2006-1056: AN L/C METER PROJECT PROVIDES A CAPSTONE EXPERIENCE IN TOPICS OF APPLIED DESIGN COURSE

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An L/C Meter Project Provides a Capstone Design Experience
in Topics of Applied Design Course

Abstract

This paper focuses on both the analog and digital facets of an inductance-capacitance (LC) Meter Project designed as a capstone experience for pre-junior students in Electrical and Computer Engineering Technology at the University of Cincinnati. The capstone LC Meter Project is structured to support the course goals and objectives of "Topics of Applied Design" offered at the beginning of the junior year. The paper presents the analog and digital components of the "LC Meter concept" together with the theory of operation. A secondary goal of the project is to prepare students for the upcoming Senior Design Capstone Experience required for a baccalaureate degree in engineering technology. To this end, students are required to implement a product packaging concept and maintain a project journal to record ideas, data, test results, and experiences throughout the project. To date, student feedback on this project has been very positive and a representative selection of student comments is included in the paper.

Introduction

The course "Topics of Applied Design" is offered autumn quarter of the junior year for students in Electrical and Computer Engineering Technology at the University of Cincinnati. Prerequisites for the course include three course sequences in electronics, electric circuits, and digital electronics. The third course in digital electronics is a course in assembly language programming. In essence, students have completed the requirements for an associate degree in engineering technology. The primary focus at the beginning of the junior year is to introduce students to a course in applied design utilizing a "capstone project" as a learning vehicle to bring together concepts previously introduced in both analog and digital electronics.

The analog component of the project consists of a 500 kHz oscillator implemented with an LM311 comparator integrated circuit, together with an LC "tank circuit" formed with inductance and capacitance elements that determine the oscillating frequency. At the outset of the course students are presented with a set of equations that characterize the unknown element, L or C, via a change in oscillator frequency. Initially hand calculations for the unknown L or C are encouraged. Subsequently, students are required to modify an existing Visual Basic program in order to rapidly implement solutions for unknown inductance or capacitance values. A group of 5% silver-mica capacitors are measured with a known standard instrument and the results are compared with the "frequency-shifted oscillator method." These measurements are tabulated and "percent error" is used as a figure of merit for accuracy comparison.

The digital component of the project features an Atmel AVR AT90S2313 microcontroller programmed in assembly language to determine the oscillator frequency and to compute the value of the inductor or capacitor under test. Finally, the paper discusses the project prototype which is constructed using "Manhattan Style" building techniques described by Adams [1]. This technique consists of gluing isolated pads of printed circuit board material to a base copper-clad

board and then arranging and soldering circuit components to build a functional circuit. Students are also required to develop a printed circuit board layout of the project using ExpressPCB software [2]. The assembly time for the electronic components required approximately four hours with a total project cost, excluding the enclosure and printed circuit board, being $12.56.

Theory of Operation

This section presents an overview of the analog portion of the LC Meter specifically highlighting the operation of the frequency-shifted oscillator. The oscillator operation is based on an LM311 voltage comparator shown in Figure 1. When power is applied to the comparator circuit, the voltage at pin 2 is 2.5 volts causing the output to be at a level of 5 volts. This charges capacitor C_4 through resistor R_5 until the voltage at pin 3 equals 2.5 volts. As the voltage reaches 2.5 volts the circuit switches to a low level inducing a transient into the "tank circuit" composed of L_1 and C_1. The ringing causes a square wave at the LC "tank circuit" resonant frequency to appear at pin 7, the output of the voltage comparator. To sustain oscillation the square wave voltage is coupled back to the tuned circuit via circuit components R_3 and C_3. The usefulness of the "frequency-shifted oscillator method" is dependent on a single calibrating capacitor and a calibration procedure is required prior to using the technique.

Calibration Equations

During initial calibration L_1 and C_1 form a parallel resonant circuit coupled to the non-inverting input of the LM311 by a 10 µF electrolytic capacitor as shown in Figure 1. For parallel resonance the oscillation frequency is given by the familiar formula from circuit theory.

$$F_1 = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{1}$$

A nominal resonant frequency, F_1, with the values shown in Figure 1 is measured to be 503.027 kHz. The values of C_1 and L_1 shown in equation (1) contain stray capacitance and inductance and differ from the practical values shown in Figure 1. In order to determine the effective values of C_1 and L_1 two equations are required.

