Research-Centric Project-Based Learning of Optomechanical Design

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Abstract

In the Spring Semester of 2011, Univ. of Central Florida's CREOL introduced an elective course in Optomechanical Design. In addition to homework assignments and exams, one component of the course grade was a design project. Rather than the traditional "assigned" project, the instructor experimented with a novel research-centric approach. Specifically, students were asked to select a project directly applicable to their graduate research. While challenging for the instructor to grade, student motivation and performance remained exceptionally high throughout the semester. This paper summarizes the background, projects, and pedagogical benefits of such a research-centric approach to project-based learning.

Background

George Polya, author of the classic mathematics book *How to Solve It*, once stated: “I have an old-fashioned idea about the aim of teaching. I believe the aim, first and foremost, is to teach young people to *think*. *Teaching to think* means that the teacher should not merely impart information, but should try to develop the ability to *use* this information” [1].

A number of innovative approaches to enhancing student learning, comprehension, and the ability to use the information being taught have been tried over the years [2]-[6]. More recently, design projects have captured the attention of the engineering educational community – and with good reason, as such projects typically provide solid hands-on experience with the beginning-to-end process of designing and assembling hardware.

The benefit of projects over conventional classroom lectures is motivated by the adage: “I hear and I forget; I see and I remember; I do and I understand.” That is, it is easy from listening to a lecture to think one understands the material, but it is not until the information is made concrete by using it does it become clear. Essential to the process, of course, are *concurrent* lectures providing the theory and conceptual background to what the students are “doing” – thus providing an integrated “hands-and-mind” approach to learning and discovery.

Polya describes this additional benefit of projects as that of active learning: “Learning should be active, not merely passive or receptive. Merely by looking at television or moving pictures, listening to lectures, or reading books, you can hardly learn anything…*The best way to learn anything is to discover it yourself*” [1].

The active learning found in the classic “egg drop” or “bridge building” projects in introductory engineering courses may prove motivational at the freshman and sophomore level; the relevance to “real-world” problems, however, becomes paramount to most students as they move into their junior and senior years. At this point, client-centric projects such as those employed by Olin College and Rose-Hulman have a significant pedagogical advantage, namely, the opportunity for the student to engineer “real things” [4]. As well, graduate students in the Design Division at Stanford University’s Dept. of Mechanical Engineering can select from a list of projects proposed by industrial clients – projects that in some cases result in products that are used by the clients in the commercial market.

While client-centric projects focused on solving customer problems can often be motivating, the process leaves little room for the student to obtain “entrepreneurial” experience in *defining the problem*. As is well known, defining the problem correctly is a key element of problem-based learning, and critical to obtaining a reasonable, working solution. Yet assigned projects leave out the pedagogical benefits of the students defining – or in Polya’s words, *discovering* through trial and error – the problem to be solved. As McWhorter states, problem definition “…is a view or attitude that is encouraged by leaving part of the laboratory course work…undefined. If the student has to decide what he wants to do and how…he will be better for it…” [1].

At the same time, there is no guarantee that client-centric projects will interest all. For example, some students may be extremely interested in an assigned or client-centric project on alignment mechanisms (as one possible topic in Optomechanical Design), while the other students may be less enthusiastic. Or in Polya’s words: “Learning should be active, yet the student without a motive will not act. What will induce the student to make the necessary effort? Is there something the teacher can do? Simple interest in the subject is surely the best stimulus, and the pleasure of success in intensive mental activity should be the best reward…There is nothing worse than starting with a problem that interests nobody” [1].

While “interests nobody” is an extreme case, assigned projects can often have this character, and secondary motives then become important: potential future need for using the information during employment, good grades, or approval from the instructor, other students, or an industrial client. Unfortunately, “simple interest in the subject” is often unsustainable without further encouragement, and it is not always the case that these secondary motives are sufficient.

Stated differently, there is nothing more motivating than trying to come to grips with a problem that one has “ownership” of, with “skin in the game” and a strong interest in seeing the problem solved. This is less likely to come from assigned projects; instead, there is a better chance it will come from course projects directly relevant to a research topic the student has already invested time in, namely, the PhD dissertation or MS thesis. It is of course possible that this is not the case – that the student has little interest in their dissertation or thesis – but the likelihood of that scenario is lower than that of dislike for a problem or project manufactured specifically for a course.

