AC 2010-1240: ENHANCING THE UNDERGRADUATE DESIGN EXPERIENCE WITH SURFACE MOUNT SOLDERING AND PRINTED CIRCUIT BOARD TECHNIQUES

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Enhancing the Undergraduate Design Experience with Surface Mount Soldering and Printed Circuit Board Techniques

Abstract

In 2006, the Department of Electrical and Computer Engineering at Duke University rolled out extensive revisions to the undergraduate curriculum. One of the overarching goals of the curriculum reform was to provide students with practical experiences solving realistic challenges from their freshman introductory course through their senior design course. As a direct result of these curricular modifications, goal-oriented and design-focused projects have become the norm, rather than the exception. Within a year of the reform, students taking courses as part of the revised curriculum were designing projects using the very latest available integrated circuits and software. As student projects increased in sophistication, a growing need for state-of-the-art Surface Mount Technology (SMT) facilities and Printed Circuit Board (PCB) etching capabilities was recognized. To support these projects, an SMT facility with PCB etching capability was developed. The use of SMT and PCB etching techniques enables students to pursue much more complex and creative design projects using current, industry-standard technology. The introduction of SMT/PCB facilities has had a significant impact across the entire undergraduate curriculum, from sophomore year core courses through senior design projects, and has improved the overall educational experience and outcomes.

Introduction

Recent curriculum redesign in the Department of Electrical and Computer Engineering at Duke University funded by the National Science Foundation has focused on real-world problems as a means for the successful training of modern engineers. The redesigned curriculum provides our students with more opportunities for hands-on experiences in applying theory to practical applications.[1] Project-based learning is a central driver in this process which has been shown through prior work to motivate students to learn actively.[2] It has also been shown that introducing design projects in introductory courses increases motivation and creative thinking skills, especially when design is targeted toward realistic projects[3]. In addition, the introduction of extensive project assignments and discussion of design skills early and often in the curriculum serves to better prepare students for their capstone design projects in their senior year.[4]

Student surveys and focus groups conducted in conjunction with the ECE curriculum reform efforts indicated a desire for more project design and practical implementation opportunities. Similarly, feedback from industry has suggested that our students would benefit greatly from additional occasion to apply theory to practice through design projects. This feedback motivated a number of reform initiatives relevant to the SMT/PCB laboratory including: 1) developing a new, first-year introductory course with a significant design component, 2) revising the core curriculum, increasing the amount of design students encounter early in the curriculum, and 3) revising current, and offering new, design courses with an increased focus on realistic design, more sophisticated implementation techniques, and the continued development of skills such as project management and communication.

As a direct result of these curricular innovations and enhancements, students are now introduced to both the technical aspects of design and the associated project management concepts in the introductory ECE course.[5] Students have become more confident in their design abilities, which has led to more complex and sophisticated work in subsequent project-based courses. Upper-level electives, the majority of which had little project-based work previously, now further emphasize design and require physical space and specialized tools. Not surprisingly, senior capstone design courses, required of all graduates, place the greatest demand on our project facilities. In conjunction with the reforms, project complexity has increased and we have observed an increase in the need for more state-of-the-art tools and resources such as the SMT/PCB laboratory.

An expanded laboratory supporting the increasing number of students completing design projects and the shifting curricular emphasis toward more complex, team-based design became necessary. This required not only the addition of new facilities, but also a shift in the operation and availability of such facilities. Previously, only courses with a formal, supervised laboratory component were officially assigned laboratory space and hours. In general, students taking courses in which they completed a design project had to restrict their laboratory work to times when other, heavily used instructional laboratories were available. In addition, these students had no permanent work or storage space. Thus, each project had to be transported back and forth between a student's dorm room and the laboratory or left in an unprotected, highly-trafficked area where it could be inadvertently damaged. Because such projects were the exception, rather than the rule, it was relatively straightforward to accommodate the few students who required informal or unsupervised access to the laboratories. However, as the number of courses and students pursuing these projects increased, changes were needed.

