr>
</tbody>
</table>

or AS.110.107 | Calculus II (For Biological and Social Science) | 4       |
AS.110.202  Calculus III
or AS.110.211  Honors Multivariable Calculus
EN.553.291  Linear Algebra and Differential Equations
or AS.110.201  Linear Algebra
or AS.110.212  Honors Linear Algebra

Each math requirement listed above may be satisfied by one of the specific courses listed, or by an equivalent course as determined by CIS advisor.

**Required Fundamental Computer Integrated Surgery Courses**
- EN.601.455 Computer Integrated Surgery I
- A design course in CIS. Either EN.601.456 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 adviser in the CIS minor.

**Required Four Other Courses Related to CIS**
Students must also complete at least four other courses related to CIS. Of these, AT LEAST ONE must be in EITHER the Imaging Subgroup or the Robotics Subgroup.

**Imaging**
EN.520.414  Image Processing & Analysis  3
EN.520.432/EN.580.472  Medical Imaging Systems  3
EN.520.433  Medical Image Analysis  3
EN.601.461  Computer Vision  3

**Robotics**
EN.530.420  Robot Sensors/Actuators  4
EN.530.421  Mechatronics  3
EN.530.603  Applied Optimal Control  3
EN.530.646  Robot Devices, Kinematics, Dynamics, and Control  4
EN.601.463  Algorithms for Sensor-Based Robotics  3

**Other**
EN.520.448  Electronics Design Lab  3
EN.530.445  Introduction to Biomechanics  3
EN.580.471  Principles of Design of BME Instrumentation  4
EN.601.454  Augmented Reality  3
EN.601.476  Machine Learning: Data to Models  3
EN.601.482  Machine Learning: Deep Learning  3.0


**Graduate Program**

**Robotics M.S.E. Program**
For complete and up-to-date M.S.E. information, visit [https://lcsr.jhu.edu/mse](https://lcsr.jhu.edu/mse).

The Master of Science in Engineering in Robotics (Robotics MSE) program at Johns Hopkins University is designed to advance interdisciplinary robotics knowledge in students coming from a wide variety of engineering, scientific, and mathematical backgrounds.

Johns Hopkins University recognizes the growing need in industry for engineers with the broad multi-disciplinary training and fundamental knowledge needed to develop and deploy advanced robotics systems that function effectively in the real world.

Johns Hopkins University's broad interdisciplinary approach to robotics research makes it uniquely situated to offer such a comprehensive program. The Laboratory for Computational Sensing and Robotics (LCSR), with its reputation as one of the top robotics research sites in the world, particularly in the area of medical robotics, is pleased to offer this MSE in Robotics.

**Program Goals**
- To provide students with multi-disciplinary engineering education and training that will enable them to develop and deploy innovative advanced robotics systems that function effectively in real-world applications.
- To develop students' ability to relate individual technical and design elements to the functioning of complete engineered robotic systems.
- To develop students' ability to work effectively within and to lead multi-disciplinary teams.
- To provide students with a basis for life-long learning and professional growth.

**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)
- Statement of Purpose – in your short statement of purpose please take a couple of sentences to explain/answer the following:
  - Why are you interested in doing an MSE in Robotics? No need to over-think this: it is fine if it is as simple as wanting to get a job in this field!
  - What do you hope to learn during the Robotics MSE?
  - What do you want to do after you graduate, and how do you see the MSE degree from JHU as assisting in that goal?
- Transcript
- 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.
- IELTS or TOEFL for international applicants. Please note: while the Robotics program accepts both the TOEFL and the IELTS tests, we strongly prefer the IELTS.
- Three letters of reference
- $75.00 Application fee
- The Office of Graduate Admissions and Enrollment strongly recommends you submit a professional evaluation from one of the recommended resources (more information here [http://grad.jhu.edu/apply/international-students])) for any academic work completed outside the USA. At this time, however, LCSR does not require the evaluation for the Robotics MSE application package.

To apply, please fill out the application and submit the required documents here [https://grad.jhu.edu/apply/apply-now](https://grad.jhu.edu/apply/apply-now).

In making its final decisions, the Admissions Committee 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 includes proficiency in:

- Multivariable integral and differential calculus;
- Linear algebra;
- Ordinary differential equations;
- Physics – undergraduate calculus-based mechanics, electricity, and magnetism;
- Probability and statistics.

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 includes proficiency in:

- 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 MSE degree requirements must be at the 400 level or above. Any dual listed courses (e.g. listed at both the 600 and 400 level) must be taken at the 600 level. All courses counting towards the foundation, track, or elective requirements must be for a letter grade (e.g. no pass/fail). Any exceptions must be approved in writing by your academic advisor and the LCSR Education Director. Non-credit and one-credit courses such as the weekly seminar course offered by LCSR may not count toward this course requirement.

- **Foundation Course Requirements:** Two core courses and a weekly seminar course.
- **Track Course Requirement:** Four courses fulfilling one of the following track requirements (see website for track course listings):
  - Medical Robotics and Computer Integrated Surgical Systems (has special track requirements, please see website)
  - Perception and Cognitive Systems
  - Automation Science and Engineering
  - Control and Dynamical Systems
  - BioRobotics
  - General Robotics

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. 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 adviser. 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 (EN.500.603)
- **AS.360.625 Responsible Conduct of Research (online):** Online tutorial required for all incoming MSE students.
- **AS.360.625 Responsible Conduct of Research (in-person):** may be required for certain research projects. More information: (http://eng.jhu.edu/wse/page/conduct-of-research-training).
- **EN.500.601 Research Laboratory Safety:** required for all incoming M.S.E. students.
- **Title IX Training:** Students are auto-enrolled in their first semester.
- **Opioid Training:** Students are auto-enrolled in their first semester.

**Academic Policies**

- **Course Grade Requirement:** A course is satisfactorily completed if a grade from A+ to B# is obtained. Up to one C+, C, or C# can be counted toward the degree requirements. A grade of D or F or a second grade below B- results in probation. A second D or F, or a third grade below B- typically results in termination from the program.
- **Transfer Courses:** Standard WSE policy and limitations on M.S.E. transfer credits apply (http://engineering.jhu.edu/graduate-studies/academic-policies-procedures-graduate/). 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://engineering.jhu.edu/graduate-studies/academic-policies-procedures-graduate/).
- **Duration:** Students must complete degree within 5 years from matriculation in the M.S.E. program. An university-approved leave of absence does not count toward this limit.
- **Graduate Research Courses:** No more than one 1-semester or 3 credits of a graduate research course (e.g., EN.530.600 MSE Graduate Research) may be counted toward one class in the course-option degree requirements.
- **WSE Engineering Management Courses:** Two (2) 1.5 credit hour courses taken for credit (i.e. a letter grade) may count towards one class of the MSE degree elective requirements if they are pre-approved in writing by the student's academic advisor.
- **Residency Requirement:** Minimum residency of two full-time academic semesters at WSE (note that summer and intersession terms do not count towards this requirement).

For complete and up-to-date M.S.E. information, visit https://lcsr.jhu.edu/mse/
Courses

Computer-Integrated Surgery Minor

Please always check lcsr.jhu.edu for the most up-to-date course listings.

AS.110.106/AS.110.108 Calculus I
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.

AS.110.107/AS.110.109 Calculus II
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.

AS.110.201 Linear Algebra

AS.110.202 Calculus III
Calculus of Several Variables. 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.

AS.110.211 Honors Multivariable Calculus
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.

AS.110.212 Honors Linear Algebra
This course includes the material in AS.110.201 with additional applications and theory, and is recommended only for mathematically able students majoring in physical science, engineering, or mathematics who are interested in a proof-based version of linear algebra. This course can serve as an Introduction to Proofs (IP) course. Prerequisites: Grade of B+ or better in 110.107 or 110.109 or 110.113, or a 5 on the AP BC exam. Area: Quantitative and Mathematical Sciences.

