On the ability to design engineering experiments

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ABSTRACT:
The US Accreditation Board for Engineering and Technology recently put a new spin on experimentation skills in engineering education. Specifically, outcome 3b of Engineering Criteria 2000 states that engineering graduates must have *"an ability to design and conduct experiments, as well as to analyze and interpret data"*. While the ability to conduct experiments, as well as the ability to analyze and interpret data has been addressed by traditional laboratory courses, the ability to design an experiment presents a new challenge for engineering educators and students alike. The paper first discusses inquiry-based learning, which forms the foundation for the design of any experiment. Subsequently, engineering experiments are classified in three broad categories and a general process for experimental design is presented. Finally, the paper presents examples of how this process is used to teach design of engineering experiments in three SJSU courses.

HISTORY

Engineers have always experimented on their way to creating various products. For example, Leonardo da Vinci, starting in 1483, spent a considerable amount of time and effort trying to prove the efficacy of human flight. His efforts included the design of two distinct devices for measuring wing lift. One of them was a balance mechanism [1], while the other is shown in figure 1 [2].

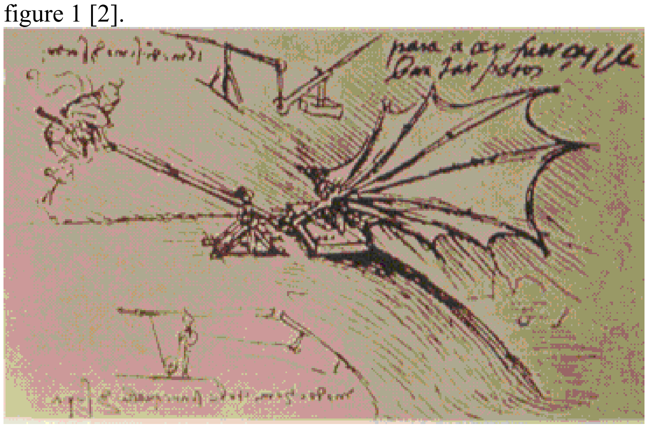


Figure 1. A device for measuring wing lift, designed by Leonardo da Vinci [2].

In 1804, Sir George Cayley, considered by many the inventor of the airplane, also designed and built experiments to study wing aerodynamics. Figure 2 shows a whirling-arm apparatus powered by a weighted cord dropped over a pulley and down a stairwell, that he used to measure the lift of various airfoils [3].

This quick overview of experimentation in engineering – and aeronautics in particular – would not be complete without a few words on the experimental research of the Wright brothers [1,3]. After a series of failures in 1901, attributed to the fact that the existing scientific data of their time was not very accurate, Wilbur and Orville designed and built a wind tunnel with a force balance (figure 3) and measured accurately lift and drag on more than 200 airfoils. Their experimental results led them to the proper design of the Flyer wing, the first successful powered, controlled, manned airplane.

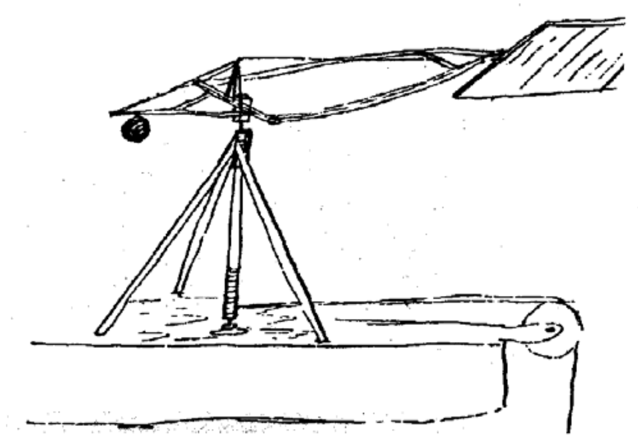


Figure 2. A whirling arm apparatus used by Sir George Cayley for measuring airfoil lift.

Moreover, unable to find a commercial engine suitable for their airplane, they resorted again to extensive experimentation. Their results showed them the way to the design of their own engine, which produced 12 hp and weighed only 200 lb. They could not even pick a propeller off the shelf, simply because all the existing propellers at the time were designed for marine applications and were obviously unfit for use on an airplane. One more time, they had to perform extensive experiments with different types of propellers before they were able to design an effective propeller for their airplane.