A measured calibration capacitance, Co, is inserted in the slot intended for the unknown capacitor Cx. Co is a 2% polystyrene capacitor having a measured value of 1017 pF. This capacitor is placed in parallel with C_1 resulting in a lower "tank circuit" resonance frequency designated as F_2:

$$F_2 = \frac{1}{2\pi\sqrt{L_1(C_1 + 1017pF)}} \tag{2}$$

Squaring equations (1) and (2) and solving yields equations for both C_1 and L_1:

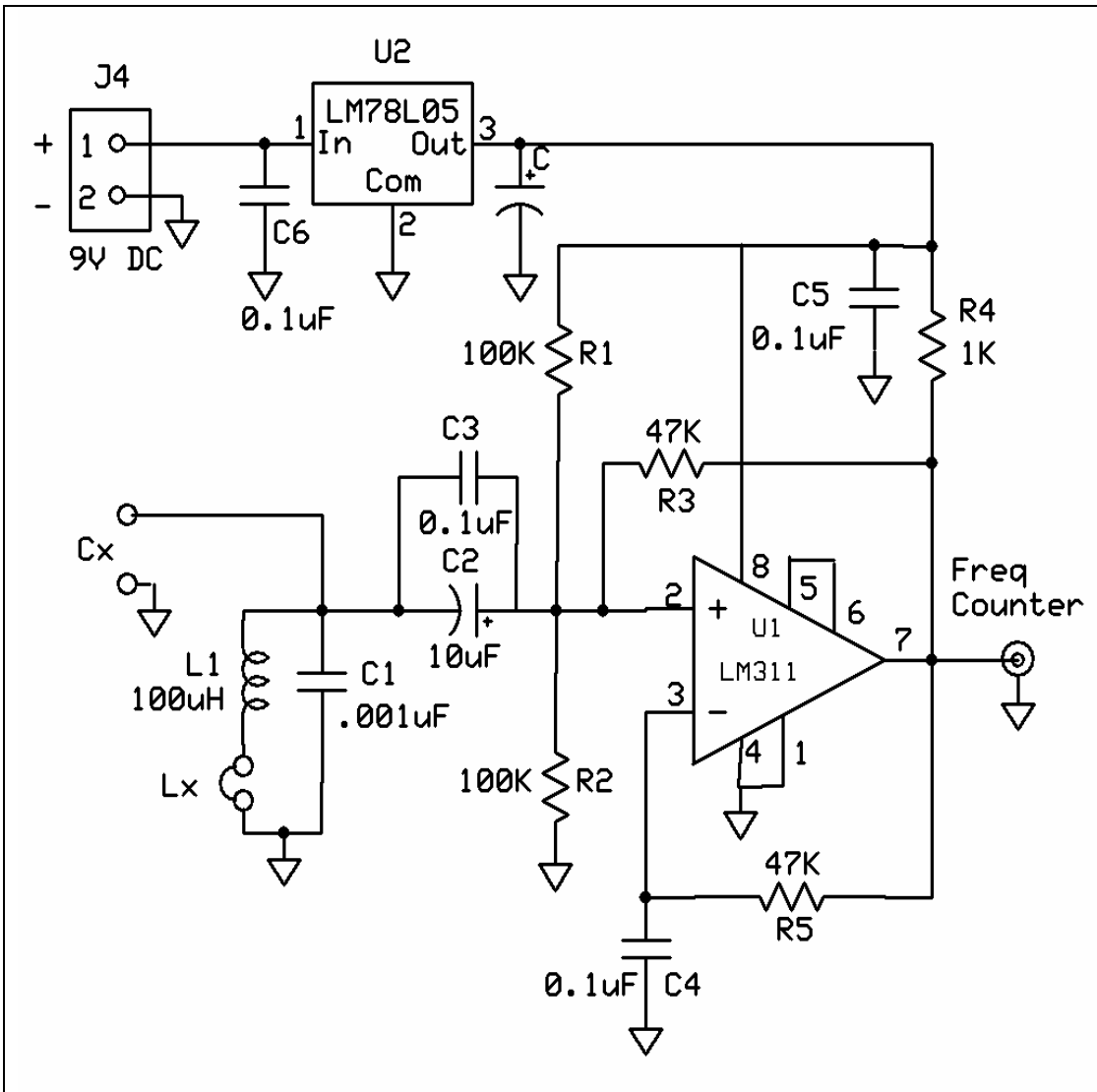$$C_1 = \frac{F_2^2}{F_1^2 - F_2^2}C_0, \quad \text{and} \quad L_1 = \frac{1}{4\pi^2 F_1^2 C_1} \tag{3}$$

