Design in the Rowan University Freshman Engineering Clinic

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ABSTRACT

Freshman engineering students at Rowan University are introduced to engineering design through a series of hands-on engineering laboratories and design projects. The objective is to involve them in incrementally progressive design experiences. For example, students design a modified flashlight switch, a complete flashlight, undertake the design of proof-of-concept experiments, and finish with a system-level design of an environmentally friendly coffee machine. Thus, the freshman design experience at Rowan specifically avoids “gimmicky” competitions and focuses instead on the design of real engineering devices such as flashlights and coffee machines. In order to achieve this focus, freshman students must be exposed to a variety of engineering principles, experimental methods, and design tools not typically encountered at the freshman level. The challenge is to achieve this ambitious focus while maintaining an atmosphere conducive to retention.

INTRODUCTION

Rowan University is developing an innovative and forward looking engineering curriculum that will produce engineers who can serve as innovators and entrepreneurs in a highly competitive marketplace.[1,2] Key program features[3] include: (i) inter- and multi-disciplinary education created through collaborative laboratory and coursework; (ii) stressing teamwork as the necessary framework for solving complex problems; (iii) incorporation of state-of-the-art technologies throughout the curricula; (iv) and creation of continuous opportunities for technical communication. To best meet these objectives, the four engineering programs of Chemical, Civil, Electrical, and Mechanical Engineering include a common engineering clinic throughout all eight semesters of their programs of study. We believe that the clinic is a major hallmark of the Rowan engineering programs. The clinics present a broad-based approach to engineering starting at the freshman level, progressing in depth and industrial relevance as students advance. The nature of the clinics allows students and faculty to work together in a hands-on, project environment that promotes teamwork to find solutions to complex multidisciplinary problems.

The Freshman Engineering Clinic sequence, taught in the Fall and Spring semesters, has laboratory components dealing with the four disciplines. These areas are used as the basis for delivering instructional goals in the principal engineering science and engineering design topics, and provide an environment for treating a variety of supporting issues such as ethics, safety, communication skills, teamwork, etc. Like others, we believe that it is essential to involve freshman students in a meaningful engineering experience. Some institutions have utilized traditional discipline-specific laboratory experiments at the freshman level[4] while others engage students in discipline-specific freshman engineering design projects.[5] One of the NSF coalitions, *ECSEL* has major efforts in freshman design, which have been widely reported.[6, 7]

In summary, our Freshman Engineering Clinic activities:

- show the interrelationship of engineering and science required for product design and fabrication, and
- demonstrate the role of laboratory experimentation[8] in the engineering decision-making process using stimulating and challenging experiments that relate the labs to familiar consumer products.

The remainder of the present paper will focus on the how design is integrated into the Freshman Engineering Clinic at Rowan University. The experimental components of the Freshman Engineering Clinic at Rowan University is described in detail elsewhere[8].

FLASHLIGHT FABRICATION AND DESIGN

Freshmen start their clinic experience with a “team-building” exercise. Each team is provided with a box of blocks and given 30 minutes to construct the tallest tower possible. Actually, this exercise is an introduction to teamwork rather than an exposure to any engineering design principles. More significantly, it marks a departure from what is often done in the freshman experience. From this point on, we strive to avoid “gimmicky” design/build competitions (e.g., bridge building, egg drops, etc.) and instead choose to focus on the design of real products and devices such as flashlights and coffee machines.

For the next 3 weeks, students complete a combined mechanical drawing and fabrication module. During lecture periods, students learn how to produce mechanical drawings using a CAD software package. The three, 3-hour laboratory sessions are conducted at the nearby Center for Integrated Manufacturing (CIM) at Camden County College. The 40,000 square foot CIM center is a state-of-the-art facility with over $1 million dollars worth of equipment purchased or donated by companies such as IBM, GE, Texas Instruments, and Bridgeport. At this facility, students are trained in the basics of manufacturing through the fabrication of a working aluminum-body flashlight.

