Design of a Laboratory to Teach Design of Experiments

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Abstract

A capstone mechanical engineering laboratory course is being revised in order to develop a student's ability to confidently design and conduct experiments involving complex thermo-mechanical systems. This paper and the associated presentation describe the laboratory experiences that are being implemented to develop this ability. The approach includes an integrated series of experiments on a racecar. The amount of student design of experiments increases with each laboratory experiment in the series. The course culminates in a true "open ended" design of an experiment.

Background

The Mechanical Engineering program at the University of South Carolina includes a capstone laboratory course titled "*Engineering Systems Laboratory*." A major objective of this laboratory is for the students to gain the ability to design experiments on complex mechanical engineering systems. "Design of experiments" in the sense used here describes the process of identifying the important parameters associated with a complex thermo-mechanical system; selecting sensors appropriate to the measurement of these parameters; designing tests of the system in which these parameters are measured and recorded, and finally evaluating the system performance by analyzing the data collected. The engineering education literature contains numerous references to methods for teaching statistical design of experiments in the [1, 2, 3]. However, teaching methods and educational materials that enable mechanical engineering students to develop true "design of experiments skills" are not presently available.

A project is underway to demonstrate that the *Engineering Systems Laboratory* develops the students' ability to confidently design and conduct experiments involving complex thermo-mechanical systems. The laboratory also develops their understanding of mechanical engineering systems and gives them experience in applying computer-based instrumentation to study system performance, exercising their life learning skills, documenting their results in writing, and making oral technical presentations. The course is based upon an integrated sequence of laboratory experiments on an automobile and its subsystems. The automobile is chosen as the system to study because it is compact, relatively inexpensive and in the direct realm of experience of most students. More importantly, its many complex subsystems provide opportunities for the students to apply the spectrum of their mechanical engineering knowledge, including the principles of mechanics, dynamics, thermodynamics, heat transfer, and controls.

The project described herein is an extension of work being performed with the support from the NSF DUE ILI Program. The goal of the ILI project (NSF 98-50749 "A Vehicle for Delivering a Mechanical Systems Laboratory Experience") is to procure all of the equipment and instrumentation needed for a capstone mechanical engineering systems laboratory course. The ILI project has been previously described [4] , so only a brief review is given here.

In developing the *Engineering Systems Laboratory,* careful consideration was given to selecting an appropriate system for the student experiments. It is not desirable or even possible to attempt to expose students to every type of system that they might work with throughout their professional career. In designing the systems lab, one must select a few systems for the students to investigate in detail. The selected systems must provide opportunities for the students to apply the spectrum of their mechanical engineering knowledge, including the principles of mechanics, dynamics, thermodynamics, and heat transfer. This laboratory course is being implemented at the University of South Carolina using a Legends racecar similar to the one shown in Figure 1. The Inter-Collegiate Association for Racing (ICAR), an academic motorsport involving engineering colleges throughout the country, currently races these 5/8-scale replica vehicles. There are several reasons to use the Legends car:

- It is compact, yet it incorporates such a variety of subsystems that it involves almost all of the fundamental principles of mechanical engineering;
- For all its complexity, it is a relatively inexpensive system for study;
- It is in the realm of experience of all students, so they can easily relate to system performance criteria such as efficiency, handling and other factors affecting vehicle operation; and
- The students are excited experimenting with a car similar to the one raced in competition. Such enthusiasm can be a tremendous asset to any required course, particularly a laboratory course.

Figure 1. Legends car raced by USC's ICAR Engineering Team

An important aspect of the laboratory design is the use of remote wireless telemetry equipment, which allows the entire lab section to control and monitor the experiments while the car is driven. Other equipment being procured through the ILI grant is listed in Table 1. It should be noted that because the instrumentation is of general purpose, the experiments can be modified from semester-to-semester to keep them from getting "stale."

