SESSION 2320

Project TUNA—The Development a LabVIEW Virtual Instrument as a Class Project in a Junior-Level Electronics Course

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Abstract

The Department of Electrical Engineering of the University of Texas at Tyler has a required two-semester sequence in electronic devices and circuits. The second course of this series (EENG 4409, Electronic Circuit Analysis II) includes a traditional laboratory component with exercises in amplifiers, active filters, non-linear circuits, oscillators, and CMOS devices. The laboratory exercise in active filters required measurement of complex voltage gain (magnitude and phase shift) of various low-pass, bandpass, and high-pass filters, a state-variable filter, and an all-pass (phase-shift) filter. The tediousness and repetitiveness of manual measurement elicited student complaints and obscured the purpose of the experiment. An automated instrument to measure voltage gain was conceived in response to this problem. Development took place in EENG 4409 in the spring of 1999 as Project TUNA (Texas Universal Network Analyzer). The prototype instrument was used with success in the active-filter laboratory exercise prior to the end of the semester. Project TUNA allowed the course lectures to be enriched with material on phase-sensitive demodulation and design of constant phase-difference (quadrature) networks. The prototype has since been used as a laboratory instrument in other courses and construction of permanent copies is planned. This paper describes the Project TUNA instrument and the integration of its development into EENG 4409, including lessons learned along the way.

I. Introduction

Measurement of the sinusoidal steady-state frequency response of active and passive networks is performed in several electrical engineering laboratory courses at the University of Texas at Tyler. Voltage gain and input-to-output phase shift were computed from measurements of oscilloscope traces of the input and output signals. This was tedious and repetitive and particularly onerous in the laboratory exercise on active filters in EENG 4409 (Electronic Circuit Analysis II). This particular exercise involved construction and characterization of various active filters, including several Sallen-Key active filters, a state-variable filter, and an all-pass (phase-shift) filter. The drudgery of data taking obscured the purpose of the experiment.

Project TUNA (Texas Universal Network Analyzer) was launched in response to this problem. It was conceived as an instrument for automated measurement of voltage gain (magnitude and phase) of an external active or passive network in a range of frequencies from 1 Hz to 1 MHz. Each workbench in the electrical engineering laboratory is equipped with an NT workstation (Compaq, Houston, TX). Models E3631A Triple-Output Power Supply, 34401A Digital Multimeter (DMM), and 33120A Arbitrary Waveform Generator (Agilent Technologies, Palo

Alto, CA) comprise the test equipment. LabVIEW virtual-instrumentation software (National Instruments, Austin TX) is installed on each of the workstations. The workstation and all test equipment communicate via an IEEE-488 General-Purpose Instrumentation Bus (GPIB). Project TUNA was conceived as GPIB-based LabVIEW virtual instrument (VI) with custom external hardware as shown in Fig. 1.

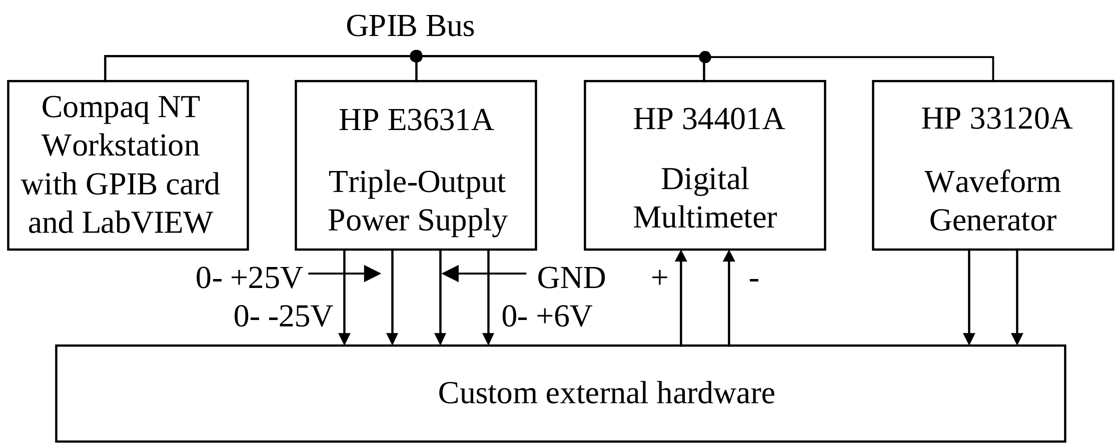

Fig. 1. General structure of Project TUNA as a LabVIEW virtual instrument in conjunction with GPIB-based test equipment.

