2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39288

Board 36: Case Study: Sequential Development of Sensing Skills in a Civil and Environmental Engineering Curriculum

Dr. Sarah Jane Christian P.E., Carnegie Mellon University

Sarah Christian serves as an Associate Teaching Professor in the Department of Civil and Environmental Engineering at Carnegie Mellon University. She is interested in curricular innovation including integrating applications of emerging technology into projects and laboratory experiences, project-based learning, curricular content threading, methods for instilling teamwork skills, and implementing pedagogical methods that help students to make sense of difficult technical content. Sarah earned her BS in Civil Engineering at Carnegie Mellon University in 2003, MCE at Johns Hopkins University in 2004, and PhD at Stanford University in 2009.

Dr. Fethiye Ozis, Carnegie Mellon University

Dr. Fethiye Ozis is an Assistant Teaching Professor in the civil and environmental engineering department at Carnegie Mellon University. Dr. Ozis holds a B.S. in environmental engineering from the Middle East Technical University, Ankara, Turkey and M.S. and Ph.D. degrees from the University of Southern California. Dr. Ozis is a licensed Professional Engineer, Environmental, in Arizona. Before joining CMU, Dr. Ozis was a faculty member at Northern Arizona University.

Katherine Ann Flanigan
Joe Dallas Moore, Carnegie Mellon University

Joe teaches across the environmental engineering program at Carnegie Mellon University. He first taught high school science through Teach For America in Chicago Public Schools. He later earned his PhD in Civil and Environmental Engineering from Carnegie M

Prof. Gerald J. Wang, Carnegie Mellon University

Jerry Wang is an Assistant Professor of Civil and Environmental Engineering, and Mechanical Engineering and Chemical Engineering (by courtesy), at Carnegie Mellon University. He received his BS in 2013 from Yale University (Mechanical Engineering and Math

Case Study: Sequential Development of Sensing Skills in a Civil and Environmental Engineering Curriculum

Abstract

The burgeoning use of technology and sensing within civil and environmental engineering (CEE) applications has created a need for future engineers to gain skills and understanding in the effective use of sensing and interpretation of massive amounts of data to understand and improve infrastructure. In response to these changes, our faculty have been defining learning outcomes necessary to prepare students to be successful engineers in this new era in CEE engineering practice. The faculty have added two laboratory courses focused on sensing and additional computation and data science courses focused specifically on CEE applications. Sensing has been incorporated into projects in our project-course sequence. Finally, we have developed and continue to adapt a threading document that maps how our students gain the desired sensing knowledge and skills through our curriculum.

Through vertically-scaffolded, sequential courses, our department aims to produce graduates who can effectively design sensing systems for different applications and environments, interpret large quantities of data, and use that data to control infrastructure systems and enhance management strategies. The courses are structured sequentially so that students gain greater autonomy over testbed selection and sensor choice as they gain skills and knowledge. These skills are first activated in the second-year-level design course where students dive into a CEE domain-specific application, learn how sensors are an electrical manifestation of a physical property, collect data subject to context-specific constraints, and infer desired outputs from data collected using an Arduino-based data acquisition system. After this initial exposure, second-years develop a deeper understanding of the physical principles of sensors, analyze sensor data, construct their own sensors, and develop code to control a small-scale infrastructure sensing system in a hands-on laboratory environment. In their junior-level design course, students design, construct, and implement a sensing system to collect data that is interpreted to aid in infrastructure decision making. In their final sensing laboratory course, field-based CEE problems are posed that require students to deploy appropriate off-the-shelf sensing hardware to collect data that is used for analysis of the problem.

Our sensing thread and courses are still in development and will continue to evolve as we better understand how students best learn these skills and refine our understanding of the key learning objectives. This case study presents the current learning objectives in our sensing thread, describes how we are teaching sensing through hands-on activities, and shares observations on the effectiveness of our efforts, challenges we are encountering, and guidance for integrating sensing into civil and environmental engineering curricula at other institutions.

