A New Laboratory Curriculum Focused on Teaching Mixed-Signal Testing Concepts Using Low-Cost Test Equipment

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Abstract

As the density of integrated circuit technology continues to increase, many commercial devices are combining both analog and digital electronics onto a single chip. As the complexity of these chips increases, familiarity with testing mixed-signal devices is essential for the successful entry-level engineer. This paper discuss a laboratory curriculum being developed at Texas A&M University designed to introduce these concepts to students before they graduate. The curriculum emphasizes the use of standard electronics bench equipment combined with additional low-cost personal computer technology to ensure that all interested academic institutions can afford to offer these labs.

I. Introduction

With the increasing use of digital signal processing in modern electronics, the role of mixed-signal components such as analog-to-digital converters (ADC) and digital-to-analog converters (DAC) is becoming more and more important. These devices are typically combined onto a single, highly dense integrated circuit[1]. As these chips become more complex, familiarity with testing these devices is essential for the successful entry-level engineer. With this in mind, semiconductor design and manufacturing companies are looking to educational institutions to provide this experience as an integral component of an undergraduate curriculum. Industry has even sponsored a textbook specifically about mixed-signal testing[2] to facilitate this. The text, by Mark Burns (Texas Instruments) and Gordon Roberts (McGill University), covers all aspects of mixed-signal test from actual measurement techniques to the economics of production testing.

Presently, the Electronics Engineering Technology program at Texas A&M University offers two courses in mixed-signal test based on this book. The original intent of these courses was to teach test concepts using a standard production tester donated by Texas Instruments and Teradyne[3]. The use of a commercial tester allowed students to become familiar with industry-grade automated test equipment (ATE). However, the cost of an ATE, which can easily be in excess of one million dollars, makes it prohibitively expensive for wide spread academic use. For this reason, a laboratory-based mixed-signal curriculum is currently being developed that allows students to experiment with mixed-signal test concepts using low-cost equipment.

The Burns and Roberts textbook previously mentioned is being used as a template for developing the laboratory experiments. Each experiment is being developed to demonstrate one or more of the fundamental concepts presented in the text. One of the major problems that arise in the implementation of mixed-signal labs is that the equipment requirements differ from those for traditional analog (or digital) electronics labs. Therefore, one of the first steps in this process was to identify the needs of a mixed-signal bench setup. It was determined that to perform mixed-signal test experiments, the bench equipment had to provide the ability to source and capture analog and digital static and dynamic signals; to perform complex, customizable post-processing calculations; and to rapidly automate repetitive measurements. These criteria were then used to identify possible hardware solutions that could be used to teach mixed signal test.

After making these determinations, the development of a laboratory curriculum centered on demonstrating various aspects of test was begun. This paper describes the details of this curriculum and also provides insights on how these experiments can be implemented using standard analog and digital electronics laboratory equipment.

II. The Characterization Curriculum

Since the goal of the experiments is to demonstrate the concepts discussed in the text by Burns and Roberts, the flow of the lab curriculum is designed to track the flow of the book. Table I shows a list of the labs currently being developed. Each lab is being designed to be a stand-alone experiment; however, many of the labs inevitably depend on knowledge gained previously to be successful.

While twenty-five separate experiments have been defined, the number could be reduced by combining consecutive lessons into one laboratory session. For example, the three experiments on the FFT could be shortened and combined into a single lab session. Similarly, the two experiments on testing digital-to-analog converters (DAC) could also be combined. Alternatively, this new curriculum could be used over a period of two semesters as a two-course sequence. In the Electronics Engineering Technology program at Texas A&M University, two separate courses are currently being taught. The first course covers the material through Chapter 8 and the second covers the balance of the material.