Computer-based laboratory instruments using LabVIEW are not new at the University of Texas at Tyler; faculty-designed semiconductor curve tracers are incorporated into the curriculum of EENG 4409 and EENG 3406 (Electronic Circuit Analysis I). These instruments have been described elsewhere.[1] It was felt, however, that students should be involved in the design of Project TUNA. It would provide the sort of open-ended design problem encompassing establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation as mandated by ABET accreditation criteria.[2]. EENG 4409 was deemed an appropriate venue for development of this instrument. Students were given a brief written description of the proposed project at the first class meeting in the spring semester of 1999 and given the choice of following the established syllabus or replacing approximately half of that syllabus with Project TUNA. (The experiment on active filters would be postponed until a workable TUNA prototype instrument was available). The consensus was to undertake Project TUNA.

II. Hardware design

The original specifications of the proposed instrument are summarized in Table 1 below.

Table 1. Original performance specifications of the Project TUNA instrument

Performance specification	**Parameter range**
Frequency range:	1Hz –1 MHz
Input voltage range:	$0.02V_{pp}$ to $10V_{pp}$
Magnitude accuracy:	±1 dB
Phase accuracy:	± 5°

The 34401A DMM may be used as an ac voltmeter, and a virtual instrument which read only the magnitude of the voltage gain would have required minimal external hardware. Ability to measure phase was however considered indispensable and none of the available laboratory instruments would directly measure phase. The first concept of Project TUNA used the 34401A DMM as an ac voltmeter to read the input and output voltages of the network under test and as a dc voltmeter to read the output of a phase detector consisting of a Set-Reset (*SR*) flip-flop and low-pass filter (Fig. 2). Assuming the flip-flop output voltage levels to be 0V and $+V_{DD}$, the phase shift in degrees of the network under test is $\phi = 360 \cdot V_\phi / V_{DD}$ where V_ϕ is the dc voltage measured across the capacitor in Fig. 2. Students constructed and tested this phase detector but it was abandoned because it would produce erratic results in the presence of phase jitter when the phase shift of the network under test was close to an integer multiple of 360°.

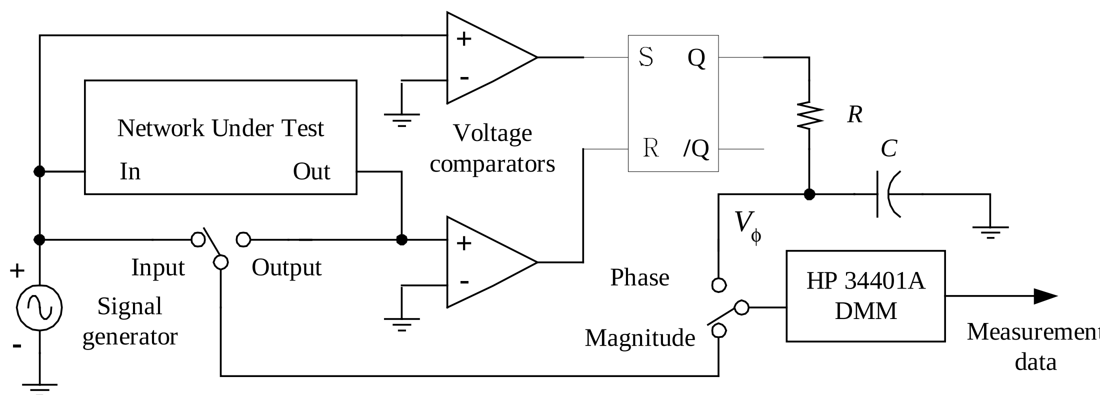

Fig. 2. First design of Project TUNA. This configuration was abandoned because of erratic behavior of the phase detector when the phase shift of the network under test was near an integer multiple of 360°.

