A New Approach to Equip Students to Solve 21st-Century Global Challenges: Integrated Problem-Based Mechanical Engineering Laboratory

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Our paper is assigned to the ME Division, titled "A New Approach to Equip Students to Solve 21st-Century Global Challenges: Integrated Problem-Based Mechanical Engineering Laboratory."

Thank you so much! Please let us know if additional information is needed.

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Abstract

Our curriculum offered subject-based laboratory courses in five different disciplines using structured procedures to accommodate our large undergraduate student population. Like many other universities, lack of critical thinking became a significant problem in these traditional laboratory courses. Besides, students learn fundamental engineering knowledge as isolated subjects. This affects their ability to understand engineering problems holistically and creates barriers to learning transfer. This Work-in-Progress paper summarizes our current effort to redesign the Penn State Mechanical Engineering laboratory curriculum using a new approach, in which laboratory activities based on 21st-century engineering problems are used to enhance students' higher-order thinking skills and reinforce fundamental knowledge. Topics of the laboratory activities included Sustainability, Machine Learning, Additive Manufacturing, Autonomy and Robotics, and Energy. In this course, students apply their prior knowledge in Heat Transfer, Fluid Mechanics, Solid Mechanics, Materials, and Chemistry and integrating with new material to solve complex engineering problems involved multiples principles. To gradually improve student's critical thinking ability, we structured this course into six levels, following the Revised Bloom's taxonomy. Students use their cognitive skills to plan and conduct investigations on a series of engineering problems with increased complexity. Opportunities to utilize essential practical skills for engineers, include Data Acquisition, Data Analysis, Critical Thinking, Numerical Simulation, Problem Solving, Design of Experiments, and Communication Skills, have also been incorporated into these lab modules. In this work, we summarize a total of nine multiple-week lab activities, which are designed to prepare students to work in fields related to both thermal and mechanical systems.

Introduction and Literature Review

The engineering teaching laboratory is intended to be a place to integrate theory with practice. Its purpose is widely accepted as a place to develop technical and personal skills and establish cognitive abilities to solve complex engineering problems. [1], [2] However, these goals have evolved from practical-focused to more theory-oriented throughout the decades. Maintaining and updating instructional labs requires high equipment, space, and human resources cost. [2] These reasons lead to traditional engineering experiments often became procedure-orientated and focused on reinforcing a fundamental principle in a narrow discipline. [3], [4] Holmes et al. demonstrated that labs designed to reinforce concepts show no added value in enhancing students' understanding of fundamental physics material. [5] They compared exam performance between students who did and did not enroll in a closely-coupled laboratory course. Their results show no improvement or even worse understanding by the students on conceptual knowledge based on their laboratory experience. The main reason for the failure of the traditional lab is the lack of thinking. Instructors erroneously assume the students will go through a thought process as they follow the instructions. [6] However, obtaining a result by following the procedure does not necessarily require cognitive skill in thinking. Cognitive skills here include, but are not limited to, analyzing and interpreting data, determining dependencies between parts, predicting and evaluating performance, and making engineering judgments. [7] These abilities require high-level critical thinking skills and align with ABET expectations. [7], [8] According to Bloom's taxonomy, thinking separates into six levels, knowledge, comprehension, application, analysis, synthesis, and evaluation, also known as the cognitive domain of learning. In 2002, ABET approached the Sloan Foundation to define the Fundamental Objectives of Engineering Instructional Laboratories. [9] The first five objectives focus on the cognition domain's knowledge, two involve the psychomotor domain, and the remaining objectives combine the cognitive and affective domain. [2] The Objectives clearly stated the importance of cognitive skills training in laboratory instruction. However, traditional engineering laboratory courses often lack opportunities for students to develop higher-order thinking.

