A Closer Look at Printed Circuit Board Milling

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Abstract

Several schools have recently incorporated printed circuit board (PCB) mills into EE/EET education as a means of producing PCB's in-house. Compared to breadboards or protoboards, the obvious benefit of the milling technology is the ability to build circuits with more robustness and permanence. Compared to commercial board manufacturers, PCB milling offers quicker turnaround and lower per-board cost. Previous papers have described how PCB mills have been integrated into the curriculum, but there has not been any detailed comparison of the tradeoffs between in-house milling and commercial manufacturing. In this paper we draw upon our experiences in using both circuit board milling and commercial PCB manufacturing for several student design projects. We compare costs, circuit board quality and ease of assembly, faculty time investment, support issues, and most importantly, how the two approaches to PCB construction fundamentally affect engineering instruction. We have identified several disadvantages of PCB milling, including high initial cost, more complex board layout and routing, and consequent limits on circuit complexity. We have also been surprised by some unexpected advantages of PCB milling, such as higher modularity in project designs and greater risk-taking. Our goal is to provide the benefit of experience to schools considering an investment in PCB milling.

1. Introduction

Students have two broad options for constructing electronic circuits: i) prototyping methods, including breadboards, wirewrap, and protoboards, and ii) circuit boards with soldered components. Circuit boards are most suitable for projects that are too complex for breadboards or require some degree of permanence, reliability, compactness, or required shape. The design of a circuit board (placement, layout, and routing) also affords the students exposure to modern CAD tools that are prevalent in the industry but are not applicable to the prototyping approaches.

In our junior level course on digital design, we incorporate a semester-long project culminating in a circuit board realization of a student team's circuit design. We initially used a commercial board manufacturer that was capable of producing inexpensive bare boards. Recently we purchased a circuit board mill in order to produce bare boards in-house. In this paper we compare these two methods of board fabrication. We provide a brief look at the details of circuit board milling and how it differs from commercial fabrication. We also discuss the impact that a circuit board mill has had on student learning, both in our courses and in other projects.

We are assuming that the circuit boards that need to be fabricated are at most two-layer boards, have low-to-moderate density, comprise mainly through-hole components, will be populated and soldered by hand, and are needed in only small quantities. We expect that these assumptions are consistent with the needs of most EE/EET departments for instructional use.

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2. Overview of Commercial Board Fabrication

Having circuit boards fabricated by a commercial manufacturer is a fairly simple process that requires the electronic submission of Gerber (i.e., RS274X) files for artwork, a drill drawing, an Excellon drill file, and any special instructions. Modern CAD programs are capable of generating these files automatically from a board layout. Other files and file formats may be involved (for example, solder mask or silkscreen) depending upon the board manufacturer, and some manufacturers directly accept saved workspaces from popular CAD programs. Prices vary depending upon the required turnaround time, the number of board layers, the board area, the number and variety of drills, whether or not silkscreen and solder mask are included, and so on. Feature widths of 0.008” are commonly supported.

As an example, we had two 3”x4” two-layer boards fabricated for approximately $65 with a two-day turnaround. These boards were through-hole plated but did not have silkscreen or solder mask. Several circuit board manufacturers[1,2,3] serving the low-volume prototype market are listed in the bibliography.

3. Overview of Circuit Board Milling

We describe the process of circuit board milling from experience with our own system (an LPKF Protomat C30/s[4]). While some details may differ between systems (for example, T-Tech offers a comparable milling system[5]), the essential processes are the same.

A circuit board mill is essentially a three-axis plotter in that the “plotting head” is capable of fine-grain movement in the X-Y plane, and may also be lifted up or pressed down. Since this is a mill, the “plotting head” is actually a high-speed motor that is fitted with either a router bit or a drill bit. For creating copper traces, a router bit is used. The router is pressed down onto the surface of copper-clad board and is then moved in the X-Y plane. As it moves, the router removes copper thus creating an *isolation channel*. A copper trace is created (or, more precisely, left behind) when two isolation channels are milled on either side. See Figure 3.1 for an example of a trace created by milling and a photograph of a typical circuit board mill. The latter shows the three main components of a milling system: the mill, the controlling computer, and a vacuum machine.

The holes in the circuit board are created by replacing the router bit with a drill bit. The drill bit is moved (with the milling head up) to the desired X-Y position, then the head is pressed down briefly then released. A variety of drill bit sizes are used depending upon the needs of the circuit board.

The milling process begins with the same files described in Section 2. That is, Gerber files for artwork and an Excellon file for drill information. Specialized *isolation software* (included with the mill) converts these files into a set of instructions that indicate where the mill should travel in order to leave behind copper in the desired places (and also where the mill head is to drill holes). A separate *mill controller program* (also included with the mill) reads these instructions and sends commands to the mill over a serial connection to actually move the head, start the motor, etc.