The second alternative solution to be investigated was the phase-sensitive demodulation method shown in Fig. 3. Reference signals $\cos(\omega t)$ and $\sin(\omega t)$ are converted by voltage comparators to square waves which determine the states of a pair of high-speed analog switches. Each switch alternatively connects the input of a single-pole *RC* low-pass filter to the input signal V_{in} or to ground. Assume $V_{in} = A\cos(\omega t + \phi)$; with proper phasing of the analog switches relative to the reference signals, the in-phase output voltage V_{OI} and quadrature output voltage V_{OQ} are given by:

$$V_{OI} = \frac{A}{\pi}\cos(\phi) \tag{1a}$$

$$V_{OQ} = -\frac{A}{\pi}\sin(\phi) \tag{1b}$$

Phase and amplitude of the input signal can be computed from the measured values of V_{OI} and V_{OQ}:

$$A = \pi\sqrt{V_{OI}{}^2 + V_{OQ}{}^2} \tag{2a}$$

$$\phi = \tan^{-1}\left(\frac{-V_{OQ}}{V_{OI}}\right) \tag{2b}$$

This phase-detector circuit could unambiguously determine phase in a range of ±180° when the signs of both V_{OI} and $-V_{OQ}$ were considered. Measurement of the amplitudes and phases of both the input and output signals of the network would permit measurement of voltage gain and phase shift of the network. Measurements at both input and output would also eliminate the effects of propagation delay in the voltage comparators and actuation time in the analog switches. This method is also known as *I-Q* demodulation for its measurement of the in-phase (*I*) and quadrature (*Q*) components of the input signal.

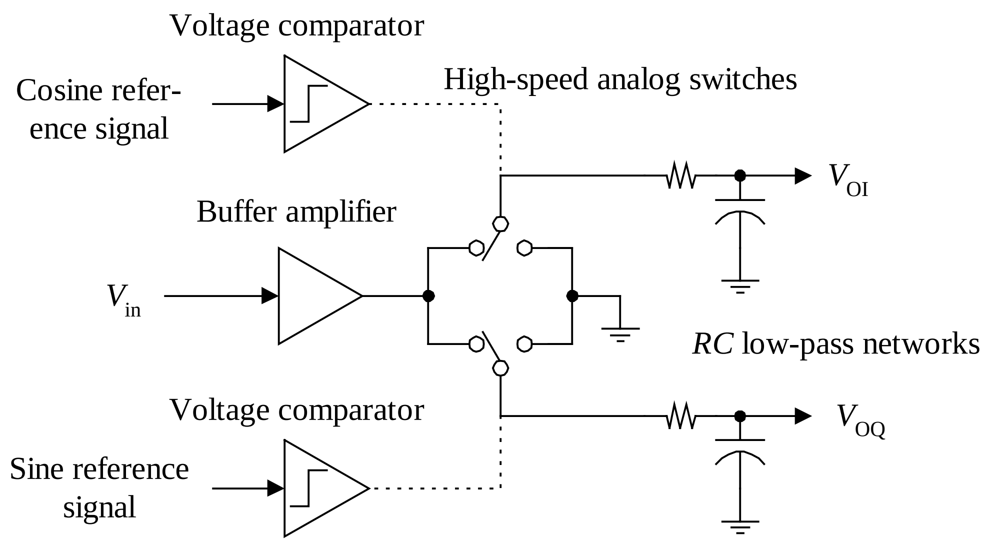

Fig. 3. Phase-sensitive *I-Q* demodulation using high-speed analog switches.

