Integrating Instrumentation and Mechatronics Education in the Mechanical Engineering Curriculum

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Abstract
A diverse and effective undergraduate mechanical curriculum should integrate learning from the different spheres of mechanical engineering, educate students about recent technological advances, and motivate them to pursue careers in this field. However, a seamless integration of varied topics in mechanical engineering curriculum is challenging, as courses range from traditional engineering classes in thermal fluids, solids and controls, to courses covering emerging technological aspects of instrumentation, sensors, measurement techniques, advanced control algorithms, electronics, and electrical components.

Mechatronics is a newer branch of mechanical engineering that is a synergistic combination of mechanical, electrical, electronics, computer science, control techniques, and information systems. Integrating mechatronics content in mechanical engineering curriculum has been a challenge since it has been viewed as a significant deviation from traditional courses. In the past, pedagogical approaches like semester-long, project-based classes, or linking mechatronics to other engineering disciplines, have been used to integrate mechatronics into the mechanical engineering curriculum, with varying results. Furthermore, teaching an interdisciplinary class of this nature within a semester is a difficult pedagogical endeavor. To overcome these issues, the topics and concepts in the measurement laboratory/lecture (ME 335/L) and introduction to mechatronics (ME 435/L), a traditional mechanical engineering course, are interlinked to provide students with a unified learning experience. As a first step in this direction, ME 335/L was made a prerequisite to ME 435/L, which allowed the students to learn about the fundamental topics in ME 335/L, and thus be prepared to tackle more complex topics in ME 435/L course. The ME 335/L was redesigned to incorporate more tools, instrumentation, and programs typically used in ME 435/L. The key experiments in ME 335/L were tailored to expose students to topics commonly encountered in ME 435/L. This integrated approach to mechatronics allowed students to build a strong fundamental understanding of data acquisition and measurement systems, and enabled them to utilize these theories and principles in ME 435/L. Although some topics are repeated in both these courses (ME 335/L and ME 435/L), the contents become more advanced and in-depth in ME 435/L. The experiments in ME 435/L were redesigned such that the students used the fundamental concepts and modern tools taught in ME 335/L in more challenging projects to reinforce the foundation of instrumentation in design of a mechatronics system. This allowed students to develop their critical thinking and problem-solving skills, which are crucial for building successful careers as mechanical engineers.
Introduction
Mechatronics is a blend of mechanical, electrical, electronic, computer control and information systems as seen in figure 1. This course is made up of measurement systems, drive and actuation system, control system, microprocessor system and computer system that are required to create more functional and adaptable products. As mechatronics is multidisciplinary in nature, proper design of the hands-on experience is crucial for the success of the educational experience.

![Figure 1: Interdisciplinary nature of mechatronics](image)

All instruments, equipment, and appliances used by us incorporate scientific knowledge and know how from the fields of engineering. It is of paramount importance that mechanical engineering students have an in depth understanding of Mechatronics, and it has therefore become a core mechanical engineering course in engineering curricula throughout the world. However, this has led to a pedagogical challenge for teachers as students need to be taught complex fundamentals and theories combining a wide range of topics from statics, kinematics, controls, and electrical/electronics engineering\(^2,3\). The complexity related to teaching mechatronics is further amplified if the syllabus includes an applied project where a clear understanding of programming languages like LabView or Matlab is crucial. These factors directly influence the learning outcome of the mechatronics course and limit students’ ability to master crucial concepts in this class\(^4,5\).

Teaching mechatronics course requires skills in all of the areas, which is hard to master. In our current institution, this course was developed with mostly electrical projects similar to fundamental electrical laboratory course. As the technology is changing and demand for mechatronics concepts are increasing, re-evaluation of the projects became important. To address these challenges, a unique approach has been adopted in the Department of Mechanical engineering at California State University Northridge. A preexisting junior level course, Measurement Lab/Lecture (ME 335/L), has been redesigned to serve as the prerequisite for the Mechatronics Lab/Lecture (ME 435/L) class. The topics covered in the traditional ME 335/L course are tailored to better prepare students for tackling advanced topics in the ME 435/L. Furthermore, the topics covered in the ME 335/L class will be streamlined to introduce students
to the necessary skills required to grasp fundamental topics in the ME 435/L class. The two faculties teaching the respective courses combined their learning objectives and modified the projects such that the students get to learn the similar fundamentals but the application levels changed.