Motivation and background

The future of civil and environmental engineering (CEE) requires the ability to adapt infrastructure to changing demands. Intelligent application of sensors will allow civil engineers to improve the performance of infrastructure by automatically measuring real-time responses and interpreting the data to control the systems. Although sensing technologies now proliferate in CEE practice, few undergraduate CEE curricula prepare graduates to work with sensors [1]. Experts in civil engineering information technology and computing have long emphasized the importance of incorporating sensing into CEE curricula (e.g., [2]-[6]). The 2019 ASCE Civil Engineering Education Summit highlighted the need for academic programs to provide education on emerging technologies in CEE [7].

At present, the literature on sensing education in the CEE context is sparse, despite a growing consensus that CEE graduates should be able to engineer intelligent systems, which are augmenting (or even replacing) more traditional approaches. While some curricula introduce sensing in CEE through presentations of specific end-use applications, others have incorporated sensing into experiments in core CEE lab classes [1],[8] or added sensors for CEE applications to existing circuits and electronics lab classes [9],[10]. Hernandez *et al.* [8] incorporated microcontroller-based sensors (e.g., Hall-effect flow sensors) into traditional fluid mechanics labs. Read-Daily and Batista Abreu [13] deployed a multi-week problem solving activity for first-year engineering students based on energy efficiency assessment of windows using temperature sensors. Others yet have incorporated sensing into upper-level elective courses like structural health monitoring and wireless networks [11],[12]. Dickrell and Virguez [16] describe the use of Tinkercad as a computational model of an Arduino-based microelectronic sensing and actuating system where the wiring and code needed to control sensors and actuators of the physical system was developed for a one-week-long, first-year, multidisciplinary engineering project. Jovanovic et al. (2020) [17] implemented a three-hour-long sensing and measurement activity for high school students to draw their interest towards engineering technology. The targeted technical skills included environmental sensing in addition to electrical circuits, electrical prototyping, microcontroller-based design, and the Internet of Things.

Moreover, there are clear pedagogical challenges in this space. For example, in [8], student surveys showed that although students developed comfort with the *use* of sensors, they did not build or program their own microcontroller-based sensors, and most responded that they would not feel comfortable doing so. Intriguingly, Ohland and Stephan [14] found that using real-time sensors to provide students with immediate feedback for hands-on lab activities did not improve learning compared to labs conducted without electronic sensors.

Fusing sensing to our curriculum

Driven by the trends discussed above, comments from our Alumni Advisory Board that engineers lack facility with the massive amounts of data now being collected in industry, and a practical need to refresh our lab course offerings – and leveraging our faculty's expertise in the area – the undergraduate curriculum at Carnegie Mellon University has undergone numerous changes to increase the focus both on sensing and on computational science. Sensing forms a backbone for our design course sequence: It has been incorporated into a project in our third-year design course since 2015 and our second-year design course since 2021. In 2018, our Undergraduate Program Committee defined key learning objectives for sensing and recommended that lab courses focus on sensing and instrumentation. These changes were adopted by the faculty in 2020 and approved by the university soon thereafter.

The sensing thread

The new sequence includes a holdover fluid mechanics lab and three new courses that prioritize practical, hands-on experiences, with a focus on the inquiry process, sensing, and data analysis. By centering the principles of self-efficacy and knowledge transferability, we aspire for our students to apply these skills to solve cross-cutting problems. These courses also explicitly acknowledge underlying shifts in CEE practice that demand an understanding of sensing and computing. The three courses are: (1) CEE Infrastructure in Action: a second year fall course focused on local excursions to learn about CEE applications in our community; (2) Sensing and Data Acquisition for Engineering Systems; and (3) Experimental & Sensing Systems Design and Computation for Infrastructure Systems, which together form a mini-sequence focused on the use of sensing to collect data related to a breadth of CEE topics, including mechanics, materials, and environmental engineering.

