Full Paper: A First-Year Computer Engineering Lab Project—Driving an LCD with an FPGA Embedded Processor

Dr. Rod B. Foist, California Baptist University

Rod Foist Professor (and IEEE student club advisor), Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, rfoist@calbaptist.edu

Dr. Xuping Xu, California Baptist University

Dr. Xuping Xu is currently professor in the Department of Electrical and Computer Engineering at California Baptist University. He received B.Sc. degrees in electrical engineering and applied mathematics from Shanghai Jiao Tong University, Shanghai, China, in 1995. He received M.Sc. degrees in electrical engineering and applied mathematics, and the Ph.D. degree in electrical engineering from the University of Notre Dame, Notre Dame, IN, in 1998, 1999, and 2001, respectively. In 2008, Dr. Xu joined the Gordon and Jill Bourns College of Engineering at California Baptist University. Between 2001 and 2008, he was an assistant professor and subsequently an associate professor in the Department of Electrical, Computer and Software Engineering at Penn State Erie, Erie, PA. His research interests include systems and control, hybrid and embedded systems, digital design, software/hardware enabled control applications, algorithms and optimization. He has published 18 journal papers, 39 conference papers, and 4 book reviews in the above areas. Since 2008, Dr. Xu has been serving as the assessment coordinator of the College of Engineering. He is a senior member of the IEEE and has been an associate editor on the Conference Editorial Board of the IEEE Control Systems Society. He also actively serves as a reviewer for a number of journals and conferences.

Mr. Timothy Gage, California Baptist University
Seth Truitt, California Baptist University
Mr. Matthias Hans Schmidt

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Rod Foist, Xuping Xu, Timothy Gage, Seth Truitt, and Matthias Schmidt
California Baptist University, rfoist@calbaptist.edu, xxu@ calbaptist.edu, MatthiasHans.Schmidt@calbaptist.edu, TimothyDean.Gage@calbaptist.edu, Seth.Truitt@calbaptist.edu

***Abstract* – Recent National Science Foundation (NSF) research, aimed at improving the Electrical and Computer Engineering (ECE) curriculum across all four years, makes strategic use of laboratory projects. The "spiral model", adapted from other research, introduces certain lab component *themes* (in the freshman year) and revisits them with increased sophistication and interconnection in the following years. Thus, labs are used as a "cohesive framework" that connects and integrates individual courses. The three themes used in this research are centered on video (and image), sound, and touch sensors. In this paper, and a companion paper, we present our own design of two new lab projects (within the video/image theme). Specifically, this paper reports on the use of a Field-Programmable Gate Array (FPGA)-based embedded processor to control a liquid crystal display (LCD). This approach is contrasted with using a state-machine for LCD control. The companion paper presents the design of a microcontroller-based voltmeter with measured voltage values shown on an LCD. The contribution of this paper is to provide a fully-working, easy-to-use, first-year lab project within the video/image theme of the spiral model approach to improving the ECE curriculum. The project design code will be made available for downloading on the internet, via the Bitbucket web-hosting service.**

Index Terms – Electrical and Computer Engineering curriculum improvement, Computer engineering lab project, PicoBlaze embedded processor, Verilog HDL, Xilinx FPGA controlling LCD.

INTRODUCTION—RECENT RESEARCH USING LABS

Recent National Science Foundation (NSF) research by Chu [1], aimed at improving the Electrical and Computer Engineering (ECE) curriculum across all four years, makes strategic use of laboratory projects—to enhance student learning and better prepare graduates for new challenges. The viewpoint given is that a good engineer must not only become knowledgeable in certain content areas (*components*, learned in individual courses), but also be able to apply and *integrate* that content to solve complex, real-world problems (or challenges).

Chu's work is motivated by an earlier 5-year study of engineering education [2] which found a deficiency in the curricula: subjects are taught in isolation, without proper context, and do not adequately prepare students to integrate that knowledge. In addition, labs were not used effectively. That study recommended a "spiral model" and effective use of labs (as design projects):

"… *the ideal learning trajectory is a spiral, with all components revisited at increasing levels of sophistication and interconnection. Learning in one area supports learning in another*." [1]-[2]

Brief "Book Highlights" of the study, available online, compares a "linear components" curricular model to their proposed "spiral model"—using two helpful diagrams [3].