EN.500.112 Gateway Computing: AVA
This course introduces fundamental programming concepts and techniques, and is intended for all who plan to develop computational artifacts or intelligently deploy computational tools in their studies and careers. Topics covered include the design and implementation of algorithms using variables, control structures, arrays, functions, files, testing, debugging, and structured program design. Elements of object-oriented programming, algorithmic efficiency and data visualization are also introduced. Students deploy programming to develop working solutions that address problems in engineering, science and other areas of contemporary interest that vary from section to section. Course homework involves significant programming. Attendance and participation in class sessions are expected.

EN.520.414 Image Processing & Analysis
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.

EN.520.425 FPGA Senior Projects Laboratory
Laboratory course for FPGA based senior projects. Students will work in teams to complete a design project that makes use of embedded FPGAs. The projects will make use of the Spartan2 XSA boards and other resources from the FPGA Synthesis lab course. Possible projects include: A 16 or 32 bit RISC processor with student designed ISA architecture, assembler, and mini operating system; or a Spartan2 emulation of an existing microprocessor such as an 8051, an optical communication system to transmit stereo music using various modulation schemes for comparison (This would include FM or AM and at least one digital scheme such as FSK); or a digital receiver for commercial AM or FM radio. Students are expected to complete a demonstration and produce a poster session final report. Senior status, no exceptions.

EN.520.432 Medical Imaging Systems
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

EN.520.433 Medical Image Analysis
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.

EN.520.448 Electronics Design Lab
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.520.214, EN.520.216, EN.520.349, EN.520.372, EN.520.490 or EN.520.491.

EN.530.420 Robot Sensors/Actuators
Introduction to modeling and use of actuators and sensors in mechatronic design. Topics include electric motors, solenoids, micro-actuators, position sensors, and proximity sensors.

EN.530.421 Mechatronics
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.
EN.530.445 Introduction to Biomechanics
An introduction to the mechanics of biological materials and systems. Both soft tissue such as muscle and hard tissue such as bone will be studied as will the way they interact in physiological functions. Special emphasis will be given to orthopedic biomechanics. Recommended Course Background: EN.530.215/EN.530.216 and Lab or equivalent. If you have not taken this course or an equivalent, please contact the instructor before registering to ensure you have the appropriate background knowledge to succeed in this course.

EN.530.446 Robot Devices, Kinematics, Dynamics, and Control
Undergraduate-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.

EN.530.603 Applied Optimal Control
The course focuses on the optimal control of dynamical systems subject to constraints and uncertainty by studying analytical and computational methods leading to practical algorithms. Topics include calculus of variations, nonlinear local optimization, global stochastic search, dynamic programming, linear quadratic (gaussian) control, numerical trajectory optimization, model-predictive control. Advanced topics include approximate dynamic programming and optimal control on manifolds. The methods and algorithms will be illustrated through implementation of various simulated examples. Recommended Course Background: Linear Algebra and Differential Equations; experience with control systems; programming in MATLAB and/or Python.

EN.553.291 Linear Algebra & Differential Equations
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.

EN.580.471 Principles of Design of BME Instrumentation
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

EN.601.107 Intro Programming in Java
This course introduces fundamental structured and object-oriented programming concepts and techniques, using Java, and is intended for all who plan to use computer programming in their studies and careers. Topics covered include variables, arithmetic operators, control structures, arrays, functions, recursion, dynamic memory allocation, files, class usage and class writing. Program design and testing are also covered, in addition to more advanced object oriented concepts including inheritance and exceptions as time permits. First-time programmers are strongly advised to take EN.601.108 concurrently in Fall/Spring semesters.

EN.601.226 Data Structures
This course covers the design and implementation of data structures including arrays, stacks, queues, linked lists, binary trees, heaps, balanced trees (e.g. 2-3 trees, AVL-trees) and graphs. Other topics include sorting, hashing, memory allocation, and garbage collection. Course work involves both written homework and Java programming assignments.

EN.601.454 Augmented Reality
Same as EN.601.654, for undergraduate students. This course introduces students to the field of Augmented Reality. It reviews its basic definitions, principles and applications. It then focuses on Medical Augmented Reality and its particular requirements. The course also discusses the main issues of calibration, tracking, multi-modal registration, advance visualization and display technologies. Homework in this course will relate to the mathematical methods used for calibration, tracking and visualization in medical augmented reality. [Applications]

EN.601.455 Computer Integrated Surgery I
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.601.220, EN.601.457, EN.601.461, image processing.

EN.601.456 Computer Integrated Surgery II
Same material as EN.601.456, for graduate students. This weekly lecture/seminar course addresses similar material to EN.601.445, 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.601.445, 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. [Applications]

EN.601.461 Computer Vision
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] Prerequisites: intro programming, linear algebra, and prob/stat.

EN.601.463 Algorithms for Sensor-Based Robotics
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.

EN.600.476 Machine Learning: Data to Models
How can robots localize themselves in an environment when navigating? Which factors predict whether patients are at greatest-risk for complications in the hospital? Can we reconstruct the brain’s “connectome” from fMRI data? Many such big data questions can be answered using the paradigm of probabilistic models in machine learning. This is the second course on machine learning which focuses on probabilistic graphical models. You will learn about directed and undirected graphical models, inference methods, sampling, structure learning algorithms, latent variables, and temporal models. There will be regular assignments, which include theory and some programming. Students will analyze real data for their final project, applying methods discussed in class and writing up a report of their results.

EN.600.676 Machine Learning: Deep Learning
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue team projects on topics of their choice.

Robotics Minor
Please always check lcsr.jhu.edu for the most up-to-date course listings.

EN.520.353 Control Systems
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). Prerequisite: 520.214

EN.520.412 Machine Learning for Signal Processing
This course will focus on the use of machine learning theory and algorithms to model, classify and retrieve information from different kinds of real world complex signals such as audio, speech, image and video.

EN.520.414 Image Processing & Analysis I
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.

EN.520.415 Image Processing & Analysis II
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.

EN.520.417 Computation for Engineers
Designing algorithms in a finite precision environment that are accurate, fast, and memory efficient is a challenge that many engineers must face. This course will provide students with the tools they need to meet this challenge. Topics include floating point arithmetic, rounding and discretization errors, problem conditioning, algorithm stability, solving systems of linear equations and least-squares problems, exploiting matrix structure, interpolation, finding zeros and minima of functions, computing Fourier transforms, derivatives, and integrals. Matlab is the computing platform. Background in linear algebra, matrices, digital signal processing, Matlab.

EN.520.424 FPGA
An advanced laboratory course in the application of FPGA technology to information processing, using VHDL synthesis methods for hardware development. The student will use commercial CAD software for VHDL simulation and synthesis, and implement their systems in programmable XILINX 20,000 gate FPGA devices. The lab will consist of a series of digital projects demonstrating VHDL design and synthesis methodology, building up to final projects at least the size of an 8-bit RISC computer. Projects will encompass such things as system clocking, flip-flop registers, state-machine control, and arithmetic. The students will learn VHDL methods as they proceed through the lab projects, and prior experience with VHDL is not a prerequisite.

EN.520.432 Medical Imaging Systems
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

EN.520.433 Medical Image Analysis
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.

EN.520.435 Digital Signal Processing
Methods for processing discrete-time signals. Topics include signal and system representations, z-transforms, sampling, discrete Fourier transforms, fast Fourier transforms, digital filters.

EN.520.448 Electronics Design Lab
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.520.214, EN.520.216, EN.520.349,
EN.520.372, EN.520.490 or EN.520.491.

EN.520.454 Control Systems Design
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.
Prerequisite: EN.520.353, AS.110.201

EN.520.601 Linear Systems Theory
A beginning graduate course in multi-input multi-output, linear, time-
invariant systems. Topics include state-space and input-output
representations; solutions and their properties; multivariable poles and
zeros; reachability, observability and minimal realizations; stability;
system norms and their computation; linearization techniques.
Recommended Course Background: Undergraduate courses in control
systems and linear algebra.