As technology evolves, so must undergraduate training – especially the practical experiences provided in the laboratory. Surface mount devices are quickly gaining popularity in industry: consumer demand for personal electronic devices and their reduction in size with increases in performance have resulted in smaller silicon die sizes and packaging.[6] The smaller component sizes available as a result of small-outline integrated circuit (SOIC) packages results in more efficiently sized and lighter weight consumer electronics. In fact, many high density integrated circuits (IC) available today can only be found in SOIC packages due primarily to industry demand and technological advances. Thus, it has become both necessary and prudent to provide state-of-the-art SMT and Printed Circuit Board (PCB) fabrication laboratory facilities for undergraduate students.

Goals and Objectives

The goal of a newly developed SMT/PCB facility is to provide a state-of-the-art laboratory in which undergraduate students can perform experiments and build devices that deepen their understanding and abilities in the field of electrical and computer engineering. This requires an excellent physical infrastructure, dedicated technical support, stimulating intellectual content, innovative delivery of that content, and a vision for the overall integration of laboratories into the curriculum. Design projects are critical to the learning process because they provide a unique opportunity for students to integrate concepts from across the curriculum and to develop important skills such as project and team management and oral and written communication.

The goals of a facility equipped with precision surface-mount technology (SMT) soldering equipment and printed circuit board (PCB) manufacturing capabilities include:

- To increase opportunities for students to pursue complex and creative design projects,
- To give students hands-on experience with technology used in industrial environments,
- To enable students to complete the full design and implementation process by eliminating the need to outsource a key step of the process, and
- To encourage students with varying levels of experience to interact with and learn from each other.

ECE students enrolled in core courses as well as in upper-division design projects are able to complete their unique project designs in this space and benefit from being exposed to each other's work. The appeal of SMT and PCB etching at all levels of study creates the opportunity for graduate and undergraduate student interactions in this facility as well. Cross-departmental project work and sharing of tools, techniques, and equipment in this space also exists based on the similar printed circuit board etching needs in more than one department.

Laboratory Facilities & Support

Circuit design and project prototyping has at least three important design and build process steps: circuit board layout, soldering, and circuit prototyping. Final-stage circuit board construction involves the layout and etching of a printed circuit board. Such boards are designed using computer-aided software packages and typically sent to a foundry for manufacture. However, for small scale, limited quantity board design, the ability to etch circuit boards in-house provides a board of similar quality at lower cost and with a much quicker turn-around time. Etching a board in-house requires about 15 minutes of process time in the laboratory whereas sending a file to a foundry for etching typically requires a one-week turn-around. Soldering of circuit components to a finished board is the next step in completing an electrical circuit project. Precision surface-mount soldering capabilities must be used at this point to populate the board. Prototyping a final circuit project for manufacturing or demonstration requires workspace and tools for building and testing final circuits and assemblies.

Surface Mount Soldering Facilities

The lab contains two hot air SMD rework stations, models JBC AM6500 ($4,000) and JBC AM6850 ($4,000, Howard Electronics, Inc.). Both stations can perform conventional through-hole soldering as well as fine-tip SMT soldering. The stations allow for quick and simple IC attachment and detachment through the use of solder paste and a convenient hot air tool. The facility also features a mini-reflow oven (Figure 1(a)) for soldering an entire board at once through the oven reflow process. In contrast to the expensive (and very large) conventional reflow ovens used in industry, the lab utilizes a Cuisinart Toaster Oven/Broiler ($300, model TOB-165, 17" x 14" x 9-1/4") to approximate the manufacturer recommended thermoprofile for solder paste reflow. A conventional hotplate ($100, VWR) is available to provide a quick and convenient way to reflow entire smaller boards (Figure 1(b)). Lastly, a 7" bench top drill press ($1,700, McMaster-Carr, model no. 8929A21) in the laboratory facilitates through-hole drilling in the final etched board. This allows students to integrate surface-mount and through-hole technology in their projects.

