Teaching Engineering Design – One University's Program

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abstract
This paper describes the design process as taught at Texas Christian University (TCU). The intent of the design course is to develop student engineers capable of a seamless transition to industry. Success in industry is primarily based on three criteria: (1) schedule – did the project get completed on time, (2) cost – did the project get completed within budget, and (3) performance – did the delivered product(s) satisfy the customer? The design process at TCU is based on these criteria. A 3-semester, team-oriented, industry-funded, electrical/mechanical, interdisciplinary design sequence, beginning in the second semester of the TCU student engineer's junior year, is described.

introduction
Early in their engineering educational process, students are typically forced to select a specific discipline (mechanical, electrical, civil, etc.). They then dutifully follow a program of studies that embraces the requisite technical courses (thermodynamics, solid mechanics, circuits, etc.) to support this discipline. While laboratory courses may provide an opportunity to stimulate group interaction, success in the majority of their engineering courses is typically assessed based upon individual performance, e.g., examination grades. What's wrong with this picture? This individual assessment process is largely disconnected from the industrial world where they will win or lose in teams.[1,2,3] Engineers in industry who rise through the managerial ranks are almost always initially identified as a byproduct of being associated with successful engineering teams early in their careers. Assessment of the effectiveness of an industrial team is principally based on three criteria: (1) schedule – did they get the project completed on time, (2) cost – did they get the project completed within budget, and (3) performance – did the delivered product(s) satisfy the customer? Thus, to create engineers capable of rising through the ranks of their peers, engineering programs must generate individuals who can contribute to, and thrive in, an industrial teaming environment.

Before I left industry for academia, it was my observation that during the latter 1980s and the early 1990s the young engineers being produced in universities were well versed in computer skills, but had little insight into the design process. Fortunately, large companies such as Boeing felt the same way and encouraged ABET (the engineering accreditation board) to require more design content in university engineering programs.[1,2] The engineering program at Texas Christian University (TCU) in which I teach is relatively new; its first seniors graduated in 1996. This program awards a Bachelor of Science degree in general engineering with mechanical and electrical emphasis options. The timing of the initiation of this program, coupled with my own convictions, afforded an opportunity to change the traditional engineering education paradigm by creating a more industrially focused model.[8] This focus is achieved through a continuous, 3-semester, team-oriented, industry-funded, electrical/mechanical, interdisciplinary design

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sequence beginning in the second semester of our junior year. The intent of this sequence is to integrate the design process into our curriculum with a strong emphasis on team development. The goals of the junior course, taken from my course syllabus, are:

"… (1) to assure that participating students understand the many contributors to the engineering design process, and (2) to enable the students to develop the requisite complementary skills to their science- and technology-based studies to enable them to succeed in the workplace."

Not all of the following material can be comprehensively covered in this junior course. However, among materials that we address are:

- Engineering economic analysis
- Budgeting
- Reliability assessment
- Fault-tree analysis
- Engineering ethics
- Product liability
- Risk assessment
- Hazard analysis and mitigation
- Needs analysis/specifications
- Feasibility studies
- Patents
- Decision making
- Project planning/scheduling/tracking
- Product testing
- Ergonomics
- Memo and report writing
- Engineering presentations

The junior students work largely in teams of 4-5. Recent assignments have been as diverse as developing a fault-tree analysis for a fiber telemetry link, performing hazard-analyses and subsequently developing safe-operating-procedures for handling steel gas pressure cylinders, performing feasibility studies to neutralize a well-defended, hardened, deeply-buried facility within an unfriendly country, performing a work-breakdown-structure (WBS) and developing a GANNT chart for landscaping a yard, etc. Within bounds, the students can propose their own topic for each type of assignment. During the semester, selected speakers (e.g., patent attorney, architect, certified program manager, small business owner) complement my lectures.

During this junior year, I enter both the students and the university into a formal contract with an outside customer for an electromechanical design project for their senior year. The company and I jointly develop the specifications. The students are not offered an opportunity for input as to project selection, nor do they have any knowledge of its content until they encounter it at the start of their senior year. *A parallel occurs in the business world when an opportune project presents itself. The most talented employees are usually conscripted to optimize its chance for success?* Typically, the interdisciplinary nature of the project places it in the area of test and evaluation or control, and it relies heavily on instrumentation. Constraints in sizing the project include: number of students (typically 20 maximum), proper ratio of electrical / mechanical content to balance the class, and a project that can be completed by the students over a 2-semester period (their senior year).