Figure 1. LM311 Oscillator Circuit

Equation (3) contains the set of "calibration equations" for the LC Meter and $C_0= 1017$ pF. In order to solve for unknown capacitances and inductances two LC Meter operational modes are introduced, namely; the C_X and L_X modes.

Cx Mode

In the Cx mode of operation the external unknown capacitor, Cx, is placed in parallel with C_1. In order to determine the unknown capacitance the following equations are used:

$$F_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}, \quad \text{and} \quad F_2 = \frac{1}{2\pi\sqrt{L_1(C_1 + C_X)}} \qquad (4)$$

Each expression is squared and simplified to yield and equation for L_1. Subsequently the equations containing L_1 are equated and an expression for Cx is obtained:

$$C_X = (\frac{F_1^2}{F_2^2} - 1)C_1 \tag{5}$$

Lx Mode

In the L_X mode the unknown inductor, L_X, is placed in series with L_1. The equations to be solved simultaneously are:

$$F_1 = \frac{1}{2\pi\sqrt{L_1 C_1}}, \quad \text{and} \quad F_2 = \frac{1}{2\pi\sqrt{C_1(L_1 + L_X)}} \tag{6}$$

A symmetry argument is invoked by examining the previous solution to yield an equation for L_X:

$$L_X = (\frac{F_1^2}{F_2^2} - 1)L_1 \tag{7}$$

Note that in equations (5) and (7) values of C_1 and L_1 are as specified in equation (3). The usefulness of the frequency-shifted oscillator technique is best illustrated by a simple hand calculation normally introduced as a pre-laboratory exercise.

Typical Pre-Laboratory Calculation

The purpose of the pre-laboratory calculation is to illustrate that oscillator frequency-shift can be used to determine the value of an unknown capacitance. The process of determining the unknown capacitor involves a calibration process together with an equation for the C_X mode capacitance. As an example of a hand calculation consider the following data:

Calibration via Hand Calculation:

The oscillator shown in Figure 1, freely oscillates at a frequency $F_1 = 503.027$ kHz. A precision 2% polystyrene capacitor, C_0, measured to be 1017 pF is used for calibration. Attaching this capacitor to the "C_X" terminals causes the oscillator frequency to decreases to $F_2 = 357.243$ kHz. Calculate the effective value of C_1 and L_1 (to include shunt capacitances and inductances) of the oscillator "tank circuit" using the previously derived formulas and measured values:

$C_0 = 1017$ pF, calibrating capacitor

$$C_1 = \frac{F_2^2}{F_1^2 - F_2^2}C_0; \quad C_1 = \frac{357.243^2}{503.027^2 - 357.243^2}1017\,\text{pF} = 1034.9128\,\text{pF}$$

$$L_1 = \frac{1}{4\pi^2 F_1^2 C_1} \; ; \quad L_1 = \frac{1}{4\pi^2 (503.027 \text{ kHz})^2 1034.9128 \text{ pF}_1} = 96.728 \text{ μH}$$

Note, the computed values for C_1 and L_1 differ from the values of the actual circuit components shown in the schematic and parts list because they include additional circuit shunt capacitance and inductance.

