ME 60601: BAYESIAN OPTIMIATION:
OPTIMAL DESIGN OF COMPLEX MECHANICAL SYSTEMS

Department of Mechanical Engineering
Indiana University-Purdue University Indianapolis

This course syllabus format incorporates requirements and guidelines of both Purdue University and IUPUI in a graduate course syllabus to encompass the substantive areas that are required in a syllabus.

I. Instructor Information

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II. Course Details

Title and code: Optimal Design of Complex Mechanical Systems ME59700

Number of credit hours: 3.0

Course description:

The objective of this research course is to prepare students to address mechanical systems design and innovation challenges through appropriate design methodologies. This course will be focused on current design approaches, which are rapidly expanding in research and industrial applications, but are not commonly included in engineering curricula. Students of this research course will acquire an understanding of state-of-the-art analysis and optimization tools through hands-on experience and the involvement in research projects. The research experiential learning will prepare students to design innovative mechanical systems and to increase their problem solving capabilities through the use of effective design methodologies.

Course prerequisites:

Student should have taken at least one ME 400-level course.
Recommended as prerequisite or co-requisite: Design Optimization Methods (ME 50601)

Description of students for whom the course was designed:

This course is intended for engineering graduate students and engineering undergraduate senior students; however, any student with knowledge of linear algebra, multivariable calculus, and numerical methods should be able to successfully follow the content of this course.

Course required text/s and related materials:

- Mastinu, Gobbi, and Miano. *Optimal Design of Complex Mechanical Systems, with applications to vehicle engineering*. Springer, 2010.
- Tovar, A., *Design Optimization Methods*. Textbook available in PDF format for students of this course.

<u>Recommended readings and bibliography</u>:

- ASME Journal of Mechanical Design
- ISSMO Journal of Structural and Multidisciplinary Optimization

III. Course Rationale/Justification

Mechanical systems are integral to our transportation (from bicycles to space exploration vehicles), production (from nano-machining to civil infrastructure construction), defense (from weapons to protective armor systems), and health support (from blood pumps to smart prosthetics and medical robots), among other fields that impact our daily life. The design of a mechanical system is a multidisciplinary endeavor involving the interaction of scientific, engineering, and technical disciplines, in the areas such as materials, mechanics, and controls. Current design challenges in mechanical systems include:

- Complexity and heterogeneity of simulation models
- Computational cost of performance analysis
- Conflicting objectives in a multidisciplinary organization
- Evaluation of social impacts
- Treatment of uncertainty

IV. Educational Goals and Objectives

<u>Educational Goal</u>:

ME 60601 uses techniques of engineering optimization methods for Multidisciplinary Design Optimization (MDO) and Optimal Design of Complex Engineering Systems. The application of numerical methods to solve engineering design optimization is presented. Students are exposed to state-of-the-art numerical optimization techniques and applications.

<u>Educational Objectives</u>:

The outcomes of the proposed course implement the Principles of Undergraduate Learning. The intended student learning outcomes of this experiential learning are:

<u>Core Communication and Quantitative Skills</u>

- Writing experience in research and academic reports
- Mathematical descriptions of multidisciplinary design problems
- Analytical solutions of design optimization problems
- Sensitivity analysis using direct and adjoint methods

- Uncertainty quantification

Critical Thinking

- Systematical treatment of mechanical systems design problems
- Assessment of limitations in traditional deterministic design
- Evaluation of simulation-based design methods effectiveness
- Resolution of computational issues in design such as such as ill-posedness and uniqueness
- Identification of errors in available literature

Integration and Application of Knowledge

- Application of numerical modeling and simulation techniques
- Concurrent design of structures and composite materials
- Understanding of design optimization methods, i.e., traditional and biologically inspired
- Use of design principles to make decisions under uncertainty
- Application of design methods in a variety of engineering problems

