Developing Computer-Based Laboratory Instruments in a New Undergraduate Electrical Engineering Program—a Summary

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ABSTRACT: This paper describes the culmination of a two-year project which had two aims: (1) development of computer-based laboratory instruments (CLIs) consisting of LabVIEW virtual-instrument programs coupled with custom external hardware; (2) integration of these CLIs into the undergraduate curriculum. Students were brought into the design process wherever possible, giving them first-hand experience with open-ended design problems. Project TUNA (Texas Universal Network Analyzer), a CLI which characterizes the frequency response (magnitude and phase) of linear networks over a frequency range of 10 Hz to 100 kHz, was designed as a class project in EENG 4409 (Electronic Circuit Analysis II) in 1999, and served as the model for this project. Project TUNA was described in a previous paper presented to the 2000 ASEE Annual Conference. A grant from the National Science Foundation (DUE-9952292) was received in April, 2000, to support further development of CLIs at the University of Texas at Tyler. An interim progress report was presented to the 2001 ASEE Annual Conference. This paper summarizes the CLIs and their use in the curriculum and describes the resources developed by this project which have been made available to other electrical engineering programs.

Project TUNA II:

Project TUNA (Texas Universal Network Analyzer), an instrument for measuring ac frequency response of active and passive networks, was described in a paper presented at the 1999 ASEE Annual Conference [1] which later appeared in an updated version [2]. Curricular resources available for Project TUNA include a tutorial describing how Project TUNA functions and how Project TUNA is used in a laboratory exercise in characterization of active filters. Construction details for those interested in duplication of Project TUNA include schematics, parts lists, AutoCAD drawings, and the Project TUNA virtual-instrument program written in LabVIEW (National Instruments, Austin, TX). Permanent copies of the Project TUNA hardware have been constructed and have been successfully used in the electrical engineering laboratory curriculum at the University of Texas at Tyler. Resources related to Project TUNA may be obtained from http://www.eng.uttyl.edu/usr/dbeams/tuna/project_TUNA.htm.

Figure 1 shows a block diagram of the Project TUNA instrument. The heart of Project TUNA is a dual switching-type phase-sensitive demodulator and a pair of low-pass filters. A GPIB-controlled HP33120A signal generator (Agilent Technologies, Palo Alto, CA) serves as the signal source; quadrature networks provide produce two sinusoidal outputs in phase quadrature relative to each other. The cosine signal is applied to the device under test through a buffer. The sine and cosine outputs of the quadrature networks are converted into square waves by high-speed voltage comparators, and these square waves serve as reference signals for the demodulator. Three quadrature networks are employed to cover the frequency range between 10 Hz and 100 kHz with the appropriate network chosen depending upon the generator frequency. Four dc voltage measurements (taken by a GPIB-controlled Agilent HP34401 DMM) are necessary to determine the voltage gain of the device under test at each frequency. The in-phase and quadrature output voltages are read for the phase detector connected to the input of the device under test to determine the magnitude and phase of the input voltage to the device under test; these voltages are read again with the phase detector connected to the output of the device under test to determine the magnitude and phase of the output voltage. Figure 1 below shows the block diagram of the Project TUNA unit.