EN.520.612 Machine Learning for Signal Processing (Grad)
This course will focus on the use of machine learning theory and
algorithms to model, classify and retrieve information from different
kinds of real world complex signals such as audio, speech, image and
video. Recommended Course Background: AS.110.201, EN.553.310, and
EN.520.435.

EN.530.343 Design and Analysis of Dynamical Systems
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.

EN.530.42 Robot Sensors & Actuators
Introduction to modeling and use of actuators and sensors in
mechatronic design. Topics include electric motors, solenoids, micro-
actuators, position sensors, and proximity sensors.

EN.530.421 Mechatronics
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.

EN.530.424 Dynamics of Robots and Spacecraft
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.

EN.530.47 Space Vehicle Dynamics & Control
In this course we study applied spacecraft orbital and attitude dynamics
and their impact on other subsystems. In the orbital dynamics part of
the course, we discuss some the issues associated with orbital insertion,
control and station keeping. Focus is on the two-body problem regime
where conic solutions are valid. Orbit perturbations are also considered.
For attitude dynamics, different attitude representations such as of
direction cosines, quaternions, and angles are introduced. Then we look
at the forces and moments acting on space vehicles. Attitude stability
and control considerations are introduced.

EN.530.475 Locomotion I: Mechanics
This is a course on the mechanics of locomotion in animals and
machines (particularly bio-inspired and biomimetic robots). Locomotion
emerges from effective physical interaction of an animal or a machine
with the surrounding environment; therefore, the ability to generate
appropriate forces (besides appropriate sensing and control) is essential
to successful locomotion. From a mechanics point of view, we will
discuss why animals move amazingly well in almost any environment,
how they have inspired some highly successful machines, and yet
why the majority of robots still struggle in environments that are
only modestly complex and how they may be improved by better
understanding the mechanics of locomotion. Primary focus will be
on terrestrial locomotion, but aerial and aquatic locomotion will be
also discussed, all with numerous examples. General principles and
integration of knowledge from engineering, biology, and physics will be
emphasized. Students from ME and other departments are welcome.
A strong understanding of Newtonian mechanics is required. Visit
http://li.me.jhu.edu/teaching for more information. Recommended
Course Background: B+ or higher in EN.530.202 Dynamics or EN.560.202
Dynamics

EN.530.476 Locomotion in Mechanical & Biological Systems
This is a course on the mechanics of locomotion in animals and
machines (particularly bio-inspired and biomimetic robots). It will
introduce you to the breadth of diverse topics within the field of animal
and robot locomotion. We will discuss why animals move amazingly
well in all kinds of environments, how they have inspired some highly
successful machines, and yet why the majority of robots still struggle
in environments that are only modestly complex. Terrestrial, aerial, and
aquatic locomotion will be discussed, with numerous examples. General
principles and integration of knowledge from engineering, biology, and
physics will be emphasized. Students from ME and other departments
are welcome. Please visit http://li.me.jhu.edu/teaching for updated
information.

EN.530.676 Locomotion II: Dynamics
Graduate course on mechanics and control in locomotion. Topics
include modeling (e.g. Lagrangian mechanics), dynamical systems
theory (nonholonomic systems, limit-cycle behavior, Poincaré analysis,
and Floquet theory), design (control synthesis, mechanical design),
and data-driven modeling from animal locomotor control experiments.
Prerequisites: A graduate course in linear systems theory (e.g.

EN.530.486 Mechanics of Locomotion
This is a course on the mechanics of locomotion in animals and
machines (particularly bio-inspired and biomimetic robots). It will
introduce you to the breadth of diverse topics within the field of animal
and robot locomotion. We will discuss why animals move amazingly
well in all kinds of environments, how they have inspired some highly
successful machines, and yet why the majority of robots still struggle
in environments that are only modestly complex. Terrestrial, aerial, and
aquatic locomotion will be discussed, with numerous examples. General
principles and integration of knowledge from engineering, biology, and
physics will be emphasized. Students from ME and other departments
are welcome. Please visit http://li.me.jhu.edu/teaching for updated
information. Co-listed with EN.530.686

EN.530.603 Applied Optimal Control
The course focuses on the optimal control of dynamical systems subject
to constraints and uncertainty by studying analytical and computational
methods leading to practical algorithms. Topics include calculus of
variations, nonlinear local optimization, global stochastic search,
dynamic programming, linear quadratic (gaussian) control, numerical trajectory optimization, model-predictive control. Advanced topics include approximate dynamic programming and optimal control on manifolds. The methods and algorithms will be illustrated through implementation of various simulated examples. Recommended Course Background: Linear Algebra and Differential Equations; experience with control systems; programming in MATLAB and/or Python.

EN.530.645 Kinematics
A theoretical treatment of the kinematics of mechanisms, machines, and robotic manipulators intended for (though not restricted to) graduate students. Topics include parameterizations of spherical motion - Euler angles, Rodrigues parameters, unit quaternions, the matrix exponential; analysis of planar and spatial linkages; robot kinematics - forward and inverse kinematics, singularities, elementary topological issues; theory of wrenches and twists; research issues in robot kinematics - redundancy resolution, grasping and rolling contact, steering of nonholonomic systems. Other advanced topics will be covered as time permits. Recommend Course Background: Undergraduate linear algebra and multivariable calculus.

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 dynam-ics, 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.

EN.530.678 Nonlinear Planning and Control in Robotics
The course starts with a brief introduction to nonlinear systems and covers selected topics related to model-based trajectory planning and feedback control. Focus is on applications to autonomous robotic vehicles modeled as underactuated mechanical systems subject to constraints such as obstacles in the environment. Topics include: nonlinear stability, stabilization and tracking, systems with symmetries, differential flatness, backstepping, probabilistic roadmaps, stochastic optimization. Recommended Course Background: multi-variable/ differential calculus, AS.110.302, AS.110.201, undergraduate linear control, basic probability theory.

EN.530.682 Haptic Applications
An introduction to the required theoretical and practical background in the design and development of haptic applications. Haptic technology enables users to touch and/or manipulate virtual or remote objects in simulated environments or tele-operation systems. This course aims to cover the basics of haptics through lectures, lab assignments, a term project, and readings on current topics in haptics. Through lab assignments, students learn to create haptic-enabled virtual environments using software development toolkits and a haptic device. Students will be required to complete a project with approval of the instructor. Recommended course background: ME, CS, and ECE graduate and senior undergraduate students who are being enthusiastic to learn about haptics and knowledgeable in basic C++ programming. Students with experience with other programming languages (Python, Java, etc.) should be able to self-tutor themselves to complete lab assignments.

EN.530.707 Robot System Programming
This course seeks to introduce students to open-source software tools that are available today for building complex experimental and fieldable robotic systems. The course is grouped into four sections, each of which building on the previous in increasing complexity and specificity: tools and frameworks supporting robotics research, robotics-specific software frameworks, integrating complete robotic systems, and culminates with an independent project of the student’s own design using small mobile robots or other robots in the lab. Students will need to provide a computer or a virtual-box (with at least a few GB of memory and a few tens of GB of disc space) running Ubuntu 14.04 LTS Trusty Tahr (http://releases.ubuntu.com/14.04 or one of its variants such as Xubuntu 14.04 LTS) and ROS Indigo igloo (http://wiki.ros.org/indigo) - note that these specific versions of Linux and ROS are required! Students should have an understanding of intermediate programming in C/C++ (including data structures and dynamic memory allocation) Familiarity with Linux programming. Familiarity with software version control systems (e.g. subversion, mercurial, git), linear algebra. Recommended Course Background: EN.530.646 Robot Devices, Kinematics, Dynamics, and Control and EN.600.636 Algorithms for Sensor Based Robotics. Students should see the course homepage http://dscl.lcsr.jhu.edu/ME530707_2016 for more information and to get started with the course. Recommended Course Background: EN.530.646 and EN.600.436.