Hand Calculation for Unknown C_X

Remove the calibrating capacitor, C_0, and connect a 5% silver-mica capacitor marked 300 pF to the C_X terminal. The oscillator frequency drops from 503.027 kHz to 443.039 kHz. The value of the unknown capacitor is easily computed using the following formula.

$$C_X = (\frac{F_1^2}{F_2^2} - 1)C_1 \quad = (\frac{503.027^2}{443.039^2} - 1)1034.9128 \text{ pF} = 299.2304 \text{ pF}$$

Using a laboratory instrument the measured value of the 300 pF capacitor resulted in 301.7 pF. The shifted oscillator technique thus resulted in 0.82% error.

Visual Basic Program

A Visual Basic program is used to expedite rapid solutions for unknown inductance and capacitance values using the "frequency-shifted" oscillator technique. The source code for the program was introduced in the course lecture and students were shown how to implement the equations presented in this paper. Moreover, students were encouraged to experiment with the software and to customize the display. A set of 5% silver-mica capacitors form a collection of test capacitors for the project. The Almost All Digital Electronics (AADE) LC Meter IIB was used as a reference instrument for comparison purposes [3]. Capacitance values ranging from 22 pF to 820 pF were measured by both instruments and the results are shown in Table 1. Note that the error appears greatest at the smaller values of capacitances. A preliminary investigation indicated that lowering resistance R_3 together with increasing R_5 may result in widening the range of capacitance values with resultant smaller errors. Further study and experimentation in this area is required.

A screen shot of the Visual Basic LC Meter calibration process is shown in Figure 2. The values shown support the pre-laboratory "hand calculations" example presented earlier. Figure 3 illustrates the calculation of the unknown capacitor C_X and gives the same result as the hand calculation example.

At the end of the laboratory measurement session some students suggested using Microsoft Excel together with its Visual Basic capability to perform the calculations. Another suggestion was to program the calibration and C_X, L_X, equations into the Texas Instrument TI-89 calculator. Instrument portability appeared to be the prime consideration for some students. These observations were noted and immediately used in the next course lecture as a "motivating factor" for the digital portion of the project.

Figure 2. Screen Shot of Visual Basic Calibration

Figure 3. Computed value of C_X =299.2 pF using Visual Basic

Table 1. Comparison of AADE LC Meter IIB with LC Meter

Marked Value	AADE LC Meter IB	LC Meter	Error
22 pF	24.48 pF	22.8 pF	7.61%
39 pF	42.20 pF	39.0 pF	7.58%
100 pF	104.20 pF	100.6 pF	3.46%
120 pF	119.90 pF	117.7 pF	1.84%
150 pF	154.80 pF	151.6 pF	2.11%
220 pF	219.40 pF	216.4 pF	1.37%
330 pF	334.20 pF	331.2 pF	0.90%
470 pF	469.60 pF	467.1 pF	0.53%
820 pF	824.90 pF	822.1 pF	0.34%

LC Meter Digital Component

The digital component of the project features an Atmel AVR AT90S2313 microcontroller programmed in assembly language to determine the oscillator frequency and to compute the value of the inductor, L_X, or capacitor, C_X, under test. The software source code for the Atmel AT90S2313 was developed by Steve Weber [4], and is available as "open software source code" at the following website [5]. The microcontroller reads the frequency of the LC "tank circuit" at pin 7 of the LM311 as shown in Figure 4. The microcontroller computes the value of the component under test and announces the reading in Morse code via a miniature piezoelectric speaker. Simultaneous each alphanumeric character is displayed on the 7-segment display.

Two classroom lectures in Topics of Applied Design were devoted to explaining the operation of the microcontroller source code. In addition, a software procedure was developed to accurately adjust the 4-34 pF capacitor, C_9, so that the oscillator frequency could be set to precisely 8.192 MHz. An AT90S2313 "calibration microcontroller" was programmed and each student lined up during the last course laboratory period to have their LC Meter calibrated.

