An Electronics Prototyping Facility for Undergraduate Electronics Laboratories

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Introduction - Why an Electronics Prototyping Facility

Most electronic laboratory projects require building simple circuits that are torn apart as soon as the lab is over -- resulting in a limited opportunity for the students to construct anything useful. Students are often frustrated in electronics courses and laboratories as they never quite get to the level where they can design and build anything practical.[1] The CSM Electronics Prototyping Facility (EPF) provides students with the tools to design and build electronics equipment for real engineering applications. It is a powerful tool to reshape the way students learn and think about electronics.

The Electronics Prototyping Facility brings a vertical integration of design software, programmable devices and local (quick) printed circuit board fabrication that gives the users the ability to create prototype electronic circuit boards in a matter of hours instead of days; the use of programmable logic devices (PLDs) permits the modification of existing circuits in minutes. This has brought a capability to our undergraduate laboratories to design and construct circuits that used to be abstract problems because the implementation was too difficult or expensive. For the first time, the process of design and construction of a significant circuit on a high-quality printed circuit board becomes possible, economical and desirable for undergraduate education.[2]

The electronics industry uses concurrent engineering and other methods to improve productivity by breaking down the barriers between design and production.[3] However, concurrent engineering cannot remedy the basic problem -- many working electrical engineers have no training in electronics production methods. With limitations in time and equipment, electrical engineering four year degree programs concentrate on developing the fundamentals and theoretical understanding of their students. It has been my experience that graduating electrical engineers have a good understanding of electronics but lack the ability to take a design from concept to fabrication. When these engineers enter the workforce, they must then learn electronics production skills on the job and industry must cope with the resulting lower productivity. Given the needs of students and industry, it seems only natural that electrical engineering degree programs ought to give their students a basic preparation in production skills to enable their graduates to function better as working engineers. [4-7]

Educational objectives

To get the real benefit from this facility, we feel it is necessary to rethink the way we teach undergraduate electronics laboratories to emphasize the ties between design and fabrication and to develop modular electronic projects that build on each other in an appropriate manner. A previous paper discusses how our Junior level electronics classes make use of this EPF as part of our standard electronics laboratory instruction.[8]

Our specific educational objectives include the following:

(1) To familiarize the students with the manufacturing process for printed circuit boards and have them learn industry-standard software design tools used in the design and production of electronic systems

(2) To revitalize our electronics laboratories by providing a new means to “build up” from smaller modules to a significant system that re-enforces learning and design

(3) To enable the students the means and the practice of implementing their design and breakdown the barriers between theoretical understanding and practical implementation.

These are far reaching objectives and cannot be the result of one project. Rather, they are the cumulative result of sequence of projects throughout our electronics curriculum.

About the Electronics Prototyping Facility

The CSM Electronics Prototyping Facility brings together an integrated set of tools to give our students the ability to design, simulate, fabricate and test electronics systems. This facility was developed to better prepare our students to enter the workforce by giving them the basic hands on skills they need in electronics system fabrication.

Our facility is currently used in our Junior level electronics laboratories and is available for use in our Senior level classes, each with a class sizes of about 40-50 students. In order to achieve our educational goals, each student team designs and fabricates a unique circuit board for each project. This results in a high mix, low volume prototyping environment, quite different from typical manufacturing needs. Over the past year, our students have completed over 100 different PCB layouts and fabricated a total of 200-300 boards. As this facility continues to become mainstream in more our of electronics classes, the number of PCBs produced will increase.

The development of this vertical integration of hardware and software tools has required a substantial effort over several years. There are many methods to accomplish each of the tasks for electronics system fabrication. For each method there are a number of competing considerations including cost, safety, space requirements and feasibility in a university setting. Educators who are considering developing a similar facility will find this information valuable in selecting the appropriate set of tools for their site. The detailed fabrication steps for a typical laboratory project is shown as follows:

Electronic System Production Steps

<u>Step 1 Identify the problem</u>

Extract design specifications

Total time: Typical for laboratory projects is a few minutes

<u>Step 2 Analysis and initial design</u>

Consider details of implementation and tradeoff considerations

Simulate to verify performance

Netlist output

Total time: Typical for laboratory projects is about an hour

<u>Step 3 Schematic Capture / Documentation</u>

Part selection and set external interfaces

Netlist output

Total time: Typical for laboratory projects is less than one hour

<u>Step 4 PCB Layout</u>

Considering physical positioning, noise issues, connectors, access, etc.

