AC 2012-3936: INSTRUMENTATION FOR AN EMBEDDED CONTROL SYSTEMS DESIGN COURSE INCORPORATING THE DIGILENT ELECTRONICS EXPLORER BOARD

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Instrumentation for an Embedded Control Systems Design Course
Incorporating the Digilent Electronics Explorer Board

ABSTRACT

Auburn University’s Electrical and Computer Engineering curricula include a junior-year, laboratory-intensive course on embedded control systems design. Teams of students design, implement, test, evaluate, and report on a microcontroller-based embedded control system that includes both analog and digital electronic elements. The laboratory infrastructure for this course has been updated around the Digilent, Inc. Electronics Explorer Board (EE Board), which is an integrated analog and digital circuit design station. In this paper, the authors present how the EE Board and associated PC-based Waveforms™ software meet the instrumentation needs of the course, and enhance the students’ abilities to effectively conduct and communicate their work.

I. Overview of Course Objectives and Student Outcomes

The course (ELEC 3050: Embedded Systems Design Lab) has these learning objectives:

1. Use modern engineering tools to design, implement, and test an embedded control system. Elements of the system include a user interface (keypad), analog signal conditioning (sensor), and power electronics (amplifier) to drive an actuator. System elements are integrated via a microcontroller module[2] and its associated software. Students design, create and integrate hardware and software to simultaneously meet several performance specifications. Throughout the engineering processes, students regularly conduct experiments to measure and collect data about their system. Computer aided design tools include: (a) CodeWarrior integrated design environment[3] (IDE) for HCS12 microcontroller[4] system design, (b) Mathworks® MATLAB™ and SIMULINK™ for data analysis, data visualization, and system level simulation, and (c) PSpice for electronic circuit simulation. Instruments used in experiments include: (a) the digital logic analyzer, (b) digital sampling oscilloscope, (c) digital volt/ohm meter (DVM), and (d) a waveform generator.

2. Practice life-long learning skills by performing their own research about unfamiliar technologies and engineering science concepts.

3. Periodically report engineering progress via memos, a midterm report, an oral presentation, and a final report. For all of these communication exercises, students perform data analysis and practice methods to concisely summarize data by designing figures and tables. Communication tools include the word processor, spreadsheet, graphics editor, and presentation software. Each student also archives his or her engineering work in a personal engineering notebook that is periodically reviewed.

4. Study how engineering practice relates to a professional code of ethics. Students examine peer-reviewed case studies, identify ethical dilemmas, and propose professional practice solutions.

The following student outcomes are assessed during the semester:

- Ability to design and realize an electronic system to meet performance constraints.
- Ability to create experiments and draw meaningful conclusions from experimental data.
• Ability to function as a member of an engineering team.
• Awareness of professional ethics in engineering practice.
• Ability to communicate effectively in both oral and written forms.

The primary assessment objects are the students’ written reports and oral presentations. To effectively communicate their work outcomes, students need laboratory instrumentation that not only supports electronic measurements, but also records data and eases integration with the previously described analysis and reporting tools. In the next section, the authors present a typical course project having multiple options for analog and digital subsystems. These design options create several instrumentation needs that will be further described in Section III.

II. A Typical Embedded System Project

The system design problem is one that may be encountered in contemporary electrical engineering practice – the control of electric motor speed. A block diagram of the control system is shown in Fig. 1. A matrix keypad is the user interface (Fig. 2a). A dc motor with integrated ac tachometer is provided (Fig. 2b), and is modeled as part of the “plant” in Fig. 1. The plant output is the ac tachometer signal. An electronic circuit conditions the tachometer signal for processing by the digital control algorithm, which is part of the “controller” in the block diagram. The controller block includes the keypad interface logic, as well as conversions of analog-to-digital forms for feedback signals, and digital-to-analog forms for output signals. The controller’s analog output is amplified to drive the electric motor; the power amplifier is part of the “plant” block. In summary, the “plant” input and output are analog signals. Therefore, the signal conditioning input and “controller” output are also analog signals, but these signals are represented and realized in digital form within the microcontroller of the embedded controller.

A typical set of system performance specification is as follows:
• The desired speed must be selected from a 16-button matrix keypad.
• The system must demonstrate nine different non-zero speeds.
• The sampling period for the system must be 10 ms +/- 1 µs.
• The measured steady-state speed of the motor must be within 5% of the desired speed, whether the motor is under load or not. The test load will be a single turn of string around the motor pulley, with a 15 g washer weighting the free end.