Literature Guiding This Laboratory's Development

Constructivist learning theory asserts that knowledge is not simply transmitted from teacher to student, but is actively constructed by the mind of the learner through experiences [5, 6]. Founded in developmental psychology, constructivism suggests: (a) the learner should be an active organism within the environment, not just responding to stimuli, but engaging and seeking to make sense of things; (b) knowledge is best generated internally, not absorbed from an external source; and (c) the motivation for learning should be intrinsic. To facilitate such learning by discovery, the teacher and instructional environment must allow repeated, prolonged experiences with the materials and events associated with the topic to be learned.

Table 1. Major Equipment and Instrumentation Being Procured For This Project through the Support of the NSF ILI Program.

Item Description	Vendor Information
Test Vehicle	Racing 600 Legends-Class
Data Acquisition Hardware and Software	Somat 2100 System
Telemetry System	Somat Freewave
Test Control and Monitoring Notebook Computer	Gateway Solo 2500
Chassis Dynamometer	Dynojet Research
Tilt Table	USC construction
Global Positioning System (GPS)	Magellan
3-Axis Accelerometer Systems	PCB Peizotronics
Torque Telemetry System for Rotating Shafts	Rotating Measurement Systems
Load Washers, Load Bolts, and Strain Gages	Omega
DC-DC Conditioned LVDT with Amplifiers	Sensotec
Portable Exhaust Gas Analyzer	Horiba HEXA
Rotation Speed Encoders with In-line Amps	AIM Sportsystems
External/Internal Air Flow Pressure Array	Modus
Liquid Micro Flow Sensors for Gasoline and Oil	Max Machinery
Infrared Pyrometer Sensor Kit	Omega

Another important concept from constructivism is that of *scaffolding,* which is the process of guiding the learner from what is presently known to what is to be known. Scaffolding allows students to perform tasks that would normally be slightly beyond their ability without that assistance and guidance from the teacher. Appropriate support from the teacher and the instructional materials can allow students to function at the cutting edge of their individual development. The engineering education literature contains descriptions of a number of courses where student knowledge is gained through a scaffolding process [7, 8, 9, 10, 11, 12]. For example, in Simon's paper *What We Know About Learning* [12], it is noted that one of the most powerful ways for learning is for the student to be given worked-out examples, i.e., problem solutions shown worked out step-by-step. This process is akin to learning by doing. As Simon states further, "…you are allowing the student to solve a series of sub-problems, step-by-step." If the sub-problems are designed properly, solution of these sub-problems by the student should culminate in the student being capable of solving the larger problem.

Design Of The Laboratory Course Materials

To accomplish the objective of developing the ability to confidently design and conduct an experiment, a series of activities are designed that will bring the student through the various learning experiences needed to establish a level of competence in the design of experiments. A constructivist or "learning by example" approach is followed to develop the students' competencies in designing experiments; specifically, a series of "learning modules" are being developed, used and evaluated. Upon successful completion of the learning modules, the students are presented with an "open-ended" problem that requires that they design an experiment that involves the entire system. The content of the learning modules and student-designed experiment modules is described in the following sections.

Learning Modules. The learning modules draw upon what the student has learned in related course work and introduces the student to a particular set of problems that arise in designing experiments. They require that the student use external sources such as the library or Internet to collect information pertinent to solution of the problems posed. Each module consists of an example experiment where the student is required to install existing instrumentation and a data collection system and then to perform measurements on a sub-system. In each module the student will learn through example what factors are important in sensor selection, how to integrate the sensor into a data collection system, how to calibrate the sensor-data collection system and finally how to reduce the data obtained. The student then operates the system in a prescribed manner in order to exercise the measurement-data collection system and thus obtain data on the particular sub-system. As the student progresses from module to module, he/she should, in addition to learning the principles in designing an experiment, develop an understanding of the various sub-systems, how required parameters are measured and how these measurements are used to evaluate sub-system performance. The approach for implementing these modules includes a two-week cycle of: (a) Designing part of the experiment and then performing it during the first week; and (b) Presenting written and oral reports on the results in the second week. The experimental design process taught in these first labs will involve selecting sensors to use from those installed or easily attached to the racecar, as well as applying statistical DOE methods to determine the operating conditions for investigation.