Each student machines a MAG-style[9] flashlight starting with a 3/4 in. diameter rod of aluminum alloy. The students fabricate the flashlight using both manual and computer numerical control (CNC) machines given a set of detailed dimensioned drawings. At the end of three, 3-hour sessions each freshman engineering student has a working flashlight. Having developed significant familiarity with their flashlights, students are asked to design a number of alternatives for implementing an on/off switch. This provides them with an incremental design problem in a complete context: they know the details of their current design and they understand some manufacturing constraints.

The *shop floor* experience is carried one step further by introducing the students to valuable design and manufacturing principles. Specifically, students are challenged with the question, "How does the performance of a machine (or process) affect the overall design of a product?" Thus, students not only build their flashlights, but afterwards they perform a detailed inspection of their product to determine the quality of each machining processes that they used. Using dial calipers, telescoping transfer gages, and micrometers, each student accurately measures 25 dimensions from their final product. Dimensions are entered into MS Excel® for each team of four students, and they later download the data from the remaining teams in their section. With data from 20 flashlights, it is possible to perform simple statistical analyses to determine the accuracy of each machining process. For each dimension, students calculate the range, mean, and standard deviation (σ). Then, using the definition of a 6σ spread, they determine the International Tolerance Grade for each fabrication procedure that they have performed. Some of the measured dimensions and tolerances are shown in Fig. 1.

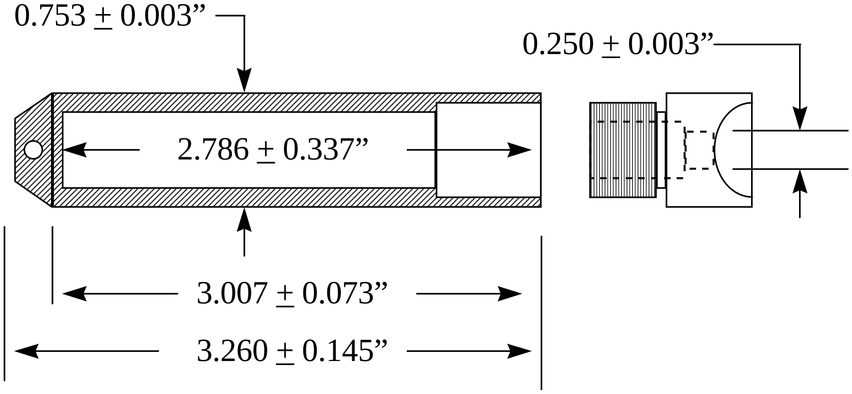

Figure 1. Measured dimensions for 20 fabricated flashlights.

By performing this inspection procedure, students are introduced to some fundamental engineering realities. First, students are exposed to the difficulties of machining parts to specified tolerances. For example, it is a humbling experience to discover that the actual variation in the length of the machined battery cavity is 2.786 ± 0.337 inches. Second, students discover that the performance of a machine is often directly proportional to its cost and complexity. Components machined using CNC machines are found to have the tightest tolerances. As shown in Fig. 1, the diameter of the light bulb housing had a variation of only 0.003 inches. Third, students develop a feel for physical dimensions that are typically encountered in manufacturing; after their shop experience, they have developed a sense for what 0.001 inch represents. Finally, students learned how to handle and operate inspection tools. This is a skill that will serve them well in the future as they continuously strive to deliver quality products.

Having determined the tolerance grade associated with each of the fabrication procedures required to build a flashlight, the students were assigned the re-design of their flashlights. The objective is to design a flashlight that takes into account the manufacturing tolerances associated with the various machining operations that will be available. Their new designs now call out tolerance specifications for each fabrication procedure required. An example of a student design is shown in Fig. 2. Since one of the major difficulties in the previous design was maintaining quality control in the depth of the battery cavity, the new design features a batter cavity that is drilled completely through.