Chu's work employs the spiral model by introducing certain lab component *themes* (in the freshman year) and lays out a plan to revisit them with increased sophistication and interconnection in the following years. Furthermore, it emphasizes design projects—because they can effectively "approximate professional practice", enhance knowledge synthesis, build teamwork, and even encourage student persistence. Thus, motivated by the spiral model, labs are used as a "cohesive framework" that connects and integrates individual courses. The three themes used in this research are centered on video (and image), sound, and touch sensors. Note that these are the main interface subsystems used in modern hand-held devices, such as smartphones.

The faculty authors acted as external collaborators for the principal investigator by implementing and testing new lab projects within two of our existing courses over a two-year period—a second-year digital logic design course and a senior course in advanced digital design. This approach inspired us to see the benefit of creating lab projects which can be useful across the ECE curriculum to provide a cohesive framework and enhance learning. For example, students are exposed to lab projects using visual feedback (LEDs and LCDs) in all four years—but with more complexity introduced in each year.

In this paper, and a companion paper, we present our own design of two new (first-year) lab projects (within the video/image theme). Specifically, this paper reports on the use of a Field-Programmable Gate Array (FPGA)-based embedded processor to control a liquid crystal display (LCD). This approach is contrasted with using a state-machine for

LCD control—and we believe that, in general, the processor-based approach is preferable. The companion paper presents the design of a microcontroller-based *voltmeter* with measured voltage values shown on an LCD. Both projects can include a soldering tutorial/review session.

Overall, we found that students really enjoyed creating hands-on lab projects that implement real-world electronic systems, and learning something of how the hardware and software components work together to create the desired functionality. In addition, students indicated a lot of interest in learning and practicing soldering skills in building both of these projects.

The spiral model approach, in a broader sense, is also consistent with the growing interest in hands-on (or project-based) learning that is becoming widespread in engineering education. For example, The *STEM Lab Report* stated [4]:

"*Throughout higher education in engineering, colleges are requiring students to pull their gaze from a text-book to perform real-world, hands-on, team-based project learning. In short, they are teaching students to become engineers by having them work as engineers.*"

In a previous work [5], we concluded:

"…the key benefits of hands-on approaches for students are better outcomes, seeing the relevance of math (and engineering) with real-world examples, deeper understanding, more enjoyment, and persistence in engineering."

FPGAs and Embedded Processors

As discussed in a previous FYEE paper [5], FPGAs are a type of (programmable) digital microelectronic circuit ("chip"), mounted onto a circuit board. They have become a popular and powerful vehicle for implementing digital circuits—especially due to their "rapid-prototyping" capability [6]. That is, they can be programmed and tested right at your desk via a USB cable connected to a computer with FPGA design software. Although FPGA technology and embedded processors are more advanced topics, they can be introduced effectively in freshman year [7]-[8]. In this context, we use the FPGA boards like we use oscilloscopes—both are complicated "instruments" (like an automobile), but students don't need to fully understand what's "under the hood", just how to "drive" them. FPGA technology was invented by the founders of the Xilinx Company in the mid-1980s and this company continues to be a leading FPGA supplier worldwide [9].

The project design presented in this paper is based on the following technology items:

- A Xilinx Artix-7 FPGA [10],
- Xilinx FPGA design software (Vivado 2017.2), free WebPACK edition [11],
- The Verilog hardware description language (HDL) [12],
- Xilinx's PicoBlaze (embedded) processor [13], and
- The Nexys 4 development board (the circuit board containing the FPGA chip) [14].

Within FPGA design, an *embedded processor* is a kind of microcontroller—which is essentially a small computer on a chip. The PicoBlaze is called a *soft processor* because it is a pre-designed functional block (written in an HDL format) that is programmed into the FPGA, but "disappears" when power is turned off. Whereas a *hard core processor* uses dedicated digital logic and is permanently "wired" into the chip. After a soft processor is programmed into the FPGA's digital logic circuits, it is controlled (like any other microcontroller) by a software program. Such programs can be written in a language like C (a high-level language) or in an *assembly language* (a lower-level language). The PicoBlaze design presented here is controlled by an assembly language program. That program tells the PicoBlaze how to control the LCD, which is connected to the pins of the FPGA (mounted on the Nexys4 board).