EN.553.493 Mathematical Image Analysis
This course gives an overview of various mathematical methods related to several problems encountered in image processing and analysis, and presents numerical schemes to address them. It will focus on problems like image denoising and deblurring, contrast enhancement, segmentation and registration. The different mathematical concepts shall be introduced during the course; they include in particular functional spaces such as Sobolev and BV, Fourier and wavelet transforms, as well as some notions from convex optimization and numerical analysis. Most of such methods will be illustrated with algorithms and simulations on discrete images, using MATLAB. Prerequisites : linear algebra, multivariate calculus, basic programming in MATLAB. Recommended Course Background: Real analysis.

EN.580.471 Principles of Design of Biomedical 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

EN.580.472 Medical Imaging Systems
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).

EN.580.571 Honors Instrumentation (2 credits)
Student must have taken 580.471/771. Students will develop a term paper and patent application and carry out a hands-on individual or team project throughout the semester. Previous projects include design of EEG amplifier, voltage clamp and patch clamp, vision aid of blind, pacemaker/defibrillator, sleep detection and alert device, glucose sensor and regulation, temperature controller, eye movement detection and device control, ultrasound ranging and tissue properties, impedance plethysmography, lie detector, blood alcohol detector, pulse oximeter, etc.

EN.601.464 Artificial Intelligence
The class is recommended for all scientists and engineers with a genuine curiosity about the fundamental obstacles to getting machines to perform tasks such as learning, planning and prediction. Materials will be primarily based on the popular textbook, Artificial Intelligence: A Modern Approach. Strong programming skills are expected, as well as basic familiarity with probability. For students intending to also take courses in Machine Learning (e.g., 601.475/675, 601.476/676), they may find it beneficial to take this course first, or concurrently. [Applications]

EN.601.463 Algorithms for Sensor-Based Robotics (Undergrad version)
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]

EN.601.456 Computer Integrated Surgery II
Same material as EN.601.456, for graduate students. This weekly lecture/seminar course addresses similar material to EN.601.445, 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.601.445, 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. [Applications]

EN.601.461 Computer Vision
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] Prerequisites: intro programming, linear algebra, and prob/stat.

EN.601.475 Machine Learning
Machine learning is subfield of computer science and artificial intelligence, whose goal is to develop computational systems, methods, and algorithms that can learn from data to improve their performance. This course introduces the foundational concepts of modern Machine Learning, including core principles, popular algorithms and modeling platforms. This will include both supervised learning, which includes popular algorithms like SVMs, logistic regression, boosting and deep learning, as well as unsupervised learning frameworks, which include Expectation Maximization and graphical models. Homework assignments include a heavy programming components, requiring students to implement several machine learning algorithms in a common learning framework. Additionally, analytical homework questions will explore various machine learning concepts, building on the pre-requisites that include probability, linear algebra, multi-variate calculus and basic optimization. Students in the course will develop a learning system for a final project. [Applications or Analysis] Required course background: multivariable calculus, probability, linear algebra.

EN.601.476 Machine Learning: Data to Models
How can robots localize themselves in an environment when navigating? Which factors predict whether patients are at greatest-risk for complications in the hospital? Can we reconstruct the brain’s "connectome" from fMRI data? Many such big data questions can be answered using the paradigm of probabilistic models in machine learning. This is the second course on machine learning which focuses on probabilistic graphical models. You will learn about directed and undirected graphical models, inference methods, sampling, structure learning algorithms, latent variables, and temporal models. There will be regular assignments, which include theory and some programming. Students will analyze real data for their final project, applying methods discussed in class and writing up a report of their results. [Analysis or Applications] Students may receive credit for EN.600.476 or EN.600.676, but not both.

EN.601.491 Human-Robot Interaction
This course is designed to introduce advanced students to research methods and topics in human-robot interaction (HRI), an emerging research area focusing on the design and evaluation of interactions between humans and robotic technologies. Students will (1) learn design principles for building and research methods of evaluating interactive robot systems through lectures, readings, and assignments, (2) read and discuss relevant literature to gain sufficient knowledge of various research topics in HRI, and (3) work on a substantial project that integrates the principles, methods, and knowledge learned in this course. [Applications]

EN.601.682 Machine Learning: Deep Learning
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue
team projects on topics of their choice. Students should also consider taking EN.601.382 Deep Learning Lab as a supplement. Students may choose to skip the lab course if they already have a strong programming background and are comfortable learning on their own using online resources and tutorials. Pre-req: (AS.110.201 or AS.110.212 or EN.553.291) and (EN.553.310 EN.553.311 or EN.553.420); Calc III and numerical optimization recommended.

EN.601.760 FFT in Graphics and Vision
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue team projects on topics of their choice. Students should also consider taking EN.601.382 Deep Learning Lab as a supplement. Students may choose to skip the lab course if they already have a strong programming background and are comfortable learning on their own using online resources and tutorials. Recommended Course Background: (AS.110.201 or AS.110.212 or EN.553.291) and (EN.553.310 EN.553.311 or EN.553.420); numerical optimization recommended.

EN.601.663 Algorithms for Sensor-Based Robotics (Grad version)
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.

EN.580.484 Ultrasound Imaging—Theory and Application
This course is designed to teach students the theory behind ultrasound imaging and provide an opportunity to apply this theory in a final project. The projects will be centered around advanced beamformers, photoacoustic imaging and thermal imaging. Recommended course background: EN.520.432 or EN.580.472 or equivalent.

EN.580.684 Ultrasound Imaging—Theory and Application
This course is designed to teach students the theory behind ultrasound imaging and provide an opportunity to apply this theory in a final project. The projects will be centered around advanced beamformers, photoacoustic imaging and thermal imaging. Recommended course background: EN.520.432 or EN.580.472 or equivalent.

Robotics MSE
Please always check lcsr.jhu.edu for the most up-to-date course listings.

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. Undergraduates can register, but only for S/U grade.

EN.520.448 Electronics Design Lab
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.520.214, EN.520.216, EN.520.349, EN.520.372, EN.520.490 or EN.520.491.

EN.520.601 Introduction to Linear Systems Theory
A beginning graduate course in multi-input multi-output, linear, time-invariant systems. Topics include state-space and input-output representations; solutions and their properties; multivariable poles and zeros; reachability, observability and minimal realizations; stability; system norms and their computation; linearization techniques. Recommended Course Background: Undergraduate courses in control systems and linear algebra.

EN.520.612 Machine Learning for Signal Processing
This course will focus on the use of machine learning theory and algorithms to model, classify and retrieve information from different kinds of real world complex signals such as audio, speech, image and video. Recommended Course Background: AS.110.201, EN.553.310, and EN.520.435.

EN.520.613 Adv Topics in Optical Medical Imaging
The course will review the recent advances in photonics technologies for medical imaging and sensing. The course is designed for graduate students with a back ground in optics and engineering. The main topics for the course are: Light Source and Devices for Biomedical Imaging; Fluorescence, Raman, Rayleigh Scatterings; Optical Endoscopy and Virtual biopsy; Novel imaging contrast dyes, nanoparticles, and optical clearing reagents; Label-free optical technologies in clinical applications; Neurophotonics and Optogenetics.

EN.520.614 Image Processing and Analysis
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. Recommended Prerequisite: EN.520.214 or equivalent.

EN.520.615 Image Process and Analysis II
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. Grad students only.
EN.520.621 Introduction to Nonlinear Systems
Nonlinear systems analysis techniques: phase-plane, limit cycles, harmonic balance, expansion methods, describing function, Liapunov stability, Popov criterion. Recommended Course Background: EN.520.601 or equivalent.

EN.520.623 Medical Image Analysis
Graduate version of 520.433. 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.

EN.520.629 Networked Dynamical Systems
Networks and dynamics are pervasive in our world today. Power systems, the Internet, social networks, and biological systems are only a few of the numerous scenarios in which objects or individuals can affect - and be affected by - other members of a large group. This course examines modeling, analysis and design of networked dynamical systems - i.e., dynamic entities interconnected by a network - as well as various applications of such systems in science and engineering. Topics covered include (algebraic) graph theory, basic models of networked dynamical systems, continuous-time and discrete-time distributed averaging (consensus), coordination algorithms (rendezvous, formation, flocking, and deployment), and distributed algorithm computation and optimization over networks. Some of the motivating applications that will be analyzed are robotic coordination, coupled oscillators, social networks, web PageRank, sensor networks, power grids, and epidemics. Recommended Course Background: Linear Algebra (AS.110.201), Control Systems (EN.520.353), or equivalents, basic Matlab skills, and sufficient mathematical maturity.