Though the labs are being designed specifically for teaching mixed-signal test, many of the concepts discussed here are useful as general material on electronics testing. Traditional electrical engineering and engineering technology courses use labs to demonstrate analysis and design techniques. Unfortunately, the concept of learning how to use laboratory instrumentation and perform meaningful measurements is typically of secondary importance. Students are often taught the minimum testing skills necessary to successfully complete their labs. In addition, some of the measurements they learn to make are frequently taught incorrectly. For example, few students learn that the correct method for making DC gain measurements is to use $G = \Delta V_{out}/\Delta V_{in}$ (a two point measurement) instead of simply using $G = V_{out}/V_{in}$ (a single point measurement). They also rarely get experience with measurement statistics and noise reduction techniques. By integrating some of these experiments into both standard analog and digital electronics courses, a concept as fundamental as learning the importance of making valid measurements can be taught.

Table I – Comparison of the mixed-signal test lab curriculum to the text by Burns and Roberts.

Textbook Chapters	Laboratory Experiments
1 – Overview of Mixed-Signal Testing	---
2 - The Test Specification Process	---
3 - DC and Parametric Testing	**L1** - Continuity Testing **L2** - Regulator Testing **L3** - Making Impedance Measurements **L4** - Measuring the DC Gain and Offset of Devices **L5** - DC CMRR and PSRR Testing
4 – Measurement Accuracy	**L6** - Quantifying Measurement Error through Statistics **L7** - Using of Filtering to Increase Measurement Repeatibility
5- Tester Hardware	---
6 – Sampling Theory	**L8** - Using the Fourier Transform
7 - DSP Based Testing	**L9** - The FFT and the Effects of Aliasing **L10** - The FFT and the Effects of Noncoherent Sampling **L11** - Synchronizing Signal Sources and Digitizers **L12** - Making Meaningful Noncoherent Measurements
8 – Analog Channel Testing	**L13** - Using Multitones to Make Frequency Response Measurements **L14** - DSP Based Distortion and Noise Testing
9 – Sampled Channel Testing	**L15** - Setting up Digital Patterns
10 – Focused Calibrations	**L16** - Using a Focused Calibration to Transfer Instrument Accuracy
11 – DAC Testing	**L17** - DC and Linearity Testing of DACS **L18** - Alternative DAC Linearity Testing Techniques
12 – ADC Testing	**L19** - The Statistical Nature of the ADC **L20** - Search Techniques and ADC Linearity Testing **L21** - ADC Testing using Histograms
13 – DIB Design	**L22** - Propagation Delay and Termination Effects in Transmission Lines **L23** - Time Domain Reflectometry
14 – Design for Test	---
15 – Data Analysis	**L24** - The Use of Guardbanding **L25** - Statistical Yield Analysis and SPC Methods
16 – Test Economics	---

III. Required Measurement Equipment

Before labs could be designed, a bench setup that could be used for mixed-signal test experiments had to be configured. Typical analog electronic lab experiments usually rely on four pieces of stand-alone bench equipment: an oscilloscope, a power supply, a waveform generator, and a multimeter. The experiments are designed to allow students to take individual measurements and then post-process the data later when writing the lab report. It is becoming increasingly common to find computers incorporated into the lab station so that students can generate lab reports dynamically and so that they can use support software such as MS Excel for entering data or PSPICE for comparing simulations to actual measurement results.

In contrast, mixed-signal testing requires a more flexible bench setup. This is because many experiments require the ability to work with both DC and AC analog and digital signals simultaneously, the ability to perform large numbers of repetitive measurements rapidly (ie, 256 measurements when testing an 8-bit DAC), and the ability to manipulate large amounts of data. To accommodate these requirements, the following fundamental pieces of equipment were identified:

- An analog source instrument: For sourcing both precision DC and AC voltages. The instrument had to have enough resolution to measure 8-bit mixed-signal devices.
- An analog capture instrument: For digitizing both DC voltages and dynamic waveforms. Again, the resolution had to be good enough to measure an 8-bit mixed–signal device.
- A digital source instrument: For sourcing both static digital codes and synchronous digital waveforms. The instrument had to have a minimum of eight digital channels. Because some devices have a serial interface, the source had to be fast enough to source eight-bit, serial signals as well.
- A digital capture instrument: For capturing both static digital codes and digital waveforms with similar constraints as above.
- An automated measurement controller: For remotely controlling the measurement instrumentation and for post-processing captured data. The controller also needed to use a flexible programming environment where students could make customized measurements during the lab.