At the heart of our curriculum redesign efforts was a threading document that explicitly charted how students would build sensing skills throughout our curriculum. This thread was used to design new sensing lab courses and to fine-tune scaffolded learning between the lab and project courses. We identified four main learning objectives (LOs) related to sensing:

- LO 1: Describe the physical principles of sensors and analyze their dynamic behavior using principles of classical mechanics and first year physics, including the origins of uncertainty in measurements.
- LO 2: Determine and analyze the communication, power, social and privacy/security requirements and constraints of a given sensing solution.
- LO 3: Proficiently evaluate alternative technologies for acquiring digital measurements of physical phenomena relevant to Civil and Environmental Engineering problems.
- LO 4: Design, configure, and assemble a sensing solution for a physical system (i.e., a cyber-physical system) using off-the-shelf hardware.

After we developed the main LOs, we mapped the progression of learning across the design and lab courses that incorporate sensing, and developed individual courses with their respective LOs (Table 1). The courses in the sequence include two project courses and two lab courses. Enrollment is 25-50 students and 15-35 students for the design and lab courses, respectively.

Second year fall (design): Students are challenged to solve complex, open-ended problems related to both conventional and emerging issues in CEE learning the design process by working through short assignments and design projects. The goal of one of the course projects is to

Table 1: Core learning objectives for each course in the sequence

Course	Sequence	LO 1	LO 2	LO 3	LO 4
Design Course	Second Year Fall	Design a weight scale: Build a circuit that converts change in resistivity in a strain gauge to voltage. Use a data acquisition system to measure voltage and convert it to strain. Estimate weight at end of cantilever beam using measured strain.	Describe the role of sensing, computing, and data acquisition through the context of structural health monitoring (SHM) and describe power, communication, and social/privacy constraints for a range of CEE applications.		
Sensing Lab	Second Year Spring	Evaluate different sensing solutions using tool specifications/characteristics and explain how a range of sensors work.	Compare performance of simple measuring tools with advanced sensors with respect to the measurement needs.	Describe the behavior of a range of sensors and construct sensing systems.	
Design Course	Third Year Fall	Construct a sensing system that considers the constraints of the system and the environmental conditions	Describe benefits of different sensing technologies, e.g., accuracy and privacy sensitivity.	Test sensing systems to confirm that data collected aligns with the goals	
Sensing Lab	Third Year Spring	Design and implement a testing protocol for sensors the account for sensor characteristics including uncertainty/error and other limitations	Evaluate privacy and security requirements as well as power and wifi access when designing a testing plan and deploying a system of sensors.	Compare a range of sensing systems for collecting data in specific conditions and calibrate sensors within the system for consistency between sensors.	Design the use of a system of sensors to collect desired data, deploy the system, and collect and analyze data.

introduce students to sensing, computing, and data acquisition in the context of a CEE domain-specific application, namely, structural health monitoring (SHM). Through this project students begin to build their knowledge with respect to LO1 and LO2. Given the backdrop of SHM, students are tasked with creating, calibrating, and validating a simplified SHM design in the form of a weighing scale constructed from a cantilever beam and electronic components. Students learn to motivate the need for sensing in CEE applications (i.e., how can we improve the performance of existing CEE systems through the integration of sensing, data acquisition, and computing), establish performance metrics, measure performance, contextualize data, and communicate data-driven results. This is realized as (1) learning how to build a Wheatstone Bridge circuit used to measure strain (i.e., establish electrical manifestation of a physical property), (2) collecting data using an Aruduino (subject to context-specific constraints), (3) relating their data to their mechanics knowledge by inferring load from measured strain, and (4) communicating their results. By introducing students to interdisciplinary concepts in the context of a practical application area (i.e., SHM), students connect their growing mechanics and physics-based domain knowledge with more advanced computing and sensing concepts.