In this Work-in-Progress paper, we summarize our work in redesigning a senior-level undergraduate mechanical engineering laboratory course to provide rich thinking opportunities for students to apply fundamental mechanical engineering knowledge to solve modern engineering problems. To gradually develop higher-order thinking skills in students, our approach is to develop a multi-level laboratory course by utilizing Bloom's taxonomy. Bloom's taxonomy is a hierarchy of thinking, in which higher-level skill builds from lower-level foundations. Good judgment requires turning knowledge into understanding. [10] Students need to practice applying engineering principles to solve a simple problem before analyzing a complex one. Applying the Revised Bloom's taxonomy's terminology, the course begins with "Remember, Understand, and Apply," followed by "Analyze and Evaluate," and ends with "Create." At each level, we emphasize a few elements of fundamental ME knowledge along with essential practical skills, suggested by our faculty and Industrial and Professional Advisory Council (IPAC) members. To help students understand the practical value of learning theoretical concepts and embrace their curiosity, we adopted the problem-based learning approach in designing our laboratory activities. Problem-based learning uses realistic problems to focus students on the course material. [10], [11] In this course, laboratory activities are connected to 21st-century engineering problems, surrounding the general topics of Sustainability, Machine Learning, Advanced Manufacturing, Autonomy and Robotics, and Energy.

Background

a. Laboratory Courses Structure in the curriculum

Our previous curriculum requires students to choose two 1-credit elective laboratory courses from a list of five course offerings: Heat Transfer, Fluids, Dynamic Systems, Vibrations, and Materials. These two lab choices are taken by students once they complete two required ME laboratory courses including a 4-credit Instrumentation lab and a 3-credit Mechatronics course. This paper focuses on our work in consolidating the five topic-based elective lab courses into one problem-based senior-level required course. Consolidation aims to offer a more consistent and scalable means to encourage students to explore and solve complex engineering problems by integrating engineering knowledge from multiple disciplines. For example, heat transfer and fluid mechanics phenomena coexist in gas turbine cooling, and material properties are closely related to structural vibration behavior. The previous subject-based laboratory formats used in our curriculum limits students to study engineering problems by parts instead of using a holistic approach.

b. Related Courses

Prior to this curricular change effort, our mechanical engineering students took an unpopular pre-recorded course on elementary circuit theory followed by a four-credit instrumentation class. Much of the circuits course was retaught in the instrumentation course. Upon completion of the instrumentation class, students would then choose two labs from the list of five choices for a total of 9 credits of instruction (6 of which were lab-based). In the new arrangement, students still receive 9 credits of instruction, but all 9 are lab-based and all use more modern systems that are relevant to today's engineer. Students now take 3 credits of instrumentation (with lab), 3 credits of systems exploration (the consolidated lab course), and 3 credits of mechatronics (with lab). An additional 3-credit course, computation tools, was added to the curriculum by eliminating a largely redundant course in solid mechanics. The computation tools class is taken first in the sequence. The net result of these changes are more credit hours devoted to hands-on practice, more exposure to modern engineering systems, and implementation of current pedagogical best practice.

(i) The Computation Tools Course

This junior-level Computation Tools course introduces students to essential dynamics, mechanics of materials, heat transfer, and fluid dynamics principles while focusing on using computation tools to solve problems in each subject. It is a prerequisite of the new consolidated laboratory course. It prepares students with introductory knowledge on the subjects and experience of using numerical simulation to predict and compare experimental results. It also provides richly detailed visualization of complex engineering phenomena such as fluid flows, vibration, and stress distributions.

(ii) The Mechatronics Course

This course focuses on sensors and actuators, data acquisition, data analysis techniques, and linear system control theories. After learning basic electronics, data acquisition, the frequency content of signals, statistics, and measurement techniques in the Instrumentation course, students master these topics by programming and integrating mechanics and electronics into a smart system using microcontrollers in the Mechatronics course. As this is a new core course, some of its course material was obtained by moving content from our junior-level Instrumentation course, for example, filtering, aliasing, and Op-amps. Mechatronics was previously our most popular elective course and is now required of all undergraduate students.

<u>c. The New Lab Course Prerequisite</u>

The prerequisites of the new consolidated laboratory course include the Computation Tools course and the Instrumentation laboratory course. Concurrent requirements include our Fluid Mechanics and Vibrations lecture-based courses. We have three more lecture courses that could possibly be made prerequisites but this is not possible because of the constraints of a large, four-year program: Heat Transfer, Mechatronics, and Dynamic Systems Modeling. The Heat Transfer course is recommended to take currently with the new lab course in our academic plan. However, some students will need to take the lab before the Mechatronics and Dynamic Systems Modeling courses.