This junior year is then singularly focused at imparting the knowledge to enable the senior year to be a focused practicum for successful teaming on an industrial project. The first day of class in their senior year the students are handed the specifications for their project. During the first week of the semester they meet and query the customer to fully understand this specification. They have been prepared to nominate and elect a program manager who will delegate the roles of the support team. Representative members include lead electrical and mechanical engineers, budget manager, machine shop interface(s), lead draftsperson, documentation manager, etc. Within a few weeks, the program manager is responsible for running the classes (now project meetings) for the remainder of the 2-semesters. I attend each meeting and, based on what I observe, may provide some opinions/comments at its culmination. It is imperative that the students not be bound by these opinions/comments since project ownership must remain with them. I am available to consult, when asked, as are other faculty members. However, it is clearly the student's responsibility to achieve project success. The students have unlimited access to phone, fax, shops, work area (day and night), appropriate secretarial support, and more. They present a design and cost proposal to the customer in November, which the customer either accepts or requests to be modified. The students place all their orders and put drawings in the shop before Christmas break. A presentation of the completed project is made to the customer, faculty, other local industry representatives, and the student's families, typically an audience of 150 people, in late April. A final report (150 pages typical) is also delivered to the customer at that time. Other faculty, who volunteer, and I review all presentations and reports.

synopses of projects

After my arrival at TCU in 1995, I had only two (2) weeks to prepare a project for the first class of graduating engineering seniors. There was not time to acquire a corporate sponsor. I had recently managed a rocket test range and developed rocket flight systems. Therefore, I based my project on those activities. I prepared a 57-item technical specification for rocket flight hardware along with a letter of transmittal to the students, just as I would have for any industrial supplier. A brief project description and results summary are below.

1995-1996

Pressure and Acceleration Measuring Systems[4,5]

Funding: $1,300 (first year project funded by TCU)

Customer: Privatized Launch Systems (Fictitious TCU company)

This project developed environmental measurement systems to acquire critical parameters associated with third-stage motor performance on a rocket system. The designs were ultimately to be fabricated and then verified as structurally, environmentally, and electrically compatible with satisfactory performance on a rocket flight system. The systems developed were proven capable of operating during a rocket flight and reporting data via flight telemetry.

Included among the deliverables from this project were a video of its final presentation and a well-documented report. The importance of these two items was to supply material to enable marketing of our program to its initial industrial customer. In reality, I "twisted the arm" of an aerospace company in California that I had worked with during my prior industrial career. They graciously provided a project and a set of specifications for the second year, which the students also completed successfully; its description follows.

1996-1997
Cold Gas Shock Tube[6,7]
Funding: $14,200
Customer: Endevco Corporation

The students designed and developed equipment capable of dynamically characterizing pressure instrumentation manufactured by Endevco to evaluate gas turbine operating performance. The developed hardware (a cold gas shock tube) had an associated computerized data acquisition and analysis system to support the characterization activity. With this equipment, the dynamic assessment of the pressure instrumentation could be performed to 20,000 Hz within seconds.

Notice that the customer provided $14,200.00. Annually, the customer-supplied funds cover material costs only. Naturally, the customer also incurs additional undocumented costs associated with engineering time and travel and materials they may contribute directly. This second project was actually "trailered" to Endevco in San Juan Capistrano, CA by the student team; they then installed the system and provided operational training. Before delivery, the successful presentation of this project to local industry in a TCU auditorium in Fort Worth, TX, served as a catalyst towards acquiring the following succession of projects.

1997-1998
Linear Displacement Measurement Standard
Funding: $10,000
Customer: Bell Helicopter Textron, Inc.

The students designed and manufactured equipment to automate the calibration processes in Bell Helicopter's metrology laboratories. Specifically, displacement transducers are used in numerous Bell measurement and control processes. These transducers require recalibration by the thousands. The equipment manufactured used stepper motors, optical encoders, versatile digital interfaces, and software control to increase the efficiency and accuracy of Bell's calibration processes.

1998-1999
Fracture Toughness Tester
Funding: $18,000
Customer: RockBit International, Inc.

The students designed a system and procedure to determine the fracture toughness of tungsten-carbide cone bit inserts procured by RockBit for use in their finished bits sold to the oil and gas drilling industry. Prior to this time, RockBit procured these cone bit inserts from its vendor with no independent verification of their fracture toughness. The system designed to effect this verification depended on a standard test specimen configuration, specific electrostatic discharge machine starter notch, ball-screw drive assembly, force and displacement measurement instrumentation, and computer-based analysis equipment.