Intellectual Depth, Breadth, and Adaptiveness

- Undertaking of challenging research projects using rigorous analysis and design methods
- Advancement in mechanical design methods using core engineering knowledge
- Development of efficient numerical methods to address multidisciplinary problems
- Deeper understanding of synergistic interactions of mechanics, materials, and design
- Rethinking traditional academic problems by considering optimality and uncertainty

Outcomes:

These rapidly expanding fields of structural and continuum mechanics have important applications in mathematics, mechanics, multi-physics, and computer science. These approaches also have an important impact on manufacturing industries and are likely to have a significant role in micro- and nano-technologies. This course is structured to accomplish the following outcomes:

- Model, simulate, and analyze performance in machines and machine components
- Apply statics, dynamics, and strength of materials to mechanical systems design
- Gain fundamental knowledge of structural and multidisciplinary design optimization methods
- Analyze effect of uncertainty on multiscale models
- Apply statistics and probability to numerical model analysis
- Enhance problem-solving and communication skills via brief reports and formal research projects

V. Course Content

This course focuses on theoretical and practical aspects of state-of-the-art modeling, analysis, and optimization methods utilized in mechanical systems design research. This course emphasizes current methodologies in material, structural, and multidisciplinary optimization, as well as design optimization under uncertainty. The main topics of this course are divided into five modules as follows:

- Module 1: Introduction and mathematical foundation (Weeks 1 to 3)
- Module 2: Engineering Design and Optimal Design of Complex Systems (Weeks 4 to 7)
- Module 3: Multi-objective optimization (Weeks 8 to 10)
- Module 4: Global approximation (Weeks 10 to 12)
- Module 5: Applications (Weeks 13 to 15)

VI. Course Policies

Attendance policy:

The schedule shows the topics to be covered in each class meeting. You are expected to come to class prepared by studying the assigned material before the lecture. This allows for a more effective use of the class time. Note that the assigned material helps you establish some useful/relevant background on the subject but this doesn't necessarily mean that the exact same material will be covered during the lecture.

The progress of the independent research portion of the course will be assessed on weekly basis. The overall effectiveness of this research experience will be assessed based on students' final research reports. These research reports will follow recommended practices in scientific writing. Their evaluation will be focused on the student's critical and independent thinking, intellectual depth, analysis rigor, quantitative skills, and the integration and application of engineering knowledge. Formative assessment (qualitative feedback) will be an integral part of the course. Research reports will be in a repository available to students taking this class in the future.

The learning experience will be assessed by the students through two course evaluations. A midterm student course evaluation will provide early feedback about the effectiveness of the course, while the final one, handled by the university, will also assess the relative effectiveness of this RISE course in comparison to other ones. Teaching practice will also be evaluated by a professional from the IUPUI Center for Teaching and Learning, who has previously evaluated Prof. Tovar's lectures.

Evaluation and grading criteria:

Homework will be collected at the beginning of each period. If you are unable to attend a class, you may attach a note to your homework and submit it in advance. Late homework will not be accepted under normal circumstances. Neatness and a proper format are considered while grading. Test problems will be of a difficulty level similar to that of homework problems. You are strongly advised to study the example solutions in the textbook/handouts and problems solved in class as well as work out additional problems from the textbook /handouts. All homework must represent your own work. Consultation with other members of the class is allowed, but all work must represent an individual effort. Academic dishonesty is subject to punishment according to the relevant regulations. See: Cheating and plagiarism.

Grading and grading scale:

Items	***Percentage***
In-class exercises	20%
Homework	20%
First exam	20%
Second exam	20%
Design project	20%
Total	**100%**

Grade	A+	A	A-	B+	B	B-	C+	C	C-	D+	D	D-
Minimum%	97	93	90	87	83	80	77	73	70	67	63	60

Cheating and plagiarism:

Academic misconduct is subject to university punishment. Academic misconduct includes, but is not limited to, the following: 1) Cheating; 2) Fabrication; 3) Plagiarism; 4) Interference; 5) Violation of course rules; and 6) Facilitating Academic Dishonesty. Consequences for such actions and refer students to the section on "Academic Responsibilities and Misconduct" in the IUPUI Student Code of Conduct (Part II – G) at this website: http://www.iupui.edu/code/#P2_G Students needed to check IUPUI Student Misconduct policy section of the IUPUI Student Code of Conduct (http://life.iupui.edu/dos/code.htm), if they are not already familiar with it.