With this in mind, several options ranging from the construction of a dedicated micro-controller based measurement platform[4] to the use of separate pieces of networkable, high-end bench equipment were explored. The final solution optimized cost while maintaining versatility and ease of implementation. Table 2 summarizes the equipment identified as necessary for a complete mixed-signal test bench setup. The cost per bench for this type of setup runs between $5000 and $11,000. While this is still expensive, a ten station laboratory is still a fraction of the cost of a single ATE. Also, an informal survey of several electrical engineering and engineering technology programs showed that most institutions already have computers and GPIB programmable bench equipment as part of their standard analog electronics lab. This means that the only additional equipment needed was the PC-based data acquisition and GPIB cards.

With this equipment, all of the measurement requirements are satisfied. The PCI 6052 is a multifunction data acquisition card compatible with standard personal computers. The card has the ability to digitize and source signals with 16-bit resolution. This is more than sufficient for testing standard 8-bit mixed-signal devices. Optionally, one can use an arbitrary waveform generator such as the 33120 (since many electronics labs already have one of these) for sourcing analog waveforms and then purchase a less expensive data acquisition card such as a PCI 6024 for capturing analog waveforms and for sourcing DC voltages. On the digital side, the PCI DIO 32HS is required if one wishes to perform dynamic tests on mixed-signal devices (ie, S/THD or SNR measurements), otherwise the static digital lines on a standard multifunction data acquisition board can be used.

Table 2 – Bench equipment needed for performing mixed-signal test experiments.

Controller	Pentium III Personal Computer with LabVIEW (National Instruments) and a PCI GPIB interface (National Instruments)
Analog Source	PCI 6052 (National Instruments) – Two16-bit D/A Analog Output Channels **OR** 33120A (Agilent) – 15 MHz GPIB Arbitrary Waveform Generator *
Analog Capture	PCI 6052 (National Instruments) – Sixteen 16-bit A/D Digitizer Channels (can also be configured as eight differential channels)* **OR** PCI 6024 (National Instruments) – Eight 12-bit A/D Digitizer Channels
Digital Source	PCI DIO 32HS (National Instruments) – Thirty-two digital channels that can be configured as either digital inputs or outputs.* **OR** PCI 6024 (National Instruments) – Eight channels configurable as asynchronous inputs or outputs.
Digital Capture	Same as above
Power Supply	E3631 (Agilent) – GPIB Controlled Triple Output Power Supply
Optional Equipment	54645 (Agilent) - Mixed-Signal Oscilloscope or any digital oscilloscope with 10 ns resolution

* - currently being used at A&M

Because experiments such as measuring power supply rejection ratio require the ability to change power supply voltages, a networked power supply such as the E3631 is required. Finally, optional equipment such as a good digital oscilloscope allows students to make timing measurements such as propagation delay as well as investigate concepts such as transmission line reflections. A picture of the complete equipment setup can be seen in Figure 1. The protoboard seen in this figure has been populated with common mixed-signal circuits and can be used during lecture to demonstrate test concepts.

The controller was chosen to be a standard personal computer running Windows. This choice allows students access to software packages such as Microsoft Word, Microsoft Excel, and Orcad PSPICE at the same workstation. The LabVIEW virtual instrumentation environment was chosen because it allows the development of intuitive graphical user interfaces. An example of this is the digital-to-analog converter test program interface seen in Figure 2. As one can see the graphical user interface is flexible enough to allow students to dynamically experiment with different test methodologies.

Figure 1. Picture of a complete lab station currently being used to deliver the mixed-signal laboratory curriculum.

