AC 2007-2217: RASCL: A PORTABLE CIRCUIT PROTOTYPING LABORATORY

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RASCL: A Portable Circuit Prototyping Laboratory

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Abstract

Circuit theory, signals & systems, and digital design courses in electrical engineering curricula are predominately lecture based and are often separated in time from laboratory courses that provide students with hands-on design experiences. While open laboratories have been proposed as a means to insert hands-on analysis and design into traditional lecture courses, this approach requires that students return to campus to complete their assignments. In addition to resource allocations associated with maintaining equipment laboratories, open laboratory traffic can be problematic, e.g., in instances where classes are offered as service courses for large numbers of students in other departments. This paper addresses the creation of a hands-on learning toolkit called the Rapid Analysis and Signal Conditioning Laboratory (RASCL), a portable analog/digital prototyping unit that provides a student with the capability to attend to hands-on assignments at home. While a few semi-portable prototyping tools exist on the market, they are generally expensive and provide functionality that does not map well to the needs of electrical engineering students. A RASCL unit, at a cost of around $250, consists of a carrying case that contains a National Instruments USB–6009 data acquisition module, a function generator, a large breadboard, a desktop power supply, and a parts/tools storage area. The data acquisition module communicates via a Universal Serial Bus interface with a LabVIEW virtual instrument running on a personal computer or a laptop. While this low-cost alternative to a regular laboratory workspace has technical limitations such as sampling frequency and instrument fidelity, it offers the potential for students to address hands-on homework assignments in their own living environment and is suitable for both on-campus and distance learning students.

I. Introduction

In electrical engineering (EE) curricula, circuits and signals courses rely primarily on lectures and handwritten homework. This is partially driven by the fact that most of the corresponding textbooks are written to satisfy a handwritten work (plus possibly software analysis) paradigm. Hands-on laboratories that reinforce these concepts usually rely on this lecture material for prerequisite knowledge, primarily because it is more efficient to organize groups of students in laboratory-only environments than to try to intersperse occasional hands-on assignments with their corresponding lecture topics. Both professors and students acknowledge that students would become more engaged in engineering education if professors could consistently assign circuit experiments that accompany the lectures. Open laboratories have been proposed and implemented in response to this awareness, but effective open laboratories require space, additional equipment resources, and possibly staff if they are to be scalable to meet the needs of, e.g., circuits classes that are offered as service courses for large numbers of students in other departments. Engineering curricula could benefit from tools that allow students to build and test
circuits at home in addition to the traditional experience they gain working with ‘real’ equipment on a laboratory bench.

This paper addresses the development of a prototyping toolkit called the Rapid Analysis and Signal Conditioning Laboratory (RASCL), a resource that would allow students to complete assignments off campus, avoiding cost and scheduling issues with which open laboratory environments must contend. The RASCL platform addresses the following general requirements, which are consistent with the needs of electrical engineering students:

- The unit should incorporate a breadboard large enough to accommodate reasonably complex circuits that map well to lecture concepts.
- The toolkit should be portable, which speaks to the need for a case, a portable power supply, a data acquisition board (for analog and digital input/output), and a software interface to view these waveforms and to provide control signals to the prototyping unit.
- To use the board to its full potential, a license-free, stand-alone executable file should accompany the data acquisition hardware. This interface could represent the features of the board and the DAQ interface using software equivalents of traditional equipment such as a digital multimeter, oscilloscope, and function generator.
- The board and case must be durable enough to survive trips to campus in a backpack.
- The kit should be affordable and flexible enough for use in several classes. In some situations, it might also be sensible for students to check out a kit from a department, their professor, or a student group such as the local IEEE student chapter.

Previous efforts have attempted to create similar tools, but the functionality that they offer and their respective prices do not map well to the requirements listed above. These products are described in more detail in section II. Background. Section III. Methods describes the functional layout of the RASCL board, provides pictures of the initial hardware/software implementation, and presents a filters laboratory used to gauge the effectiveness of the RASCL kit as a learning tool. Student feedback in the form of survey responses is provided in section IV. Results and Discussion, along with a list of improvements that will help to optimize the RASCL concept.