Finally, this previous investment of time pays off with the additional benefit of making the material concrete in a way an assigned or client-centric project cannot. That is, because the students are already familiar with the background and context of the problem they are looking to solve, they are more likely to make the connections and associations between what they are learning in the classroom and its utility, use, and applicability. As Lichtenberg states: “What you have been obliged to discover by yourself leaves a path in your mind which you can use again when the need arises” [1].

It is best, then – for reasons of learning how to discover and define problems, intrinsic motivation, and concrete connections with the material – to have the students choose a project that is of inherent interest to them. An obvious problem with this student-centric approach is that students don’t know enough about the course content to select a project that is reasonably challenging – or not overly difficult. Indeed, even choosing a project topic can be difficult if the material to be learned must first be understood!

So where are we to find projects that meet the characteristics of discovery, motivation, concreteness, and content? Through a project the students are already working on, and interested in – namely: their research for the MS or PhD degree. This is the basis for research-centric, project-based learning. The following section describes the details involved in implementing such a philosophy.

Research-Centric Projects

The goal of the Optomechanical Design course at CREOL was facility with applying basic optomechanical principles. As shown in Fig. 1, these principles include optical fabrication, alignment, structural design of mechanical and optical components, structural vibrations, thermal design, kinematic design, and optomechanical system analysis. A unique pedagogical aspect of the course lectures was to start the semester with a review of optical fundamentals, and show how these logically flow down into requirements on the optomechanical components.

In part, the basic understanding of concepts was obtained from lectures, homework, a mid-term and a (long and difficult!) final exam. As described in the previous section, these were augmented with a design project aimed at connecting the fundamentals together via Integrated Learning, using the highly-motivating goal of a research-centric project of the student’s choosing. In the paragraphs that follow, we look at the strategies and tactics for implementing such an approach.

The design project was proposed by each student in the first two weeks of classes. The proposed topic was vetted by the instructor, with each student interviewed one-on-one – in their labs, so the instructor could see their hardware – to decide on the project topic and scope. The intent was *not* for the instructor to push for a certain topic of interest to himself, but to insure that the topic was neither over- nor under-whelming for the student. Each student was assigned the task of Principal Investigator (PI) of their project, in that not just the project topics were research centric, but the methodology of organizing and managing them were as well.

1. Optical Fundamentals
2. Component Fabrication
3. Component Alignment
4. Structural Design
5. Thermal Design
6. Kinematic Design
7. System Design

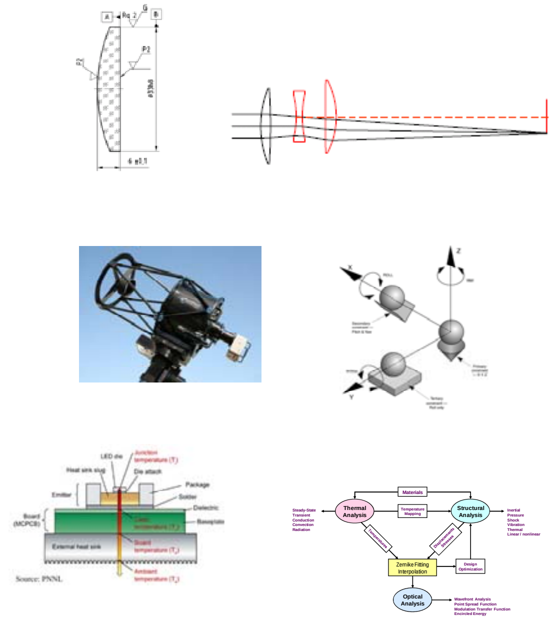

Figure 1 – Components of the Optomechanical Design course taught at CREOL.

Of the eight graduate students in the course, six selected topics directly applicable to their Ph.D. research. The other two students chose industry-related projects. One student selected a problem of inherent interest – not related to his Ph.D. research, but important to him as an entrepreneurial project potentially useful to industry. Another student working on a Master's degree selected a project relevant to her current position in industry as an optical engineer.