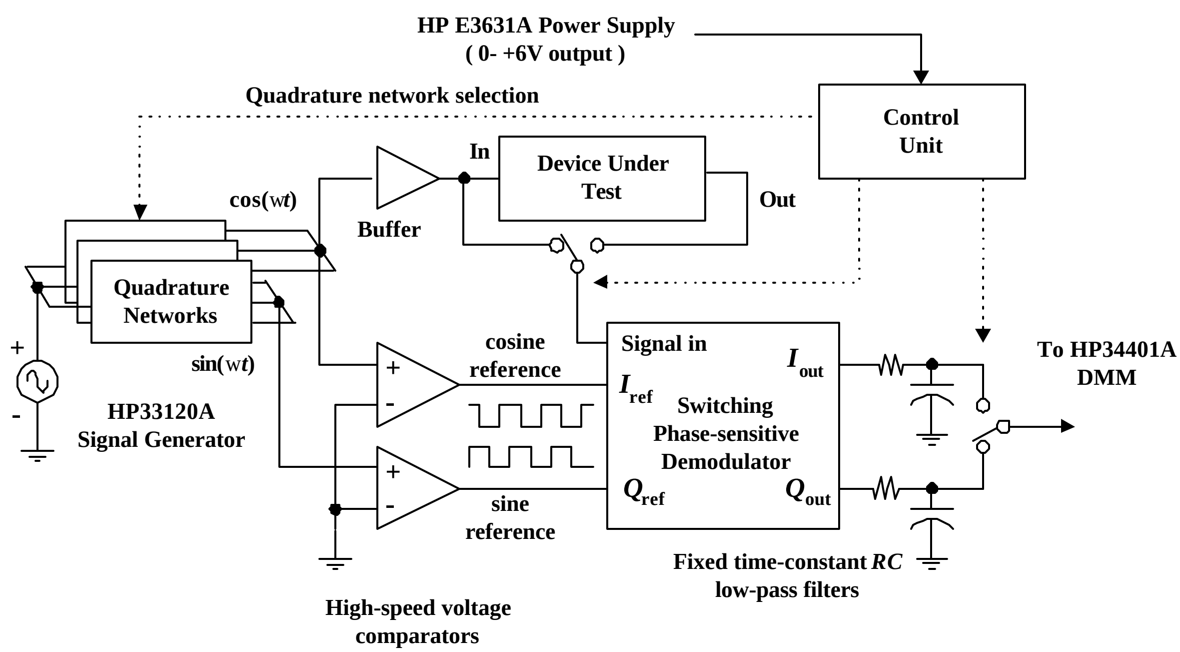

Fig. 1. Block diagram of the Project TUNA computer-based laboratory instrument.

Project TUNA is not without its shortcomings:

- It requires relatively-expensive GPIB-based test equipment for both the signal source and data acquisition. The GPIB-based equipment provides no digital I/O for direct control of the hardware. This difficulty was overcome by building a control unit to configure the hardware. This control board includes a 4-bit A/D converter connected to the 0 – +6Vdc output of a GPIB-controlled triple dc power supply (Agilent E3631A) and combinatorial logic to convert these bits into specific control signals. The LabVIEW virtual-instrument program contains code which to forces the required voltages at the power supply.
- The switching-type phase-sensitive demodulator was also found to produce unreliable results above a few hundred kHz for signals in the range of tens of millivolts or less, attributed to charge injection from the gates to the channels of the ADG201HS high-speed analog switches (Analog Devices, Norwood, MA) used in the demodulator. Thus the finished TUNA instrument was limited to 100 kHz.

- The dynamic range of the Project TUNA instrument is limited to voltage gains of ±30 dB. Significant limits to the dynamic range were imposed by the unity-gain input amplifier of the phase-sensitive demodulator and by the necessity to maintain the generator output at or above approximately $0.5V_{pp}$ to ensure proper operation of the high-speed voltage comparators.
- The fixed time constants of the *RC* low-pass filters was 160 ms, chosen to provide sufficient filtering at the lowest frequency of operation (10 Hz). This limited how rapidly the Project TUNA instrument could step from one frequency to the next.
- The use of a switching-type phase-sensitive detector with a square-wave reference signal means that the demodulator produces dc outputs from demodulator input signals containing odd harmonics of the measurement frequency.[3]

Senior electrical-engineering student Zinnour Soultanov undertook a re-design of Project TUNA as his senior design project in 2001. Project TUNA II was to include a number of improvements:

- Increased frequency range;
- Increased measurement dynamic range;
- Shortened analysis times;
- Reduced dependence upon GPIB instrumentation;
- Use of a multifunction I/O card for data-acquisition and control.