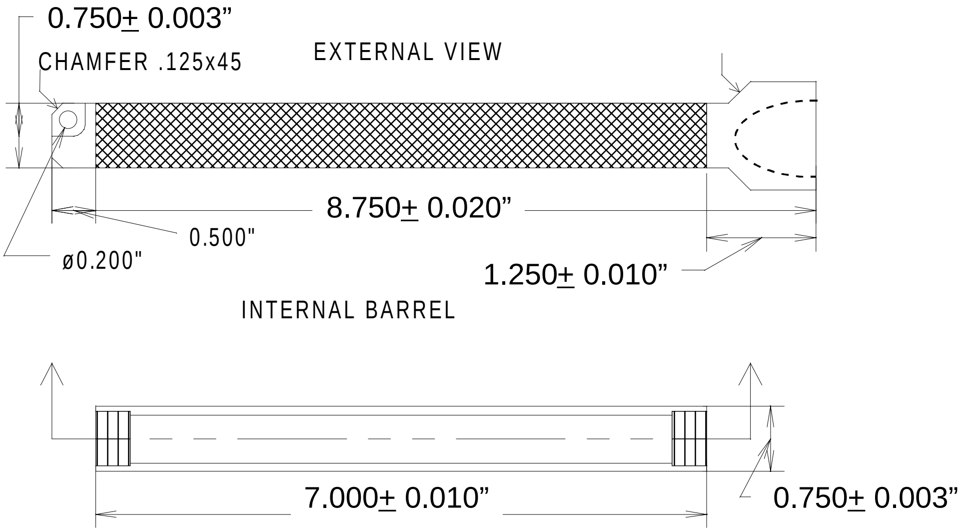

Figure 2. Example of a sketch of a student team's re-designed flashlight.

REVERSE ENGINEERING

Reverse engineering (RE) is another basic concept introduced early in the freshman clinic experience. We believe that considering the design work of others is an important starting point for the design education of our students. RE gives them an opportunity to consider a variety of design-related issues such as likely manufacturing steps, assembly methods, material selection, intellectual property rights, safety features, ergonomics, ethics of RE, and many others. The students are first introduced to RE at the conclusion of their flashlight fabrication experience. After students fabricate their flashlights, they examine representative commercial flashlights. They observe similarities and differences between their units and the commercial samples. They also get to consider the manufacturing cost implications of a retail flashlight selling for under ten dollars.

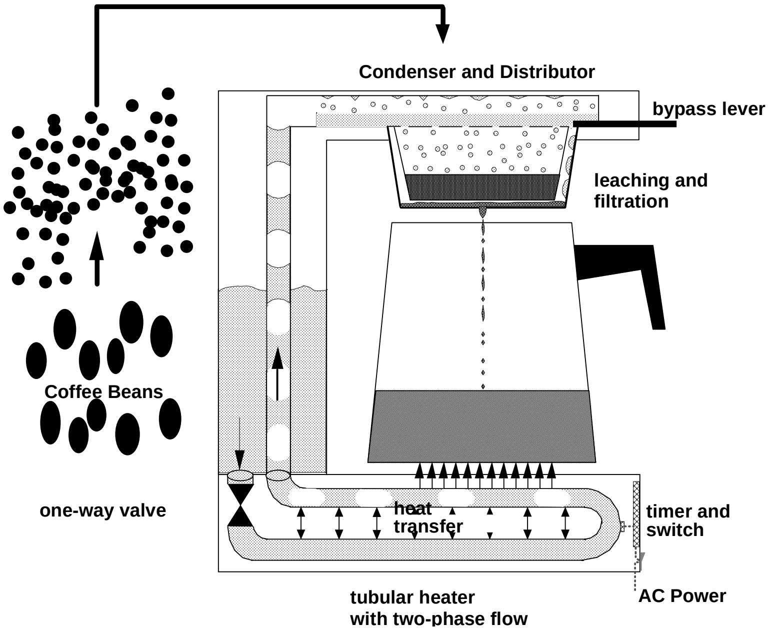

Figure 3: Coffee Machine

Next, the RE approach is continued with a different commercial product. In Fall 1996, a coffee maker was chosen as the commercial product. As discussed below and elsewhere[8], the coffee maker was used in both freshman semesters to demonstrate a number of fundamental engineering principles and to serve as a vehicle for additional design experiences. The coffee maker, shown in Figure 3, exposes students to basic principles of momentum, heat and mass transfer, thermodynamics, electronics, process control, materials, and manufacturing[10].