EN.520.631 Ultrasound and Photoacoustic Beamforming
This course will discuss basic principles of ultrasound and photoacoustic imaging and provide an in-depth analysis of the beamforming process required to convert received electronic signals into a usable image. We will cover basic beamforming theory and apply it to real clinical and pre-clinical data. The course will culminate with student projects to design and implement a new beamformer derived from the principles taught in class.

EN.520.632 Medical Imaging Systems
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

EN.520.633 Intro to Robust Control
The subject of this course is robust analysis and control of multivariable systems. Topics include system analysis (small gain arguments, integral quadratic constraints); parametrization of stabilizing controllers; $H_{\infty}$ optimization based robust control design; and LTI model order reduction (balanced truncation, Hankel reduction). Recommended Course Background: EN.520.601 or EN.530.616 or EN.580.616

EN.520.646 Wavelets and Filter Banks
This course serves as an introduction to wavelets, filter banks, multirate signal processing, and time-frequency analysis. Topics include wavelet signal decompositions, bases and frames, QMF filter banks, design methods, fast implementations, and applications. Recommended Course Background: EN.520.435, AS.110.201, C/C++ and Matlab programming experience.

EN.520.657 Product Design Lab
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.

EN.520.662 Leading Innovation Design Team
Project design course that complements and/or builds on Core Knowledge Relevant to Electrical & Computer Engineering with emphasis on multidisciplinary projects. All Projects will be sponsored, have clearly defined objectives, and must yield a Tangible Result at Completion. Project duration can vary between a minimum of 2 semesters and a maximum of 5 years. This course will afford the students the opportunity to use their creativity to innovative and to master critical skills such as: customer/user discovery and product specifications; concept development; trade study; systems engineering and design optimization; root cause; and effective team work. The students will also experience first-hand the joys and challenges of the professional world. The course will be actively managed and supervised to represent the most effective industry practices with the instruction team, including guest speakers, providing customized lectures, technical support, and guidance. In addition, the students will have frequent interactions with the project sponsor and their technical staff. Specific projects will be listed on ece.jhu.edu

EN.520.663 Leading Innovation Design Team II
Project design course that complements and/or builds on Core Knowledge Relevant to Electrical & Computer Engineering with emphasis on multidisciplinary projects. All Projects will be sponsored, have clearly defined objectives, and must yield a Tangible Result at Completion. Project duration can vary between a minimum of 2 semesters and a maximum of 5 years. This course will afford the students the opportunity to use their creativity to innovative and to master critical skills such as: customer/user discovery and product specifications; concept development; trade study; systems engineering and design optimization; root cause; and effective team work. The students will also experience first-hand the joys and challenges of the professional world. The course will be actively managed and supervised to represent the most effective industry practices with the instruction team, including guest speakers, providing customized lectures, technical support, and guidance. In addition, the students will have frequent interactions with the project sponsor and their technical staff. Specific projects will be listed on ece.jhu.edu

EN.520.683 Bio-Photonics Laboratory
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. Graduate version of EN.520.483

EN.520.691 CAD Design of Digital VLSI Systems I
Graduate students only.

EN.520.738 Advanced Electronic Design Lab
This course is the graduate expansion of the EN.520.448 Electronic Design Lab, which is 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. For this graduate expansion, all projects will be based on recently published research from IEEE Transactions. The students will be required to fully research, analyze, implement and demonstrate their chosen topic. The emphasis will be on VLSI microsystems, although other topics will also be considered. Open to graduate students only.

EN.530.414 Computer-Aided Design
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.

EN.530.420 Robot Sensors/Actuators
Introduction to modeling and use of actuators and sensors in mechatronic design. Topics include electric motors, solenoids, micro-actuators, position sensors, and proximity sensors.

EN.530.421 Mechatronics
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.

EN.530.470 Space Vehicle Dynamics and Control
In this course we study applied spacecraft orbital and attitude dynamics and their impact on other subsystems. In the orbital dynamics part of the course, we discuss some of the issues associated with orbital insertion, control and station keeping. Focus is on the two-body problem regime where conic solutions are valid. Orbit perturbations are also considered. For attitude dynamics, different attitude representations such as of direction cosines, quaternions, and angles are introduced. Then we look at the forces and moments acting on space vehicles. Attitude stability and control considerations are introduced.

EN.530.485 Physics and Feedback in Living Systems
The complex mechanisms of living systems cannot be reduced to a set of base pairs: genes are only one part of mystery of life. Rather, organisms must develop, move, interact, and function in their natural environment, and thus are constrained by the laws of physics. For example, during locomotion an animal must accelerate according to Newton’s laws by applying forces between itself and the environment. Beyond physical principles alone, biological systems extensively use feedback to enhance stability and facilitate adaptation in the presence of a changing world. This course examines the critical roles that physical principles and feedback mechanisms play in life, with special emphasis on animal locomotion and its control. Juniors and Seniors only.

EN.530.495 Microfabrication Laboratory
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.

EN.530.603 Applied Optimal Control
The course focuses on the optimal control of dynamical systems subject to constraints and uncertainty by studying analytical and computational methods leading to practical algorithms. Topics include calculus of variations, nonlinear local optimization, global stochastic search, dynamic programming, linear quadratic (gaussian) control, numerical trajectory optimization, model-predictive control. Advanced topics include approximate dynamic programming and optimal control on manifolds. The methods and algorithms will be illustrated through implementation of various simulated examples. Recommended Course Background: Linear Algebra and Differential Equations; experience with control systems; programming in MATLAB and/or Python.

EN.530.613 Mechanical Engineering Master’s Design I
This course is intended to give graduate students some practice and experience in the art of engineering design in conjunction with undergraduate students taking MechE Senior Design Project I. Students working in teams of two to four will select a small-scale, industry-suggested design problem in the area of small production equipment, light machinery products, or manufacturing systems and methods. A solution to the problem is devised and constructed by the student group within limited time and cost boundaries. Preliminary oral reports of the proposed solution are presented at the end of the first semester. A final device, product, system, or method is presented orally and in writing at the end of the second semester. Facilities of the Engineering Design Laboratory (including machine shop time) and a specified amount of money are allocated to each student design team for purchases of parts, supplies, and machine shop time where needed. Recommended Course Background: C- or higher in both 530.403 and 530.404 MechE Senior Design Project I/II. Students from other universities may ask to be considered if they have taken a course like MechE Senior Design Project i.e. two semesters, design-build-test, ideally with industry connection.

EN.530.614 Mechanical Engineering Master’s Design II
This course is intended to give graduate students some practice and experience in the art of engineering design in conjunction with undergraduate students taking MechE Senior Design Project II. Students working in teams of two to four will select a small-scale, industry-suggested design problem in the area of small production equipment, light machinery products, or manufacturing systems and methods. A solution to the problem is devised and constructed by the student group within limited time and cost boundaries. Preliminary oral reports of the proposed solution are presented at the end of the first semester. A final device, product, system, or method is presented orally and in writing at the end of the second semester. Facilities of the Engineering Design Laboratory (including machine shop time) and a specified amount of money are allocated to each student design team for purchases of
parts, supplies, and machine shop time where needed. Recommended Course Background: C- or higher in both 530.403 and 530.404 MechE Senior Design Project I/II. Students from other universities may ask to be considered if they have taken a course like MechE Senior Design Project i.e. two semesters, design-build-test, ideally with industry connection.