Figure 2 shows the block diagram of Project TUNA II. The principal changes in TUNA II are:

- A multiplying phase-sensitive demodulator using AD734 high-speed four-quadrant analog multipliers (Analog Devices) replaced the switching-type demodulator;
- A variable attenuator was added ahead of the buffer driving the device under test to permit varying the drive level to the device under test without having to change the output voltage of the generator;
- The gain of the amplifier preceding the phase-sensitive demodulator was made variable;
- Variable time-constant *RC* low-pass filters were used, permitting shorter analysis times at higher frequencies (>5 kHz);
- Direct control of TUNA II hardware by digital I/O with a PCI-1200 multifunction I/O card (National Instruments, Austin, TX) was implemented;
- Simultaneous readings are made of the in-phase and quadrature outputs of the phase-sensitive demodulator by analog inputs of the PCI-1200 multifunction I/O card.

A prototype of Project TUNA II has been constructed and tested and has substantially met its design goals. Resources available for Project TUNA II include schematics, a description of the software, and the virtual-instrument program. All are available through links found at http://www.eng.uttyl.edu/usr/dbeams/home/tuna2/project_tuna2.htm. A permanent copy of the TUNA II instrument has not yet been constructed.

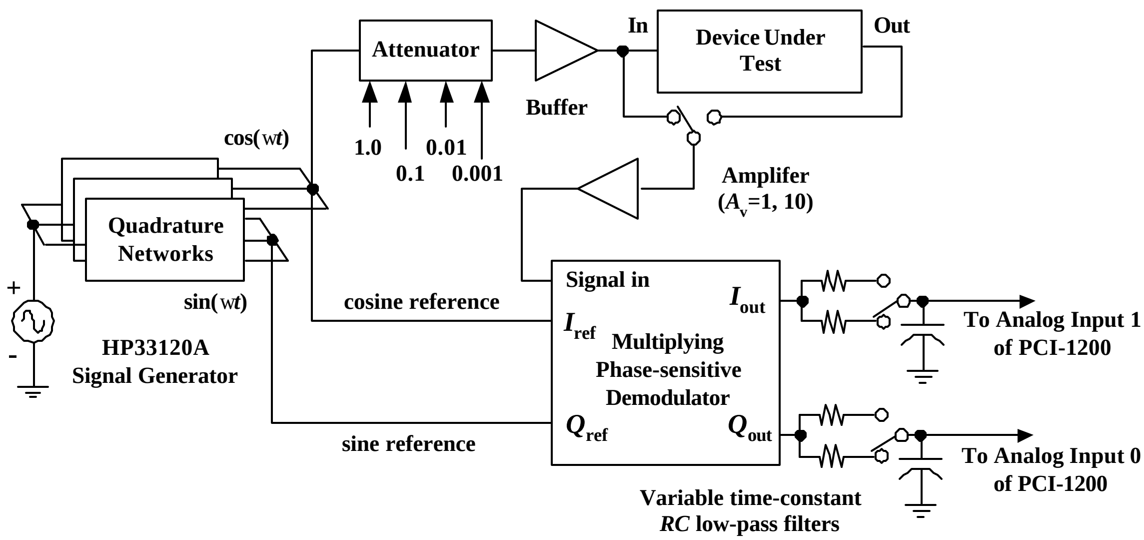

Fig. 2. Block diagram of the hardware of Project TUNA II.

Project TUGBOAT:

Project TUGBOAT (Texas UnderGraduate Basic Op Amp Tester) is a computer-based laboratory instrument designed to measure certain non-ideal characteristics of common operational amplifiers (input-offset voltage, input-bias current, dc open-loop gain, and ac open-loop gain at 1 kHz and 10 kHz). Project TUGBOAT's measurement techniques were outlined in an application note from Analog Devices [4] and the instrument itself was described in detail in a paper presented at the 2001 ASEE Annual Conference [5]. Curricular resources currently available for Project TUGBOAT include a tutorial on its operation and a laboratory exercise suitable for a junior-level course in electronics. The tutorial explains techniques for measuring these parameters and their implementation in the TUGBOAT instrument. The laboratory exercise consists of two phases. The first part leads students through measurement of input-offset voltage, input-bias currents, dc open-loop gain, and ac gain-bandwidth product of common operational amplifiers with the Project TUGBOAT instrument. The second half has students build circuits with these amplifiers to observe the effects of the measured non-idealities on circuit behavior. Resources available for duplication of the Project TUGBOAT instrument are the LabVIEW virtual-instrument program, schematic diagrams in .pdf format, printed-circuit artwork (produced with AutoCAD Release 12), and a list of components. These resources are available at http://www.eng.uttyl.edu/usr/dbeams/home/tugboat/project_tugboat.htm.