The first assignment for the course was a brief summary of the student's current research topic; an optomechanical emphasis was not required. This was followed in the second week of the course with an assignment to create a graphic: "*Project Assignment* – Make a Powerpoint (or other softcopy) sketch (1 page) of your project hardware; include critical optical and mechanical components. This sketch will likely change over the course of the semester, but the intent is to have a schematic diagram to communicate what your project is about to readers of your final report."

After the appropriate background material was developed in the lectures, this was followed in the 4th week of classes with: "*Project Assignment* – What are the critical components and parameters in your system? For next week's assignment, we will estimate the effects of changes in these parameters, but for this week, which components and parameters do you think have the most effect on system performance? List at least two components or parameters; include in your write-up at least one page of discussion as to why you chose the parameters you did."

As the lectures developed the necessary material on structural vibrations and thermal design in parallel with the project assignment, the final project direction was given with the following: "*Project Assignment* – Quantify the effects of changes in your critical parameters. For now, do not calculate *how* these changes come about; you will look at the effects of vibration and temperature changes on these parameters later on in the semester (see schedule below)."

PROJECT SCHEDULE:

1. Wed. Mar. 23 – Quantify the effects of changes in critical parameters
2. Wed. April 6 – Quantify the effects of vibrations on one critical parameter
3. Wed. April 20 – Quantify the effects of temperature changes on one critical parameter
4. Mon. April 25 – Final report due

For the Mar. 23 assignment, directions for the projects were provided in the form of suggested questions to be answered:

- Student 1 – What are the effects of changes in cavity length on linewidth? What are the effects of cavity-mirror tilt angle on cavity finesse and linewidth?

- Student 2 – What are the effects of tilt and decenter on the amount of light coupled in to the fiber coupler from the lens? What are the effects of despace on the amount of light coupled in to the fiber coupler from the lens?

- Student 3 – What is the stress at which the substrate will crack? What is the stress in a thin film bent by a plate (substrate) on which it is deposited? Is there a way to quantify the stress in the VO_2 film with the reduction of thermochromism?

- Student 4 – What are the effects of tilt and decenter of the objective on image motion? What are the effects of image motion on MTF?

- Student 5 – What are the effects of despace of the object-to-lens #1 distance on the accuracy of the basis that can be extracted? What are the effects of the DMD-to-lens #1 distance on the accuracy of the basis that can be extracted?

- Student 6 – What are the effects of changes in interference angle on fringe visibility or RIM? What are the effects of index changes across the aperture on fringe visibility or RIM?

- Student 7 – What are the effects of tilt and decenter of the test mirror on absolute system pointing angle? What are the effects of tilt and decenter of the beamsplitter on measured pointing angle of the test mirror?

- Student 8 – What are the effects of changes in the index of the Ti:Sapphire crystal on beam focusing? What are the effects of small changes in grating angle on pulse compression?

A series of assignments of increasing complexity were thus assigned to avoid the usual end-of-semester "crunch", where everything is due for every course at the same time, and learning goes to less than or equal to zero. Also note that the due date shown above for the final report was one week before finals started, to avoid reducing a student's time available for project completion (or studying for finals).

Unfortunately, the intermediate milestones in the project schedule above were assigned as voluntary. That is, they had a due date, but the students were not *required* to hand anything in. This was a mistake; as might be expected, the students who handed something in for the intermediate milestones had, at the end of the semester, a better final report. The next time this course is taught, these interim project assignments will be required, to be submitted in the format of customer reviews (with the instructor being the "customer", and the students the PIs responsible for the various design reviews of the type used in industry – PDRs, CDRs, etc. with specific due dates and positive consequences for meeting deliverables).

Also note that hardware was not required, though in many cases it was already being developed as part of the Ph.D. dissertation (Fig. 2). Nonetheless, for one of the industry projects the student spent their own money to develop a hardware demo – a great example of motivation and intellectual curiosity!