The expected outcome of this modification is two fold. Firstly, it will ensure that students are well prepared when progressing to the ME 435/L course. Secondly, it will improve the learning outcomes and students’ ability to analyze complex engineering systems in the ME 435/L course.

In the following sections, the key learning objectives for both these courses, modified course structures, and metrics for evaluating course modification, are discussed in detail, followed by conclusion and future plan.

**Learning Objectives**

ME-335/L and 435/L are aligned to several key ABET outcomes and hence are crucial courses for the Mechanical Engineering (ME) curriculum. Both these courses provide students with theoretical knowledge and hands on experience. The ABET outcomes for ME-335/L class are as follows:

1. an ability to apply knowledge of mathematics, science and engineering, outcome (a),
2. an ability to design and conduct experiments, as well as to analyze and interpret data, outcome (b),
3. an ability to communicate effectively (3g1 orally, 3g2 written), outcome (g), and
4. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice, outcome (k).

In addition to ABET outcomes in ME-335/L, the Mechatronics course (i.e., ME-435/L) is mapped to ABET outcome (c), which focuses on students’ ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability. Since both these courses are mapped to the same ABET outcomes, they can be streamlined and treated as a sequence of courses in the ME program. The faculty members teaching these classes have streamlined the course content of ME-335/L so as to better prepare students for the ME-435/L course.

**Course Structure**

**ME 335/L Instrumentation**

All junior level students are required to enroll in ME 335/L. Therefore, ME335/L serves as an ideal course to introduce to the principles of measurements, data acquisition, sensors, and programming tools. This class is traditionally focused on fundamentals of experimental design, uncertainty analysis and propagation, behavior of measurement systems, and data analysis tools and techniques. These topics do allow for direct mapping of the concepts taught in class to ABET outcomes as discussed in previous section. However, in order to streamline the course
structure to better prepare students for ME 435/L, the existing course topics in ME 335/L have been redesigned.

It was a challenge to significantly modify the ME 335/L course content to shift focus to the mechatronics component while maintaining the original intent of the course. Our objective is that students should have developed a deeper understanding of and familiarity with LabView, sampling principles, and spectral analysis methods, as they progress to ME 435/L class. With this in mind, an exhaustive introduction of LabView has been included in ME 335/L. A sequence lecture has been developed to familiarize students with programming philosophy and fundamental concepts. Furthermore, a sequence of handouts has been developed with examples and guidelines, which is provided to ME 335/L students during the first week of the class. In order to enable students to have practical insights into the topics pertinent to measurement principles, a sequence of LabView programs have been developed, a sample of which is presented here.

One of the most important concepts that students are expected to grasp in ME 335/L and be aware about in the mechatronics course is the sampling theorem. The sampling theorem may hold very little or no value to a students who are exposed for the first time to data acquisition systems, and sometime this concept is tough to illustrate in simple measurement experiments. Therefore, a simple LabView program has been developed to generate analog sinusoidal signal of 10 Hz, and is displayed using a waveform chart in LabView. A screen shot of the LabView program is shown in Figure 2. A sampled signal showing varying sampling frequency is also shown in the LabView waveform chart. Through this simple LabView program, students can visualize the impact of sampling parameters on the sampled signal. This program has therefore been very effective in helping students to visualize the concept of sampling frequency.

![LabView screen shot demonstrating impact of sampling frequency on the acquired signal.](image)
Another important concept in measurement principles that is directly applicable in Mechatronics is the concept of Fourier transform. In the measurement class, apart from learning the use of Fourier transform in identifying the dominant signal from an under-damped second order system, a new demonstration project has therefore been created, where students acquire sound signal with known frequency using their laptop microphone, and then perform Fourier transform to identify the tone in the sound frequency. Figure 3 is a screen shot of the LabView front panel showing the acquisition parameters along with original sound signal in temporal and spectral domains. This exercise allowed students to learn about sensors (i.e., microphone), real time data acquisition, and the difference between temporal and spectral domains.