Another finding of Project TUGBOAT was the existence of large differences for some op amps between their dc open-loop gains measured by the prototype instrument (which was the subject of the report in 2001) and by the instrument constructed with a printed-circuit board (PCB). A representative sample is produced below in Table 1. The results are somewhat confusing. Experiments undertaken to determine the origin of the differences showed that the measured gain was affected by the output-voltage swing forced at the output of the device under test and whether any additional load resistance was placed between the output and ground.

Further experimentation is needed to explain the phenomenon; it may be noted, however, that the gains measured by the permanent version of Project TUGBOAT are more consistent with published manufacturers' data than those of the prototype instrument.

Device Type and Test Serial No.	Manufacturer	Lot Code	DC Open-Loop Gain	
			Prototype	PCB
TL084 (#1)	Texas Instruments	82A3CFM	104,000	77,900
TL084 (#2)	Texas Instruments	82A3CFM	97,700	73,600
TL084 (#3)	Texas Instruments	03A53KM	80,600	62,100
LM741 (#1)	National	HM92AJ	2.57×10^6	467,000
LM741 (#2)	National	HM92AJ	3.37×10^6	512,000
LM741 (#3)	Harris	H9640	257,000	397,000
LM741 (#5)	Harris	H9640	251,000	393,000
LM324 (#2)	National	PM948DH	1.49×10^6	712,000
LM324 (#3)	RCA	H401	1.93×10^6	547,000
LM324 (#4)	National	209C	3.15×10^6	442,000

Table 1. Comparison of dc open-loop gains for various devices measured by both the prototype and PCB versions of the Project TUGBOAT instrument. "Lot Code" reflects markings other than device type and manufacturer's logo found on the devices.

One minor modification has been introduced to the Project TUGBOAT virtual-instrument program since the instrument was first described. It was found in testing the Project TUGBOAT instrument realized on a printed-circuit board that ac open-loop gain measurements of LM324 operational amplifiers at 1 kHz and 10 kHz were grossly in error given the specified gain-bandwidth product of this device (approximately 1 MHz) whereas measured gains of TL084 and LM741 operational amplifiers were close to what was expected. Investigation of this effect showed that the LM324 devices' ac output voltages were not sinusoidal suffered significant crossover distortion when the output stage of the device was lightly loaded. A simple fix for this unexpected difficulty (which was not seen with the prototype TUGBOAT instrument) was to introduce a user adjustment permitting a dc offset to be superimposed upon the output of the device under test during ac open-loop voltage gain measurement. Figure 3 shows the revised panel of the Project TUGBOAT virtual instrument.