PicoBlaze

PicoBlaze is a compact 8-bit microcontroller, available as a free download from Xilinx (along with program compiler) [13]. It consists of two major blocks: the processor (latest version is known as the KCPSM6) and an instruction ROM (Read-Only-Memory) which holds the assembly program. An excellent treatment of PicoBlaze, along with simple-to-advanced (but easy to use) program examples, is provided in the textbook by Chu—with code files available on his website [15].

How LCDs Work

Liquid Crystal Displays (LCDs) are a type of "flat-panel display" which do not directly emit light [16]. Rather, they use a backlight or reflector to produce images using the light modulation capabilities of liquid crystals. Figure 1 shows a picture of a 16x2 (16-character by 2-row) LCD "character module"—as used in this project. LCDs are used in a wide variety of applications—as large screens (from LCD televisions to computer monitors), and as small screens (e.g. watches and calculators). They are useful for displaying information and images for electronic projects.

FIGURE 1
16x2 Liquid Crystal Display module.

The Hitachi HD44780 [17], known as a "character LCD", has become a de facto industry standard LCD module which contains the LCD as well as a built-in controller and driver chips. The controller and driver components make the driving much simpler [18]. However, before sending character data to the display, a complicated initialization sequence—of electronic pulses and delays—must first be sent to the module to establish communication. Generally, there are two methods for controlling an LCD (module)—by state-machine (a hardware approach) or by a processor (a software approach).

Processor vs. State-Machine for LCD Control

A *state-machine*—in simple terms—is a digital logic circuit which is used to control an electronic system, such as the lights at a traffic intersection. It does this by sensing *inputs* and then generating *outputs* to turn parts of the system on or off according to a pre-determined plan (represented by "states" of activity). The machine will move from state to state, based on inputs and other information, in order to control the system. For example, at the traffic intersection, inputs might be a timer signal (meaning time to change the lights) or a pedestrian-pushed button switch. State-machines can be complicated to design, and tend to be very focused in their function. This makes them not easily "programmable", and thus not very flexible—especially in terms of LCD control, in the context of lab projects.

In contrast, a processor (like the PicoBlaze) actually runs a software program, which is much easier to modify. In the context of this lab project, the provided PicoBlaze hardware (logic circuit) design is "ready to use" for controlling messages on the LCD. To change the messages, or their motion (e.g., scrolling, etc.) only requires relatively simple changes to the initial, provided (assembly lang.) program.

THE "FPGA + LCD" DESIGN PROJECT

I. Learning Objectives

The key learning objectives for this learn-by-doing project are:

- To understand basic FPGA and processor concepts—and see them in action.
- To understand the importance, usage, and basic control of an electronic display (LCD specifically).
- To understand that control of the LCD involves hardware (logic circuits) and software—thus a system (inside the FPGA).
- To gain preliminary experience in using the design software (*Vivado*) which programs the FPGA.
- To gain basic experience in building/connecting the FPGA board and circuit components.
- To learn/practice soldering (of LCD header).

II. Project Description

Figure 2 is a photograph of the completed and working project presented in this paper. The design consists of the Nexys 4 (Nx4) FPGA board interconnected to a small breadboard which holds the LCD module plus a small 3-pin 5-volt voltage regulator. Note that the Nx4 does not have its own built-in LCD, but it can control an external one, with a few wires and components, and thus add a very useful display capability.

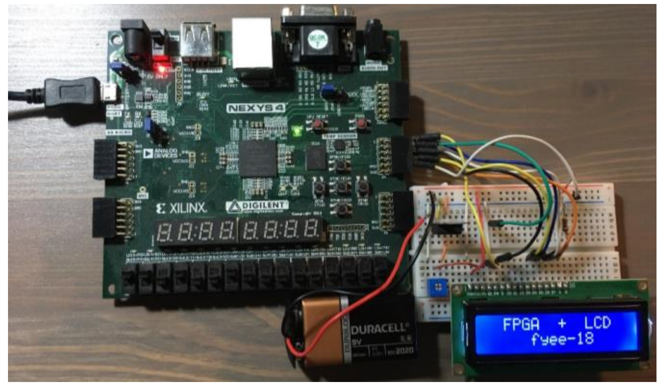

FIGURE 2
THE COMPLETE DESIGN PROJECT: FPGA + LCD.