II. Background

In light of the requirements listed in section I. Introduction for a home-based prototyping toolkit, a search for suitable existing products was surprisingly unfruitful, affirming the educational niche such a tool would fill. Information sources included the Internet, the publication database for the American Society of Engineering Education, and the XPlore search facility provided through the Institute of Electrical and Electronics Engineers. In addition to the innate desire for students to be able to design from home, the RASCL concept originated from (a) work already underway with the National Instruments ELVIS prototyping systems in the KSU Medical Component Design Laboratory and (b) the prototype in Figure 1, which is close in spirit to the RASCL concept and provides a limited but useful toolset, especially when compared to units under $1000 that were located during this search. The board in Figure 1, designed by William Durfee at the University of Minnesota, is a forward thinking tool designed to “pilot an innovative approach to system dynamics and control laboratories that incorporates proven hands-on learning principles to improve student learning.” Its primary purpose is to provide students with a means to filter acoustic signals, and the board is one of a pair of boards available for purchase as
a $100 kit. The kit includes supervisory software written in Visual Basic that allows students to communicate with the board via the left and right channels of the Line-In port on a computer sound card. Generally speaking, the functionality and resources on this board are restricted when one considers broad use in an EE curriculum. For example, if a professor were to assign students the task of building an audio filter comprised of a cascade of active filters, the breadboard would not provide enough space. Additionally, for circuit theory and signals & systems courses, EE students would need access to an array of input waveforms in addition to audio, including periodic sine, square, and triangle waveforms. Because of the importance that modern embedded systems curricula place on digital design, a board of this nature designed for EE students must also incorporate both analog and digital input/output resources. Finally, because of the array of courses offered in an undergraduate curriculum, any accompanying software interface must be flexible enough to emulate multiple types of equipment front panels.

Figure 1. Audio filtering board (William Durfee, Department of Mechanical Engineering, University of Minnesota).\textsuperscript{[10]}

National Instruments markets a signal conditioning board, the SC–2075,\textsuperscript{[11]} which provides some level of functionality consistent with the requirements listed in section I. Introduction. This board has a retail cost of nearly $400 and is not accompanied by a stand-alone interface. Rather, the expectation is that the operator of the SC–2075 board is trained to use National Instrument’s LabVIEW environment and can create their own visual interface. A separate data acquisition (DAQ) card is required at additional cost.

Global Specialties manufactures an Analog Circuit Trainer that costs $240.\textsuperscript{[12]} This product offers several varieties of input signals, a prototyping area, and a portable power supply, but it does not include a connection to a personal computer.

Several other products are available that contain similar features to the desired unit but are, like the board from the University of Minnesota, designed for a specific application. For example, Freescale offers an evaluation board used to prototype systems that employ the MPC555 microcontroller.\textsuperscript{[13]} While this board provides a great deal of digital prototyping functionality, it has limited breadboard space and costs nearly $600, resulting in a non-optimal alignment with the requirements listed earlier. A similar example is a board built by microEngineering Labs, Inc. that costs $200.\textsuperscript{[14]} This board is designed for operation with a Microchip PIC
III. Methods

RASCL Hardware and Software
Consistent with the requirements listed in section I. Introduction, the goal of this effort was to prototype a signal conditioning and analysis kit that is independent of benchtop laboratory equipment, including oscilloscopes, function generators, multimeters, and power supplies. Given a small collection of circuit components, a set of hand tools, and wires (most of which could be stored in the case of the unit), the only additional items a student would need to complete a circuit assignment at home would be a computer with a Universal Serial Bus (USB) port, which most students already own, and access to an electrical outlet. Alternatively, students could interface this kit with nearly any campus computer. Note that while an RS-232 serial connection would also prove useful, serial ports are becoming less common in laptop/handheld devices, and bit rates could be an issue. If needed, reasonably priced USB-to-serial adapters are available.