1999-2000
Laser-Assisted Tool Calibration Universal Fixture
Funding: $28,816
Customer: Bell Helicopter Textron

The students developed an optical calibration system for Bell Helicopter's Core Carver Facility - a 5-axis machine where cores for helicopter blades are machined. If the blade cores are not machined to dimensional tolerance, discarding them during the composite lamination process incurs significant time and monetary loss to Bell. The final calibration system design incorporated a precisely located tooling fixture, "sheets" of light into which a tooling ball was inserted and selectively moved, a computer based data acquisition system, and feedback to the facility's controller to cancel errors and greatly reduce the amount of time required for calibrations, which previously had to be performed manually.

2000-2001
In-Line Vacuum Detection System (winner of Design News 2^nd Annual College Design Engineering Award sponsored by ANSYS)
Funding: $27,000
Customer: Alcon Laboratories, Inc.

The students designed an automated process, on a rapidly moving conveyor line, to assess the vacuum levels in bottles containing Alcon sterile solution used in eye surgery. This assessment was based on acoustic considerations, specifically the sound emanating from pneumatically impacted bottles. The bottles were collected in small groups, grasped mechanically, tilted to wet their caps, impacted with pistons, monitored individually as to the sound they made, tracked optically along the production line, and ultimately allowed either to continue to the packaging station or to be rejected from the line by pneumatic actuators activated from a programmable logic controller.

2001-2002
Measurement Enhancement of Blast Data[9,10]
Funding: $15,000
Customer: U.S. Army Engineer and Development Center Waterways Experiment Station (WES)

The students designed/developed: (1) a portable, dynamic, field calibration system, including a digital-data-sample-and-store capability, for blast pressure measurements, (2) a characterization system for the existing WES instrumentation/cable system, (3) upgrades to the current WES instrumentation system, and (4) a prototype for a digital, data recording system hardened to withstand the effects of explosions. This work supported the WES mission to conceive, plan, study and execute engineering investigations and research and development studies in support of the civil and military missions of the Corps of Engineers and other federal agencies.

2002-2003

Design and Evaluation of a Hand-Held Measurement Device for Rivet Hole Characteristics

Funding: $25,000

Customer: Lockheed-Martin Aeronautics Company

The students designed a measuring system to characterize rivet holes and their associated countersinks for the layered, composite wing of the stealth Joint Strike Fighter (JSF). This system: a) had to assess each hole/countersink combination to 0.000050" accuracy in order to assure fatigue resistance of the wing; and b) had to perform the measurement within 3-seconds to be time-efficient. The delivered system was ergonomically designed to work from an inspector's backpack, but could also be subsequently incorporated into the automated CNC drilling process. It contained an automated data logging and record keeping process.

program insights

How do the students perform throughout the senior year? Not surprisingly, they fumble with communications, create project plans that are too dependent upon success, become testy with one another because the work load is not shouldered equally, display disappointment when suppliers miss promised delivery dates, procrastinate initially, and then work hideous hours near project culmination. Sound familiar? The difference is that the students are encountering these experiences as a requisite part of their educational process. While never required to, a number of students elect to work on the project during their Christmas and Spring breaks. As a faculty, we become concerned when some students spend as much as 60 hours a week on their project, and we attempt to assure ourselves that they also maintain a focus on their other classes. However, this is part of the process of acquiring time-management and work-prioritization skills.

Who assesses whether the students have successfully met their cost, schedule, and performance goals? The customer performs this assessment at the final project presentation in April. Since the customer has committed procurement funds, and also incurred substantial labor costs in coordinating specifications with me, and in maintaining an effective communications interface with the students, customer feedback is straightforward and candid. It is the customer's responsibility, as the funding source and the owner of the problem being solved, to critique and accept the project.

How are the students graded on these projects? They perform peer evaluation; i.e., they grade each other. The first semester I provide 50% of their grade and their peer evaluations provide the other 50%. My portion is based on engineering notebooks they must maintain and a few early quizzes to assure they each understand the project in its entirety. The second semester their peer evaluations comprise 100% of their grades. Every student has a closeout interview with me each semester. I provide them my personal evaluation of their individual effort, while he/she provides me with a grade for each class member. They also provide me with one or two sentences of professional feedback evaluating each member's individual job performance for that semester. I compile this written feedback in anonymous fashion, average the grades, and provide all of this in packaged form to each senior student. Thus, they receive not only their grades, but also the rationale behind them. Over the history of the program, grades of A through D have been awarded.

Figures 1-14 provide some insight into experiences the TCU student engineers encounter during the duration of their individual projects.