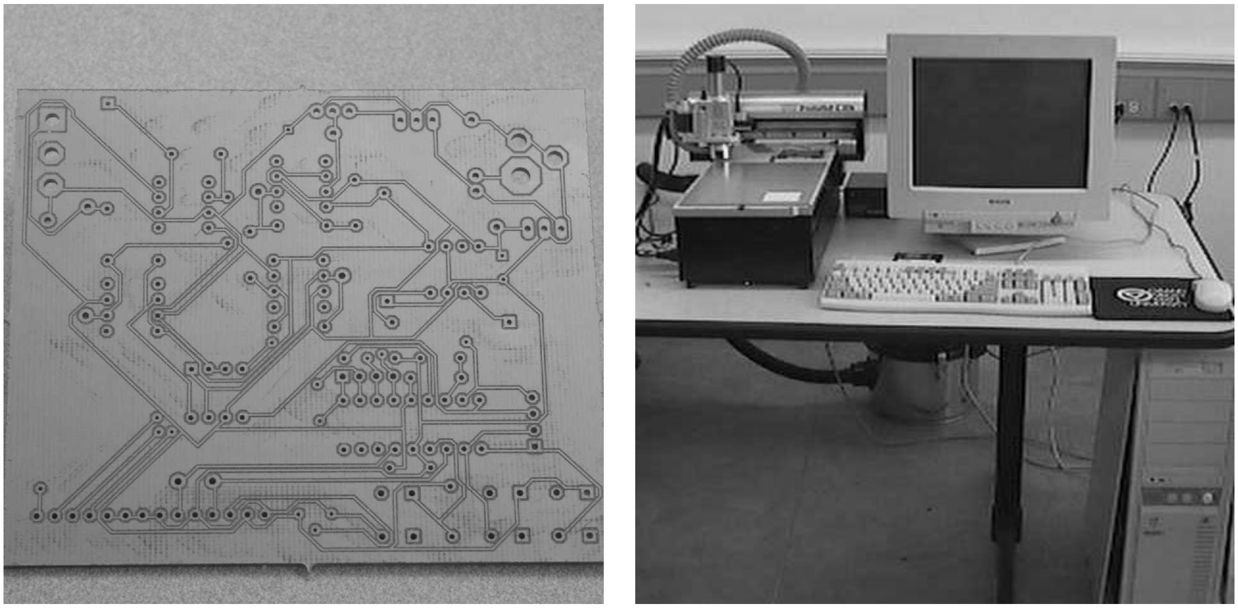

Figure 3.1: The photograph on the left shows the bottom layer of a typical milled board. The photograph on the right shows our milling system. The mill (left) is controlled by a PC computer via a standard serial port connection. The vacuum system is partially visible under the table. Not shown are the supplies (boards, drill bits, etc.) that occupy additional space to the left of the mill.

In theory, then, there is no difference in the CAD process with respect to the interface between the designer and the manufacturer or mill; the CAD files are the same. In practice, the milling process does reach down to the design level (as we discuss below). A designer will need to be aware from the beginning whether the board will be manufactured commercially or milled.

4. Comparison of milling vs. fabrication

For the EE/EET department considering the purchase of a circuit board mill, we believe it is useful to compare the processes of milling against commercial fabrication.

4.1 Per-board costs

A major benefit of in-house milling is that milled boards are very inexpensive, if fixed costs are not considered (i.e., cost of the mill itself, cost of maintenance, etc.). For example, assuming a 3”x3” board that requires 7.5 metres of mill head travel, we estimate the cost of this board (in actual board usage and router bit wear) to be $14.50. This does not include wear on drill bits, cost of vacuum bags, etc. as these have negligible per-board costs. The cost for milling a board, then, is much lower than the approximately $65 that it costs to have a board commercially fabricated (of prototype quality). The end result is that there is much less pressure on students to not make mistakes. If a board design has been so badly implemented, the cost for milling a new board is only a few dollars and some time for the mill operator (perhaps even the student).

This decreased emphasis on achieving a 100% correct board design has two benefits. Firstly, it allows students to spend less time checking the board design and spend more time on the schematic and other aspects of the design. Secondly, circuit boards that do have errors provide a concrete learning opportunity for students: they appreciate first-hand the necessity for careful, correct work as the cost of post-fabrication fixes is much larger than the cost of making sure it is right the first time. In our experience, no number of admonitions to work carefully, check all pinouts, spot-check routed connections, etc. is as good a motivation to do good work as is a board that needs several cuts and jumpers in order to fix sloppy work. If the board is truly unsalvageable, the cost of milling another is small.