A schematic of the overall design is given in Figure 3. The 5-volt regulator is necessary to supply power to the LCD, since the Nx4 primarily uses 3.3V and does not make 5V available on its connectors. A 9V battery is used to supply the input to the regulator which is then regulated down to become the 5V for the display module.

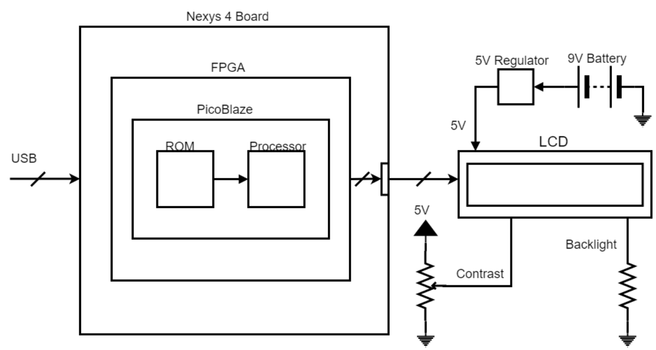

FIGURE 3
SCHEMATIC FOR DESIGN PROJECT: FPGA + LCD.

The main logic and software design presented here are derived from an original design by Xilinx engineer Ken Chapman (inventor of PicoBlaze) [19]. His design was created for an older FPGA board with a built-in LCD [20]. That original PicoBlaze logic design was more complicated (it controlled more functions) and written in another HDL known as VHDL [21]. In our work, we simplified the hardware design and translated it into the Verilog language. Consequently, with a simpler logic design, the associated PicoBlaze assembly language program was simplified also. In this process, we believe we have made Ken's original, excellent design available for almost any Xilinx-based FPGA board that needs to control an external LCD.

Note that one simplification from Ken's design was to have the FPGA/PicoBlaze design only write to (and not read from) the LCD module. This means that the FPGA's 3.3V signals can control the 5V LCD inputs without causing electronic damage—and yet still be interpreted correctly, logic-wise. In contrast, if the FPGA were to read from the LCD, additional circuitry would be necessary to prevent the incoming LCD 5V signals from damaging the 3.3V-based FPGA chip. Happily, most projects that use LCDs only need to perform write-operations, as is true in our case.

III. Lab Steps

- Instructor provides some sort of pre-lab tutorial information (could be the contents of this paper), and possibly some pre-project lab practice.
- Lab manual should list the steps to build this "kit" (on-line project code web-link is provided with this paper): 1) download and unzip the *Vivado* project code, 2) assemble/connect the board and LCD circuitry, 3) open the *Vivado* project and follow the steps to program the FPGA, 4) Verify that the design is working—message appears on LCD (per Fig. 2).
- Students can now make simple modifications to the PicoBlaze assembly language program (within the *Vivado* editor) so as to change the message (such as put their name in it—"Jill's FPGA"), then re-program the board and verify.
- We like to have students work in teams of two, but each student must build their own project, while consulting their lab partner if desired.

IV. Revisiting the Project in Second to Fourth Year Courses

In freshman year, this project is mostly just the building of a "kit", and doesn't require much design work. But each year, course work (and labs) should give students more and more opportunity and responsibility to design additional functionality onto the original implementation—so as to train-by-doing into "professional practice". Here are some potential more sophisticated versions of the project:

- Sophomore year—learn to make a message scroll across the screen, loop back, and constantly repeat, and be able to start-stop the scrolling based on push-button input.
- Junior year—add a communications block (such as Universal Asynchronous Receiver Transmitter = UART) to the design and interfaced to a computer, with some messages appearing on the LCD. See Chu's textbook for guidance [15].
- Senior year—add interrupts [15], triggered by push-buttons or other system blocks, to the design and have corresponding messages appear on the LCD.