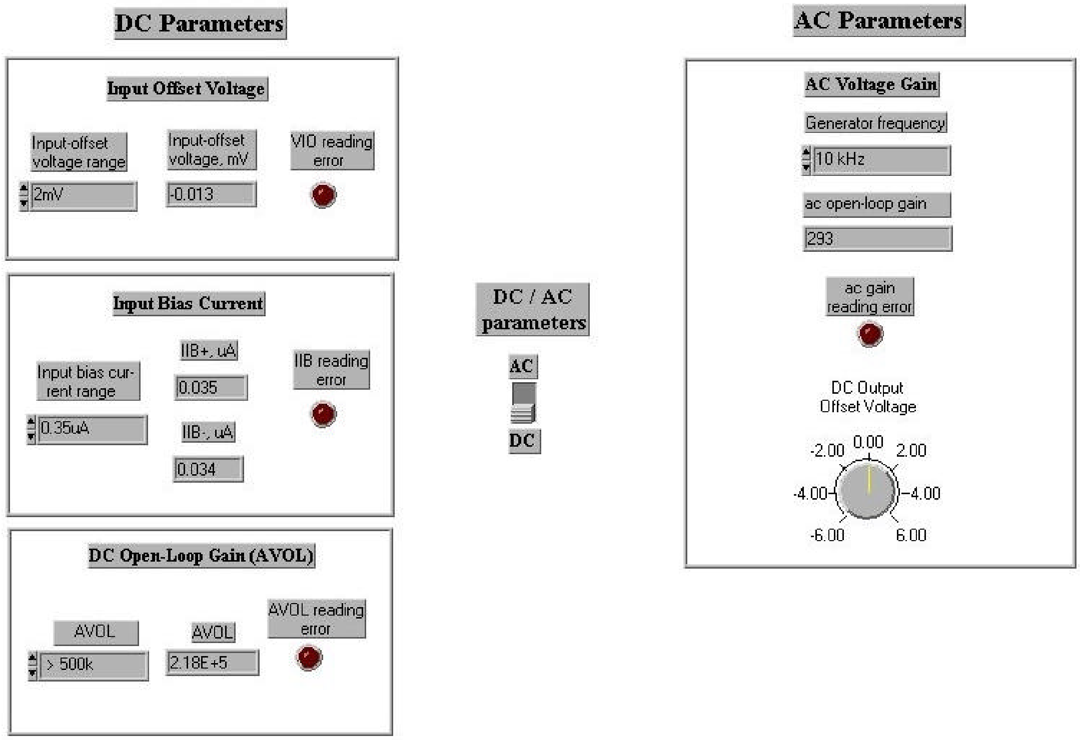

Fig. 3. Revised front panel of the Project TUGBOAT virtual instrument. The added user adjustment for dc output offset voltage during measurement of ac voltage gain is at the bottom of the "AC Parameters" sub-panel.

Project GUISE:

Project GUISE (General-purpose Universal Instrumentation System for Education) consists of a series of building blocks for instrumentation systems and a LabVIEW virtual-instrument program which configures these blocks. Figure 4 shows the block diagram of the Project GUISE external hardware. The configuration of Fig. 4 differs from that originally projected for this instrument in the following:

- Two separate ac/dc-coupled amplifiers were provided instead of one, and a variable dc output offset voltage (±10V) was incorporated in Amplifier 0.
- Both ac/dc-coupled amplifiers may be used as inverting or non-inverting amplifiers.
- Two unity-gain Butterworth low-pass filters were provided.
- A precision full-wave rectifier with gain of 2 was included.
- External amplitude control of the quadrature oscillator was deleted.
- A buffer amplifier was included for the thermocouple interface.
- Means were included to permit the instrumentation amplifier to be operated in electrical isolation from the remainder of the Project GUISE instrument. This would permit the use of the instrumentation amplifier as part of an isolation amplifier.

External cables are used to interconnect the blocks of the hardware of Project GUISE.