Fig. 1. Block diagram of a typical embedded system project
Teams of two students design and implement subsystems to perform several functions: detect and interpret user input from a keypad, measure the motor speed (sensing), execute a digital control algorithm, convert the algorithm’s digital output to an analog form (controller output), and amplify the analog signal to drive the dc motor (power electronics). Many of these functions can be realized by either analog or digital means; these various options are described below.

II.A. Options for analog subsystems

Analog signal conditioning options exist for both the feedback signal and the controller output. For feedback, the tachometer produces an ac voltage whose amplitude and frequency are proportional to the motor shaft speed. Several options exist to condition the tachometer signal. A frequency-to-voltage converter can produce an analog voltage proportional to the ac frequency. Alternatively, an envelope detector can estimate the ac signal amplitude. Either of these analog signals can be converted to digital form by the analog-to-digital converter that is included on the microcontroller chip.[4]

The controller output can be a voltage proportional to the calculated control algorithm value; a digital-to-analog converter can be used to perform the conversion. Alternatively, the digital control value can modulate the duty cycle of a pulse-width-modulation (PWM) signal. Using the microcontroller, students study two on-chip methods to produce an accurate PWM signal: employ the programmable timer, or use the PWM generator.

II.B. Options for digital subsystems

The tachometer ac signal can also be conditioned to digital logic levels, which opens additional signal processing options for the feedback signal. Students design a comparator circuit that
produces a square wave synchronized to the tachometer ac signal. The square wave has the same frequency as the tachometer signal, but the amplitude is constrained to logic levels (0-5 V). The period of the square wave can be measured by the timer subsystems within the microcontroller.

The user interface is a 16-button matrix keypad. Students design hardware and software to detect and decode button presses. Periodic scanning can be used to monitor button presses, or the keypad can be used to generate interrupts that are serviced by the microcontroller.

In summary, the student teams study several analog and digital signal options that can be used to meet requirements of the design problem. Measurement of analog and digital signals is a common thread throughout these studies. The laboratory infrastructure needs to support the students are described in the next section.

### III. Laboratory Infrastructure Needs

A variety of measurement instruments are essential in the course:

1. **Volt/ohm meter:** Typical tasks include verification of dc power supply voltages, and measurements of component values.

2. **Logic analyzer:** Tasks include verification of keypad interface signals, and analyzing signals from the timer and counter exercises. Signal bandwidths can be up to 1 MHz.

3. **Oscilloscope:** Typical signals measured include the ac signal from the tachometer, the PWM signals generated by the microcontroller, and the output of the power amplifier. The bandwidth of these signals is usually below 1 MHz. Signal amplitudes in correctly operating circuits are typically within the range of +/- 30 V. The switching power amplifier has the potential to generate much higher voltage spikes because the motor winding is an inductive load. These voltage spikes are clamped in a properly designed circuit, but the oscilloscope must be sufficiently robust to be employed in improperly designed circuits.

4. **Signal generator:** Both sinusoidal and square wave signals may be used as test signals throughout the semester. Logic level signals may be used to test timer and counter subsystems. Generated signal bandwidths are usually below 1 MHz.

5. **Power supplies:** Provide electrical energy to all hardware circuits. Both positive and negative supply voltages are typically used. Power supplies are needed for 5 Vdc logic circuits, comparator and operational amplifier circuits, and dc motor drive electronics (up to 1 A current).

6. **For low speed signals,** single pole single throw (SPST) switches are also useful to create basic digital input signals. Optoelectronic displays such as light emitting diodes (LEDS) and seven-segment displays are also useful diagnostic tools to study slower or static digital output signals.

Shown in Table A is a list of experiments conducted in the course[^1], along with instruments that are used by students. (Power supplies are needed every week, so they are not listed in the table.) Instruments that record data are especially useful, because students are taught to analyze and present data that supports their engineering decisions. There is also a challenge for physical space on the laboratory bench, which must accommodate all the aforementioned instruments, the prototype experimental plant, the embedded controller electronics, a desktop computer for the
integrated design environment, and still have space for students to write in engineering notebooks or use personal laptop computers.

Software based instruments have become increasingly available in recent years. The previous generation of laboratory instruments for this course used a set of commercially available high performance digital and analog data acquisition cards that occupy several PCI slots of a personal computer. These cards with associated software provided the logic analyzer and oscilloscope functions. Power supplies, a handheld DVM, and an in-house designed general-purpose breadboard system remained separate items on the laboratory bench. Limited bench space often precluded the presence of the function generator, and free workspace was limited.