To ensure students have proper knowledge for the lab activities, we designed most of our experiments based on material from completed, prerequisite, and concurrent courses, including Thermodynamics, Fluid Mechanics, Vibrations, Statistics and Dynamics, Basic Electronics, and Fundamental Mechanics. Essential material from concurrent and future courses will be covered in the lectures, and supported by asynchronous videos and reading materials. Since control and electro-mechanics topics are covered in the Mechatronics course, robotics-related experiments in this lab focus on kinematics, dynamics, and programming logic. Simultaneously, we introduce intelligent control techniques, for example, deep learning, image processing, path planning, and network communication. Students will select proper tools and combine these technologies to program robots to perform a given task. Experiments related to Heat Transfer and Dynamic Systems are supported by numerical simulations/visualization to reinforce students' prior knowledge from the Computational Tools course.

d. Existing Problems

In the past, we expected our graduating students to be able to apply fundamental mechanical engineering knowledge and use modern tools, both experimental and computational, to solve complex engineering problems. However, we observed our current senior-level laboratory courses did not fully prepare students to meet this expectation.

The main reason for this lack of preparation was that our five elective laboratory courses are procedure oriented, and do not encourage thinking or make direct connections to realistically complex problems. These experiments focus on a single, isolated engineering principle with overly-idealized hardware, for example, measuring temperature change along a metal bar to study heat conduction or measuring lift force on an airfoil in the wind tunnel to demonstrate stall. Most of the time, students only use lower-order cognitive skills (remember, understand, and apply) to finish the procedures, followed by instructed calculations. Activities requiring higher-order thinking skills, for instance, asking students to determine how parts relate to one another, evaluate and improve their experimental work, or design an experiment, are often not emphasized.[12] These activities required more course time than procedure-orientated labs, which is another limitation in our previous single credit laboratory courses.

Besides lacking higher-order thinking content, the five elective course structure faces problems of non-uniform student workload and inconsistent learning outcomes. Even though ABET student learning objectives confine certain aspects of the courses, student workload and time allocation on each objective vary by instructors. Some instructors provide an open-ended project, while others emphasize applying fundamental principles. Eventually, students complained about the non-uniform workload among courses.

Finally, our faculty reported the old laboratory equipment is no longer suitable for continuous improvement. A significant portion of our old equipment was designed for teaching purposes. These machines are robust and tailored to demonstrate specific engineering principles. Different users can consistently generate similar results, which is a benefit for a teaching lab. However, it raises plagiarism concerns. Since each apparatus was well-designed to demonstrate a single engineering principle, the equipment itself does not provide flexibility for instructors to make changes. Faculty members who want to make minor changes to reduce plagiarism concerns or redesign lab activities to streamline modern engineering problems encounter obstacles with the existing devices.

All the above reasons show an essential need to restructure and modernize our current senior-level laboratory courses. Consolidating the five elective courses into a three-credit course will better balance pedagogic quality and student workload. It will improve consistency, allow organizing learning objectives in a hierarchical structure to progressively develop student cognitive skills, and provide sufficient time for students to work on complex problems. To provide more flexibility for instructors to improve their courses continuously, we geared our new laboratory space mainly with measurement and testing devices. This will allow instructors to update and incorporate their research into teaching or make simple changes from semester to semester. We anticipate this new course will be piloted in FA 2021 after the new space construction is completed in SP 2021.

Course Topics and Structure

To prepare students to solve today's engineering problems, students need in-depth knowledge, understanding of current engineering topics, and practical skills for their future careers. These summarize three key components of our new senior-level laboratory course.

- Fundamental Mechanical Engineering Knowledge
- Understanding Today's Engineering Problems
- Essential Practical Skill

We initiated discussions with faculty and our Industrial and Professional Advisory Council (IPAC) members to identify the essential elements of each of the key components. Five selected fundamental mechanical engineering disciplines are Heat Transfer, Fluids, Mechanics, Materials, and Chemistry. Emphasizing today's problem, we analyzed the identified research fields in Mechanical Engineering defined by professional societies and the National Academy’s 21st Century Grand Challenges for Engineering [13], and then picked six topics: Sustainability, Energy, Autonomy & Robotics, Advanced Manufacturing, Data Analytics, and Bioengineering, to formulate our laboratory activities. These topics were then further refined into eleven subtopics, summarized in Figure 1. Based on the course learning objective and our department's research specialties, we selected six subtopics for the lab experiments: Machine Learning, Energy Storage, Renewable Energy, Power Generation, Manufacturing Automation, and Autonomous Vehicles. Based on the students’ suggestions, we added Acoustics as another subtopic. The last key component is practical skills. Our IPAC members suggested six essential skills for an engineering career: Data Acquisition, Data Analysis, Critical Thinking, Problem Solving, Numerical Simulation, and Design of Experiments.