EN.530.616 Introduction to Linear Systems Theory
A beginning graduate course in multi-input multi-output, linear, time-invariant systems. Topics include state-space and input-output representations; solutions and their properties; multivariable poles and zeros; reachability, observability and minimal realizations; stability; system norms and their computation; linearization techniques. Students cannot take EN.530.616 if they have already taken the equivalent courses EN.520.601 OR EN.580.616.

EN.530.624 Dynamics of Robots and Spacecraft
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.

EN.530.628 Nonlinear Dynamical Systems
Nonlinear dynamical systems theory are discussed in the context of mechanics, engineering and biological problems. Concepts such as stability, bifurcations, limit cycles and chaos are illustrated using simple analytic theories as well as practical examples. Emphasis are placed on developing intuition using analytic approaches and simple numerical calculations. The course is appropriate for graduate students with foundational knowledge of solid and fluid mechanics, and some notions of statistical mechanics and biological concepts.

EN.530.639 Comparative Biomechanics
Comparative Biomechanics refers to the mechanics of biological organisms, including both humans and many non-human organisms. This course introduces the biomechanical principles of organism morphology, function, and interactions with their environment, as well as how these principles have inspired useful engineering devices. There is an emphasis on both the diversity of natural and artificial biomechanical systems and the underlying unifying principles. Many interesting topics will be discussed. Some examples include: Why can a mouse falling from a skyscraper walk away with little injury, but a horse will smash? Why do horses walk at low speeds but run at higher speeds? Can T-Rex run? Why do larger animals become more erect in their leg posture? How do geckos adhere to almost any surface? Can we learn from it to create a spider man? How can fleas jump to hundreds times of their body height? How does a chameleon shoot out its tongue to catch bugs? Why do British archers use the yew trees to make long bows? What other functions can muscles serve besides doing work? Why do animals need lungs for ventilation and a heart for blood circulation? How do prairie dogs get fresh air into their nest underground? How can giraffes drink by bending their head down to the ground without blowing their brains out, with a large blood pressure required to pump blood up when their head is up? Why do many tiny organisms have hairs? How do water striders walk on water and how do Jesus Christ lizards run on water? Can humans run on water? Students from ME and other departments are welcome. Students are assumed to be familiar with introductory physics. Although this is an upper lever undergraduate and graduate course, freshman and sophomore undergraduate students with sufficient physics background may take it with instructor approval. Closely-related course: EN.530.475/675. Locomotion I: Mechanics. Visit https://li.me.jhu.edu/ teaching for more information.

EN.530.645 Kinematics
A theoretical treatment of the kinematics of mechanisms, machines, and robotic manipulators intended for (though not restricted to) graduate students. Topics include parameterizations of spherical motion - Euler angles, Rodrigues parameters, unit quaternions, the matrix exponential; analysis of planar and spatial linkages; robot kinematics - forward and inverse kinematics, singularities, elementary topological issues; theory of wrenches and twists; research issues in robot kinematics - redundancy resolution, grasping and rolling contact, steering of nonholonomic systems. Other advanced topics will be covered as time permits. Recommend Course Background: Undergraduate linear algebra and multivariable calculus.

EN.530.647 Adaptive Systems
Graduate-level introduction to adaptive identification and control. Emphasis on applications to mechanical systems possessing unknown parameters (e.g., mass, inertia, friction). Topics include stability of linear and nonlinear dynamical systems, Lyapunov stability, input-output stability, adaptive identification, and direct and indirect adaptive control. Required Prerequisites: Calculus I, II, and III; Physics I and II; Linear Algebra; Differential Equations; Graduate linear systems theory such as EN.520.601 Introduction to Linear Systems Theory is required prerequisite. Please see the course home page here for additional information: https://dscl.lcsr.jhu.edu/courses/530-647-adaptive-systems- fall-2017. Audit registration not permitted.

EN.530.648 Group Theory in Engineering Design
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.

EN.530.649 System Identification
This course will cover several fundamental approaches system identification, including spectral, prediction error, subspace, and "online" (adaptive) identification methods. The emphasis will be on LTI systems, but some time will be devoted to system identification for classes of nonlinear dynamical systems, such as those that are linear in parameters.

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, Lagrange, 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 relates the topics of this course to his or her research.

EN.530.654 Advanced Systems Modeling II
A continuation of EN.530.653, this course covers the following topics at an advanced level: Newton’s laws of 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, Lagrange, 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 relates the topics of this course to his or her research.

EN.530.663 Robot Motion Planning
This course provides a graduate-level introduction to robot motion planning. Topics include geometric representation of rigid bodies, configuration space of robots, graph search algorithms, shortest-path motion, and various approaches to motion planning problems (e.g., combinatorial and sampling-based motion planning algorithms, and potential field method). The emphasis is both on mathematical aspects of motion planning (which provides fundamentals in understanding the state-of-the-art planning techniques) and computational implementation of algorithms.

EN.530.675 Locomotion I: Mechanics
This is a course on the mechanics of locomotion in animals and machines (particularly bio-inspired and biomimetic robots). Locomotion emerges from effective physical interaction of an animal or a machine with the surrounding environment; therefore, the ability to generate appropriate forces (besides appropriate sensing and control) is essential to successful locomotion. From a mechanics point of view, we will discuss why animals move amazingly well in almost any environment, how they have inspired some highly successful machines, and yet why the majority of robots still struggle in environments that are only modestly complex and how they may be improved by better understanding the mechanics of locomotion. Primary focus will be on terrestrial locomotion, but aerial and aquatic locomotion will be also discussed, all with numerous examples. General principles and integration of knowledge from engineering, biology, and physics will be emphasized. Students from ME and other departments are welcome. A strong understanding of Newtonian mechanics is required. Visit http://li.me.jhu.edu/teaching for more information. Recommended Course Background: B+ or higher in EN.530.202 Dynamics or EN.560.202 Dynamics

EN.530.676 Locomotion II: Dynamics
Graduate course on mechanics and control in locomotion. Topics include modeling (e.g. Lagrangian mechanics), dynamical systems theory (nonholonomic systems, limit-cycle behavior, Poincaré analysis, and Floquet theory), design (control synthesis, mechanical design), and data-driven modeling from animal locomotor control experiments.

Prerequisites: A graduate course in linear systems theory (e.g. EN.520.601). Suggested background (not required): 530.475/675.

EN.530.678 Nonlinear Control and Planning in Robotics
The course starts with a brief introduction to nonlinear systems and covers selected topics related to model-based trajectory planning and feedback control. Focus is on applications to autonomous robotic vehicles modeled as underactuated mechanical systems subject to constraints such as obstacles in the environment. Topics include: nonlinear stability, stabilization and tracking, systems with symmetries, differential flatness, backstepping, probabilistic roadmaps, stochastic optimization. Recommended Course Background: multi-variable/ differential calculus, AS.110.302, AS.110.201, undergraduate linear control, basic probability theory.

EN.530.691 Haptic Interface Design for Human-Robot Interaction
This course provides an introduction to haptic interface design and analysis for human-robot interaction involving virtual environments, augmented reality, and teleoperation. Topics include human touch perception, haptic-focused mechatronic design, system modeling and analysis (kinematic and dynamic), human-in-the-loop feedback control, and haptic feedback evaluation. Recommended: coursework or knowledge of Dynamics and knowledge of feedback control, mechatronics, and Matlab.

EN.530.707 Robot System Programming
This course seeks to introduce students to open-source software tools that are available today for building complex experimental and fieldable robotic systems. The course is grouped into four sections, each of which building on the previous in increasing complexity and specificity: tools and frameworks supporting robotics research, robotics-specific software frameworks, integrating complete robotic systems, and culminates with an independent project of the student’s own design using small mobile robots or other robots in the lab. Students will need to provide a computer or a virtual-box (with at least a few GB of memory and a few tens of GB of disc space) running Ubuntu 14.04 LTS Trusty Tahr (http://releases.ubuntu.com/14.04 or one of its variants such as Xubuntu 14.04 LTS) and ROS Indigo Igloo (http://wiki.ros.org/indigo) - note that these specific versions of Linux and ROS are required! Students should have an understanding of intermediate programming in C/C++ (including data structures and dynamic memory allocation) Familiarity with Linux programming. Familiarity with software version control systems (e.g. subversion, mercurial, git), linear algebra. Recommended Course Background: EN.530.646 Robot Devices, Kinematics, Dynamics, and Control and EN.600.636 Algorithms for Sensor Based Robotics. Students should see the course homepage http://dsc1.lcsr.jhu.edu/ ME530707_2016 for more information and to get started with the course. Recommended Course Background: EN.530.646 and EN.600.436.