Electronic package densities continue to rise and communication interfaces improve in performance and flexibility, so it is now possible to find electronic breadboard systems that integrate even greater laboratory instrument functionality. One example is the National Instruments Educational Laboratory Virtual Instrumentation Suite (NI ELVIS), which is an integrated suite of more than a dozen instruments in a compact package designed for education. In fact, the NI ELVIS II+ version is used in two of Auburn University’s sophomore year laboratories. The NI ELVIS system is not considered suitable, however, for the junior year course for several reasons. First, the data acquisition system bandwidth was marginally acceptable for studying the signals in a microcontroller based electronic system (the most recent version of ELVIS does include upgraded performance). Second, the system does not have a true logic analyzer function. In addition, the high cost of replacement in the event of damage is considered a drawback. Unlike the sophomore year laboratories that are characterized by clearly defined experiments and step-by-step procedures, the junior year course is one in which students design their own experiments and some open-ended projects. Student inexperience often leads to damages in laboratory instruments.

In contrast, the Digilent Electronic Explorer Board (EE Board) is a relatively lower cost
IV. Features of the Digilent, Inc. Electronics Explorer Board

Built around a large solderless breadboard, the EE Board includes the instrument functions listed in Table B (at the end of the paper). Shown in Fig. 3 is the topside (user side) of the EE Board, with different areas for signal connections highlighted. Students build their prototype electronics in the breadboard area, and make connections to power supplies and instrument functions with 20-22 AWG hookup wire. Not shown in Fig. 3 is the underside of the board, which is populated by the EE Board electronics, all powered by a single external 12 V, 2 A power supply. A high-speed universal serial bus (USB 2.0) is the sole connection to a personal computer. At Auburn University, each student design team stores their prototype embedded system and EE Board within a foam-lined plastic carrying case (12 x 9.5 x 3.5 inches) that can be secured and stacked with other cases for storage.

The EE Board is controlled by free, Windows-based WaveForms™ software[^7] that provides the user interface to the instrument functions, as well as more advanced data analysis, data filtering, and data visualization functions. The breadboard system with associate software can acquire, store, analyze, produce and reuse analog and digital signals, and is a way to introduce students to the flexibility of “virtual instruments.” Shown in Fig. 4 is an example user interface for the fixed and programmable power supplies and voltmeter. Instructions for selecting a 5 Vdc fixed voltage supply and enabling the instruments are highlighted in red. The actual supply voltage and current are also highlighted.

WaveForms™ data files are stored using standard formats. Therefore, data can be shared.

Fig. 3. Digilent EE Board, showing areas for signal connections. Digital signal connections are along the top. Analog inputs and power supplies are accessed along the bottom. Board dimensions are 7.8 x 6.3 inches (198 x 160 mm).
between virtual instruments, and it is also straightforward to export experimental data to third party software packages such as word processors, spreadsheets, or data visualization packages. The network connections of the host computer enable world-wide communication of data measured using the EE Board. Since the introduction of the EE Board and WaveForms™ software, Auburn University students have been able to produce well-documented reports and presentations about their design projects, using standard office communication tools. Some examples are presented in the next section.

V. Examples of Virtual Instrumentation Usage

Several examples of student work using the Digilent EE Board and WaveForms™ software are shown in Figs. 5-7. In Fig. 5, the student reports two oscilloscope measurements. The measurements are the input signal (sinusoidal) and output signal (square wave) from a comparator circuit that conditions the ac tachometer signal. The figure is generated using the Windows operating system screen-capture feature, yet all labels are sufficiently clear for reading, and the plots are legible without additional post-processing effort. A white vignette effect draws the reader’s attention to the middle of the window.

Shown in Fig. 6 is an example of the logic analyzer output, captured from the computer screen in a similar manner, and then cropped in post-processing. The eight green traces represent the eight bits of EE Board digital i/o pins 8-15. The white colored plot displays the equivalent
decimal value of the eight digital bits. The lower four green traces and the white trace show the progression of a counter with decimal values from 4 to 9, and then rolling over and restarting from 0. Drawbacks of using screen capture are more evident in this example of student work. The black background and colored traces can be very clear on a computer screen, but legibility often suffers when used in the print medium. Background colors of user-selectable traces can be modified in WaveForms™ software, but students have generally been unaware of this feature. Students are encouraged to export data to third party software for plotting on white background.

In Fig. 7, another oscilloscope plot is shown with additional annotation. The oscilloscope window has been captured using screen capture, and the student then uses a graphics editor to create the red arrow and red text, which highlight a particular feature in the measurement.