Gerber and drill files output

Total time: Typical for laboratory projects is 2-3 hours

<u>Step 5 PCB Production:</u>

Method A: Commercial PCB board shop:

Modem Geber files to PCB board shop, pay for production

Total time: 1-7 days (depending on cost and complexity)

Method B: In-house chemical processing:

Drill PCB

Create PCB photomasks from Gerber files, cover PCB board with photoresist

Align mask onto PCB, expose photoresist, remove unexposed photoresist with stripper

Etch off copper not covered with photoresist. Remove all photoresist, clean PCB

Continue with other steps for multiple layers, plate-through holes, solder masks, silk-screening, etc.

Total time: 2-8 hours for one batch (1 to many) of PCBs

**** Method C: Mill/drill production of PCBs (used at CSM):**

Enter Gerber files to PCB preparation program for board preparation (isolation of traces, positioning, text, etc.)

Enter output of PCB preparation program to CAM program to control drilling/milling

Drill, mill (one or two sides), route out PCB board

Total time: 1-3 hours for 1 to a few PCBs

<u>Step 6 PCB Assembly</u>

Test PCBs (if necessary)

Manually populate with parts

Manual soldering, clean PCB

Total time: Typical for laboratory projects is 1-2 hours

<u>Step 7 Electronic system integration</u>

Test sub-systems for functionality

Connect sub-systems into a system and add user interface as necessary

Assembly into enclosure (optional)

Test system

Total time: Typical for laboratory projects is less than an hour

Total time for entire project: Typical for laboratory projects is about 9-12 hours using the Electronic Prototyping Facility

Function	CSM Electronics Prototyping Facility Tool	Pros	Cons
Simulation	Microsim Pspice (student version)	Free	Some limits, generally good for student projects
Schematic capture	Protel Schematic Capture	• Educational Discount • Full feature • Coupled to PCB Layout	No connections to circuit simulation, not industry standard
PCB Layout	Protel PCB Layout	• Educational Discount • Full feature • Coupled to Sch. Cap.	Not industry standard
Programmable Logic Devices	Altera MaxPlus2 and Logical Devices CUPL	• Educational grant • HDLs Industry accepted • Simplifies prototyping by allowing fewer ICs	• Time to teach • Cost and maintenance • Fine pitch ICs are hard to manual solder
Printed Circuit Board (PCB) Manufacture	T-Tech QC-7000 Mill/drill machine	• Local/quick PCB fab. • Good for single/double sided PCBs • Low cost per PCB • Traces/holes aligned	• High initial cost ($10-15k) • Space, dust issues • Additional software and board preparation tasks
Part Insertion	Manual	• Cheap/easy/quick	• Time, reliability issues
Soldering	Manual soldering Metcal SMT Stations	• Industry standard • High quality soldering experience	• High cost limits wide use • Lower cost stations are adequate for most projects
Inspection	Vision System Mantis optical inspection (stereo, wide view)	• Easy to use • Needed to see details (esp. surface mount)	• High cost • Not required for simple PCBs
Operational Testing	Standard laboratory bench test equipment (scopes, DVMs, etc.)	• Easy to use • Uses available equipment	Limited ability to test

Table I. A detailed description of our implementation of the main functions for the CSM Electronic Prototyping Facility.

Greater detail into the particular methods we use here at CSM to accomplish the various design/production functions previously mentioned is provided on Table I. For each function there are many possible methods/tools available on the market. A number of our choices were driven by cost -- some tools are used because we were able to receive substantial educational discounts and grants. Another issue is that all of our computers available for general use are personal computers, not workstations. Thus, the CAD/CAM tools we selected were constrained to run on personal computers.