The modification and streamlining of ME 335/L course will help the students to understand the topics and experiments covered in ME 435/L in greater detail. The topics & experiments covered in ME 435/L that will directly benefit from these modifications are discussed in the next section.

**ME 435/L Mechatronics**

During the semester, mechatronics course covers multidisciplinary approach to system design where senior level students build projects bridging electromechanical systems; learn the microcontroller interface and understand communication with the outside world. The first few weeks of the course implements the synthesis of mechanism, electrical circuits, integrated circuits, sensors, motors, and signal processing. The later half of the curriculum introduces prototyping circuit boards, microcontroller programming, sensor calibration, motor speed control, energy transfer mechanism and lastly, designing, building, and training an interactive robotic system.

The students first taking ME 335/L course and passing with C or better grade before taking ME 435/L, were ready with the foundation of instrumentation that is very important for mechatronics.
system design. The current ME 435/L mechatronics course focuses on the following specific learning objectives in addition to the ABET outcomes mentioned previously:

- Integrate the interdisciplinary knowledge of mechanical systems, electronics and computer science
- Understand general principles with computer controlled machinery
- Demonstrate the fundamentals of system modeling and approaches to control
- Undertake independent research to think creatively
- Effectively of approaches to the design process for mechatronics systems
- Function effectively working on teams.

Here is the list of mechatronics experiments that students’ gain hands-on experience during the semester:

- Experiment 1, 2, 3, and 4: Familiarize the student with electrical measurement devices and basic electronic components (resistor, capacitor, inductors, diodes, ICs, build fun circuits).
- Experiment 5: introduce the students to the main building block of modern electronic systems, i.e. the transistors, switches, timers, drivers, etc.
- Experiment 6: introduce the operational amplifier, filters, sensors, relays, motors (DC and stepper motors), signal processing.
- Experiment 7, 8, 9 and 10: introduce microprocessor based projects
- Class Project: small group project in which students build a microprocessor based system of their choice, requires oral presentation and report submission
- Experiment 11 and 12: robotic system and competition
- Final Project: participate in a group project where students build a mechatronics system of their choice to demonstrate the acquired knowledge, requires oral presentation and final report submission.

Evaluation of topics

The theory portion of mechatronics course which is 2 units, covers topics such as electrical and electronics circuit review, system response, digital circuits, microcontroller programming, data acquisition, sensors, and actuators. The laboratory portion, which is 1 unit, covers experiments on the topics covered in class to the most part. The theory portion of instrumentation course covers topics such as: measurement systems, experimental design, probability, uncertainty analysis and propagation, system behavior and Fourier transform which are important foundation topics for mechatronics course. The challenges with the experiments in ME 435/L are, the students’ work with electrical and mechanical components and to read the signals which carries disturbances, that is not taught in theory. There are some topics we can cover in theory and there are some extra concepts we learn only from experiments. Having this big gap bridging the theory and projects, we identified that basic instrumentation concepts are very critical for mechatronics projects. Students had trouble understanding the accuracy of the signal and that it needs to be filtered. Reading sensor signals, real time data acquisition, understanding sampling frequency, characterizing the components and removing the noise, were a part of the experiments in ME
The fundamental topics were covered in ME 335/L course, which made it easy on students as they were seeing it for the second time. The programming part was another challenge, as students took programming course many semesters back and did not use coding in other courses. ME 335/L course reinforced programming using Labview and Matlab software which is used again in ME 435/L course. The coding experience with respect to instrumentation, measuring signals and processing the information for control techniques were very important for student learning. Overall, students used the similar programming tool, in two semesters and application to similar experiments with different complexities.