The functional core of the package is a USB–6009 data acquisition (DAQ) unit manufactured by National Instruments. A disassembled unit and its accessories are shown in Figure 2, where a U.S. quarter illustrates its comparative size. The two pieces on either side of the circuit board are terminal blocks that plug into the DAQ unit. Note that the DAQ unit can potentially be removed from the kit and used separately for other projects. The USB–6009 retails at $269, but National Instruments has agreed to offer the DAQ to students for $149.

![Figure 2. National Instruments USB–6009 data acquisition unit.][15]

The main RASCL board includes a built-in waveform generator whose core is an Exar XR–2206 monolithic function generator integrated circuit (IC). With the exception of a few capacitor changes, the circuitry proposed in Exar application note TAN–005 is used in the RASCL design. This IC provides periodic sine, triangle, and square waveforms, where each type of waveform

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[15]: https://example.com/figure2.png
has limitations but is useful in different situations. The RASCL unit also incorporates a low cost, desktop power supply similar in size and shape to a laptop power supply. The power supply (see Figure 5B) provides three options to the user: +12 V @ 1 A, –12 V @ 0.5 A, and +5 V @ 3 A. The dual supply (±12 V) allows students to easily construct active circuits, whereas the +5 V supply provides students with the option to use CMOS ICs or single-supply ICs in their circuits. An 840 tie-point breadboard is also part of the RASCL design, providing students sufficient area to build and test reasonably large circuits. The RASCL printed circuit board was designed using Cadence v15.1 and the board was manufactured by the Advanced Circuits board house. Figure 3 contains a picture of the RASCL board removed from its carrying case, and Figure 4 contains a closer view of the function generator controls.

A – Data Acquisition Device: National Instruments USB–6009 DAQ. A USB cable (Figure 5A) connects the DAQ to a personal computer.

B – Terminal Connects: Electrically connect the DAQ to the printed circuit board.

C – Function Generator Controls: Select and adjust the waveforms provided by the on-board function generator chip (see Figure 4).

D – Quick Test Sockets: Give the user easy access to the power supplies and the DAQ channels.

E – Breadboard: Circuit prototyping area.

F – Power connector: Provides access to three power levels (+12 V @ 1.0 A, –12 V @ 0.5 A, and 5 V @ 3.0 A) once the power block in Figure 5B is plugged into an outlet.

Figure 3. The RASCL board.
A – Frequency Select:  A switch to select between two capacitors for coarse frequency selection. 
B – Frequency Adjust:  A potentiometer to fine tune the frequency of the sine, triangle, or square wave. 
C – DC Offset Adjust:  A potentiometer that adjusts the DC offset of the signals. 
D – Sine Symmetry Adjust:  A potentiometer to compensate for signal distortion (with Sine Distortion Adjust). 
E – Amplitude Adjust:  A potentiometer to adjust the voltage amplitude of the output signals. The Square wave amplitude is constant at ±12 V. The sine and triangle amplitudes occupy a lesser range. 
F – Sine Distortion Adjust:  A potentiometer to adjust for signal distortion (with Sine Symmetry Adjust). 
G – Triangle/Sine Select:  A switch to select between a triangular or sinusoidal output waveform. These waveforms cannot be accessed concurrently. The square wave output is always available. 

Figure 4. RASCL function generator controls.
National Instruments provides a free LabVIEW Student Edition license with the purchase of a USB-6009 DAQ. In addition, a pre-built LabVIEW virtual instrument (VI) is provided for students who do not know how to construct a LabVIEW interface. The VI provides a virtual oscilloscope and a spectrum analyzer that can be used to view and analyze circuit signals. This VI is open for editing if students wish to modify it to create a custom interface. A screenshot of the virtual oscilloscope customized for the needs of the RASCL unit is shown in Figure 6.