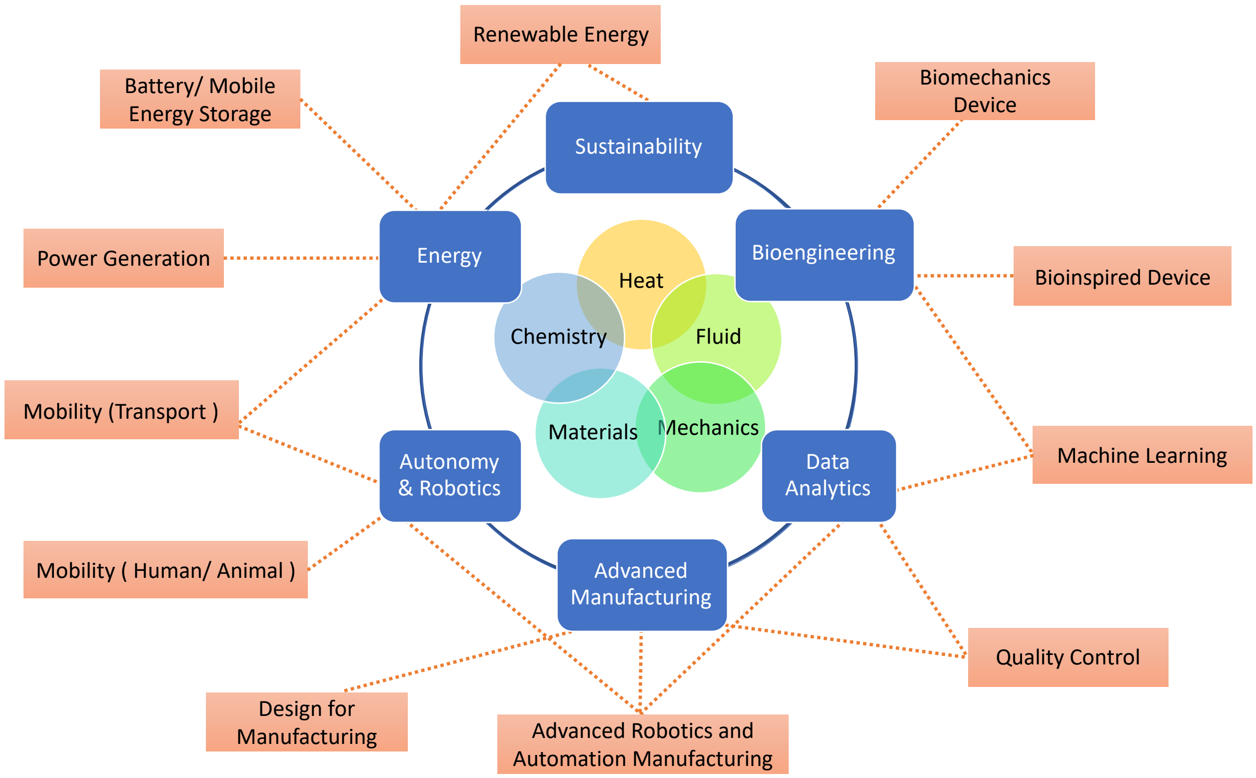

Figure 1. Eleven Modern Mechanical Engineering Subtopics elaborated from six modern ME topics summarized from research fields defined by professional engineering societies and the 21st Century Grand Challenges. The circle in the center summarizes five selected fundamental mechanical engineering disciplines identified by our faculty and IPAC members.