The key step in the Electronics Prototyping Facility is the production of PCBs. This is the means from the circuit design/layout becomes a reality. There are a number of issues to consider in this selection process. First, a school/university environment is much different than a production facility. To get the benefit of hands-on instruction, each student must take their PCB through the production process. As a result, each student then must be trained to complete the production steps in a safe and timely manner. Additionally, the student projects tend to be very sporadic with a high demand for PCBs when projects are due. To alleviate this bottleneck we provide access to our facilities outside of the scheduled laboratory periods.

There are a number of methods to produce a printed circuit boards including using commercial board shops, various chemical means and mill/drill. Shown on Table II is a list of the standard methods with tradeoffs and costs for a school environment.

Method	Pros	Cons	Comments / Cost
Commercial production of PCBs	• High quality • Plate through holes, vias • Multi-layer • Lowest cost for many PCBs	• High cost for 1 to few of many different projects • Longer turn around than in-house	• No startup costs • Direct cost per boards: 1-sided, small PCB: $75-200 2-sided, medium PCB: $150-400 • No indirect costs
In-house facilities for photo-exposure, chemical etching and automated drilling	• Industry standard methods • Good for production of many of the same PCBs • Low cost in quantity	• Chemical handling: storage, safety, waste disposal • Large floor space needed (darkroom, etching tanks, etc.) • Difficult for students to control production processes ("art") • Drill alignment issues	• Good for production training • In use in a number of schools • Requires substantial maintenance • Startup cost of $2-10k for facility • Direct cost per boards: Single sided, small PCB: Few $ Double sided, medium PCB: Few $ • Indirect costs of chemical handling and space can be high
Use of pre-sensitized PCBs, photo-processing, manual drilling	• Low startup cost (~$100) • Easy to use	• High cost per cm^2 of PCB material • Chemical handling issues • Production "art" • Time and alignment issues in manual drilling	• Startup cost from $100-$1,000 • Direct cost per boards: Single sided, small PCB: $10+ Double sided, medium PCB: $20+ • Indirect cost per board depends on chemical disposal costs
Mill/drill machine	• Quick • Low $ per PCB • Alignment of holes and pads • Most tasks automated • Modest space & maintenance requirements	• High initial cost for machine and software • Must learn/use 2 new CAM programs • Dust removal • PCBs differ from industry standard • Harder to solder • Manual vias	• Best for prototyping, high mix • Startup cost from $10-20k • Direct cost per boards: Single sided, small PCB: Few $ Double sided, medium PCB: Few $ • Indirect cost per board depends on space and maintenance costs (relatively low)

Table II. Alternatives for printed circuit board manufacturing in a university environment. Costs assume PCB design is complete and labor is not included.

Most PCB fabrication methods use a significant amount of chemicals which leads to very real safety concerns given students are directly involved and issues in handling dangerous chemicals (acids with heavy metals, photoresist, etc.). With appropriate instruction, production of PCBs can be safely accomplished using this standard chemical method in a university setting as demonstrated by CalPoly[9] and others. Here at CSM, there is a high direct cost for chemical disposal and this was a major factor in the decision to acquire a mill/drill machine for PCB fabrication.

Electronic Prototyping Facility Components

The list below itemizes the major components in the CSM prototyping facility. A number of the vendors for these items offer educational support programs to help sponsor schools to acquire their products.

Space: One enclosed room of size 18 m^2 (200 ft^2) with outside venting.
Computers:

- One (1) 486-level PC dedicated to mill/drill machine control
- Two (2) dedicated P5-133s workstations for circuit simulation, PLDs, PCB layout, etc.
- Sixteen (16) shared "CAD Lab" (for general engineering use) 486-level computers for circuit simulation, PLDs, PCB layout, etc.

Special Software:

- Microsim's Pspice (free student version) for circuit simulation
- Protel's Schematic Capture and PCB Layout for dedicated workstations and CAD Lab computers (educational discount).
- Altera's MaxPlus2 PLD Toolset (education grant). Used for complex PLDs
- Logical Devices CUPL PLD Tools (educational grant). Used with simple PLDs (GALs).
- Gcode's Isolator for PCB preparation for CAM (sold through T-Tech, Inc.)
- T-Tech's CAM program for control of mill/drill machine (free with machine)

Hardware

- One (1) T-Tech, Inc. QC-7000 Mill/drill machine with vacuum/filter to remove dust
- Three (3) Metcal surface mount solder stations (educational discount) for high quality soldering/fine pitch plus various standard low cost soldering stations
- One (1) Vision System "Mantis" optical inspection station for PCBs, soldering, etc.