Another benefit of low per-board cost is that students appear more likely to take risks. When we used a commercial fabrication process, we clearly told the students that they had only one opportunity to get it right since we simply couldn't afford to have multiple boards fabricated. Students, then, were very cautious, and understandably so. With in-house milling, some students chose riskier (and more interesting!) projects because the cost of failure was simply some redesign and another milling pass.

4.2 Other costs

With the assumed per-board costs detailed above ($14.50 for milling, $65 for commercial fabrication) it would require the milling of over 200 boards for the savings to recover the initial cost of the mill ($9100). Whether or not a circuit board mill is a wise financial investment clearly depends upon the board making needs and habits of a particular department, as well as the nature of the funding for the mill.

The largest recurring costs of a circuit board mill are likely to be a yearly warranty contract ($910), copper-clad boards and backings ($110 for a package of 10), and router bits ($170 for a package of 10).

4.3 Through-hole plating

Perhaps the most significant difference between circuit board milling and commercial fabrication is the issue of through-hole plating. A two-layer board with plated through-holes has two major benefits: vias do not need to be manually soldered and device pins act as vias. The first benefit represents a savings in soldering time and effort, but the latter benefit can fundamentally affect the design of the board. When a device pin is not a via, it must be soldered on the solder side of the board (unless the device package lends itself to component-side soldering, e.g., resistors, capacitors, etc.). For single-layer boards, this is not an issue. For two-layer boards, this restriction can greatly increase the number of vias that are required and thereby decrease the routability of the board. The end result is that boards without through-hole plating are limited in complexity for a given size.

The lack of a through-hole plating process should be considered at the design stage. A dense board layout may not be achievable without a high number of vias. Also, the CAD program being used must be able to support autorouting without the assumption of through-hole plating. For example, the Eagle CAD program we use[7] can not be directly instructed to route on two layers but not route directly to device pins on the top layer. Fortunately, this program allows user scripts to be written to directly manipulate the CAD data. We had to write such a script to place “restriction circles” above each device pin on the top layer to forbid the autorouter from making a connection there and forcing it to use a via to switch layers. While workable, this represents an extra step in the design process and generally increased complexity (e.g., greater autorouting time).

Our mill manufacturer (LPKF) offers three options for implementing a through-hole plating process. We have not purchased any of these process components thus only briefly discuss their capabilities. One method presses copper bails into each hole and then solders them. This method is intended for a small number of holes and is fairly slow (two bails per minute). Another method uses conductive paste that is injected into each hole (using the same milling machine) and then removed to leave a paste residue. This residue then hardens into a thin conductive layer after baking at 160°C for 45 minutes. This method is intended to be faster and to plate more holes than the copper bail process. Finally, an electroplating process using several chemical baths is offered. This process can be used to plate any number of holes but requires up to 2 hours of processing time. The process also requires some fairly expensive chemicals, as well as proper disposal of these chemicals.

Before investing in a circuit board mill, it is important to consider the boardmaking needs of the department (i.e., will high-density boards be commonplace?) and determine whether an additional investment should be made in a plating process, or whether commercial manufacture is the best alternative.

4.4 Breadboarding support

A benefit of having an in-house mill is the ability to create inexpensive circuit boards for use in a variety of courses. For example, in our course on Dynamic Systems (a course only taken by Mechanical Engineering students), the LM675 high-current op-amp is used in a motor control laboratory, but the pins of this device are not on 0.1” centers. This makes the device not suitable for breadboarding in the laboratory. It was a simple matter to design and mill adapter boards that provided an interface between the pins of the LM675 and a single-row connector with 0.1” centers that could be inserted into a breadboard.

4.5 Modular circuit design

Another benefit of low per-board cost is that a student project can be partitioned over multiple boards without additional expense. One recent student project used three small circuit boards to implement an RPM meter for a motor shaft. This project had one circuit board with a reflective photosensor mounted to it, along with the detector logic. Another circuit board had an LCD display and connector mounted to it (for remote display). The third circuit board comprised the main logic for the system. Multi-board systems such as these would be discouraged when each board incurs fabrication cost with a commercial manufacturer.

Another student project involved the use of a high-quality analog-to-digital converter interacting with a microcontroller-based design. The latter part of the design was complete and well understood but the students were not confident in the analog-to-digital converter and associated circuitry. The students decided to build a circuit board with a connector instead of the A/D converter circuitry and later build a separate board with the A/D converter that could be plugged in to the connector. This allowed them to experiment with the A/D design and replace it with a different design if necessary. This modular approach to their design allowed them to proceed with both hardware and software development even when they were not yet completely confident in one part of their design.

Dividing a circuit into separate, connecting parts (as in the above example) is a method of managing riskier projects (which we mentioned in Section 4.1 are more likely to be pursued when per-board costs are low). The cost of using commercial fabrication for this approach, however, would have been nearly double the cost of a single board. With in-house milling, the additional cost of the modularized design was negligible.