Second year spring (lab): Students build familiarity with methods for collecting, analyzing, visualizing, and acting upon data. Through a series of lab-based and systems-level studies and workshops, students learn how to select and use a range of measuring tools (including simple hand tools and more advanced sensors) to collect data, methods to filter and analyze data, and schemes for real-time control using data. Through interactive workshops and experiments, students learn the fundamental physics that governs the behavior of sensors. Examples of measurement tasks include measuring the load and deformation in metal and wood loaded in tension and flexure using a load cell, an extensometer, and an LVDT; constructing an Arduino-based sensing system to measure pressure and temperature throughout a building; and identifying the presence of toy cars at a model intersection using Hall-effect sensors and photoresistors. Visualizations (e.g., stress-strain curves or contour maps of pressure) were produced in computational environments including MATLAB and Excel, reinforcing computing skills developed throughout our curriculum. In the traffic intersection project, sensors were used to count cars queuing at and passing through signals and to control traffic signals in real time.

Third year fall (design): Students continue building design skills through increasingly complex projects that account for ethical, social, and economic constraints and the impact of diverse stakeholders, community engagement, and sustainability. One of the projects challenges students to design a sensing system that can gather data to support decision-making in a CEE setting. For the past two years, a smart-cities-inspired project has been used to gather sensing data and provide recommendations for managing campus resources. Students have studied the use of different hallways to access our department, when the university's health services offices are most visited, and connections between bathroom utilization patterns and gender identity. To do this, teams design and construct privacy-preserving sensing systems to detect the number and velocity of pedestrians using Arduino-microcontrollers and IR sensors. They conduct tests to ensure that their system accurately collected data at their chosen location. Finally, they analyze and interpret the data to recommend changes to relevant resources or infrastructure management.

Third year spring (lab): In the first half of the course, teams of students are given freedom to identify a problem of collective interest. Each team is given a geographical boundary on campus where they may deploy sensors. Students present their plans to the University Engineer, who works with them to install their sensors around campus. This experience is eye-opening for many students, who learn about practical infrastructure management challenges (e.g., many electrical outlets do not work, some locations have inconsistent access to Wi-Fi, devices may be damaged or unplugged). After approximately a month of data collection, they analyze the data, share their findings with the University Engineer, and recommend if and how the data should be shared with the campus community. As one of many examples, students have collected air quality data around campus to inform recommendations to the campus community on days the air quality is poor. In the second half of the course, students use IR cameras to assess the thermal performance of the envelope for a campus building. Data is used to validate simple heat-transfer models, to identify thermal bridges, or to identify locations of air leaks. Emphasis is placed on systematic and aleatoric uncertainties associated with these measurements. All projects conclude with a focus on communicating results for both technical and lay audiences.

Observed outcomes, future work, and recommendations

Qualitatively, students have been achieving our designated LOs, developing facility with the physical principles of sensing, ability to select or develop sensing systems and deployment plans, comfort with manipulating and analyzing large datasets, and skill in communicating their findings. One structural challenge for our department is that Civil Engineering (CE) students take the entire sensing sequence, while students majoring in Environmental Engineering (EE) only take the design courses. In the third-year design course, differences between CE and EE students are conspicuous: CE students are more comfortable with both the sensing systems themselves and the data analysis required to make sense of the attendant data. As a result, CE students tend to play an outsize role in their groups' sensing project. We intend to collect data to quantify these differences and eventually mitigate this disparity in future cohorts.

Since we are only beginning to offer these courses, we are still measuring the achievement for the LOs and listening to student feedback. This information will be used to determine how our courses and threading will adapt over time. An area of particular interest and ongoing study is how the new curriculum affects student assimilation and retention of knowledge in their core mechanics, materials, and environmental engineering courses.

To make it easier for faculty to incorporate sensing into their courses, it is recommended that they gradually introduce projects and labs into their existing courses over a few years. This will help distribute the workload of developing new expertise and course content. Arduinos and sensors are low-cost and reusable. Moreover, online documentation makes it easy to learn how to construct and program these systems.

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