![Figure 6. StudentScope: a LabVIEW virtual instrument built for the RASCL kit.](image)

**Initial Learning Experience**
To gauge early student responses to the RASCL platform and to assess its potential as a learning tool, the authors of this paper prepared an extra credit laboratory for the Fall 2006 section of EECE 512 – Linear Systems, a course with an enrollment of 38 students. The exercise, intended to take approximately two hours, briefly addressed different areas of RASCL functionality by requiring students to build a predefined circuit and analyze its properties. Specifically, students were asked to (a) build a 2nd-order, lowpass, voltage-controlled-voltage-source (VCVS) filter, (b) apply different signals to its input terminals, and (c) analyze the filter output signals in several different ways. Students were asked to experimentally determine the filter transfer function based on input/output signal amplitudes, compare the transfer function to theory, analyze the effect of this filter on different time domain waveforms, and investigate how the DAQ unit and sample parameters affect the frequency spectra of periodic signals. Questions were interspersed during the exercise to assess student understanding of the laboratory concepts. The following paragraphs summarize this laboratory exercise in more detail.
Learning Objectives. Upon laboratory completion, each student should be able to do the following:

- Utilize the basic functionality of a RASCL board and its LabVIEW virtual instrument
- Construct, debug, and evaluate an active, second-order Butterworth lowpass filter
- Describe the behavior of a lowpass filter given input sinusoids of different frequencies
- Compare experimental transfer function values against the theoretical $H(\omega)$ curve using Microsoft Excel
- Explain the output signal from a lowpass filter given an input square wave

Equipment and Materials. Personal computer with a Universal Serial Bus (USB) port; Rapid Analysis and Signal Conditioning Laboratory (RASCL) toolkit; LabVIEW StudentScope VI; Microsoft Excel; Electronic components – Operational amplifier chips, resistors, capacitors, and wires; Small standard screwdriver

Protocol. Every student was first allowed a few minutes to become familiar with adjusting the frequencies/amplitudes of the sine and triangle waves; these effects were viewed in the StudentScope VI. They were then instructed to tune the potentiometer to obtain a sine wave at a frequency of 100 Hz and confirm that the frequency and amplitude of each signal (channel) was displayed below the corresponding plot in the StudentScope VI. Each student then switched the StudentScope VI to the Spectrum Analyzer interface and was taught about its functionality.

Once a student was familiar with the general RASCL features and the software interface, they built a 2nd-order Butterworth filter (see Figure 7) on the RASCL breadboard. They were then given access to a Microsoft Excel spreadsheet and asked to adjust the frequency of the input sine wave to the values listed in the spreadsheet (10, 15, 20, …, and 200) while recording the voltage amplitudes of the input and output signals in the appropriate cells. Upon completion of this data entry, the measured data would be plotted along with the theoretical data as shown in the left hand side of Figure 8. Finally, they were asked to change the input waveform to a square wave and adjust the frequency of the waveform so that the output signal would almost reach its maximum amplitude just prior to a direction change in the square wave. This allows them to see the effect of filtering out the higher frequency components of a signal while retaining the more slowly varying signal elements. A typical result is illustrated in the right hand side of Figure 8.

![Figure 7. 2nd-Order VCVS Butterworth lowpass filter.](image-url)
Figure 8. Typical results from the filter laboratory that utilizes the RASCL platform. Left: filter transfer function with a plot of the magnitude response (measured data: blue line with data points; theory: purple line). Right: StudentScope VI screen shot illustrating the input square wave and the filter output waveform.

IV. Results and Discussion

Survey Results
Upon completion of the exercise, the students were asked to complete a short survey to assess their learning experience. The survey consisted of 20 items to which the students would provide a numerical response (see Table 1), followed by a short set of open-ended questions to which the students would write responses. Of the 38 students enrolled in the course, 30 students participated in this extra credit exercise.