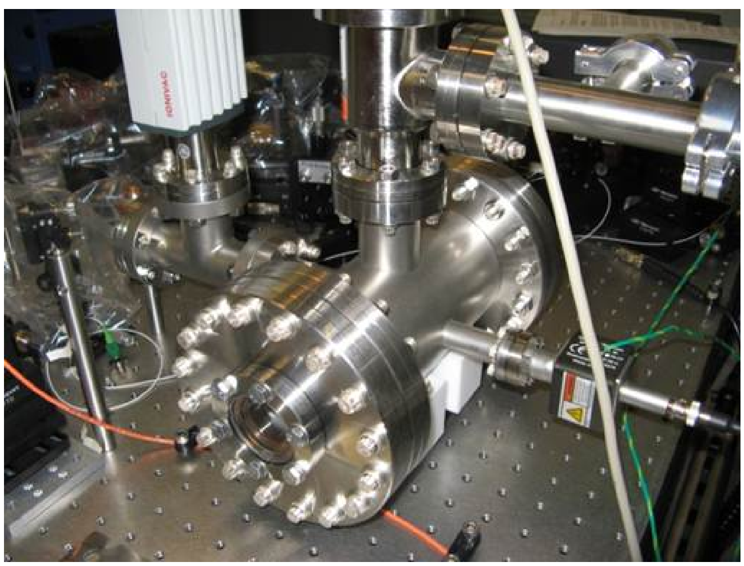

Figure 2 – A typical hardware setup for the types of research projects studied at CREOL.

Pedagogical Benefits

The primary benefit (or "outcome") of research-centric, project-based learning is an extremely high level of quality in the student's results. For example, the projects submitted by the students at CREOL were:

- Marcus Bagnell, “A study of the effect of vibration noise and its effect on the stability of a Fabry-Perot etalon reference for a narrow-linewidth laser system”

- Jeff D’Archangel, “Optomechanical design considerations in optical emission spectroscopy”

- Alexander W. Dillard, “Thermal oxidation of metallic vanadium as a method of fabricating thermochromic thin films of vanadium (IV) oxide on silicon and sapphire substrates”

- Kyle M. Douglass, “Effect of objective misalignment and vibrations on a wide-field optical microscope”

- M. S. Mills, “Exploring compressive imaging with the single-pixel camera”

- Dan Ott, “Critical parameters in the recording of volume Bragg gratings”

- Victoriya Relina, “Boresight retention of various mounting adhesives and methods under thermal changes”

- Benjamin Webb, “Optomechanical analysis of a Ti:Sapphire amplifier upgrade”

These range from topics on which Nobel prizes have been won to projects extremely important to industry. The quality of student effort for an introductory course in Optomechanical Design is clearly outstanding.

The reasons for the high quality were those motivating the use of research-centric projects, namely: learning how to discover and define problems, intrinsic motivation on a topic of interest to the student, and the opportunity to “connect the dots” with the material from the lectures. In addition, the students greatly appreciated having material they could add directly to their thesis or dissertation.

But there were pedagogical advantages for the instructor as well. The grading was of course a challenge, as the instructor stayed up late reading both the final reports and background papers on Pound-Drever-Hall stabilization techniques, Ti:Sapphire femtosecond lasers, and compressive sensing (among others), to understand the context and results of the student’s work. This was an obvious benefit, in that it gave the instructor the opportunity to learn about the many ongoing projects at CREOL, and think about how he might solve the student’s problems. As a disadvantage, the research-centric approach is only appropriate for graduate students with on-going research projects, in classes with small enrollments.

Summarizing by stepping back a bit from the details, we can identify a meta-theme of research-centric projects, a “big-picture” benefit outlined by Polya: “…your students…occasionally may learn more from your attitudes than from the subject matter presented" [1]. By encouraging student initiative, the attitudes in this case were best described by Maria Montessori: "There exists, then, the 'spirit' of the scientist, a thing far above his mere 'mechanical skill', and the scientist is at the height of his achievement when the spirit has triumphed over the mechanism. When he has reached this point, science will receive from him not only new revelations of nature, but philosophic syntheses of pure thought"[7]. By letting the student choose, then – within the appropriate bounds of difficulty and challenge – we are educating the "spirit", and not just the mechanism.

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