Proper planning and organization are required to systematically integrate the above content into one course. To gradually improve student's academic, practical work, and cognitive skills, we designed a multiple-level course structure based on the Revised Bloom's Taxonomy structure – Remember, Understand, Apply, Analyze, Evaluate, and Create. We divided the course into five levels. Levels 0 to 2 support the development of lower-order cognitive skills (remember, understand, and apply) and prepare students for activities that require higher-order cognitive skills (analyze, evaluate and create). An engineering problem is used to initiate thinking and connect multi-week hands-on activities at each level. Together, we introduce a few practical skills at a time. For example, at Level 0, in the academic domain, we focus on review of statistics knowledge. Students recall their knowledge from their junior-level statistics course and apply them to extract machine learning features. In the practical skill domain, these activities are designed for practicing data analysis and using critical thinking skills to evaluate their method choices. Table 1 summarizes the structure of the course.

Table 1. The multilevel laboratory course structure.

Level	0	1	2	3	4
ME Knowledge **(Knowledge Domain)**	Statistics	Materials	Thermofluid	Thermofluid / Dynamics and Vibration	Mechanics
Topics	Machine Learning	Thermal Fluid Properties or Mechanical Properties	Energy Storage or Renewable Energy	Power Generation or Acoustic	Manufacturing Automation or Autonomous Vehicles
Practical Skill **(Practical Domain)**	Data Analysis Critical Thinking	Data Acquisition Data Analysis Critical Thinking	Numerical Simulation Problem Solving	Problem Solving Numerical Simulation	Design Experiment
Bloom's Taxonomy **(Cognitive Domain)**	Remember, Understand and Apply		Apply and Analyze	Analyze and Evaluate	Create

In short, the course starts with reinforcing statistics knowledge, which students need for data processing throughout the course. Students then perform material characterization by implementing professional standards. At levels 2 and 3, students use Thermodynamics, Heat Transfer, Fluid Mechanics, Dynamics, and Vibrations principles to solve engineering problems. They predict, perform, validate and evaluate their experiments using computer-aided methods. Lastly, students design and create programs to control simple robots. Following the curriculum requirement on the ABET program criteria, these experiments are designed to prepare students to work on either thermal or mechanical systems. The two options indicated in Table 1, starting from level 1, provide students with alternatives to choose from depending on their interests.

Experiments and Objectives

This laboratory course is arranged in a five-level hierarchical structure, as shown in Table 1. Students spend multiple weeks at each level to solve an instructor-defined problem related to one of the modern engineering subtopics listed in Figure 1. We designed nine multiple week experiment modules, including one module for level 0 and two options for each of the other levels. In the following discussion, we explain how we use different engineering problems to connect theory, cognitive skill development, and practical skill training in each module. We called these three areas as the knowledge, cognitive and practical domains.

<u>Level 0</u>

Level 0					
Knowledge Domain	Statistics	**Cognitive Domain**	Remember, Understand, Apply	**Practical Domain**	Data Analysis, Critical Thinking
Topic	Machine Learning				
Problem	How can a smartwatch classify human activity?				
Objectives	Review basic statistics for data analysis. Apply statistical knowledge to extract features from data. Understand data input and output relationship.				

This level aims to review statistics and prepare students for analyzing data in the upper-level labs Students practice retrieving knowledge from junior-level courses. They select and apply proper statistical analysis methods to extract machine learning features from open-source datasets [14]. Extracted features are then input into MATLAB for classification using the classification learner tool. Students analyze how input features and classification algorithms affect the positive predictive rate to obtain a desired predictive model. Students must understand and evaluate the input and output correlations to complete this task. Details of the experiment can be found in our earlier publication. [15]

Level 1

Level 1 (Option A)					
Knowledge Domain	Materials	**Cognitive Domain**	Remember, Understand, Apply	**Practical Domain**	Data Acquisition, Data Analysis, Critical Thinking
Topic	Mechanical Properties and Additive Manufacturing				
Problem	Which materials should we choose to build an aircraft part?				
Objectives	Conduct mechanical material property measurement. Understand the American Society for Testing and Materials (ASTM) standard. Apply material knowledge to extract material properties from experimental results. Investigate the impact of the manufacturing process on material properties.				