EN.530.761 Mathematical Methods of Engineering I
This course is a fast-paced overview of some fundamental topics in applied mathematics including: linear algebra and matrix theory, ordinary differential equations, Laplace and Fourier transforms, as well as an introduction to partial differential equations.

EN.530.663 Network Models in Operations Research
In-depth mathematical study of network flow models in operations research, with emphasis on combinatorial approaches for solving them. Introduction to techniques for constructing efficient algorithms, and to some related data structures, used in solving shortest-path, maximum-volume, flow, and minimum-cost flow problems. Emphasis on linear models and flows, with brief discussion of non-linear models and network
EN.553.693 Mathematical Image Analysis
This course gives an overview of various mathematical methods related to several problems encountered in image processing and analysis, and presents numerical schemes to address them. It will focus on problems like image denoising and deblurring, contrast enhancement, segmentation and registration. The different mathematical concepts shall be introduced during the course; they include in particular functional spaces such as Sobolev and BV, Fourier and wavelet transforms, as well as some notions from convex optimization and numerical analysis. Most of such methods will be illustrated with algorithms and simulations on discrete images, using MATLAB. Prerequisites: linear algebra, multivariate calculus, basic programming in MATLAB. Recommended Course Background: (AS.110.202 OR AS.110.211) AND (EN.553.291 OR AS.110.201 OR AS.110.212)

EN.553.761 Nonlinear Optimization 1
This course considers algorithms for solving various nonlinear optimization problems and, in parallel, develops the supporting theory. The primary focus will be on unconstrained optimization problems. Topics for the course will include: necessary and sufficient optimality conditions; steepest descent method; Newton and quasi-Newton based line-search, trust-region, and adaptive cubic regularization methods; linear and nonlinear least-squares problems; linear and nonlinear conjugate gradient methods. Recommended Course Background: Multivariable Calculus, Linear Algebra, Real Analysis such as AS.110.405

EN.553.762 Nonlinear Optimization 2
This course considers algorithms for solving various nonlinear optimization problems and, in parallel, develops the supporting theory. The primary focus will be on constrained optimization problems. Topics for the course will include: necessary and sufficient optimality conditions for constrained optimization; projected-gradient and two-phase accelerated subspace methods for bound-constrained optimization; simplex and interior-point methods for linear programming; duality theory; and penalty, augmented Lagrangian, sequential quadratic programming, and interior-point methods for general nonlinear programming. In addition, we will consider the Alternating Direction Method of Multipliers (ADMM), which is applicable to a huge range of problems including sparse inverse covariance estimation, consensus, and compressed sensing. Recommended Course Background: Multivariable Calculus, Linear Algebra, Real Analysis such as AS.110.405.

EN.553.792 Matrix Analysis and Linear Algebra
A second course in linear algebra with emphasis on topics useful in analysis, economics, statistics, control theory, and numerical analysis. Review of linear algebra, decomposition and factorization theorems, positive definite matrices, norms and convergence, eigenvalue location theorems, variational methods, positive and nonnegative matrices, generalized inverses.

EN.580.616 Introduction to Linear Systems Theory
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. BME EN.580.616 can be used to fulfill the requirement of ME EN.530.616 or ECE EN.520.601.

EN.580.630 Theoretical Neuroscience
Theoretical methods for analyzing information encoding and functional representations in neural systems. Models of single and multiple neural spike trains based on stochastic processes and information theory; detection and estimation of behaviorally relevant parameters from spike trans; system theoretic methods for analyzing sensory receptive fields; network models of neural systems. Both theoretical methods and the properties of specific well-studied neural systems will be discussed. Recommended Course Background: EN.580.422 or equivalent, EN.550.420 or equivalent, EN.580.222 or equivalent.

EN.580.673 Magnetic Resonance in Medicine
This course provides the student with a complete introduction to the physical principles, hardware design, and signal processing used in magnetic resonance imaging and magnetic resonance spectroscopy. The course is designed for students who wish to pursue research in magnetic resonance. Recommended course background: EN.580.222 or EN.520.214. Co-listed with EN.580.476.

EN.580.679 X-ray Imaging and Computed Tomography
This course provides students with an intermediate-level understanding of the physics, engineering, algorithms, and applications of medical x-ray imaging and computed tomography (CT). It is intended for senior undergraduates (EN.580.479) and/or graduate students (EN.580.679) in Biomedical Engineering, Computer Science, Electrical and Computer Engineering, or related fields in science and engineering. Topics include the physics of x-ray interaction and detection, image quality modeling and assessment, 3D image reconstruction (including analytical and iterative approaches), and applications in diagnostic and image-guided procedures. Recommended Course Background: EN.580.472 and/or EN.580.473 and familiarity with Matlab.

EN.580.684 Ultrasound Imaging: Theory and Applications
This course is designed to teach students the theory behind ultrasound imaging and provide an opportunity to apply this theory in a final project. The projects will be centered around advanced beamformers, photoacoustic imaging and thermal imaging. Recommended course background: EN.520.432 or EN.580.479 or equivalent.

EN.580.693 Imaging Instrumentation
This course is intended to introduce students to imaging instrumentation. The class will be lab-oriented, giving hands-on experience with data collection and processing using a configurable optical system. Specific topics will include the programming and control of electromechanical elements, imaging data acquisitions, image formation and processing (e.g. 3D reconstruction), and imaging system analysis and optimization. Recommended Course Background: EN.580.222 Systems and Controls or EN.520.214 Signals and Systems. Programming experience highly desirable.

EN.580.740 Surgery for Engineers
This course provides an introduction to basic principles and emerging techniques in surgery, interventional radiology, and radiation therapy for engineering students. Basic principles include introduction to fundamental surgical approaches and tools as well as sub-specialties, including neurosurgery, orthopaedic surgery, ENT surgery, thoracic surgery, and laparoscopic surgery as well as minimally invasive (body and neurovascular) interventional radiology as well as radiotherapy (external beam and brachytherapy). Introduction to cutting edge and emerging technologies include intraoperative imaging (all modalities), surgical navigation, and robotics. Requisite background for engineering students includes analytic geometry, linear algebra, computing (Matlab, Python, or C++), and basic familiarity with the physics of medical imaging. Safety
Training: certificate in Bloodborne Pathogens and HIPAA & Research. Recommended course background: 580.472, 601.455

EN.601.654 Augmented Reality
This course introduces students to the field of Augmented Reality. It reviews its basic definitions, principles and applications. It then focuses on Medical Augmented Reality and its particular requirements. The course also discusses the main issues of calibration, tracking, multi-modal registration, advance visualization and display technologies. Homework in this course will relate to the mathematical methods used for calibration, tracking and visualization in medical augmented reality. Students may also be asked to read papers and implement various techniques within group projects. Recommended Course Background: EN.601.220, EN.601.226, and AS.110.201. [Applications]

EN.601.655 Computer Integrated Surgery 1
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.601.220, EN.601.457, EN.601.461, image processing.

EN.601.656 Computer-Integrated Surgery 2
Same material as EN.601.456, for graduate students. This weekly lecture/seminar course addresses similar material to EN.601.445, 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.601.445, 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. [Applications]

EN.601.661 Vision
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] Prerequisites: intro programming, linear algebra, and prob/stat.