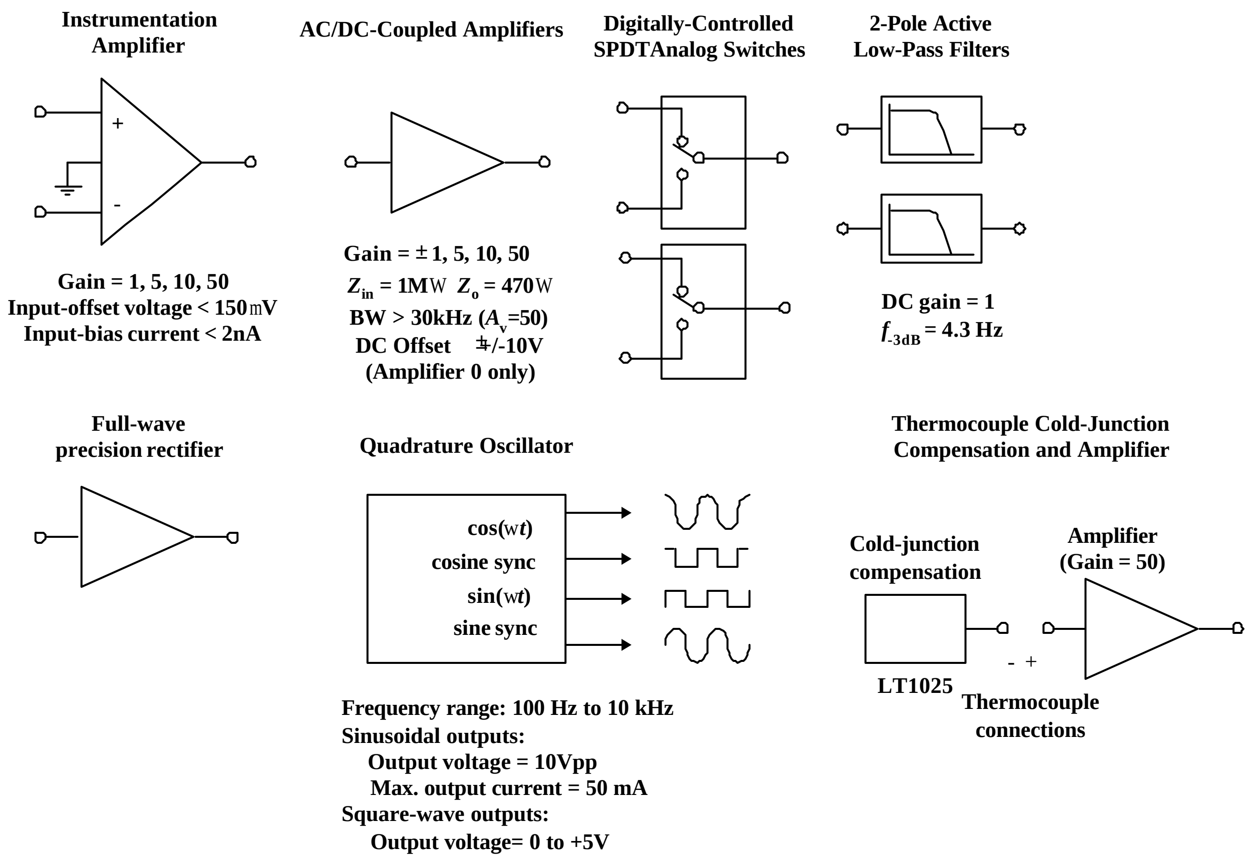

Fig. 4. Block diagram of the Project GUISE hardware.

Figure 5 shows the panel of the Project GUISE virtual instrument. The controls for the instrumentation amplifier, thermocouple selection, and the ac/dc-coupled amplifiers are at left; controls for the quadrature oscillator are at the upper right. Slope and offset adjustments are provided for calibration of the oscillator frequency. The middle sub-panel on the right-hand side provides real-time readings of the voltages at analog channels 0 and 1 of the PCI-1200 card. It also contains the parameters of a quadratic function to convert the raw voltage readings to calibrated readings in other units (e.g., temperature). The sampling rate of the analog channels is adjustable with a control at the lower-left corner.

Curricular resources available or in process for Project GUISE include a tutorial on the operation of its various sections and laboratory exercises (measurement of common-mode rejection ratio of the instrumentation amplifier; construction of chopper-stabilized and lock-in amplifiers; construction of an isolation amplifier; construction of a thermocouple amplifier; and construction of a strain-gage amplifier). Resources available for duplication of Project GUISE include schematic diagrams, artwork (created with AutoCAD Release 12), and the virtual-instrument program. See http://www.eng.uttyl.edu/usr/dbeams/home/guise/project_guise.htm. (As a parenthetical note, the prototype of the instrumentation amplifier achieved measured common-mode rejection ratios of 84dB at 200 Hz with a differential-mode gain of 50).