SURVEY RESULTS AND STUDENT FEEDBACK

As mentioned above, the faculty authors acted as external collaborators for the principal investigator by testing some new lab projects within two of their existing courses (in 2016 and 2017). These labs employed aspects of the three themes (image, sound, touch) from the spiral model. One of the courses was a senior-level electronic design course using FPGAs. A special student survey was conducted at semester's end (only for the senior course). Six selected questions are analyzed here:
1) *The lab work I do for this course is relevant to my learning*,
2) *Learning the content in this course will help me get a good job*,
3) *The labs for this course show me how to problem-solve in Electrical and Computer Engineering*,
4) *The labs in this course make the content more understandable*,
5) *I enjoy doing the labs for this course*,
6) *Doing the labs shows me real life applications of the information*.
Possible responses (with numerical values) were: Strongly Agree (5), Agree (4), Undecided (3), Disagree (2), Strongly Disagree (1). Table 1 summarizes the data.

TABLE I
STUDENT SURVEY RESULTS: SELECTED QUESTIONS—AVERAGE SCORE
(FROM A SENIOR COURSE USING THE "SPIRAL APPROACH")

Question	2016 (10 students)	2017 (8 students)
1	4.4	4.4
2	4.2	4.3
3	4.6	4.3
4	4.5	3.9
5	4.0	4.1
6	4.7	4.3

Overall, the table shows that students generally *agree* or *strongly agree* with each of the six questions about course labs. For example, question 1 (*The lab work I do for this course is relevant to my learning*) got an average response/score of 4.4 (out of 5.0 maximum) for both years—calculated by adding student response values (5 to 1) and dividing by the number of students. Thus, per the questions, on the whole, students find these labs to be relevant, helpful, and enjoyable in their learning.

Now this data only reflects positive feelings for labs in a senior-level course that was partly re-designed to include some spiral model aspects/themes. However, from this apparent success in effective labs, we extrapolate that redesigning earlier-year labs with the spiral model's recurring themes (e.g., using an LCD)—that become more sophisticated year by year—will enhance learning. Hence, in this paper we offer a freshman version of the "FPGA + LCD" lab with reasonable confidence that it will be effective across the full ECE curriculum by forming part of the "cohesive framework" that connects and integrates individual courses.

DISCUSSION AND CONCLUSION

This paper presents a fully-working, relatively easy-to-use, first-year lab project within the video/image theme of the spiral model approach to improving the ECE curriculum. The project demonstrates a Xilinx FPGA controlling an LCD with an embedded PicoBlaze processor, and is designed using the Verilog HDL. Note that this design would not work for non-Xilinx FPGAs. Design code and helpful documentation—which should help instructors to readily recreate this design—have been posted on the following Internet site:

https://bitbucket.org/CBUCoEFYEE2018

Since we (the faculty authors) have used FPGAs and LCDs with both freshmen and senior students, we believe that this project makes a useful connection between first-year introduction of "FPGA + LCD" to more sophisticated versions of this design in second to fourth years of study. Since the project is based on the PicoBlaze, the topic could be easily "*revisited at increasing levels of sophistication and interconnection"* in the following years by using examples mentioned above, as well as the variety of designs in Chu's earlier text [15]. For example, these include reading switches, controlling LEDs, using multiplexors, reading/writing UART data, and responding to interrupts. These could also be coupled with designs from Chu's latest text [22], which was an outgrowth of the research presented here [1].

Thus based on written student surveys and observing the general delight of students when building the projects, we believe this approach (spiral model plus themed labs across the four years), and this specific lab project, will be effective—in improving student learning and preparing graduates for new challenges.

FUTURE WORK

More first-year lab projects, within ECE, will be explored—drawing on all three themes of Chu's research: video/image, sound, and touch sensors.

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AUTHOR INFORMATION

Rod Foist Professor (and IEEE student club advisor), Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, rfoist@calbaptist.edu

Xuping Xu Professor, Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, xxu@calbaptist.edu

Timothy Gage Student (and IEEE student club officer), Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, TimothyDean.Gage@calbaptist.edu

Seth Truitt Student (and IEEE student club officer), Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, Seth.Truitt@calbaptist.edu

Matthias Schmidt Student (and IEEE student club president), Electrical and Computer Engineering, Gordon & Jill Bourns College of Engineering, California Baptist University, MatthiasHans.Schmidt@calbaptist.edu