4.6 Turnaround time

From the time that CAD files are sent to a commercial manufacturer to the time boards are received can be as short as 2 working days. The time to mill in-house, however, is approximately 1 hour. This reduced turnaround time opens up some interesting possibilities in instruction. We are considering a single 3-hour laboratory in which students design a (simple!) circuit, perform the board layout and routing, then all designs are milled as a group. After soldering, students have a physical realization of their design, along with an appreciation for the design-layout-mill process. This type of laboratory would still be possible with commercial manufacture but it would require a break of a few days in the laboratory until the boards were received, plus the cost may be prohibitive.

4.7 Ease of soldering

We have found commercially fabricated boards to be slightly easier to solder. This is owing to two factors: these boards are tin plated and they do not have the large areas of copper remaining on milled boards. Tin plating can be applied to milled boards prior to soldering for fairly low cost, but this represents an extra process step and additional time expense. The large copper areas on a milled board present opportunities for solder bridges. These copper areas can be removed with an extra milling step known as *rubout* in which a special end mill removes wide swaths of copper. The rubout process, however, incurs extra milling time and extra cost as the end mills are quickly worn out and are relatively expensive.

4.8 Process availability

A benefit of commercial board manufacturers is that they are always available, and even if one is not, others are. A circuit board mill may need repair, which may require shipment of the unit to and from the manufacturer. This can lead to a delay of days or even weeks (in addition to the cost of shipping, which is not insignificant for a heavy yet delicate unit). If Murphy's Law applies, the mill will fail at the worst possible time and student projects waiting for completion will be stalled.

If a circuit board mill is a central resource for a course, the instructor must consider carefully the consequences of mill failure at a critical time in the course.

4.9 Silkscreens and solder mask

The processes of applying silkscreen and solder mask are separate from milling. Some commercial manufacturers offer these options. If these additional process steps are required, commercial manufacture is the preferred solution (unless in-house facilities for applying silkscreen and solder mask exist). Note that a form of solder mask is possible using a process that mills out holes from a special foil[9].

4.10 Project support

A circuit board mill can support departments outside of EE/EET and find other uses supporting student projects where commercial milling costs may be too high. Our mill has been used to construct circuits for extracurricular student activities, such as the Solar Boat competition and the Firefighting Robot competition. In this role, the circuit board mill enhances the quality of student education outside of the classroom and increases the level of service and recognition of the EE/EET department.

4.11 Time investment

The degree of time investment by faculty and laboratory support personnel must be considered. Circuit board milling requires knowledge and experience with the operation and interaction of three separate software programs (CAD program, isolation program, milling control program) and a new hardware device (the mill itself, which may be a very unfamiliar form of equipment for EE/EET faculty, such as the author of this paper). A circuit board mill is by no means "plug and play". The department purchasing a mill must consider carefully where the expertise for operating the mill will reside and who will be responsible for operating the mill. Faculty time commitments must be balanced against continuity of knowledge, the time it takes to train students on the software and hardware, the potential for damaging the equipment, etc.

5. Conclusions

We have presented several details of circuit board milling that will hopefully be of use to the department considering an investment in circuit board milling. This investment, we have argued, should be in an improved learning experience for the students, not in cost, as hundreds of boards need to be milled for solely the purchase price of the mill to be recovered. The major benefits of the circuit board mill are low per-board cost (encouraging modular project designs, higher-risk projects, and supporting extracurricular activities), and turnaround time on the order of hours instead of days. The drawbacks of circuit board milling are lower allowable board density (unless through-hole plating equipment is also purchased), high initial cost, lack of silkscreen and solder mask (and slightly more difficult soldering), and service interruptions during repair. In Table 5.1 below we summarize the main points from Section 4.

In our case, the investment in the circuit board mill has been a positive experience. Despite the drawbacks listed above, we firmly believe that our students have derived benefit from in-house milling capabilities and that the investment (in time and money) was well worthwhile.

Table 5.1: Summary comparison of circuit board milling vs. commercial fabrication

Factor	Advantage for Circuit Board Milling	Advantage for Commercial Fabrication
Per-board costs	Approximately $14.50 rather than $65	
Other costs		No initial mill cost ($9100) and no costs for milling supplies.
Through-hole plating		Commonly available, enables greater board density
Breadboarding support	Inexpensive way to support non-standard pin spacings for breadboards	
Modular circuit design	Modular circuits are more cost effective and less risky	
Turnaround time	One hour instead of two days	
Ease of soldering		Tin plating and less residual copper improves solderability
Process availability		Always available, does not have down time for machine service or repair
Silkscreens/solder mask		Easily available (possibly for extra cost)
Project support	Easy to support extra-curricular and extra-departmental projects	
Time investment		No need to support equipment/software and lower learning curve

6. Acknowledgments

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