The columns of Table 1 list the survey item number, the items to be addressed, and the aggregate response (average ± standard deviation) for this group of 30 survey responses. Note that items 1–2, 3–16, and 17–20 correspond to different 1-to-5 rating schemes. As indicated by items 1–2, students responded positively to the overall experience and felt that hands-on exercises would provide effective learning opportunities when compared to traditional, lecture-only course offerings. Regarding items 3–7, students clearly note that both the hands-on portion of the experience and the visual software interface engaged their interest and promoted effective learning. While the response to item 8 was expected (i.e., students found the circuit building process to be a minor distraction), the distraction was outweighed by the variety that it added to the learning experience. The average responses to items 10–15 imply that some understanding was gained for every learning objective. Additionally, when examining the individual responses that were used to compute the averages for items 10–15, no student reported that they learned nothing, and nearly all reported learning at least a small amount in every subject. The response to item 16 reinforces these conclusions: students felt there would be a significant level of ownership and interest gained (both of which are important to learning) if they were to assemble the RASCL toolkit themselves as part of their early coursework. Items 17–20 show that ease of use for the collection of RASCL tools was rated very highly across the board.
### Table 1. Survey items and results.

<table>
<thead>
<tr>
<th>Item #</th>
<th>Item</th>
<th>Average ± σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rate your overall experience.</td>
<td>4.2 ± 0.6</td>
</tr>
<tr>
<td>2</td>
<td>Rate the potential impact that these types of hands-on exercises would have on the effectiveness of traditional lecture-only courses.</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>3</td>
<td>How much learning occurred during this session?</td>
<td>3.5 ± 0.9</td>
</tr>
<tr>
<td>4</td>
<td>• the hands-on element?</td>
<td>3.8 ± 1.0</td>
</tr>
<tr>
<td>5</td>
<td>• the visual nature of the software interface?</td>
<td>4.1 ± 0.9</td>
</tr>
<tr>
<td>6</td>
<td>• the hands-on element?</td>
<td>4.0 ± 0.9</td>
</tr>
<tr>
<td>7</td>
<td>• the visual nature of the software interface?</td>
<td>4.0 ± 1.0</td>
</tr>
<tr>
<td>8</td>
<td>• What level of distraction did it add?</td>
<td>2.1 ± 1.0</td>
</tr>
<tr>
<td>9</td>
<td>• What level of welcome diversion did it add?</td>
<td>3.6 ± 1.2</td>
</tr>
<tr>
<td>10</td>
<td>• How filters affect sinusoids at different frequencies</td>
<td>3.3 ± 0.8</td>
</tr>
<tr>
<td>11</td>
<td>• How filters affect non-sinusoidal signals</td>
<td>3.5 ± 0.8</td>
</tr>
<tr>
<td>12</td>
<td>• The process by which you can build an analog filter</td>
<td>3.5 ± 1.0</td>
</tr>
<tr>
<td>13</td>
<td>• Difficulties that analog filters pose during construction</td>
<td>3.1 ± 1.1</td>
</tr>
<tr>
<td>14</td>
<td>• Theoretical versus experimental signal spectra</td>
<td>3.7 ± 0.9</td>
</tr>
<tr>
<td>15</td>
<td>• Theoretical versus experimental filter transfer functions</td>
<td>3.7 ± 0.7</td>
</tr>
<tr>
<td>16</td>
<td>What level of ownership and interest would be added on your part if assembling your own RASCL unit was part of the curriculum?</td>
<td>4.0 ± 1.0</td>
</tr>
<tr>
<td>17</td>
<td>• RASCL prototyping area?</td>
<td>4.3 ± 0.9</td>
</tr>
<tr>
<td>18</td>
<td>• RASCL function generator?</td>
<td>4.5 ± 0.8</td>
</tr>
<tr>
<td>19</td>
<td>• RASCL quick connect terminal?</td>
<td>4.6 ± 0.8</td>
</tr>
<tr>
<td>20</td>
<td>• LabVIEW software interface?</td>
<td>4.8 ± 0.4</td>
</tr>
</tbody>
</table>

Students were also asked open ended questions. First, they were asked “Would you prefer to learn concepts using handwritten assignments, hands-on assignments, or both?” The authors were surprised to note that none of the students answered this question as ‘handwritten only.’ A significant number of the students (26, or 87%) said ‘both,’ leaving only 4 students to state they prefer hands-on learning only. These responses demonstrate that most students realize the importance and value of both theory and handwritten work.