(a) *(b)*

Figure 1. Circuit board reflow options available in the SMT/PCB facility: (a) Cuisinart TOB-165 toaster oven with thermocouple temperature gauge for larger area boards and (b) conventional hotplate ideal for reflowing boards of a smaller footprint

Printed Circuit Board Etching

In addition to the soldering stations, equipment and supplies are available so that PCB etching using pre-sensitized photolithographic copper clad boards ($350, MG Chemicals 416-series Exposure and Process kits, available from Allied Electronics) can be performed (Figure 2). This process involves layout software to design the circuit which is then printed on a transparency slide using a laser printer. The transparency containing all of the circuit board traces and pads is used to mask the pre-sensitized copper clad board during ultraviolet light exposure (the printer ink serves as the opaque masking material). Either a standard 100W incandescent light bulb mounted in a conventional desktop lamp stand or a 1 ft, T8 fluorescent light bulb installed in an under-the-cabinet lighting fixture provides the exposure source. A separate small, windowless room near the main SMT/PCB facility creates a suitable darkroom developing environment for board exposure and etching.

(a) *(b)*

Figure 2. Printed Circuit Board (PCB) etching (a) occurring in the dedicated PCB etching area of the SMT/PCB facility and (b) the final etched SMT circuit board

Additional Laboratory Facilities

The facility is also furnished with basic test and measurement instruments, including an oscilloscope, a multimeter, a function generator, and a power supply at three laboratory benches. Each laboratory bench includes a PC equipped with a GPIB card to interface with the test and measurement equipment. A networked laser printer is installed in the lab for use by all three benches. One specialty piece of equipment, an HEI stereozoom microscope with CCD camera, is available for PCB inspection ($3,000, Howard Electronics, Inc.). The microscope has digital imaging capability which allows students to capture images of their work for documentation and design review.

Other stocked items in the lab include a supply of pre-sensitized copper-clad printed circuit boards of various sizes, etching and developing chemicals, spray bottles, and safety equipment including smocks, gloves, and goggles. An assortment of standard surface mount resistors, capacitors, and inductors are also kept in the facility where students can access them for project work.

In addition to the above listed equipment, the laboratory also offers a design review area for regular project updates and feedback from colleagues and instructors. The design review area is outfitted with a projector and conference table. It is used by instructors and students during class and by project teams outside of class for the review and discussion of projects. The fixed projector in the lab is aimed at a whiteboard at the front of the room. The conference table, designed to seat ten, is kept small to support project and design activities.

Timeline

The set-up of the SMT/PCB facility was completed in three stages. Initially (Fall 2005), the facility was outfitted with only one surface mount soldering and rework station which included fine tip irons for SMT component soldering as well as a hot-air rework tool (JBC AM6500). As the lab's popularity and usage increased, a second, newer-model tool was purchased and installed in the lab in 2006 (JBC AM6850). At the same time, test and measurement equipment was set up so that students could troubleshoot and iterate their designs. Also, the design review area was established. Subsequently (in 2008), PCB etching capabilities were added allowing students to complete an SMT circuit from conceptual design to working prototype all in the same facility. The most recent purchase of a stereozoom microscope with CCD camera allows students to better visually inspect components for accurate placement as well as check solder joints immediately after reflow.

Laboratory support

Due to the specialized nature of the SMT/PCB facility, both instructional and technical support for students using the laboratory is needed. A one hour introduction to the laboratory, required of all students enrolled in courses that will use the space, is offered once every semester. In addition, several practical sessions to familiarize students with the facility are offered. A qualified staff member, who can dedicate two hours per week to supporting the facility, plus a trained student teaching assistant, who staffs the lab for ten hours per week, has proven to be an efficient model. The staff member provides the necessary oversight and departmental knowledge of the equipment and its capabilities, including laboratory safety and compliance with standards. The teaching assistant supervises the space while students work: orienting, assisting, and ensuring safe lab practices.