Level 1 (Option B)					
Knowledge Domain	Materials	**Cognitive Domain**	Remember, Understand, Apply	**Practical Domain**	Data Analysis, Critical Thinking
Topic	Thermal Fluid Material Properties				
Problem	Which one is the best engine coolant?				
Objectives	Conduct thermal fluid material property measurements. Understand the ASTM standard. Explain the thermal property requirements of engine coolant. Apply heat transfer knowledge to predict heat dissipation from a radiator.				

Starting at level 1, there are two options for lab activities. Both options share the same cognitive and practical domain, while engineering theories being focused within the knowledge domain vary, and the problems to be solved are different. A learning objective of level one is to apply ASTM standards to conduct material property testing. Depending on students' interests, they can choose between material mechanical properties characterization or thermal properties characterization. They select the best material for a given application, for example, material to build an aircraft wing or the best engine coolant. First, students will conduct literature reviews to identify appropriate material properties for their application, followed by performing material testing on unknown materials being provided. Students will need to use their experimental results to identify the given materials and select the most appropriate choice.

We plan to assess students' understanding by their ability to describe methods in their own words, follow a given procedure, and make appropriate data precision choices by following the ASTM standards. For example, select rounding digital on measurements based on specimen choices, determine the needs of a replacement specimen, or use repeatability coefficient to judge whether samples are within the laboratory expectations. Students' accuracy in data analysis and mathematical calculation determine their ability to apply engineering knowledge to new material. For example, extracting Young's modulus and yield strength from a stress-strain curve, and predicting radiator heat dissipation. In Option A, we introduce students to metal additive manufacturing processes. Students will investigate why material properties change based on manufacturing processes by understanding the processes and studying the micro and nanostructures using microscopy techniques.

Level 2

Level 2 (Option A)					
Knowledge Domain	Thermofluids	**Cognitive Domain**	Apply and Analyze	**Practical Domain**	Numerical Simulation and Problem Solving
Topic	Energy Storage (Battery)				
Problem	How to preheat Lithium-ion batteries in cold weather?				
Objectives	Apply heat transfer knowledge, including conduction and convection, and thermal insulation, to design strategies for preheating batteries in cold conditions. Compare and explain the difference between numerical prediction and experimental results.				

Level 2 (Option B)					
Knowledge Domain	Thermofluids	**Cognitive Domain**	Apply and Analyze	**Practical Domain**	Numerical Simulation and Problem Solving
Topic	Renewable Energy				
Problem	Why changing the pitch angle can enhance wind turbine power generation?				
Objectives	Apply fluid mechanics knowledge, including the angle of attack, and lift and drag, to understand the relationship between pitch angles and power generation in a wind turbine. Develop proper simulation models and compare experimental data with computation results.				

At this level, we introduce problems that involve multiple engineering principles, including heating strategies to preheat Li-ion batteries in subzero conditions and power generation with wind turbines. Students will study and solve the problem experimentally, while numerical simulations are used to predict experimental results and support parameter selections. Students will perform battery analysis in option A, followed by evaluating different heating strategies to preheat batteries to room temperature from a cold environment using heat conduction, heat convection, and insulation methods. They will use computational tools to study the heat transfer rate within a battery and design parameters. The design of this lab is adopted from research works conducted in our department.[16] In option B, students will perform experimentation to compare the angle of attack (AOA) with maximum Lift/Drag ratio in a wind tunnel and the optimum pitch angle in a wind turbine model where the power generation is maximum. Students will need to infer their AOA findings from an airfoil to explain the pitch angle setting in a twisted turbine blade. At the same time, they will compare their experimental results with computational simulation to analyze the source of errors.

Level 3

Level 3 (Option A)					
Knowledge Domain	Thermofluids	**Cognitive Domain**	Analyze and Evaluate	**Practical Domain**	Problem Solving and Numerical Simulation
Topic	Power Generation				
Problem	How to improve turbine blade internal cooling using microchannels?				
Objectives	Analyze the correlations between microchannel dimensions, mass flow rate, pressure drop, heat transfer rate, and the nondimensional Nusselt number, Reynolds number, friction factor. Choose an appropriate microchannel design that achieves adequate heat transfer rate at a defined pressure drop.				