Figures 4 and 5 show the course outline and highlight synergy between ME335/L and ME435/L. For ME335 topics shown in figure 4 are new additional exercise and these new exercises will help students to understand the topics covered in ME435. Figure 4, shows three new exercise in ME335/L that has been added, these exercise highlight the fundamental principles like concept of normal distribution, importance of sampling frequency, and application of Fourier transform. Exposure to these topics along with detailed introduction to Labview programming in ME335/L will aid students to grasp the concepts and fundamentals in mechatronics (ME435/L). These additions in ME335/L provide a prior understanding of measurement systems, types of errors, signal sampling, data acquisition, and Fourier transform. The six new exercises in figures 4 and 5 show addition and modification done in ME435/L prior to focusing mostly on electrical experiments. The additional mechatronics projects with electromechanical design and analysis,
emphasizing in signal processing and conditioning gives students’ better hands-on experience as the fundamentals are covered in ME335/L. The assessment plan, which is discussed in the next section, will help both the faculty tune the curriculum even further.

**Assessment**

All the experiments cover basics of mechatronics system design, collect data and analyze, emphasize on programming and microprocessor control at different levels. From building a simple interactive calculator, to building an automatic water conservation system to robotics design, students focus on system integration and implementation. Students gain tremendous amount of instrumentation design, debugging, coding and mechanical design experience out of these experiments. Using guidelines of ABET criteria, the design and analysis rubrics developed examines the following elements:

- Complexity of the problem
- The design process
- Use of the modern tools and techniques
- Quality of the design solution and performance

The described elements are discussed and reviewed with students for grading purposes. During the semester, the students design two projects of their choice and they are required to follow the problem analysis rubrics which examines the following elements:

- Background concept
- Identification and formulation of the problem
• Technical design and analysis
• Sustainability
• Conclusion

The rubrics used for assessment purposes are given in table 1\(^1\) (APPENDIX). Assessing the rubrics and its effectiveness is still undergoing some modifications. But the goal of this common learning outcomes for ME 335/L and ME 435/L is to ensure that we continue the similar rubrics and students realize that the software, and fundamentals that they learn are actually implementable into product testing and development. Along with assessing the design and problem solving skills, we also use teamwork rubrics to ensure participation of the team members. The teamwork rubric used has the following elements with columns to rate yourself and your team members:

• Individual contribution
• Problem solving collaboration
• Punctuality
• Communication among team members

The projects had oral and written presentation components, therefore communication rubric that we use has five different assessment levels for each selected elements as shown in table 2\(^6\) (APPENDIX) The instructor has a choice to modify the rubric depending on its particular deliverable, for example either oral presentation or written report.

**In-class Survey**
As we make the changes to both of our curriculums, it is very important that we incorporate the comments from the student experience. Here are the questions that is used to evaluate the student experience:

1. Did the technical concepts taught in ME 335/L prepare for ME 435/L?
2. Did the projects improve your technical skills in
   a. Modeling dynamic system
   b. Analyzing time response of dynamic system
   c. Analyzing frequency response of dynamic systems
   d. Designing a mechanical systems with sensor integration
   e. Designing a mechatronic system with microcontroller integration

**Conclusion and future plan**
In spite of the changes made to both the curriculums, we still feel there is room to incorporate more changes. Using rubrics for the project assessment helps the students and the instructor to follow the same expectations for both laboratory portions of the courses. Implementing the same rubrics in two semesters gives students training in problem solving while working in team environment. Goal of creating a common set of rubrics not only helps with outcome assessment but also encourages reflection in the curriculum to make positive enhancements. Inclusion of
ethics discussion is important as students manipulate data and understanding the representation is critical. As we continue with our assessment plan for at least one academic year, we will certainly identify several areas of improvement to modify the course even further. The investigators plan on continual refinement of the curriculums to match as closely as possible to students learning expectations.