Integration of the Laboratory Facilities throughout the Curriculum

With the advent of the redesigned ECE curriculum, the number of courses with extensive hands-on, project-based content has increased dramatically over course offerings of just a few years ago. Whereas previously, students often did not encounter a design project until their senior year, they now have their first team design experience in the introductory course, *Fundamentals of Electrical and Computer Engineering*.[5] Subsequent core courses, usually taken in the sophomore year, emphasize design and circuit development in the laboratory. Both the *Microelectronic Devices and Circuits* and *Introduction to Digital System*s core curricular courses require students to complete a project from initial concept to complete fabrication in one semester. The result has been a dramatic transformation from theoretical courses with traditional, closed-ended laboratory experiences, to courses where the theory is put into immediate practice through hands-on design. Integration of design throughout the curriculum has now poised students to pursue much more sophisticated design projects in their curricular concentration electives and their capstone course. Figure 3 shows core, elective, and capstone courses currently making use of the SMT/PCB facility.

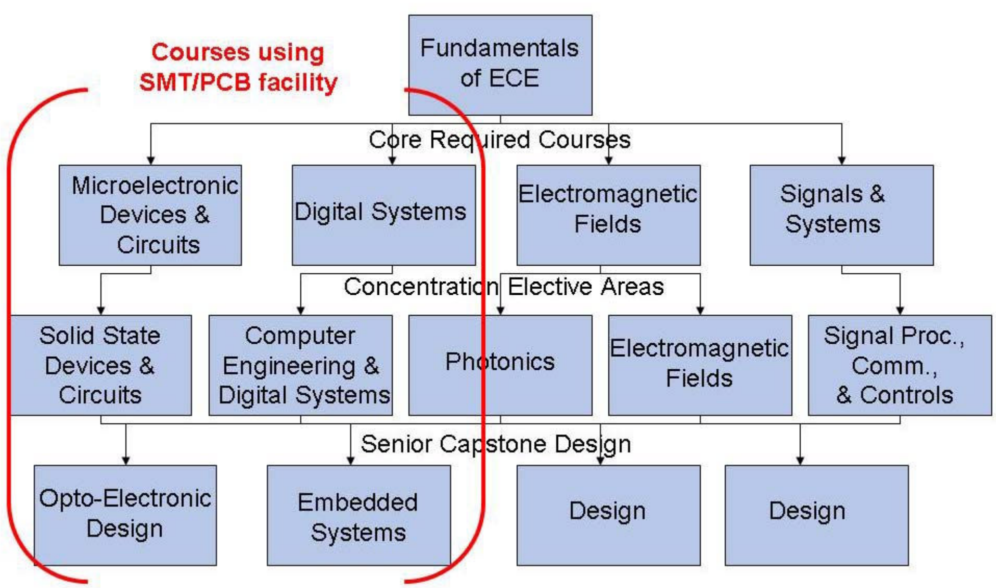


Figure 3. ECE Undergraduate curriculum with courses using SMT/PCB facility bracketed

Students are initially introduced to the SMT/PCB facility through core courses early in their ECE major. For example, in the core, sophomore-level undergraduate course, *Microelectronic Circuits and Devices*, students have benefited from the ability to choose surface-mount integrated circuits to complete their designs. Before the availability of the SMT/PCB laboratory, students were limited to primarily thru-hole component layouts, usually on a standard breadboard. Any surface-mount soldering, if needed, was done using bulky standard soldering tools, malformed for the purpose. As a result, the scope, practicality, and applications of the projects were quite limited. By comparison, in a recent iteration of the 6-week design experience in the course, students populated and soldered SMT components on a manufactured printed circuit board designed to perform wireless radio-frequency communication.[7] This board then formed the basis of unique team projects, such as an RF-controlled blimp (Figure 4).