LC Meter Construction

As indicated earlier in this paper, the prototype of the LC Meter was built "Manhattan Style" and is shown in Figure 5. This technique consists of gluing isolated pads of printed circuit board material to a base copper-clad printed circuit board which serves as an electrical ground plane for the project. The isolated pads are arranged to accommodate the requirements of the schematic diagram. These pads form isolated islands which serve as "tie points" for circuits components which are soldered to the strips. The result is a functional circuit which offers an alternative to the standard plastic prototyping board used for laboratory experiments. Moreover, students gain practical soldering experience using this technique. An additional advantage of this technique is that it provides insight to the layout of the printed circuit board.
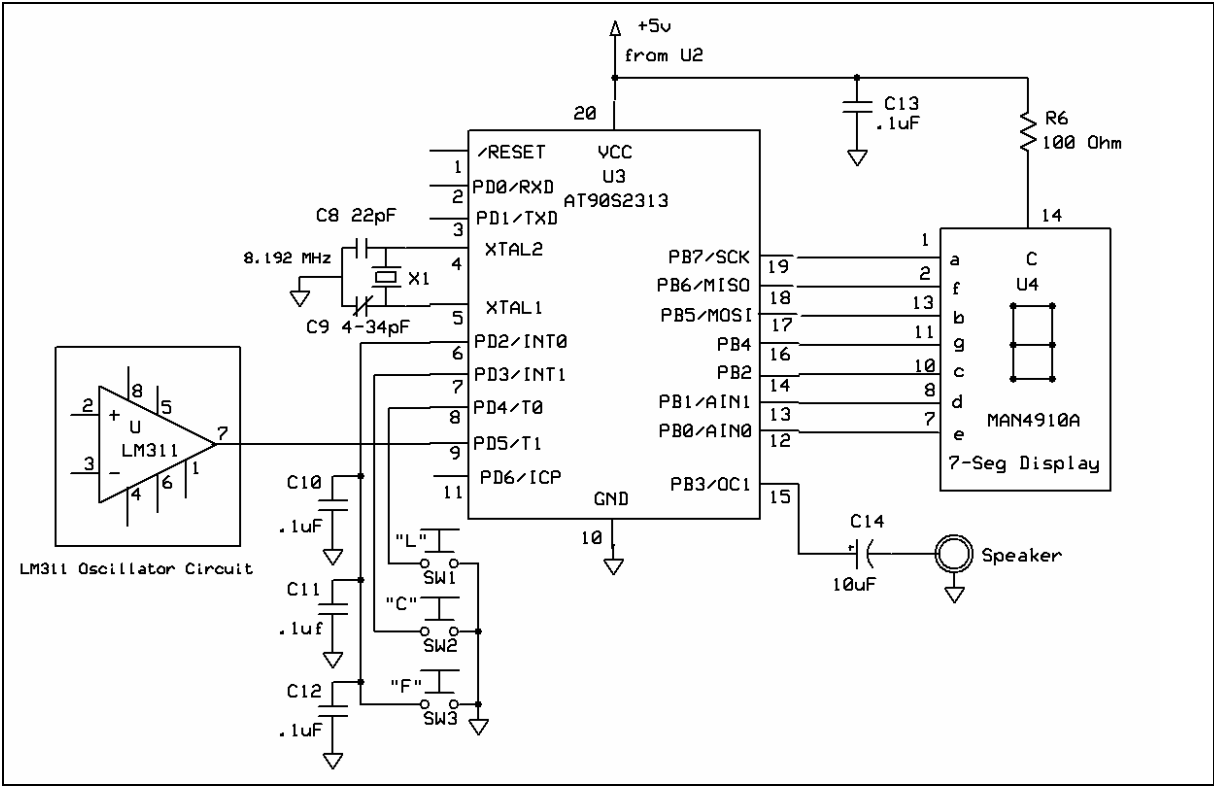
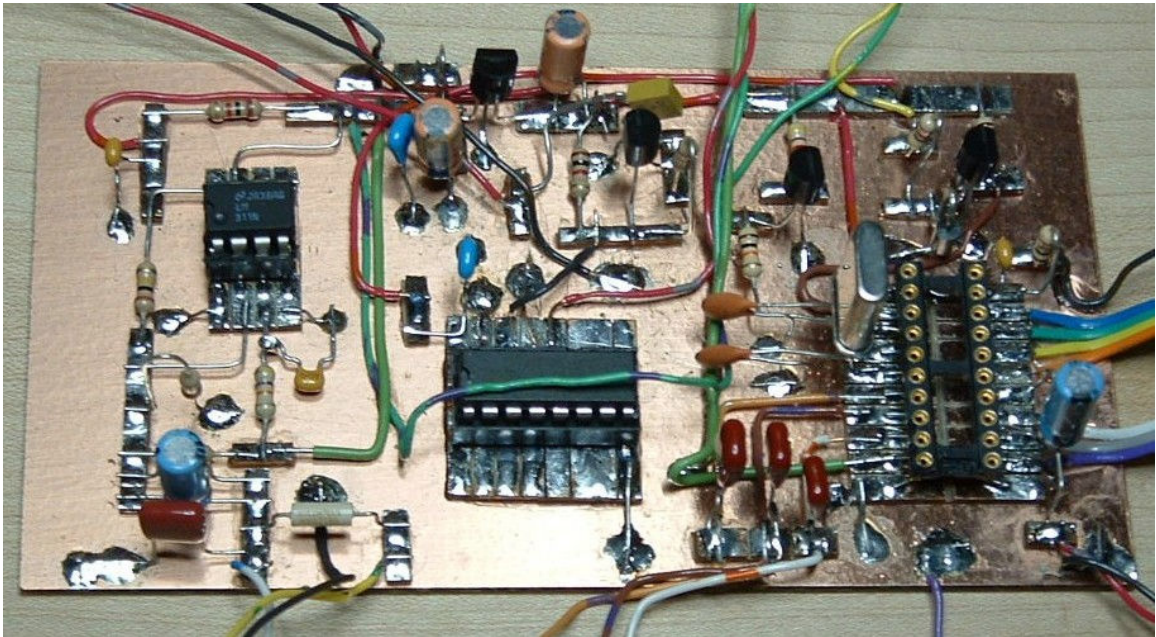Figure 4. Digital Portion of the LC Meter Circuit