The next question referred to their hands-on experiences outside of EECE 210 – Introduction to Electrical Engineering, a course recently added to the electrical and computer engineering
curricula at Kansas State University to give freshmen an early glimpse into what an EE degree offers: “With the exception of EECE 210, have you ever built circuits and tested the theoretical issues learned in lecture-format classes?” Since EECE 512 – Linear Systems is taken primarily by juniors and seniors in electrical and computer engineering, the responses were a bit surprising. Half of the students responded “no.” Those that responded “no” to this question reported above-average responses to items 2, 4, and 6 in Table 1, implying that students with no prior experience in building and analyzing circuits found this exercise to be especially effective and that it increased their desire to learn.

The students were then asked “What improvements/features might be added to the RASCL system based on this experience? Several students had great things to say about this tool. Some (8, or 27%) felt there was nothing wrong with the tool at all. The remaining 22 (73%) had minor suggestions, where ¾ of these students reported an upgrade to the user controls on the function generator as the only suggested change.

Finally, students offered the following thoughts:

- Most (22, or 73%) of the students would pay $200 to $400 for a tool like this to use in their courses. This range is consistent with the current cost of the unit: the DAQ costs $149 and the additional RASCL components cost $100.
- Irrespective of the amount students would be willing to pay for such a unit, 19 students (63%) would prefer to pay that fee as a lump sum as opposed to a series of payments across semesters.
- Were the option available, 20 students (66%) noted an interest in paying a smaller equipment fee each semester to make RASCL units available for checkout to all students.
- If the unit were available but not required for class, 22 students (73%) stated they would use this tool for learning anyway.

**Future Work**

While the first version of the RASCL toolkit appears to promote successful learning experiences, the next iteration of the RASCL design should incorporate minor improvements in several areas:

- A power switch and fuses for power supply protection need to be added.
- The printed circuit board layout can be improved to optimize the available board space.
- Minor circuit improvements and corrections are needed.
- The user controls need to be updated for easier access and improved durability.
- An additional prototyping board (doubling the current area) would be beneficial.
- An audio connector needs to be added to allow audio signal processing.

**V. Conclusion**

This paper addressed the development and initial testing of a hands-on learning toolkit called the Rapid Analysis and Signal Conditioning Laboratory (RASCL), a portable prototyping unit that would allow an engineering student to address circuit and signal assignments at home. The current RASCL toolkit incorporates a large-area breadboard, a function generator, a portable power supply, a USB DAQ board, a carrying case, and an easy-to-use software interface. A student only needs access to a standard power outlet and a PC capable of running the LabVIEW software interface.
Student Edition to use the toolkit. To gauge initial student responses to this type of learning tool, a laboratory experience addressing a second-order lowpass Butterworth filter was created for a Fall 2006 Linear Systems course. Student survey feedback confirmed that student responses to the overall experience were highly positive: students felt strongly that hands-on exercises would add effective learning opportunities when compared to traditional, lecture-only courses. They found the experience to be engaging and indicated that personal ownership and interest would be gained if they were to assemble the RASCL toolkit themselves as part of their early coursework. While students acknowledged the importance of theoretical learning, they expressed a strong preference for coursework that combined both theory and hands-on learning experiences. An important observation was that students with no prior experience in building and analyzing circuits found this exercise to be especially effective and that it increased their desire to learn. Finally, students would be willing to invest resources to gain access to this type of tool. While minor improvements can be made to the current design of the RASCL toolkit, the results of this work apply clear merit to the idea that a portable prototyping laboratory would greatly enhance learning experiences in electrical and computer engineering curricula.

Acknowledgements

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References