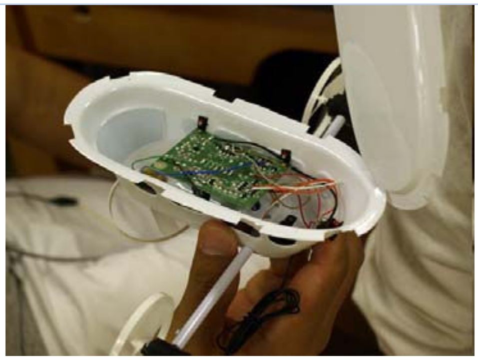
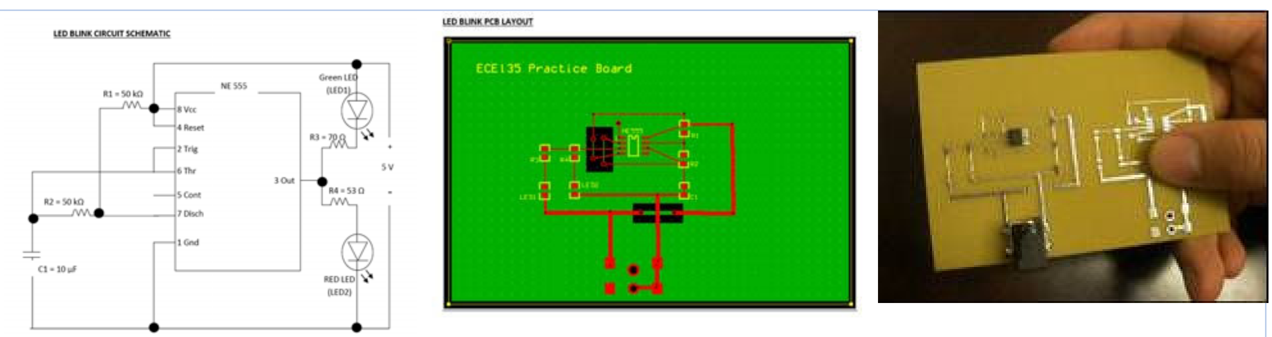


Figure 4. SMT reworked PCB for an electronically controlled blimp as part of the* Microelectronic Devices and Circuits *core undergraduate project-based course

The *Opto-Electronic Design Project* senior capstone design course utilizes the SMT facility to such an extent that it is now taught in a classroom adjacent to the facility itself. As early as their first week in class (after receiving safety training), students are asked to fabricate and test an SMT circuit on a pre-etched printed circuit board. Students implement a surface-mounted 555 timer blinking-LED circuit, beginning with the circuit schematic, through the PCB layout process, and finally to the actual board with soldered components (Figure 5). The goal being for students to gain confidence in their SMT soldering abilities and are more comfortable pursuing SMT designs later in the course. As a result, final design projects in the *Opto-Electronic Design Project* course all take advantage of the SMT soldering capabilities available in the SMT/PCB facility. One example of a final design project is shown in Figure 6. This project tested local water samples using infrared spectroscopy.



(a) ***(b)*** ***(c)***

Figure 5. SMT soldered 555 timer blinking LED circuit from (a) schematic to (b) PCB layout to (c) final SMT soldered board in the senior capstone* Opto-Electronic Design Project *course

Figure 6. IR spectroscope final design project soldered using tools available in the SMT facility as part of the senior capstone **Opto-Electronic Design Project** *course*

The availability of the SMT/PCB facility has also had a great impact on another senior design project course, *Embedded Systems Design*. Many of the integrated circuit packages suitable for embedded system design on the market today are available only in SOIC format. The SMT facility has made it feasible for such components to be used by students, thereby expanding their design options and solutions. Not only are final projects more sophisticated in their technical design, but the projects have also evolved such that the final products are much more compact and well-packaged. This is due, in part, to the availability of advanced manufacturing capabilities like SMT soldering in the laboratory. An example of a recent project in the course illustrating the more polished finish now typical of the final projects is shown in Figure 7.

Figure 7. SMT soldered finished design project in the **Embedded Systems Design** *senior capstone course*

The impact of the facility is not limited to senior design courses and other undergraduate courses. The graduate program also directly benefits from the SMT/PCB facility. Proof-of-concept research designs using surface mount or PCB technology are implemented in the laboratory in advance of groups investing in what can be one-off designs that may utilize hard-to-find or expensive components. Such work has included metamaterials circuit board etching, acoustic detection circuitry, high-frequency/small scale radar circuitry, optical waveguide circuit design, mobile telephony circuit construction, microelectronic semiconductor circuit layout and testing, and VLSI chip soldering and testing. It is not uncommon to find a graduate student using the SMT facility to work on an advanced circuit for a research project while an undergraduate student prepares to solder or rework a PCB of their own design. In this way, the laboratory serves as a venue where undergraduates are exposed to advanced, applied research. Such interactions between undergraduate and graduate students serve to motivate and inform undergraduates about cutting-edge research.