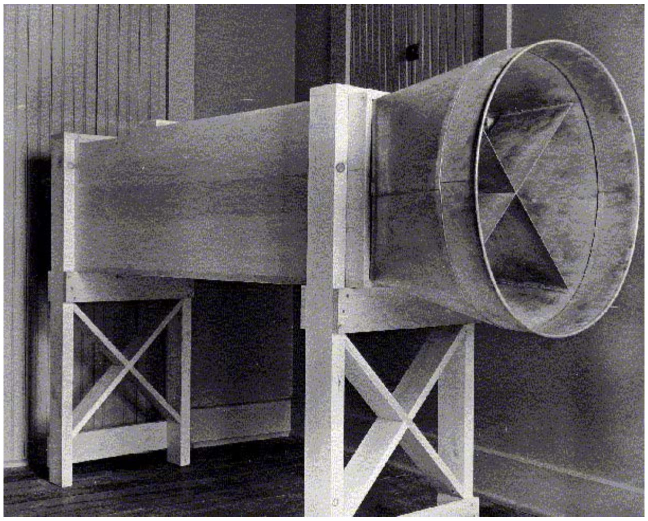


Figure 3. The Wright brothers wind tunnel, used to obtain their wing and airfoil data.

INQUIRY-BASED LEARNING AND THE PROCESS OF EXPERIMENTAL DESIGN

The inquiry continuum, adapted from reference [5] and shown in table 1, may be used as a tool to understand the process and the skills needed to design an engineering experiment. As we move from the left end of the continuum (demonstration / cookbook lab) towards the right (student-directed / student-designed inquiry), the responsibility for the various tasks outlined on the left column, gradually shifts from the professor to the student. This is a very important observation because research has shown that taking responsibility for one's own learning is one of eight conditions that must be satisfied in order to master a task or subject matter [6]. It is also a necessary condition for the development of students as lifelong learners. Hence, it must be understood that without an opportunity to take responsibility for the decisions about the various tasks of an experiment, students cannot master the process of experimental design.

Table 1. Inquiry Continuum

	Lecture / Demo	Cookbook Lab	Structured Lab	Challenge Lab	Student-Directed Inquiry	Student-Designed Inquiry
	Professor is doing science; students watch	Students confirms known result	Professor sets one procedure; students reach own conclusion based on evidence.	Professor poses the problem; students design / test solutions.	Professor selects topic; students pose questions.	Students select topic, identify problems, formulate questions, design & carry out experiments.
Scientific / Engineering Concept	Professor	Professor	Professor	Professor	Professor / Student	Student
Questions Posed	Professor	Professor	Professor	Professor	Professor / Student	Student
Equipment / Materials	Professor	Professor	Professor	Professor / Student	Student	Student
Design of Procedure	Professor	Professor	Professor	Professor / Student	Student	Student
Analysis of Results	Professor	Professor	Professor / Student	Student	Student	Student
Conclusions	Professor	Professor	Professor / Student	Student	Student	Student
Student Skills	Collect information.	Follow directions. Use lab equipment. Collect data.	Make inferences, draw conclusions from one set of data. Replicate results, (variability of results).	Design & test analytical & experimental solutions. Evaluate how well the design solves the problem. Confidence to put forth ideas. Draw conclusions from a range of results.	Pose the right questions. Develop own procedures.	Complete experimental design.
Cons	Little critical thinking. Concepts & processes not internalised.	Outcome is known. Does not model true scientific process.	Students are not involved in experimental design.	Students do not pose the questions.	Takes more time. Increased materials / equipment needs.	Takes more professor time to guide each student or team. Increased materials / equipment needs.

Engineers typically perform one of three types of experiments:

A. A theoretical relationship between two or more variables is already known (or at least suspected) and an experiment is needed to verify or quantify this relationship.
B. A theoretical relationship between two or more variables is not available but rather sought through an experiment.
C. A new product is being developed and a test is needed to confirm that it meets the design specifications, before committing it to production.

The first two types of experiments are shared between engineering and all science. The third type is unique to engineering.

Just like with the design of an engineering product, it is desirable to have a fairly general process that one can follow to design an experiment under any circumstances. This process can also serve as a tool for teaching students experimental design. An attempt to create such a process is shown below:

1. Define the goals and objectives of the experiment. While the goal may be general, the objectives need to be more specific and measurable, directly or indirectly.
2. Research any relevant theory and previously published data from similar experiments. Performing computer simulations may also be part of this research, assuming that appropriate software is available. The purpose of this step is to have an idea about what to expect from the experiment.
3. Select the dependent and independent variable(s) to be measured.
4. Select appropriate methods for measuring these variables.
5. Choose appropriate equipment and instrumentation.
6. Select the proper range of the independent variable(s).
7. Determine an appropriate number of data points needed for each type of measurement.