Level 3 (Option B)					
Knowledge Domain	Dynamics and Vibration	**Cognitive Domain**	Analyze and Evaluate	**Practical Domain**	Problem Solving and Numerical Simulation
Topic	Musical Vibrations				
Problem	Why does the same musical note sound different in different instruments?				
Objectives	Analyze how the shapes of a wooden block alter vibration modes. Determine proper resonators for sound cancellation or amplification.				

At level 3, we increase the complexity of problems and replace some of the experiments that are hard to perform in a classroom setting with numerical simulations. Computational experiments also allow students to step back, evaluate and improve their design continuously. The comprehensive visualization of computational results reveals details that would be difficult or impossible to measure within a reasonable amount of time. In option A, students will use experimental and computational methods to study how cooling microchannels inside a gas turbine engine blade are necessary to remove the extreme heat generated in the gas turbine. Using microchannel test coupons and a custom-made test rig for gas turbine research developed by researchers in the department [17], students will study the related heat transfer and fluid mechanics principles. Then, they will analyze the correlations between microchannel dimensions, mass flow rate, pressure drop, heat transfer rate, and the corresponding Nusselt number, Reynolds number, and friction factor, using numerical methods. After fully understanding the correlations between multiple principles, students will design a microchannel for a given pressure drop limitation that produces a minimum required amount of heat transfer rate. In option B, students will perform vibration measurements and modal analysis to answer why the same musical note on marimba and xylophone bars sound different. Using Solidworks, students can virtually fine tune the shape of a wooden block to mimic the musical instrument manufacturing process and then perform modal analysis to study how changes alter vibration modes. Lastly, similar to the concept of installing a resonance tube underneath a marimba or a resonator in car exhausts, students will evaluate how a resonator can cancel or amplify sound based on constructive and destructive interference.

Level 4

Level 4 (Option A)					
Knowledge Domain	Mechanics	**Cognitive Domain**	Create	**Practical Domain**	Design Experiment
Topic	Autonomous Vehicles				
Problem	How to control an autonomous vehicle to follow a planned route?				

Objectives	Apply basic programming and kinematics knowledge to plan robot movement. Integrate image processing, deep learning, and/or path planning techniques to control a differential drive robot to follow a planned route autonomously.

Level 4 (Option B)					
Knowledge Domain	Mechanics	**Cognitive Domain**	Create	**Practical Domain**	Design Experiment
Topic	Manufacturing Automation				
Problem	How to integrate smart technology into the assembly line?				
Objectives	Apply basic programming and kinematics knowledge to manipulate a robot arm. Design an automated station by integrating sensors, actuators, image processing and intelligent technologies. Practice inter-team communications.				

At Level 4, our goal is to provide students with opportunities to design experiments. Students will integrate technologies or machine parts to create and control a small robot. They need to plan, organize, and evaluate their experiments. In terms of engineering knowledge, we focused on robot kinematics and programming techniques. We will also introduce intelligent control methods at these labs, including deep learning and image processing techniques. These topics are selected to explore aspects of machine learning that go beyond the required Mechatronics course and prepare students for making use of artificial intelligence in their future workplace. Students will combine the newly-learned materials to control an autonomous vehicle to follow a planned route in a miniature model town in option A, while in option B, students will be provided with robot arms and related components to create an assembly line. Related components include end effectors, industrial camera, conveyor belts, speed and distance sensors, and color sensors. After understanding each component, each student team will develop an assembly station, followed by obtaining a completed production line by combining their station with other teams' stations. Students will have to communicate with other groups to design the overall process and plan for transition between stations. This activity requires inter-team communication, which is unique in the option B.

Mapping to ABET Outcome 3

ABET student outcome (3) "an ability to communicate effectively with a range of audiences" emphasizes the importance of audience-specific communication. Instead of the traditional laboratory report, we decided to use different types of documentation to let students practice their communication skills in this course. Students will write emails, prepare presentations, and create video journals in different laboratory modules to document their work. These assignments are audience-specific, such as email to a supervisor and video journal for the general public. Using email as an example, besides appropriate language and format, students must understand the need to be brief and precise, and always prepare for follow-up questions. Today, communication has expanded beyond written reports and oral presentations. Leveraging new media is one of the essential soft skills in the modern workplace. Because of that, we choose a video journal as one of our assignments. Video journal is now widely used in scientific publications. Video resumes and digital portfolios are a new trend for job interviews. Although social media is popular among younger generations, we are surprised to observe many students have never edited a video. Our expectation is students will be able to plan the storyline of a video journal to summarize their 3-4 weeks of developments by performing simple video editing, e.g., trim and merge videos, add transitions and insert titles. In this course, a few lectures are planned to focus on writing and communication methods while our main focus remains on hands-on experience and cognitive skill development.