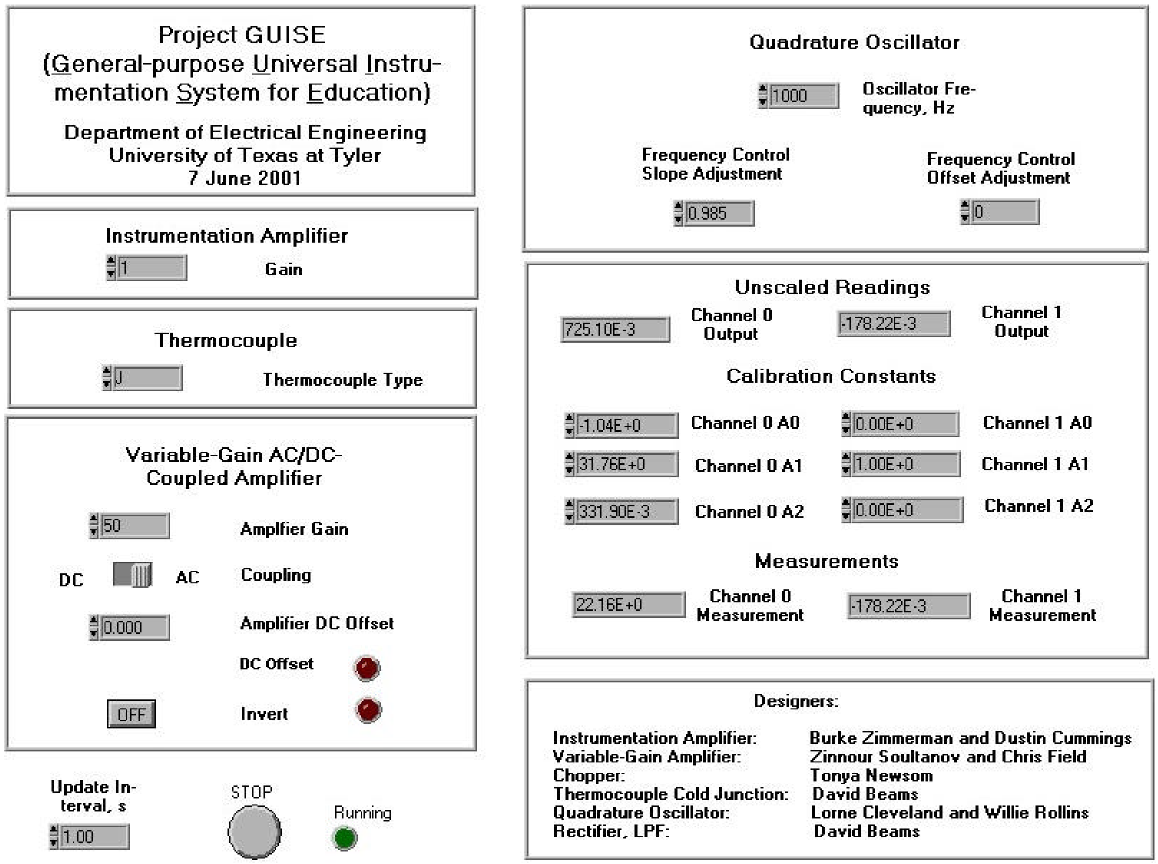

Fig. 5. Project GUISE virtual-instrument panel.

ZAP (Impedance Apparatus Project):

The last project planned in this sequence will be developed as a class project in EENG 4309 (Electronics II) and EENG 4109 (Electronics II Lab) in spring, 2002. It has been tentatively named "Impedance Apparatus Project," or "ZAP" using "Z" to stand for "Impedance." (The name is subject to change should the students devise a better one).
ZAP will be an impedance-measuring instrument similar to an *LRC* bridge. *LRC* bridges are neither excessively expensive nor difficult to obtain; the rationale for designing and building such an instrument in this course is three-fold:

1. to give students experience in open-ended design problems;
2. to give students experience in modern engineering tools (e.g., LabVIEW);
3. to give students understanding of how such an instrument makes its measurements.