Other students come to the lab as a result of involvement in extracurricular engineering-related groups. The SMT/PCB facility sees regular work being performed by members of the Robotics Club, SmartHome, IEEE Student Chapter, and the Motorsports team. Outreach teaching programs use the lab in the development of new teaching aids for community instructors. A national teacher training organization, Project Lead the Way, has used the laboratory for course work and as an example of industrial and university facilities that might be used at the high school level.

Results and Evaluation

A large increase in the number of students and hours spent utilizing the SMT/PCB facility has been noted since the lab opened in 2005 (Figure 8). During its first year of availability, the laboratory witnessed a surge in student use, thereby making an immediate impact on the overall quality of hands-on learning and implementation of engineering skills in the curriculum. Specifically, two senior capstone design classes, *Introduction to Embedded Systems* and *Opto-Electronic Design Projects*, both found the laboratory to be invaluable for student project work. It is also worth noting that enrollment in these two courses has steadily increased with combined annual enrollments nearing 50 students. We attribute this success, in part, to the new opportunities to use state-of-the-art tools in the service of more complex projects and to develop project management and communication skills.

ECE students enrolled in core courses as well as in upper-level curricular electives and capstone senior design projects are now able to complete their unique project designs in the newly equipped SMT/PCB facility. Both students and their projects benefit from early exposure to state-of-the-art components and manufacturing techniques. The facility also enables higher quality and increased complexity of upper-level design course work. In this way, the SMT/PCB facility has contributed to the advancement of student projects.

The SMT/PCB facility has directly addressed the goals of the ECE departmental curriculum reform and ABET criteria. The impact of this project on the undergraduate engineering experience includes:

1. **Providing the physical resources necessary to support a greater number of student design projects**. Enrollment in courses using the design project laboratory, as well as the number of independent projects supported by the laboratory, has continued to grow. Student utilization has grown from 100 students using the lab in the 2005 academic year and logging 200 collective hours in the lab to nearly 250 students using the lab in the 2009 academic year and logging over 550 hours. Enrollment has grown in these courses from 75 students in the 2005 academic year to 97 students in the 2009 academic year.

2. **Providing access to state-of-the-art SMT soldering and circuit prototyping equipment that facilitates the completion of more complex and creative design projects.** The SMT/PCB facility is used by students in introductory core courses working on their first major design project all the way through to upper-level students in design courses. Early exposure to this state-of-the-art equipment is excellent training for students and facilitates the design of more complex projects.