For experiments in the third category (new product) the last step may be replaced by some kind of evaluation (see ME106).

Naturally, additional skills are needed to meet the other three components of outcome 3b. For example, to conduct an experiment, an engineer should be able to:

1. Familiarize himself / herself with the equipment.
2. Calibrate the instruments to be used.
3. Follow the proper procedure to collect the data and / or measure the performance of the product.

To analyze a set of experimental data an engineer should be able to:

1. Carry out the necessary calculations.
2. Perform an error analysis.
3. Tabulate and plot the results using appropriate choice of variables and software.

Finally, to interpret the data an engineer should be able to:

1. Make observations and draw conclusions regarding the variation of the parameters involved.
2. Compare with predictions from theory or design calculations and explain any discrepancies.

The following sections provide three examples of how mechanical and aerospace engineering students at SJSU are taught experimental design.

ME120 EXPERIMENTAL METHODS IN MECHANICAL AND AEROSPACE ENGINEERING

ME 120 is a senior-level, lecture-lab course (1 hr lecture, 3 hrs lab per week) that is required for all mechanical engineering and aerospace engineering majors [7]. The goals of the course are to help students:

- Understand modern engineering experimentation including experiment design, system calibration, data acquisition, analysis and presentation
- Develop and apply an understanding of statistical methods to select the best experimental approach to satisfy given requirements of accuracy.
- Understand how to quantify error and uncertainty in physical measurements.
- Understand how to apply statistical methods to the analysis and presentation of experimental results.
- Understand modern data acquisition concepts and requirements.
- Understand the various categories of mechanical measurements and the sensor technologies that they are based on.
- Gain hands-on experience with modern instrumentation and systems-level experimentation.
- Improve written and oral communication skills, develop the ability to write high quality engineering reports, and improve their ability to function as a member of an engineering team.

Our approach to educating students in ME 120 with regard to experimentation has evolved over the last three years since we began an effort to modernize the laboratory in 2001. Prior to 2001, there was little data acquisition using computer-based systems and all “experiments” were pre-defined measurement exercises. Since 2001, we have introduced a new set of experiments almost all of which are interfaced to personal computers with data acquisition hardware and software. We have also introduced more open-ended experiments including a term project, where the definition, execution, and documentation of an engineering experiment is left entirely up to the student (see student-designed inquiry in table 1). An example of one student’s term project from the Spring of 2004 is summarized below in light of the seven-point framework outlined above.

The experiment the student designed was to investigate the power output of a solar panel with a fixed orientation to that of a solar panel whose orientation tracked the sun [8]. He also tried to verify that the power output of a photovoltaic cell was a function of temperature.

1. <u>Define:</u> The goals and objectives for the experiment were to verify that:
   - A logarithmic relationship exists between angle of incidence of sunlight on a solar panel and power output
   - A tracking system increases power output by 20%
   - The power output of a solar cell is a function of temperature
2. <u>Research:</u> The student investigated various sources of information along the way of designing his experiment:
   - Internet and published sources
   - Interview with a solar energy system contractor
   - Interview with SJSU Environmental Studies Prof. Frank Schiavo, an expert on passive solar home design.

3. Select the independent / dependent variables: The key variables were identified to be:
   - Angle of orientation of solar panel (independent)
   - Output power of solar panel (dependent)
4. Select appropriate methods: The student chose a direct method for measuring the angle of the solar panel and measured voltage and current to determine power output of the solar panel.
5. Choose equipment and instrumentation: The student used a camera tripod, protractor, and plumb bob to orient and determine the angle of the solar panel for the fixed panel measurements, and a sundial rod to orient the panel normal to the sun's rays for the tracking measurements; a digital multimeter to measure current and voltage; and a thermometer to measure the temperature of the solar panel.
6. Select the range of the independent variable: The 55-degree range of motion that the tripod allowed, set the range for the angle of incidence. For the tracking measurements, the range of measurements took place from 6:45 am – 6:00 pm. The student was limited by the available resources for investigating the effect of temperature to that obtainable under ambient conditions and by cooling the solar panel using ice cubes.
7. Determine the appropriate number of data points: To investigate the logarithmic relationship between angle of incidence and power output, the student chose 5-degree increments, which resulted in 12 data points. Figure 4 shows the results. For the tracking measurements, the student reoriented the panel to be normal to the sun's rays using the following schedule:
   - 15 min. intervals 6:45 am – 10:00 am
   - 30 min. intervals 10:30 am – 4:00 pm
   - 30 min. intervals 10:30 am – 4:00 pm