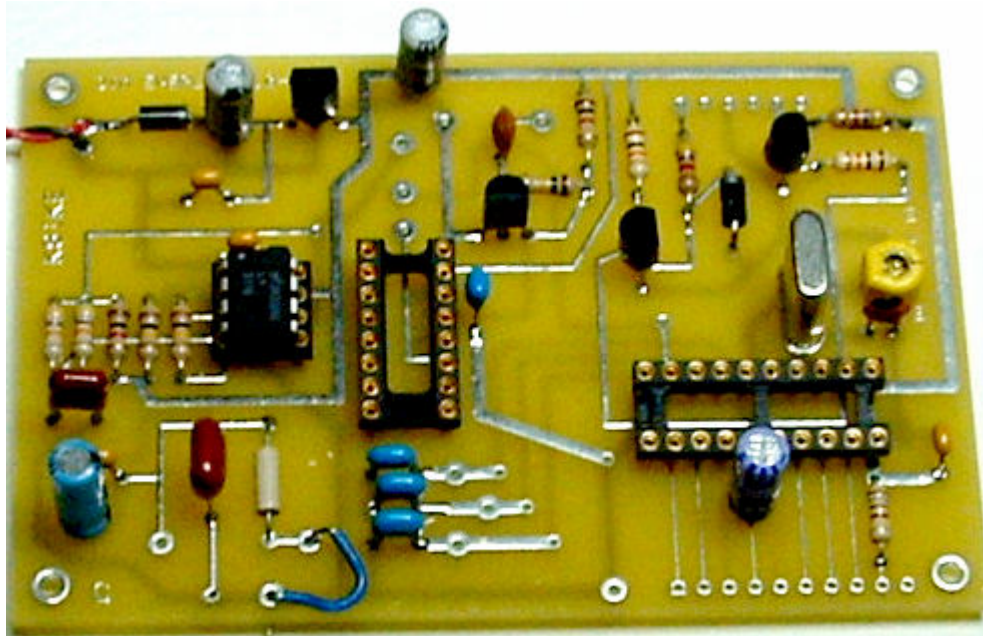Figure 5. Illustration of LC Meter Manhattan Construction Technique

Figure 6. Printed Circuit Board for LC Meter

The LM311 oscillator is located on the left-side of Figure 5 and occupies significant surface area. On the right-side of the prototype board is the microcontroller 20 pin integrated circuit socket. As shown, the wires connecting to the 7-segment display emanate from the right-side of the microcontroller socket. After considering packaging concepts and the location of the 7-segment display, the microcontroller socket was rotated 90 degrees. The resulting minimum cost ExpressPCB printed circuit board for the project, 3.8" by 2.5", is shown in Figure 6.