The modules are the individual steps in the step-by-step learning process. The *Engineering Systems Laboratory*'s design includes four modules: Telemetry and Data Acquisition, Engine Performance, Vehicle Performance, and Vehicle Dynamics. Each learning module consists of three elements: Module Description, Material to Student, and Lectures. The content of the Module Description element involves the purpose and overview of the experiment. The Material to Student element includes specific information that needs to be provided to the student for that experiment. The Lectures section includes the material to be covered in the lectures lecture outlines and source material for the instructor. As an example, the three elements for the *Telemetry and Data Acquisition Learning Module* (Module 1) include the following:

- *Module Description Element.* Learning Module 1 introduces the student to the data acquisition and telemetry system. This includes the sub-system installed in the vehicle and the home station. In this module the student will learn how to calibrate the data acquisition system, how to install sensors and how to reduce data obtained through the data acquisition and telemetry system. Temperature and pressure sensors are installed in various positions within the vehicle and the output routed to the master on-board computer. Input from the sensors is used to exercise the complete data acquisition system.

- *Material to Student Element.* The student is provided with a Laboratory Manual that includes chapters relevant to the modules. The student is assigned reading from the Laboratory Manual pertaining to the specific module prior to reporting to the laboratory. Material including theory, experiment objectives and other guidance is also provided to the student in lecture form. Also, a library/internet research exercise that relates directly to the module is assigned to the student. Before reporting to the laboratory the student submits a report summarizing information collected through this exercise.

- *Lectures Element.* Three lectures are to be delivered prior to the student performing the Module 1 experiment. One lecture covers error and uncertainty in measurements and sensors used in the experiment, while the second lecture covers telemetry and data acquisition. A third lecture on safety is also included. All three lectures are general in nature and provide a foundation for performing experiments in the remaining modules, yet provide specific information for the Module 1 experiment.

Student-Designed Experiment Modules. The final five weeks of the semester are for the students to perform an "open-ended" experiment, which they have to design completely, conduct and report both verbally and in writing. The previous labs have to be organized to prepare the students for this "open-ended" lab, where the students will have to be completely familiar with the instrumentation available, the system itself (the race car), and the theory and concepts behind design of engineering experiments. These experiments can naturally vary from semester to semester, and problems identified by the ICAR racing team during practice or competitive events will be one source for ideas for this laboratory module.

For example, the students may be asked to determine what effects a steady-state turn has on the suspension and tires. The experiment they develop could consist of using a circular or oval track to study steady state cornering, quantified by lateral acceleration. Both lateral and front-to-back shifts in suspension could be measured as functions of lateral acceleration. Using wheel encoders, the difference in distance traveled by each wheel could be compared to theoretical predictions, and how this distance changes with cornering effort could be examined. The effects of cornering on tire temperature could be correlated with different turn radii and vehicle speeds. In this example, the students would estimate the lateral accelerations, suspension positions and forces, vehicle roll and pitch magnitudes and tire temperature. They would specify the types and operating ranges for the sensors needed to quantify these variables. With this appropriate experimental design justification, they would procure the needed sensors from those in the laboratory stockroom. Here, the sensors might include rotation speed encoders, load bolts, accelerometers, LVDTs, infrared pyrometers and a global positioning system. The experiences of the students and faculty involved in this final "open-ended" exercise will be fully documented and appropriately disseminated so that others who wish to adapt the proposed approach can themselves "learn by example."

Concluding Remarks

The *Engineering Systems Laboratory* course should do more than support upper-level mechanical engineering classes. Students should learn to approach and analyze engineering problems from a systems viewpoint, design experiments, apply computer-based instrumentation to study system performance, document their results in writing, and make technical presentations. By using a Legends car as the test system, such a course can channel the enthusiasm among students for the ICAR motor sport into a useful and productive educational experience. Further, the approach where students perform increasingly more complex experiments with the same system throughout a semester, and then culminates in an open-ended task, can be viewed a model for all engineering programs that seek to produce graduates who can design experiments.

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