Figure 1: Clarifying Specifications with Customer

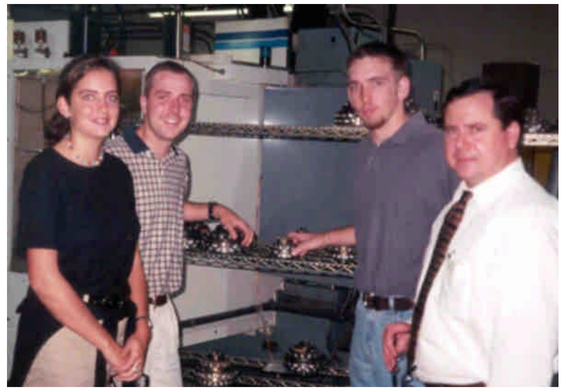

Figure 2: Visiting the Customer's Facility

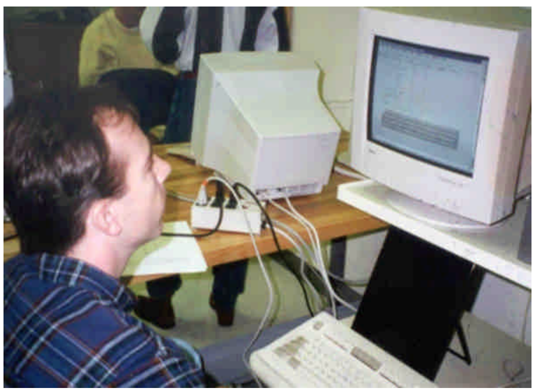

Figure 3: Generating CAD Drawings

Figure 4: Moving Hardware to Shop

Figure 5: Bread-Boarding Circuits

Figure 6: Manufacturing Circuit-Boards

Figure 7: Making It Work

Figure 8: Keeping the Schedule

Figure 9: Solving Problems

Figure 10: Delivering the Hardware

Figure 11: Performing Factory Acceptance Test

Figure 12: Presenting the Work

Figure 13: Posing After Final Presentation

Figure 14: Celebrating Results

program assessment

Does the program succeed? The TCU Engineering Department's Industrial Board of Advisors strongly supports the program. In addition, an ongoing industrial "pull" for the program has been established. Each class seems to raise the bar higher for the one behind them. In 2000-2001, its fifth year of operation, the program was judged winner of the *Design News* National College Design Competition[11] sponsored by ANSYS Corporation. This resulted in $20K and other awards being presented to TCU's Engineering Department at a black-tie dinner in Chicago and at a subsequent presentation in Pittsburgh (Fig, 15). However, the success of the program can best be evaluated by the quote of one of our students from last year, also a former TCU football player and now a Lockheed-Martin employee: "It doesn't matter if one person gets an A and another a C. If you don't get the project done, you've all failed."

Figure 15: Chicago Award Presentation

To date our design program has grown from 9-11 seniors to 17-21, annually. A future challenge will arise as we approach 25-30 students annually. It's currently envisioned that we will still work on a single, large project. However, these projects will be broken into complementary electrical and mechanical portions and managed as in industry - with interface control drawings (ICDs).

conclusions

The results the students have produced in this program seem to speak for themselves. The Endevco Corporation-sponsored shock tube is in a glassed in area of their calibration laboratory in San Juan Capistrano, CA, where it is routinely used. Bell Helicopter Textron's Linear Displacement Measurement Standard is similarly in routine use in their facility in Fort Worth, TX. As noted, the In-Line Vacuum Detection System, which was built for Alcon Laboratories, won the Design News 2nd Annual College Design Engineering Award, sponsored by ANSYS, in 2002. The Measurement Enhancement of Blast Data[9,10] project's resultant hardware has been used by its customer, U.S. Army Engineer and Development Center Waterways Experiment Station, in testing in Europe. This same customer has presented two papers to the DoD community on the results of the project and is filing for a patent on the hardware. While only two (2) percent of engineering departments have projects with hardware costs in excess of $5,000[2], our average industrial funding for hardware has been $20,000. Students and faculty are uniformily enthusiastic about the program, and the dedicated Senior Design suite in the Tucker Technology Center is a routine stop for visitors to the TCU Engineering Department. There the visitors can interact with the working students and also look at documented projects from prior years. Oncor's electrical power portion of its energy-distribution business has all ready agreed to sponsor the project for our engineering class of 2003-2004. More important, the students are aware that they are contractually involved in a project, which satisfies a real need for an industrial customer. This program is enabling TCU's Engineering Department to satisfy its goal of developing student engineers capable of a seamless transition to industry.

acknowledgement

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Before accepting his current position at Texas Christian University, Dr. Walter completed a 30-year professional career at Sandia National Laboratories. This career included 18 years in the management of large-scale tests, test laboratories, and weapon and test system design. Aside from his full-time teaching position, he consults extensively for the aerospace and defense industry.