The final LC Meter packaging concept, shown in Figure 7, emerged after several laboratory "group discussions" sessions. The enclosure, described in the Table 2 parts list, is an LMB project box which gives the LC Meter a "finished-product" look.

Figure7 shows the piezoelectric speaker element positioned on the right-side of the front panel grouped together with the 7-segment display. Note that the mode determining pushbutton switches are aligned vertically in the center of the front panel. The unknown capacitance, C_X, is placed between the top two terminals on the left, whereas the unknown inductor, L_X, is placed between the two vertical terminals. As an after thought, the large rubber "stick-on" feet were required to lift the meter above the counter surface in order to provide additional clearance for attaching inductors.

Project Notebook

The project notebook is used to record the student's journey through the course with emphasis being placed on recording events and ideas as the prototype concept develops. Many students also use the notebook as a journal and often record their frustrations as well as their successes. Laboratory time is used to form discussion groups which deal with problems encountered during

the building and testing phase of the project. The final packaging concept is often discussed and students share ideas during group discussions. Each student is required to develop a "Gantt Chart" to show project progress during the course. A handout is given in lecture that describes the Gantt Chart technique for implementing the project schedule, but the actual development and updating of the chart occurs during the course laboratory period. The chart must be included in the student notebook. In Topics of Applied Design the project is weighted at 30% of the lecture grade. The project scoring is shown in Table 3.

Table 3. Sample Project Scoring

Topic	Points
Journal entries complete	5
Code in notebook	1
Parts list	2
Sketch of packaging concept	2
Gantt Chart	2
ExpressPCB Layout	5
Does project work as intended	2
Schematic diagram	1
Prototype construction	5
Construction & soldering	2
Actual product packaging	3
TOTAL	**30**

Figure 7. LC Meter Packaging Concept

Project Parts List

A complete parts list for the LC Meter project is shown in Table 2. The cost of the major electronic components for the project is $12.56. The introduction of an enclosure adds an additional $9.19 to the project bringing the cost to $21.75 exclusive of the printed circuit board cost.

Table 2. Parts List for LC Meter

Qty	Component	Description	Designator	Supplier	Part Number	Unit	Cost
1	Pwr Connector	2.1 mm Coaxial	P1	Mouser	163-5004	$0.63	$0.63
1	Diode, 1N4148	Polarity Protect	D1	Digi-Key	512-1N4148	$0.05	$0.05
1	Speaker	Miniature Piezo	SPKR	Digi-Key	433-1020-ND	$1.81	$1.81
1	IC, 8 Pin DIP	LM311	U1	Digi-Key	LM311NNS-ND	$0.96	$0.96
1	5V Regulator	78L05(TO92)	U2	Digi-Key	NJM78L05A-ND	$0.34	$0.34
1	Microcontroller	AT90S2313	U3	Digi-Key	90S23-13-10PC-NI	$2.02	$2.02
1	LED-7 Seg	Common Anode	U4	Digi_Key	604-SA04-12EWA	$1.05	$1.05
1	Crystal, 20pF	8.192MHz	X1	Mouser	559-FOXS081-20	$0.57	$0.57
1	Inductor (axial)	100 µH	L1	Jameco	372242CB	$0.42	$0.42
1	Polypropylene	0.001µF @2%	C1	Digi-Key	P3102-ND	$0.65	$0.65
4	Ceramic Disc	0.1 µF	C3,C4, C5,C6	Digi-Key	P4910-ND	$0.09	$0.36
4	Ceramic Disc	0.1 µF	C10,C11, C12,C13	Digi-Key	P4910-ND	$0.09	$0.36
3	Electrolytic	10 µF	C2,C7,C14	Jameco	607849CB	$0.20	$0.60
1	Ceramic Disc	22 pF	C8	Jameco	32838CB	$0.09	$0.09
1	Trim Capacitor	4-34 pF	C9	Jameco	32838CB	$0.99	$0.99
2	Resistor	100 KΩ, 1/4 W	R1,R2	Mouser	291-100K	$0.07	$0.14
2	Resistor	47KΩ, 1/4 W	R3,R5	Mouser	291-47K	$0.07	$0.14
1	Resistor	1 KΩ, 1/4 W	R4	Mouser	291-1K	$0.07	$0.07
1	Resistor	100 Ω, 1/4 W	R6	Mouser	291-100	$0.07	$0.07
1	Socket-1	IC Skt,8-pin	Skt-1	Mouser	571-113308	$0.35	$0.35
1	Socket-2	IC Skt,20-pin	Skt-2	Mouser	571-113320	$0.89	$0.89
					Electronic Parts:		$12.56
1	Chassis Box	3.0 x 51/4x 21/8	LMB Box	Mouser	PN-537-136-P	$9.19	$9.19
						Total	**$21.75**