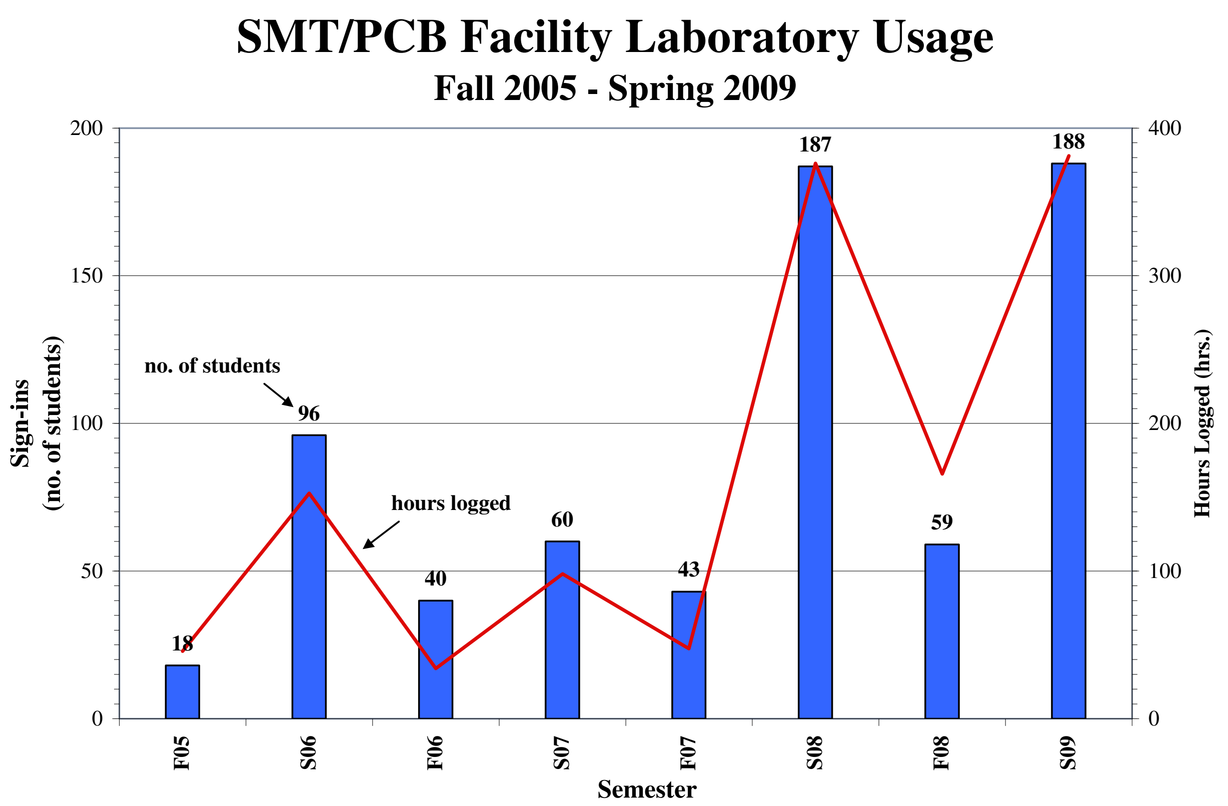


Figure 8. SMT/PCB facility usage Fall 2005 – Spring 2009

3. **Reducing the need to outsource PCB fabrication, thereby enabling students to have a more complete learning experience** by completing each step in the design process themselves. With the associated elimination of production delays, students are able to implement and test more iterations of their design, producing higher quality final products.

4. **Supporting the curricular initiative driving the development of more design courses and hands-on projects early in the curriculum**. The ECE curriculum introduces students to design in their first course and follows up with design projects in subsequent core and design courses. Theory is now put into immediate practice through many early opportunities for hands-on design. Integration of design throughout the curriculum also raises the level of student design projects in their senior capstone course.

5. **Encouraging interaction between students of different levels and experience** (e.g., Master's and undergraduate students; ECE and BME students) by providing a shared resource used for a variety of applications. Cross-departmental project work in this laboratory exist based on the similar SMT soldering and printed circuit board etching needs in other engineering departments, most notably biomedical and electrical and computer engineering. Collaboration amongst students working in the space happens naturally due to the nature of design projects.

Conclusions

Recent curriculum reforms, which aim to provide students with practical experiences solving realistic challenges from their freshman introductory course through their senior design course, have generated a need for an undergraduate-accessible prototyping facility. To meet this need, an SMT/PCB etching facility was created at Duke University in the Department of Electrical and Computer Engineering. SMT exposure as early as the sophomore year makes current technology accessible to students for use in subsequent elective and design courses. PCB etching capabilities in the lab give students a more complete learning experience where they are part of each step of the design process. Since its inception, utilization of the SMT prototyping facilities has increased annually, enabling students to complete the design cycle and generate more finished final products. With the more recent addition of in-house PCB etching capabilities, students are now be able to iterate their designs multiple times with more rapid turnaround than sending board designs out to be manufactured. Cross-departmental fertilization through project work using shared printed circuit board etching and SMT resources has also resulted in unique interdisciplinary collaboration amongst students and researchers.

Acknowledgments

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