Closing Remarks

In this Work-in-Progress paper, we summarize our new senior-level mechanical engineering laboratory course design. It aims to improve students' cognitive skills, prepare them to solve complex and realistic problems while equipping them to work in the 21st-century workplace. Unlike textbook problems, where theory is often illustrated by simple components in an idealized way, this course embraces the complexity of more realistic problems. These problems involve multiple disciplines and consist of many interconnected parts. To obtain a solution, one has to dissect the problem, evaluate interconnections between components, and understand the problem holistically. Besides the knowledge we have learned, we acquire new concepts and integrate them to obtain a solution. High-order thinking skills are required to solve these problems.

With the aim to support the development of students' higher-order thinking, we designed a multiple-level approach, following the six levels of the Revised Bloom's taxonomy. At first, students will apply prior knowledge and professional standards to conduct experimentation. They will then evaluate engineering problems that involve multiple components and engineering principles. Students will compare experimental work with numerical simulation results to improve their modeling skills and to study the benefits and limitations of the two methods. The course ends with the design of robots to perform given tasks. Lastly, audience-specific deliverables are being used to replace traditional lab reports in this course. As students progress through the course, we balance the writing amount while the problems students need to solve become technically more challenging.

Here, we summarize the eight student learning objectives we defined for this senior-level laboratory course. Upon completion of the course, students will be able to

- Identify fundamental engineering knowledge in complex thermal or mechanical systems.
- Understand the connections between components in a complex problem.
- Apply ASTM standards to perform material testing.
- Evaluate the benefits and limitations of computational and experimental works.
- Analyze and interpret data to explore a hypothesis and draw a conclusion.
- Devise and conduct experiments to evaluate parametric dependence.
- Create a vision-aided robotic system.
- Produce appropriate documentation for different audiences.

We anticipate this new course will be piloted in FA 2021 after new lab space construction is completed in SP 2021. Preparation of this curriculum change was started years ago with inputs from faculty, staff, IPAC members, and students in year-long discussions. We are currently renovating our teaching space, equipping the lab, and finalizing the teaching materials. After the soft launch of this course, our future work will focus on assessing these two project objectives: (i) Impact on students' problem solving and cognition skills, and (ii) Impact on students' ability to communicate to a wide range of audiences. Evaluation of the learning objectives will draw on assessment incorporating pre-and post-surveys, student performance, and student/faculty interviews. Laboratory reports will be used to generate formal assessment data to evaluate students' cognitive skills at each level. We will study students' self-confidence in problem-solving and their learning gain in the affective domain using self-reflections and faculty observations.

Throughout the development, we learned the importance of intensive communication with all department stakeholders, including students, faculty, staff, alumni, and IPAC members, for initiating a similar curriculum change. We conducted multiple faculty discussions to analyze existing courses' problems, identify course contents, brainstorm laboratory activities, and evaluate the final course design concept. Input from IPAC members provided insight on essential skills for students' future careers in the field. Students' feedback and concerns on the course design are essential. Their interest in the material affects their engagement in the course. Initially, we proposed the Bioinspired Robot lab module instead of the Manufacturing Automation lab module in Level 4. However, all the undergraduate students we interviewed prefer the Autonomous Vehicles Lab. These early student discussions allow us to redesign the topics to avoid a potential future problem of most students choosing one option at a level. Our new course covers all mechanical engineering fundamentals in one. A committee formed by faculty members who teach related lectures and elective laboratory courses is essential to identify development opportunities and lead discussions among stakeholders. To identify opportunities, we first analyze the pros and cons of our existing labs, select topics critical to retain, identify modern engineering challenges that can map to the department's research interest, and then conduct discussions with faculty members in the related field. Faculty research interest will provide unique opportunities for each institution to create different laboratory experiences. For example, the Battery lab and Power Generation lab, described in this paper, are designed based on our department's energy systems research.

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