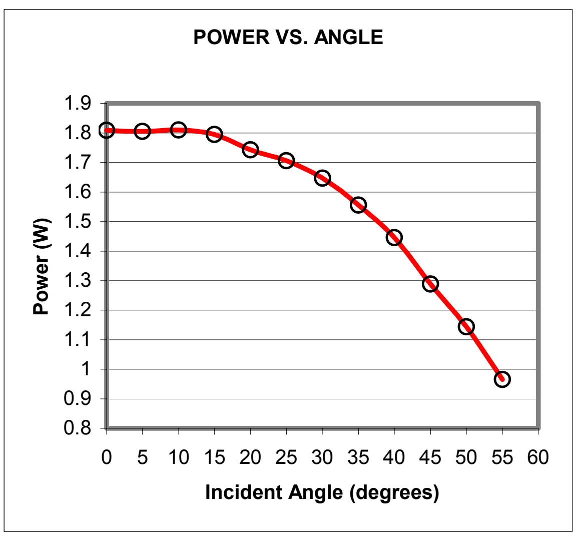


Figure 4. Power output vs. insolation angle for polycrystalline silicon solar panel [8].

Figure 5 shows a comparison between the power output of the solar panel for fixed and tracking configurations. The student found that tracking a solar panel with the sun produces more than the expected 20% improvement over a fixed orientation. With regard to the third objective of investigating the power output of a solar cell as a function of temperature, the student was not able to detect a significant difference using the conditions he imposed.

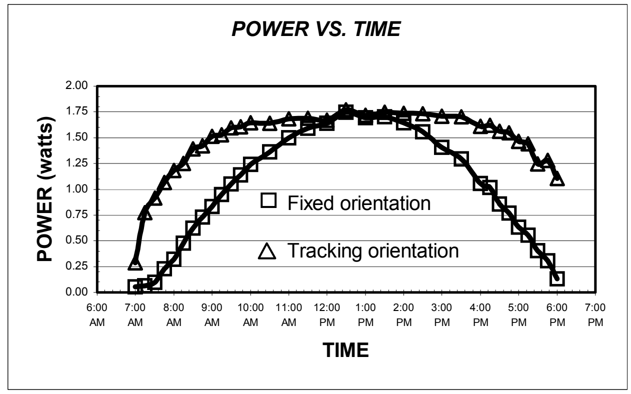


Figure 5. Power output for fixed orientation and tracking polycrystalline silicon solar panel [8].

ME106 DESIGN OF EXPERIMENTS IN MECHATRONICS

Fundamentals of Mechatronics Engineering (ME106) is a required course for mechanical engineers and also a cross-listed elective for electrical engineers (EE106). Students learn about analogue, digital and semiconductor electronics including sensors, transducers, actuators, and microprocessors. The course consists of three components: lecture (2hrs / week), laboratory (3hrs / week), and course project. The lectures introduce the students to basic concepts in mechatronics and make them familiar with common elements of mechatronic systems. The laboratory experiments are designed to give students hands-on experience with components and measurement equipment used in the design of mechatronic products. Finally, the course project provides students an opportunity to apply the spectrum of their knowledge, including mechanical design, circuit analysis and control, to design and build a mechatronics device for instructional use in the lab.

Historically, this course was taught following a traditional engineering laboratory procedure. The students worked through a series of rigidly prescribed experiments in which they followed instructions on how to operate the equipment, collect the data, perform a prescribed data analysis and write a report. In terms of the four elements in ABET outcome 3b, these experiments satisfied three out of the four (students conducted an experiment, analysed and interpreted data) but missed experimental design altogether.

Starting in Fall of 2001, the scope of the course project was modified to address the first part of ABET outcome 3b, namely to give students opportunities for developing experimental design skills. Students are now divided in groups and required to design and implement a truly open-ended laboratory experiment (see student-designed inquiry in table 1) as their course project [9]. More specifically, students are expected to:

1. Define the educational need that this experiment will meet and the learning objectives for the students who will perform this experiment in the future. These objectives may include, for example, (a) familiarity with the principles, operation, and features of a specific sensor and (b) ability to integrate this sensor into a microcontroller and other mechanical devices to perform a specific measurement.
2. Research the various mechatronics devices already available for the task. This is important because one of the

goals in generating a new experiment is to integrate new technologies, such as wireless control, new microprocessors, new sensors, new software and new display devices.