Tentative goals for ZAP are as follows:

1. Frequency range from 10 Hz to 1 MHz;
2. Measurement range of magnitude of 50Ω to 100kΩ, and phase of ±90°;

3. User-selectable readout of impedance or admittance.

Figure 6 below shows one possible implementation of ZAP. One of the open questions to be settled in the early phases of the design process will be the design of the signal source. One possibility is to use an HP33120A signal generator as a sinusoidal source and use quadrature networks to generate sine and cosine reference signals as in Projects TUNA and TUNA II. This has the advantage that any frequency within the intended frequency range of ZAP can easily be synthesized; it has the disadvantage of requiring an IEEE-488 interface. Another possibility is to use a square-wave oscillator at $4f_{meas}$ and a simple state machine to produce two square waves in phase quadrature at f_{meas}.(where f_{meas} is the frequency of measurement). A cosinusoidal signal can be produced from the cosine-reference square wave with a bandpass filter. This approach can be readily realized in hardware but is restricted to a few discrete measurement frequencies.

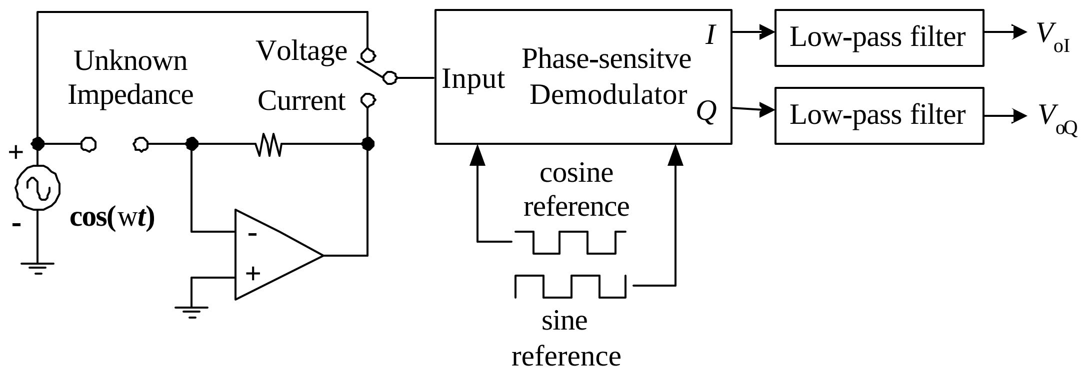

Fig. 6. Block diagram of the proposed ZAP instrument to be developed in EENG 4309 / 4109 in the spring semester of 2002 at the University of Texas at Tyler.

Developments of ZAP will be detailed at the 2002 Annual Conference of ASEE.

Rotating-Machine Laboratory Instrument:

The original proposal for this project included a computer-based laboratory instrument for a laboratory in electric-power systems and rotating machines. This development was shelved, however, after the departure of the faculty member for whom this instrument was to be developed.

Publication:

A booklet describing these computer-base laboratory instruments and the resources available for them will be prepared in the spring of 2002 and disseminated according to the dissemination plan included in the proposal for NSF DUE 9952292.

Acknowledgement:

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References:

1. D. M. Beams, *Project TUNA: the development of a LabVIEW virtual instrument as a class project in a junior-level electronics course.* Presented at the 2000 Annual Conference of the American Society for Engineering Education, St. Louis, MO, June 18–21, 2000.
2. D. M. Beams. Project TUNA – the development of a LabVIEW virtual instrument as a class project in a junior-level electronics course. *Computers in Education Journal* **11**:1 (Jan–Mar 2001), 28-33.
3. R. Pallas-Areny and J. G. Webster, *Analog signal processing.* New York: John Wiley and Sons, 1999, 259–264.
4 Anonymous. *How to test basic operational amplifier parameters*. Application note published by Analog Devices Inc., Norwood, MA. No date given.
5. D. M. Beams, *Developing Computer-Based Laboratory Instruments in a New Undergraduate Electrical Engineering Program.* Presented at the 2001 Annual Conference of the American Society for Engineering Education, Albuquerque, NM, June 24–27, 2001.

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