American with Disabilities Act (ADA) compliance:

If you need any special accommodations or assistance due to a disability, contact Adaptive Educational Services (AES) at (317)-274-3241. The office is located in Joseph T. Taylor Hall (UC), Room 100. AES website: http://aes.iupui.edu/services.html. No qualified individual with a disability shall, by reason of such disability, be either excluded from participation in or be denied the benefits of the services, programs, or activities" of Indiana University-Purdue University Indianapolis.

Additional help:

During the semester, if you find that life stressors are interfering with your academic or personal success, consider contacting Counseling and Psychological Services (CAPS). All IUPUI students are eligible for counseling services at minimal fees. CAPS also performs evaluations for learning disorders and ADHD; fees are charged for testing. CAPS is located in UN418 and can be contacted by phone (317-274-2548). For more information, see the CAPS web-site at: http://life.iupui.edu/caps/

VII. Class Schedule/Course Calendar

Weekly topics of this course include the following (each period is equal to 75 minutes of lecture time):

- Introduction/Overview of Engineering Design Optimization Methods
- Review of Basic Calculus Concepts I
- Review of Basic Calculus Concepts II
- Review of Basic Calculus Concepts III
- Optimization Concepts and General Problem Statement
- Existence and Uniqueness of an Optimal Solution
- Standard Linear Programming Form
- The SIMPLEX Method
- Polynomial Approximations
- Golden Section Method
- Constrained Functions of One Variable
- General Strategy for Minimizing Functions of One Variable
- Zero-Order Methods
- First-Order Methods
- Second-Order Methods
- Scaling and Convergence Criteria
- Isight Design/Optimization Software
- Exterior Penalty Function Method
- Interior Penalty Function Method
- Augmented LaGrange Multiplier Method
- Design Variable Linking and Reduced Basis Concept
- Response Surface Methods I
- Response Surface Methods II
- Design of Experiments I
- Design of Experiments II
- Random Search, Genetic Search
- Sequential Linear Programming
- Multi-objective Design
- Six Sigma Design (Uncertainty in Design)
- Computer Usage
- Student use MATLAB for some HW problems

In the event of a major campus emergency or inclement weather, course requirements, deadlines and grading percentages are subject to changes that may be necessitated by a revised class schedule or other circumstances. Students will be informed of such changes by e-mail and through the course website in Canvas.

VIII. Other Information Relevant to the Course

<u>Student learning outcomes:</u>

Understand the concept of the existence and uniqueness of an optimal solution [a, e]; Understand basic optimization methods for a single variable [a, e, k]; Understand the use of applying various type of constraints to numerical optimization [a, e, k]; Apply response surface methods to model complex engineering systems [a, e, k]; Apply design of experiments techniques to model a design space [a, e, k]; Solve numerical optimization problems of n-variables with constraints [a, k]; Use of a practical software package to solve typical engineering problems [a, e, k]; Model a realistic engineering design optimization problem as a semester project [a, c, e, f, g, j, k]. Note: The letters within the brackets indicate the general program outcomes of mechanical engineering. See: Relevant ME program outcomes.

Relevant ME program outcomes:

[a] Demonstrate and apply knowledge of mathematics, science, and engineering with: probability and statistics and mechanical engineering sciences (solid mechanics, material science). [c] Design a system, component, or process to meet desired needs with applications to mechanical systems. [e] Identify, formulate, and solve engineering problems. [f] Understand professional and ethical responsibilities. [g] Communicate effectively, in writing and orally. [j] Demonstrate knowledge of contemporary issues. [k] Use the techniques, skills, and modern tools of engineering effectively and correctly in engineering practice with: Mechanical engineering analysis tools, engineering design and manufacturing tools, Internet and library resources, and mathematical computing and analysis tools.