3. Select the variables: Decide which physical parameters will be measured with their device.
4. Select appropriate methods: Decide what will be the sensing / measurement mechanism and how they will perform the data acquisition and calibration of the system.
5. Choose equipment and instrumentation: Select the various sensors to be used based on the desired range and accuracy of each measurement. Subsequently, they choose the main components of their device (e.g. micro-controller) and they integrate the entire system.
6. Evaluate system performance and look for ways to deal with measurement error and eliminate signal noise, temperature fluctuation, etc.

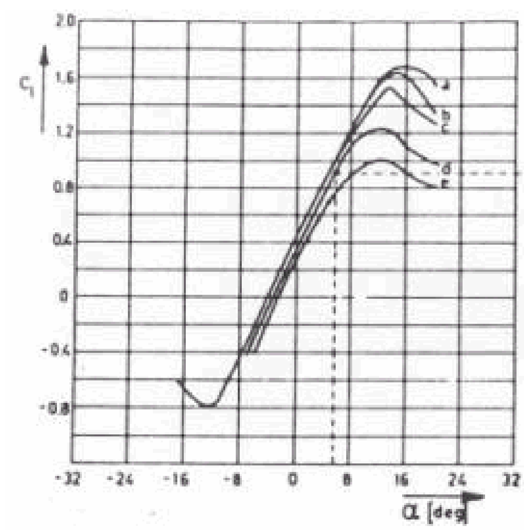
Students demonstrate their device / experiment in class at the end of the semester. Moreover, they author a complete experiment manual, which includes objectives, pre-lab questions, component list, experimental set-up with graphical illustration, procedure and the necessary software. Some of the devices designed and built by the students in this class, include:

- A device that takes a body temperature reading through contact with a finger. The device can also read room temperature and trigger a fan, should the temperature exceed a certain value.
- An intelligent door, which detects an object at a certain distance and opens automatically.
- A guitar player, which plays several tunes, each corresponding to a code in a computer program.
- A feeder device, which weighs a desired amount of food and pours it into a bowl for a dog to eat, at a certain time of the day and a certain location in a room.
- An automatic tracking system, which detects a stranger entering a space and tracks his / her movements.

AE162 DESIGN OF EXPERIMENTS IN AERODYNAMICS

Aerodynamics is a junior level, lecture / laboratory course. It is an elective for mechanical and required for aerospace engineering majors. The lecture is 3 hours per week while the laboratory is by arrangement and usually takes six hours to complete all the experiments. Students are asked to design their experiments beforehand. For example, they are asked to design and perform a wind tunnel experiment to study the performance of a NACA 4412 airfoil (see student-directed inquiry in table 1). Using the steps outlined earlier, the students proceed as follows:

1. Define: Students already know from theory that airfoil performance is a function of angle-of-attack and Reynolds number [Re = Vc / ν, where V is the airspeed, c is the airfoil chord length and ν is the kinematic viscosity of air]. However, they must define "airfoil performance" in more specific terms, so they can measure it in the lab. Thus, they generate the following questions, the answers to which form the objectives of the experiment (refer to fig.6 for the questions regarding lift):
   - How much lift does the airfoil generate at different angles-of-attack and Re?
   - At what angle-of-attack does the airfoil stall?
   - At what angle-of-attack does the airfoil produce zero lift?
   - What is the maximum lift coefficient of the airfoil? Does it change with Re?
   - What is the lift slope of the airfoil?
   - How much drag does the airfoil generate at different angles-of-attack and Re?
   - What is the lowest possible drag of this airfoil?
   - For what range of angles-of-attack does the airfoil give reasonably low drag (i.e., what does the drag bucket of the airfoil look like?)
   - What is the best lift-to-drag ratio we can expect from this airfoil?
2. Research: The aerodynamics text provides a theoretical relationship between lift coefficient and angle-of-attack for thin airfoils. There are no theoretical predictions for the drag of an airfoil. However, students search the internet and the library to find previously published data for the particular airfoil. They can easily find the lift (fig.6) and drag characteristics of the airfoil as well as surface pressure distributions for different Re. Students also run a computer program, which predicts the pressure, lift and drag as functions of angle-of-attack.