Student Assessment

The following comments are extracted from student LC Meter Project Assessment forms developed by the author. The student population is drawn from ECET students at the

University of Cincinnati at the outset of their junior year. Four questions were presented to the students during the last laboratory period of Topics of Applied Design during Autumn Quarter of 2004 and 2005. Overall, I found the comments to be very encouraging [6]:

Describe how the LC Meter Project illustrates the concepts of applied design as taught in the lecture portion of Topics of Applied Design.

- "The LC meter project illustrates the concept of applied design because I had to take a design off of a schematic; go out and get all the parts; design a PCB; populate the board; and apply my own design to the construction of the project box. All aspects of the project were dealing with applying a design."

- "By taking a project like the LC meter, we were able to apply all of the basic concepts of applied design. By working in steps we were able to plan, design, select, prototype, test, build, and test again. These steps are taken directly from the applied design concepts."

- "The project takes a sample of circuits we have studied throughout the course of study in EET and combine them into one project. Not only do we get to see it work in theory and on the chalkboard, but also in the lab. Taking these designs and applying them to component selection and construction is what it all about."

Describe what you learned about the process of product development.

- "I learned the importance of making good connections and solid construction. A product must be solid, clean and presentable when presented to the market. But also, I learned that there are many steps including troubleshooting in the process of product development."

- "Time is critical! When dealing with so many decisions it is important to take your time and consider all things and possibilities. This will in turn provide a great base for completing a project successfully."

- "Consideration of parts pricing, orientation within packaging, time management (I give myself a C- in that department), and how the user will interface with the project. Overall, I learned a lot!"

What was the most rewarding aspect of this project?

- "The most rewarding aspect was that I was able to take a schematic, and implement it onto a PCB, and to design an enclosure. Once I started it up my display and speaker came on and I was very relieved."
- "Being able to put it all together and observe what all the time and effort provided."

- Seeing it come together and the look of dismay on my friends and family's faces that I could ever understand such a thing …"

Can the "Project" or the "Process of Completing the Project" be improved?

- "For my project, more organization and planning."

- "Not sure…This one's pretty solid. Maybe more study of the microcontroller source code."

- The project could be improved by having more class time dedicated to the project."

Conclusion

This pre-junior capstone project relies heavily on knowledge and skills previously learned in both the analog and digital electronic sequences at the University of Cincinnati. In addition, the capstone project provides a vehicle to introduce applied design concepts, construction techniques, printed circuit board layout techniques, and packaging concepts. Only a modest amount of construction, testing, and calibration skills are required for successful completion of the project. Throughout the course several product enhancements were suggested by students. A liquid crystal display was suggested most often. One student suggested an updated version of the "Digi-talker" integrated circuit to announce values of inductance and capacitance. Overall, I found the student attitude towards the course and subsequent feedback to be most rewarding, and I was very encouraged by the level of student involvement in the project.

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