In the fall semester, students devote an entire 3-hour lab to reverse engineering a coffee machine. First, students examine the physical characteristics, read the product documentation and make several dimensioned diagrams of their machine. Next, process measurements are taken of the liquid volume and temperature in the receiver vessel (carafe) as a function of time. Finally, students take apart the coffee machine and make measurements to construct drawings of the internals. They summarize their findings in oral and written reports. The written material must detail "how the coffee machine works." They are required to draw a process flow diagram and address other areas of reverse engineering such as mechanical, materials, fabrication, assembly and electrical design elements.

In addition, they are required to perform an overall energy balance analysis based on their measurements of electrical resistance, temperature, and liquid volume. They are able to calculate the amount of energy produced by the heater vs. that which was actually added to the water during the entire brewing process. The students can therefore derive an overall thermodynamic efficiency of the coffee brewing process:

$$\eta = \frac{m_w C_v (T_{f,w} - T_{o,w})}{\int \frac{V^2}{R} dt}$$

where m_w is the total mass of water brewed, C_v the specific heat of water, $T_{f,w}$ the initial water temperature, $T_{o,w}$ the final water temperature, V the RMS voltage, and R the measured resistance of the heating element. This short engineering calculation introduces the students to engineering equations employing measured quantities of temperature, time, resistance, and flow. These simple equations also give students practice handling—and converting between—typical engineering units. A further benefit of using this real product, is that it is convenient for showing obvious connections to co-requisite courses such as calculus; for example, examining power consumption provides an integration example for the calculation of total energy. The concept of efficiency and power consumption of the coffee maker is revisited in the spring semester design project.

SPRING SEMESTER DESIGN PROJECT: *GREEN COFFEE MACHINE*

In the spring 1997 semester, the Freshman Engineering Clinic focused on the design of a "green" (i.e. environmentally friendly) coffee brewer. First, students built on their problem solving skills presented in the previous semester, employing a 5-step heuristic.[11] They started from the question, "What is not green about a coffee machine?" They defined several problem areas such as power consumption, construction materials, waste reduction, and materials recycling and reuse. This was followed by research to gather more specific information relating to their interest areas, followed by a brainstorming session to generate new ideas to solve the problems posed. Each student design team presented an oral and written proposal for their chosen approach. The approved proposal was then developed into an implementation plan. Each stage of the project was evaluated by the group and their professor through the use of project review sessions, progress memos, and individual journals.[12]

One requirement for each team was to develop tests for selected aspects of their proposed designs. We believe that this is another essential component in developing our students' design skills by presenting them with opportunities to design experiments in support of their design hypotheses. Experiments could be based on a series of product-related labs (described below) developed by the faculty, or they could be based on labs developed as a faculty-student partnership.

Table 1 Directed laboratory experiences for the coffee maker.