References
## APPENDIX

Table 1. Problem solving rubric

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1 - No Demonstration</th>
<th>2 - Attempted Demonstration</th>
<th>3 - Partial Demonstration</th>
<th>4 - Proficient Demonstration</th>
<th>5 - Sophisticated Demonstration</th>
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</thead>
<tbody>
<tr>
<td>Identification of Problem</td>
<td>No attempt to identify a problem</td>
<td>Poses a question for inquiry</td>
<td>Formulates a question with a plan for inquiry that identifies skills, knowledge, people, tools, or other resources associated with the solution</td>
<td>Formulates a question with a plan for inquiry that details the skills, knowledge, people, tools, and other resources needed to answer the question</td>
<td>Formulates a compelling question with a plan for inquiry that details the skills, knowledge, people, tools, and other resources from two or more disciplinary perspectives</td>
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<tr>
<td>Data Collection</td>
<td>No attempt to record data</td>
<td>Records and/or references observations, concepts, or details from primary or secondary sources</td>
<td>Records, interprets, and/or references observations, concepts, and details from primary and secondary sources</td>
<td>Applies standards to properly record, interpret, and reference relevant observations, concepts, and details from primary and secondary sources</td>
<td>Consistently applies high standards to properly record, interpret, and reference relevant observations, concepts, and details from primary and secondary</td>
</tr>
<tr>
<td>Representing Data</td>
<td>No attempt to represent data</td>
<td>Data is poorly represented in written or graphic form</td>
<td>Data is represented in written or graphic form using technical terms</td>
<td>Data is represented in written or graphic form using appropriate technical terms appropriate to the field</td>
<td>Data across a variety of disciplines is synthesized in written or graphic form using appropriate technical terms appropriate to the field</td>
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<tr>
<td>Verify and evaluate information</td>
<td>Makes no attempt to evaluate resources or data</td>
<td>Attempts to evaluate some resources but draws no reasonable conclusions</td>
<td>Evaluates some resources and data OR evaluates data and resources but draws incomplete or inaccurate conclusions</td>
<td>Evaluates resources and data accurately, considering credibility of sources, verification of findings, and reasonableness</td>
<td>Evaluates and verifies resources and data by generating original data to compare with others’ findings OR by locating additional primary sources</td>
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<tr>
<td>Draw conclusions and make appropriate applications</td>
<td>Makes no attempt to draw conclusions or make appropriate applications</td>
<td>Attempts to draw conclusions from research or data analysis but they are inaccurate or irrelevant to the project</td>
<td>Draws some conclusions that are inaccurate or irrelevant to the project and/or uses some of the information appropriately in planning and carrying out activities</td>
<td>Draws accurate conclusions that are relevant to the project from research or data analysis AND uses the information appropriately in planning and carrying out activities</td>
<td>Draws accurate, relevant conclusions from research or data analysis and uses the information to justify and applies them in a sophisticated manner.</td>
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<tr>
<td>Assessment Level</td>
<td>Outstanding</td>
<td>Satisfactory</td>
<td>Unsatisfactory</td>
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<td><strong>Written Mechanics</strong></td>
<td>Production quality that is compelling and engaging.</td>
<td>Acceptable production quality: accurate spelling and grammar; appropriate choice of fonts and colors; appropriate use of language.</td>
<td>Marginal production quality: minor errors of spelling and grammar; some noticeable defects in the layout or design.</td>
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<td><strong>Oral Performance</strong></td>
<td>Commands the attention of the audience throughout.</td>
<td>Professional tone and body language; clear, oral presentation enhances the audience's understanding of the work being presented.</td>
<td>Unprepared; inaudible; nervous habits may be distracting; unable to answer reasonable questions.</td>
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<td><strong>Graphical Representations</strong></td>
<td>Compelling and engaging; pictures worth “a thousand words”.</td>
<td>Professional use of figures, tables, and images that complement the written/oral components: properly labeled, plotted, sized.</td>
<td>Distracting, confusing, or inappropriate graphics that detract from the written or oral content.</td>
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<td><strong>Organization and Clarity</strong></td>
<td>Leads audience towards scientific and technical insight.</td>
<td>Professional layout and organization: appropriate division of sections, logical order helps audience understand problem and resolution in time/space limits.</td>
<td>Information is disorganized making it difficult for audience to understand the content.</td>
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<tr>
<td><strong>Content</strong></td>
<td>Complete and inspiring technical story from start to finish.</td>
<td>Professional-level of content: appropriate audience; complete, accurate, appropriately-stated recommendations and conclusions; citations and references are accurately and properly included.</td>
<td>Expected content is sparse or missing; and/or proper citations of sources are missing.</td>
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Table 2. Communication Rubric

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