a: Re = 9 x 10^6, b: Re = 6 x 10^6, c: Re = 3 x 10^6, d: Re = 1.64 x 10^5, e: Re = 4.21 x 10^4

Figure 6. Lift coefficient as a function of angle-of-attack and Re for NACA 4412 airfoil [10]

3. Select the variables: The dependent variables of interest are simply the lift and drag of the airfoil. The independent variables are the angle-of-attack and the test-section airspeed V, which determines Re.
4. Select appropriate methods: The lift can be found using two methods: (a) integration of measured pressure distributions on the surface of the airfoil and (b) direct lift measurements from a dynamometer. The drag can also be found using two methods: (a) using Newton's 2nd law to calculate the momentum loss in the wake traverses behind the airfoil and (b) direct drag measurements from the dynamometer.
5. Choose equipment and instrumentation: Students use one model with perforations (static ports) to measure pressure distributions on the surface of the airfoil. Pressure distributions may be taken either with pressure sensors or with a multi-tube manometer. The pressure sensors

constitute a part of a data acquisition system, which allows real-time plotting of the pressure distribution on a computer screen. However, the accuracy and repeatability of the measurements is sometimes questionable. The multi-tube manometer is a more primitive, yet more direct method and therefore less prone to error. Students debate the pros and cons of each and choose one of the two methods. Some teams use both methods for comparison purposes and also for redundancy. Students use a different model of the same airfoil with a dynamometer for direct lift and drag measurements. Finally, they use a pitot tube for measuring wake traverses (airspeed) behind the airfoil.

6. Select the range of the independent variables: A careful study of published experimental data reveals that the (maximum) lift and (minimum) drag of an airfoil depend on Re, however, the variation of Re must be significant (ex. from 10^3 to 10^6 or from 10^6 to 10^9) to measure a drastic change in maximum lift and / or minimum drag. Students quickly find out that changing the test section airspeed from the lowest possible value (1.5 m/s) to the highest (48 m/s) gives only a narrow range of Re (from $1.5x10^4$ to $4.5x10^4$), not enough to explore Re effects. In regards to the range of angle-of-attack, the key is to (a) collect data for a sufficient number of angles (say 8 - 10) to be able to reproduce the lift curve and calculate the lift slope, (b) choose several negative angles-of-attack (from -1^0 to -6^0) to capture the zero lift angle of the airfoil and (c) choose several angles in the range between 12^0 and 20^0, to capture the stall angle and the maximum lift of the airfoil. If students do not select the proper range of angles they will have to revisit the lab and re-run the experiment to collect sufficient data for comparisons with theory and published data, even though they may have a sufficient number of data points.
7. Determine the appropriate number of data points: The number of data points needed for each type of measurement depends on the kind of relationship between the variables involved. For example, to capture the slope in the linear portion of the lift curve two points may suffice and a third one may be taken to confirm the linear shape. In the wake traverse, however, where the flow velocity varies in a highly non-linear fashion with vertical distance from the wind tunnel walls, students need to select as many as 20 points to capture the shape of the curve and calculate accurately the drag of the airfoil.

It is obvious that students need to design their experiments very carefully, otherwise, they will not have enough data points and / or the right kind of data to make comparisons with theory and published data. If this is indeed the case, they will not be able to satisfy the objectives of the experiment. An easy solution, of course, is to prescribe all the information in steps 1 through 7 by providing a "cookbook" lab. However, these types of experiments do not train students in experimental design.

CONCLUSION

The faculty of Mechanical and Aerospace Engineering at San Jose State University have used the inquiry continuum (table 1) as a guide to help them design laboratory exercises that meet ABET outcome 3b. The results from the three courses described in this paper seem quite promising. In ME120 students use their newly acquired skills from several highly structured experiments to design and implement a variety of very interesting, open-ended experiments. Similarly, in ME106 students design and build a variety of mechatronics devices for every day applications, while integrating state-of-the-art technology. Finally, in AE162 students gain extensive experience in design of experiments by taking responsibility to define objectives, select appropriate methods to measure their variables, and design laboratory procedures.

It should be mentioned that it is not our intent to completely eliminate structured experiments from every laboratory, as they can serve as models to help students develop the basic skills described in table 1 and which form the basis for more complex experiments. However, the design of experiments, like any high-level skill, requires several opportunities for practice and a variety of laboratory experiments. Hence, we expect that open-ended experiments will eventually find their way in most of our laboratories.

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