Experiment	**Description**
Data Acquisition	Provide a basic foundation of data acquisition including concepts of Input/Output, instrumentation, sampling, aliasing, and analog *vs*. digital signals. Introduce the basic tools of data acquisition. Students use DaqView, DaqViewXL (an MS Excel add-in) and voltage and thermocouple signal conditioning cards.
Materials Beam Bending Thermal Expansion	Introduction to basic engineering concepts of free body diagrams, forces, moments as well as the material properties of elasticity and coefficient of expansion. Material properties , momentum. In both experiments, data acquisition was employed to measure linear displacement. An icon-based environment (HP VEE) was used to analyze data.
Mass Transfer	Three experiments were conducted to examine the rate of leaching of coffee. The effects of water temperature, particle size, and concentration driving force were examined. Concentrations were determined from transmission measurements from a spectrometer and a data acquisition system.
Heat Transfer	Conduction and convection principles were demonstrated through two experiments. The first experiment examined the time required to cool a cup of coffee in three different covered cups (paper, styrofoam, and an insulated travel mug). The second experiment examined conduction in three vertical rods (SS 304, Al alloy, and brass) with cooling by natural convection. Temperature measurements were recorded using a data acquisition system and plots were constructed using Excel.
Water Quality	The laboratory introduced students to concepts concerning water quality and major treatment processes used to produce a required water quality. Students gained hands-on experience measuring pH, conductivity, turbidity and chlorine residuals for given water samples.
Microcontrollers	Students developed a simple routine to control the timing of an LED. This exposed them to the basic concepts of what microcontrollers are and how they can be applied to measurement control and how they can be used to implement product features.

In order to provide students with the engineering fundamentals and experimental methods necessary to design their own experiments, six laboratory experiments were developed by faculty as summarized in Table 1 and detailed elsewhere[8]. All experiments expose students to fundamental engineering units and their conversions appropriate to each module. Another intention of the lab modules is to instill the principles of data acquisition. Real time data analysis and graphing are performed using DaqView XL and MS Excel®. Finally, since the engineering clinic course is taken by all engineering students, these experiments provide students with valuable exposure to engineering fundamentals *outside* their typical area of expertise. For example, Rowan chemical engineering students have been given a solid introduction to the concepts of stress, strain, moment of inertia, thermal expansion and beam bending. Meanwhile, Rowan civil engineering students have built circuits and programmed microcontrollers.

PROOF-OF-CONCEPT EXPERIMENTS

Experimental proposals were collected from all students and evaluated to arrive at eight categories of experiments that covered the majority of testing objectives identified. The detailed design and fabrication of the following 8 experiments was performed by a combination of faculty and students.

Fully instrumented coffee maker testing. The previous semester, some limited testing was performed to begin to characterize the brewing process of the coffee maker. In support of their “green” coffee maker design, the students quickly realized that they required significantly more data on the operating characteristics of a typical coffee maker. By instrumenting the coffee maker with 15 thermocouples, a flow meter, a pressure transducer and a power transducer, it was possible to completely characterize the performance of the machine during the brewing cycle and the heating cycle. The students measured the instantaneous efficiency of the coffee maker during the brewing cycle and determined the energy losses. They determined the heat lost from the top of the machine, the heat loss from the top of the carafe and the heat loss from the sides of the carafe. They also quantified the actual power savings associated with using an insulated carafe *vs*. the hot plate for each hour of operation. Finally, to substantiate or refute manufacturers claims they determined the actual temperature of the coffee exiting the coffee filter and the temperature distribution within the grounds during brewing.

Insulated carafe testing. Since many of the student designs eliminated the hot plate in favor of an insulated carafe, experiments were proposed to determine the properties of insulated carafes. The students were able to determine how long the insulated carafe keep coffee warm, whether the space between the two layers of the carafe needs to be a vacuum, and how the taste compares between coffee that has been sitting in a carafe *vs*. coffee on a hot plate.

Coffee filter comparison. Experiments were designed to evaluate various types of coffee filters currently available. Filter types include paper, hemp and cotton cloth. Experiments were conducted to determine the effect of filter type on the taste, strength and the brewing time for a typical coffee making cycle. Durability of the filters was also tested. The strength of coffee was determined spectrophotometrically. These experiments aided students in analyzing filter performance with respect to the coffee making process and costs.

Water filter comparison. Experiments were conducted to evaluate the water quality in coffee makers equipped with commercially available water purification filters. Filters were tested to determine their effectiveness in removing organics, residual chlorine, turbidity and bacteria.