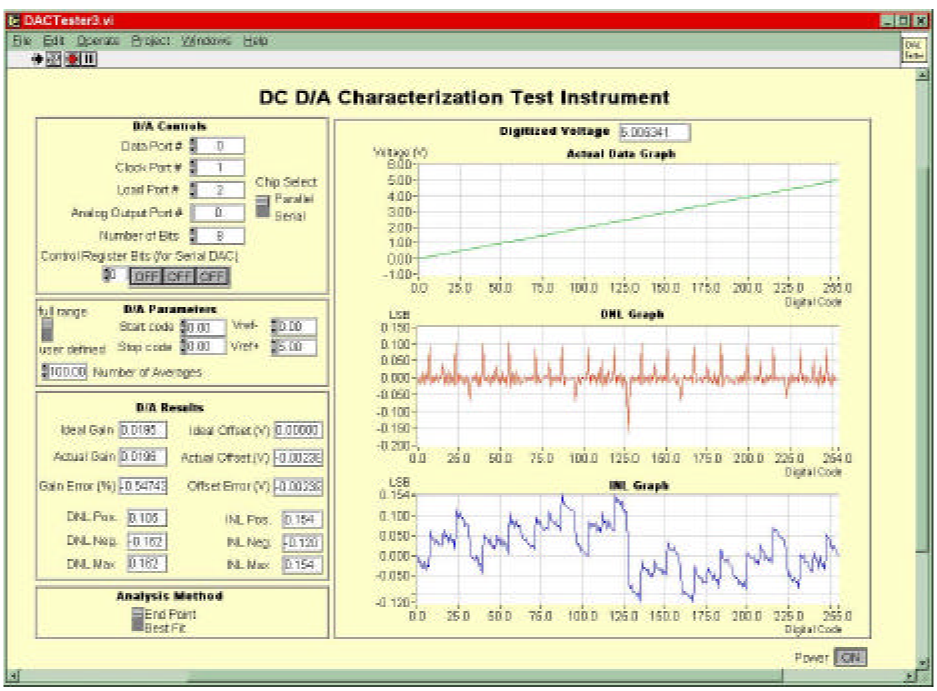

Figure 2. Linearity testing of a digital-to-analog converter.

The LabVIEW environment also gives students a flexible, intuitive programming environment for designing new experiments and modifying existing mixed-signal test experiments. LabVIEW's graphical programming environment and use of modular subroutines made it easy to design experiments where students had to supply a particular part of the program, such as their own data processing routine. LabVIEW also supports drivers for all of the equipment discussed above, GPIB communications, and a comprehensive library of data post-processing subroutines (ie, FFT routines, time-domain windowing, histogram routines, etc.) needed for making mixed-signal measurements. Finally, because students in the Engineering Technology program are exposed to LabVIEW in other classes, this choice had the advantage of not introducing a new learning curve into the class.

IV. Conclusions and Future Work

Through the use of these experiments, students are being introduced to concepts that they would not normally see in a standard analog electronics laboratory. The response of the students to the new labs has been excellent and after working through the concepts presented in the classroom, students are demonstrating a better comprehension level of the material. Additionally, while these experiments are being designed specifically to better prepare students entering the field of test engineering after graduation, they are useful in giving all students a much better understanding of measurement concepts. While students normally learn to make simple measurements as a by-product of standard analog and digital labs, these experiments are specifically designed to teach the theory and implementation of most common measurements.

To continue this work, each of the discussed experiments is tested both in the lab and in a classroom setting. Student and instructor feedback is then used to make continual improvements. Industry feedback is also being solicited. Finally, work is still continuing on the development of a complete stand-alone, low-cost mixed-signal tester. This tester has a targeted cost of $500 and will reduce the overall cost of a complete bench setup substantially.

Bibliography

1. Zorian, Y. "Testing the monster chip," *IEEE Spectrum* (July 1999), pg. 54-60.
2. Burns, M. and Roberts, G. *An Introduction to Mixed-Signal IC Test and Measurement*. (New York: Oxford University Press, 2001).
3. Fink, R. and Porter, J. "Mixed-Signal Test Initiative in Engineering Technology," *Proc. of the 1999 Gulf Southwest ASEE Conference, Dallas, TX* (March, 1999).
4. Warren, M., Kemp, J., Fletcher, B., Zoghi, B., Porter, J. "A Low-cost Embedded Control Tester for Teaching Mixed Signal Test Concepts," *Proc. of the 2000 Gulf Southwest ASEE Conference, College Station, TX* (March, 2000).

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