VI. Summary

The Digilent Electronics Explorer board (EE Board) and associated Waveforms™ software form a suite of relatively inexpensive virtual instruments in a breadboard environment. Instruments include a logic analyzer, digital signal and pattern generator, general-purpose digital input/output channels, multichannel oscilloscope, 4-channel voltmeter, triple output fixed and programmable power supplies, and arbitrary waveform generator. The measurement bandwidth is sufficient high to support microcontroller-based experiments. Input channels are adequately robust and the overall system cost is within the reach of student budgets. At Auburn University, a junior year laboratory has been updated around the Digilent system. Students design their own experiments to develop and test an embedded system based on the Freescale HCS12 microcontroller. The Digilent system enables students to build and study their prototype system, and also record data for reporting in oral and written communication. Students have offered positive comments about the breadboard environment on course evaluations.

Bibliography

Table B. Instrumentation functions of the Digilent, Inc. EE Board

<table>
<thead>
<tr>
<th>Function</th>
<th>Electrical specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>logic analyzer</td>
<td>32 channel (shares pins with digital signal generator and digital I/Os)</td>
</tr>
<tr>
<td></td>
<td>100 MSa/sec sampling frequency</td>
</tr>
<tr>
<td></td>
<td>internal/external selectable clock</td>
</tr>
<tr>
<td></td>
<td>Up to 16 KSa per pin buffer depth</td>
</tr>
<tr>
<td></td>
<td>Multiple trigger options</td>
</tr>
<tr>
<td>digital signal generator</td>
<td>32 channels (shares pins with the logic analyzer and digital I/Os)</td>
</tr>
<tr>
<td></td>
<td>100 MSa/sec sampling frequency</td>
</tr>
<tr>
<td></td>
<td>Algorithmic pattern generator (no memory buffers used)</td>
</tr>
<tr>
<td></td>
<td>Custom pattern editor, up to 16 KSa per pin buffer depth</td>
</tr>
<tr>
<td>digital I/Os</td>
<td>buttons, switches, LEDs (shares pins with logic analyzer and digital signal generator)</td>
</tr>
<tr>
<td>oscilloscope</td>
<td>4-channel, 40 MSa/s sampling frequency</td>
</tr>
<tr>
<td></td>
<td>70 MHz bandwidth</td>
</tr>
<tr>
<td></td>
<td>9 MΩ /10 pF input impedance, ac/dc coupling</td>
</tr>
<tr>
<td></td>
<td>+/-20 V input range</td>
</tr>
<tr>
<td></td>
<td>10 b analog-to-digital converter (0.8mV to 40mV/lsb resolution)</td>
</tr>
<tr>
<td></td>
<td>Pp to 16 KSa buffer depth</td>
</tr>
<tr>
<td>voltmeter</td>
<td>4 channels, 1.2 MΩ input impedance</td>
</tr>
<tr>
<td></td>
<td>+/-10 V range, protected up to +/-200 V</td>
</tr>
<tr>
<td>reference voltages</td>
<td>2 programmable outputs, up to +/-10 V</td>
</tr>
<tr>
<td>arbitrary waveform</td>
<td>2 programmable channels, 40 MSa/s sampling frequency</td>
</tr>
<tr>
<td>generator</td>
<td>14 b digital-to-analog converter</td>
</tr>
<tr>
<td></td>
<td>10 V amplitude with +/-10 V offset</td>
</tr>
<tr>
<td></td>
<td>Output impedance 35Ω</td>
</tr>
<tr>
<td></td>
<td>Standard and user definable waveforms</td>
</tr>
<tr>
<td></td>
<td>2 KSa buffer depth (carrier), up to 32KSa buffer depth (modulator)</td>
</tr>
<tr>
<td></td>
<td>am/fm modulation with frequencies up to 4MHz</td>
</tr>
<tr>
<td></td>
<td>swept and damped waveforms</td>
</tr>
<tr>
<td>power supplies</td>
<td>Triple output:</td>
</tr>
<tr>
<td></td>
<td>• 1 fixed supply: selectable 3.3 or 5 V @ 2 A current</td>
</tr>
<tr>
<td></td>
<td>• 2 programmable voltage/current supplies: up to +/-9 V, up to 1.5 A</td>
</tr>
</tbody>
</table>
Fig. 5. Example of the Digilent EE Board/WaveForms™ virtual oscilloscope measurement, submitted by a student using the Windows screen capture function. Axes labels and traces are legible without additional post-processing. The student added a white vignette effect to the window border using graphics editing software.

Fig. 6. Example of the Digilent EE Board/ WaveForms™ virtual logic analyzer measurement, submitted by a student using the Windows screen capture function, after cropping the figure. Eight digital bits (green traces) and the equivalent decimal value (white trace) are shown. Black background can be very clear on a computer screen, but is less satisfactory in the print medium.
Fig. 7. Example of the Digilent EE Board/ WaveForms™ virtual oscilloscope measurement, submitted by a student using the Windows screen capture function, after adding figure annotation in red.