Caffeine leaching experiment. Experiments were designed to determine the caffeine concentration in successive coffee cups along a brewing cycle. Caffeine concentrations were measured using a liquid-liquid extraction procedure. Tests were run with different coffee filters to study their impact on caffeine concentrations.

Heater sizing of down-flow coffee machine. In these experiment the appropriate heater size and corresponding liquid flow rate was determined for the gravity-fed coffee machine. In nearly all of the proposals, the water reservoir was designed to be located above the heater, leaching unit and coffee carafe. These experiments allowed each group to examine the possibility of reducing the power required by their "green" coffee machines.

Modified leaching unit. Several proposals presented ideas for modifying the current design for the drip style coffee machine. These experiments tested the new leaching units to determine if coffee can be produced of equivalent quality to the drip style coffee machine using a lower mass of coffee. Most of the leaching unit modifications involved the principal of a longer contact time between the water and the coffee grounds compared to the conventional drip style machine.

Solar Cell and Alternative Heating. A sequence of experiments were designed to allow students to investigate the use of alternative heating—e.g., the use of microwaves—and the possibility of using solar cells as a source of energy. This also provided an introduction to the use of secondary battery storage technologies.

Each student team not only designed their experiment, but also wrote a detailed laboratory manual, since the experiment that they designed was subsequently conducted by their fellow engineering students. The laboratory manual included the following:

- an *introduction*, detailing the need, objectives, required measurements and the design of the experiment,
- a *description of apparatus*, including a list of equipment, instrumentation, data acquisition system, and a detailed schematic diagram,
- an *experimental procedure* including a step-by-step process for setting up the data acquisition system (e.g. DaqView), performing the experiment and acquiring the data, and,
- an *analysis procedure*, stating how the data will be presented graphically and what calculations would be performed using the data.

GREEN MACHINE DESIGN

After designing, building and executing the proof-of-concept experiments, the students submitted the final reports for their proposed "green" coffee machine. Given the time constraints of one semester, the final designs were paper designs only in that there was no requirement to construct a prototype. The final designs were, however, quite comprehensive. The students submitted detailed design drawings along with the experimental results of the 8 experiments outlined above. In addition, the students performed a break-even analysis to determine how many units they would need to sell in order to start turning a profit. To determine fixed and variable costs associated with manufacturing a coffee maker, one of the students contacted an engineer at Mr. Coffee. The data obtained by the student was disseminated to the entire freshman class via email.

One of the strengths of the 8 semester engineering clinic sequence at Rowan University is that, since all engineering students must follow the same sequence, topics such as the "green" coffee machine can be revisited at a later date. Thus, in a later clinic, students can build and test a prototype based on their original designs. Or, given their experience in reverse engineering, product testing, and design, students might be called upon to re-design and develop a prototype for a different product.

DISCUSSION

Our Freshman Engineering Clinic experience approaches design in an incremental fashion. We believe that this approach provides our students with a structured experience that helps them build on a continually evolving foundation of design sophistication and confidence. Assessment of our efforts are on-going; however, one source of continuing challenge is to strike a balance between excessive student and faculty workload on the one hand and the desire to deliver meaningful laboratory experiences on the other.

The course is, indeed, a challenging one for the freshman engineering student. Student feedback indicates that the engineering clinic is at least as demanding as the freshman Physics, Calculus and Chemistry courses that are frequently cited as being responsible for “weeding out” would-be engineers. Since a major goal of the freshman clinic (and, arguably, all freshman engineering courses throughout the country) is to foster retention, we continue to pay careful attention to the demands of the clinic. For example, since the semester-long design project itself is so demanding, we try to minimize the homework assignments given in conjunction with the directed laboratory experiences (See Table 1). Furthermore, we have also found that by emphasizing *quality of the learning experience* over *quantity of material covered* it is possible to create a low-stress environment during the laboratory experience.

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