EN.601.663 Algorithms for Sensor-Based Robotics
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]

EN.601.664 Artificial Intelligence
Same material as EN.601.464, for graduate students. The class is recommended for all scientists and engineers with a genuine curiosity about the fundamental obstacles to getting machines to perform tasks such as learning, planning and prediction. Materials will be primarily based on the popular textbook, Artificial Intelligence: A Modern Approach. Strong programming skills are expected, as well as basic familiarity with probability. For students intending to also take courses in Machine Learning (e.g., EN.601.475/675, EN.601.476/676), they may find it beneficial to take this course first, or concurrently. [Applications] Prereq: EN.600.226. Recommended: linear algebra, prob/stat.

EN.601.675 Machine Learning
Machine learning is subfield of computer science and artificial intelligence, whose goal is to develop computational systems, methods, and algorithms that can learn from data to improve their performance. This course introduces the foundational concepts of modern Machine Learning, including core principles, popular algorithms and modeling platforms. This will include both supervised learning, which includes popular algorithms like SVMs, logistic regression, boosting and deep learning, as well as unsupervised learning frameworks, which include Expectation Maximization and graphical models. Homework assignments include a heavy programming components, requiring students to implement several machine learning algorithms in a common learning framework. Additionally, analytical homework questions will explore various machine learning concepts, building on the pre-requisites that include probability, linear algebra, multi-variate calculus and basic optimization. Students in the course will develop a learning system for a final project. [Applications or Analysis] Required course background: multivariable calculus, probability, linear algebra.

EN.601.676 Machine Learning: Data to Models
Same material as EN.601.476, for graduate students. How can robots localize themselves in an environment when navigating? Which factors predict whether patients are at greatest-risk for complications in the hospital? Can we reconstruct the brain’s "connectome" from fMRI data? Many such big data questions can be answered using the paradigm of probabilistic models in machine learning. This is the second course on machine learning which focuses on probabilistic graphical models. You will learn about directed and undirected graphical models, inference methods, sampling, structure learning algorithms, latent variables, and temporal models. There will be regular assignments, which include theory and some programming. Students will analyze real data for their final project, applying methods discussed in class and writing up a report of their results. [Analysis or Applications] Recommended Background: EN.600.475 or EN.601.675 or equivalent. Students may receive credit for EN.600.476 or EN.600.676, but not both.

EN.601.682 Machine Learning: Deep Learning
Deep learning (DL) has emerged as a powerful tool for solving data-intensive learning problems such as supervised learning for classification or regression, dimensionality reduction, and control. As such, it has a broad range of applications including speech and text understanding, computer vision, medical imaging, and perception-based robotics. The goal of this course is to introduce the basic concepts of deep learning (DL). The course will include a brief introduction to the basic theoretical and methodological underpinnings of machine learning, commonly used architectures for DL, DL optimization methods, DL programming systems, and specialized applications to computer vision, speech understanding, and robotics. Students will be expected to solve several DL problems on standardized data sets, and will be given the opportunity to pursue team projects on topics of their choice. [Applications] Students should also consider taking EN.601.382 Deep Learning Lab as a supplement. Students may choose to skip the lab course if they already have a strong programming background and are comfortable learning on their own using online resources and tutorials. Recommended Course Background: (AS.110.201 or AS.110.212 or EN.553.291) and (EN.553.310 EN.553.311 or EN.553.420); numerical optimization recommended.
EN.601.691 Human-Robot Interaction
This course is designed to introduce graduate students to research methods and topics in human-robot interaction (HRI), an emerging research area focusing on the design and evaluation of interactions between humans and robotic technologies. Students will (1) learn design principles for building and research methods of evaluating interactive robot systems through lectures, readings, and assignments, (2) read and discuss relevant literature to gain sufficient knowledge of various research topics in HRI, and (3) work on a substantial project that integrates the principles, methods, and knowledge learned in this course. [Applications] Required course background: EN.601.220 and EN.601.226.

EN.601.760 FFT in Graphics and 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.

EN.601.783 Vision as Bayesian Inference
This is an advanced course on computer vision from a probabilistic and machine learning perspective. It covers techniques such as linear and non-linear filtering, geometry, energy function methods, markov random fields, conditional random fields, graphical models, probabilistic grammars, and deep neural networks. These are illustrated on a set of vision problems ranging from image segmentation, semantic segmentation, depth estimation, object recognition, object parsing, scene parsing, action recognition, and text captioning. [Analysis or Applications] Required course background: calculus, linear algebra (AS.110.201 or equiv.), probability and statistics (AS.553.311 or equiv.), and the ability to program in Python and C++. Background in computer vision (EN.601.461/661) and machine learning (EN.601.475) suggested but not required.

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

Faculty Professors
Gregory Chirikjian

Noah Cowan
Professor (Mechanical Engineering): Robotics, Neuroscience, Dynamics, Controls, & Locomotion. Courses: System Identification, Robot Devices, Kinematics, Dynamics, and Control; Physics and Feedback in Living Systems; Locomotion in Mechanical and Biological Systems; Linear Systems.

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

Gregory Hager
Professor (Computer Science): Computer Vision, Human-Machine Systems, Medical Applications; Courses: Data Structures, Computer Vision, Sensor-Based Robotics.

Jin Kang
Professor (Electrical and Computer Engineering): Biophotonics, Optical sensing and Imaging, Fiber Optic Devices and Systems; Courses: Advanced Topics in Optical Medical Imaging, Bio-Photonics Laboratory, Light, Image and Vision.

Jerry Prince
Professor (Electrical and Computer Engineering): Medical Imaging and Computer Vision; Courses: Medical Imaging Systems.

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

Rene Vidal
Professor (Biomedical Engineering): Machine Learning, Computer Vision, Biomedical Data Science; Courses: Biomedical Data Science, Mathematics of Deep Learning, Unsupervised Learning.

Louis Whitcomb

Associate Professor
Dennice Gayme

Assistant Professors
Jeremy Brown
Assistant Professor (Mechanical Engineering): Haptic feedback, upper-limb prosthetics, surgical robotics, rehabilitation robotics, human-machine interaction; Courses: Haptic Interface Design for Human-Robot Interaction.

Muyinatu (Bisi) Bell
Assistant Professor (Electrical and Computer Engineering): Medical Imaging, Medical Robotics, Image-Guided Surgery; Courses: Introduction to Medical Imaging, Ultrasound and Photoacoustic Beamforming.

Emad Doctor
Assistant Professor (Radiology): Image-Guided Intervention Ultrasound Imaging.

Chien-Ming Huang

Marin Kobilarov
Assistant Professor (Mechanical Engineering): Computational Dynamical Systems, Robot Control and Motion Planning; Courses: Applied Optimal Control, Nonlinear Control and Planning in Robotics.

Chen Li
Assistant Professor (Mechanical Engineering): Terradynamics, Locomotion, Comparative Biomechanics, Bio-Robotics, Robophysics; Courses: Locomotion: Mechanics, Comparative BioMechanics.

Enrique Mallada
Assistant Professor (Electrical and Computer Engineering): Networked Dynamical Systems, Power Systems, Control Theory, Optimization; Courses: Networked Dynamical Systems.

Research Professor
Mehran Armand
Research Professor (Mechanical Engineering) and Principal Staff (JHUAPL): Medical Robotics and Computer-Integrated Interventional Systems, Biomechanics; Courses: Kinematics and Dynamics of Robots, Robot Control.

Peter Kazanzides
Research Professor (Computer Science): Medical Robotics; Space Robots; Software Systems and Architectures; Robot Control Systems, Augmented Reality.

Nassir Navab

Associate Research Professor
Iulian Iordachita
Associate Research Professor (Mechanical Engineering): Medical Robotics; Mechanical Design, Medical Instrumentation, Sensorized Surgical Tools.

Assistant Research Professor
Simon Leonard

Mathias Unberath

Lecturer
Jin Seob Kim
Lecturer (Mechanical Engineering): Robot Kinematics, Medical Robotics, Computational Biology/Mechanobiology; Application of non-commutative harmonic analysis; Courses: Robot Devices, Kinematics, Dynamics and Control; Robot Motion Planning; Dynamics of Robots and Spacecrafts; Kinematics; (Intermediate Dynamics; Intermediate Vibrations)