Miscellaneous

- Workbenches and various handtools, drill bits, PCB material
- Resistors, capacitors, inductors, logic devices, etc.
- Tables, cabinets, chairs

Summary

We have developed a new type of electronics prototyping facility to provide our students the tools they need to fabricate electronic systems. This facility is a vertical integration of software design/simulation tools with the means to produce printed circuit boards and then assemble/test the system. This facility has been used as a standard part of our electronics laboratories and student projects. Using this facility our students have constructed projects ranging from simple power supplies to RF communication systems to complex data acquisition systems. The students not only learn key skills in electronics production, but also benefit from the satisfaction of designing, building and using several working electronic systems. The enthusiastic response from both the students and industry employers indicates this approach may be of interest to other sites.

There are a number of challenges still ahead. One of the drawbacks is the substantial investment in time to train the students. We are looking at developing on-line computer tutorials, videos, etc. to aid in the instruction process. One very import trend to note is the rapid movement by the electronics industry towards surface mount devices. It is more difficult to handle surface mount than standard through-hole parts because of the finer track sizes/spaces and we are exploring ways to best deal with that issue here.

Based on my discussions with industry employers and my own experience, I believe it is important for students to graduate with the knowledge on how to make their designs become a reality. Without sacrificing other aspects of their education, we are able to improve our students learning experience and make it more relevant to their future needs as working engineers through the use of our prototyping facility.

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[9] CalPoly's Industrial Engineering Program facilities include a chemical PCB facility, sheet metal shop and NC mills for prototyping of electrical/mechanical systems

Bibliographic Information

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In addition to his research in power electronics, Dr. Braun has been working for several years towards a new approach in teaching electronics to students. In this approach, students would acquire the practical skills they need to fabricate their electronic system designs. He can be reached at cbraun@mines.edu for questions or comments.

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Vendor List, including some alternative sources:

PCB prototype fabrication:

T-Tech, Inc. 5591-B New Peachtree Rd., Atlanta, GA 30341. (770) 455-0676
LPKF Systems Inc. PO Box 6209, Beaverton, OR. 97007. (800) 345-5753
DirectImaging 2 Technology Dr., Airport Business Park, West Lebanon, NH 03784. (603) 298-8383

PCB CAD Tools:

Protel Technology, Inc. 4675 Stevens Creek Blvd. Suite 200, Santa Clara, CA 95051. (800) 544-4186
Accel Technologies (TangoPro) 6825 Flanders Dr., San Diego, CA 92121-2986. (800) 488-0680
OrCAD, Inc. 9300 SW Nimbus, Beaverton, OR 97005. (503) 671-9501
Mentor Graphics 8005 S.W. Boeckman Road, Wilsonville, Oregon 97070-7777. (800) 547-3000.

PLD Tools:

Altera Corporation 2610 Orchard Parkway, San Jose, CA 95134-2020. (408) 984-2800
Logical Devices 130 Capital Dr. Suite A&B, Golden, CO 80401. (303) 279-6868

Soldering Stations:

Metcal 1530 O'Brien Dr., Menlo Park, CA 94025. (800)-776-1778
Pace, Inc. 9893 Brewers Court, Laurel, MD 20723-1990. (301) 490-9860
OK Industries Inc., 4 Executive Plaza, Yonkers, NY 10701. (914) 969-6800

Optical inspection stations:

Vision Engineering, Inc., 745 W. Taft Ave., Orange, CA 92665. (714) 974-6966
Nikon Inc. Instrumentation Group, 1600 Corporate Court, Irving, TX 75038. (214) 550-0046

Distributors of PCB and related equipment:

Marshall Industries, Inc. 9320 Telstar Ave., El Monte, CA 91731. (303) 457-2899
The EMF Company, 6135 W. Belmont Ave., Chicago, IL 60634. (800) 621-0080