I-Q demodulation over a range of frequencies requires that the sine and cosine reference signals remain in phase quadrature over that range. Design methods for all-pass networks with a single sinusoidal input and two outputs in phase quadrature were described by Keely.[3] The final form of the network analyzer is shown in Fig. 4. Multiple quadrature networks permit a wider frequency range than was possible with a single network. Students constructed, tested, and evaluated the *I-Q* demodulator and several prototypes of quadrature networks during the hardware-development phase of Project TUNA.

Measurement of network gain and phase with the system of Fig. 4 requires reading V_{OI} and V_{OQ} for both the input and output voltages of the network under test. This requires switching the input of the *I-Q* demodulator between the input and output of the network under test and switching the input of the 34401A DMM between the demodulator V_{OI} and V_{OQ} outputs. It is also necessary to select the quadrature network appropriate to the measurement frequency.

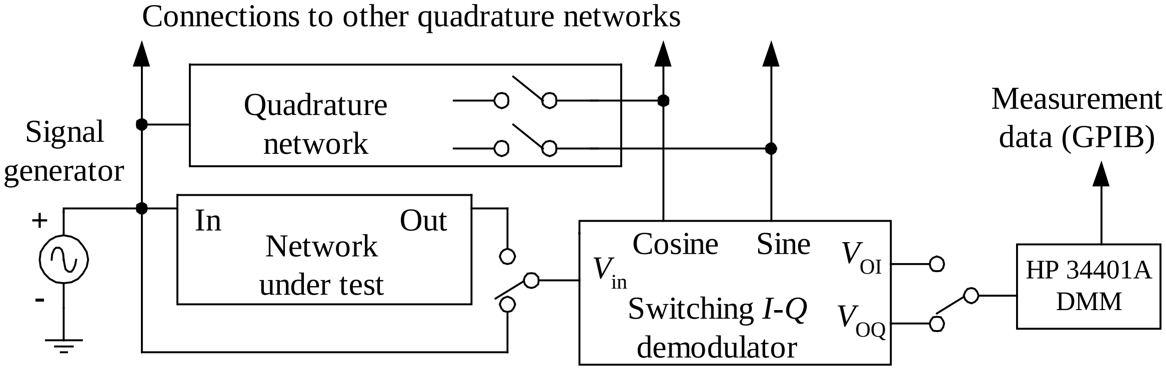

Fig. 4. Final configuration of Project TUNA hardware. Provision was made for as many as four quadrature networks to be installed; only one network is switched on at any given time.

Switching was a major design obstacle since no digital I/O ports directly addressable by LabVIEW were available. A 4-bit analog-to-digital converter (ADC) with an operating range of 0–+5V was developed and LabVIEW software was written to command specific voltages from the otherwise-unused 0–+6Voutput of the power supply. This voltage is converted to a four-bit output code by the ADC. These four bits activate electromechanical relays which perform the switching functions. Table 2 below gives the functional description of the ADC codes.

Table 2. ADC output codes and their actions in configuring TUNA hardware.

ADC output	Quadrature Network	Phase detector signal source	34401A input
0000	0	Network output	V_{OI}
0001	0	Network output	V_{OQ}
0010	0	Network input	V_{OI}
0011	0	Network input	V_{OQ}
0100	1	Network output	V_{OI}
0101	1	Network output	V_{OQ}
0110	1	Network input	V_{OI}
0111	1	Network input	V_{OQ}
1000	2	Network output	V_{OI}
1001	2	Network output	V_{OQ}
1010	2	Network input	V_{OI}
1011	2	Network input	V_{OQ}
1100	3	Network output	V_{OI}
1101	3	Network output	V_{OQ}
1110	3	Network input	V_{OI}
1111	3	Network input	V_{OQ}

III. Software design

Figure 5 shows the structure of the TUNA software. Frequency sweep is logarithmic. Generator voltage is adjusted to attempt to keep the network output voltage within a range of approximately $1.5V_{pp}$ to $15V_{pp}$. (A second variant of the software uses a fixed user-specified generator amplitude).

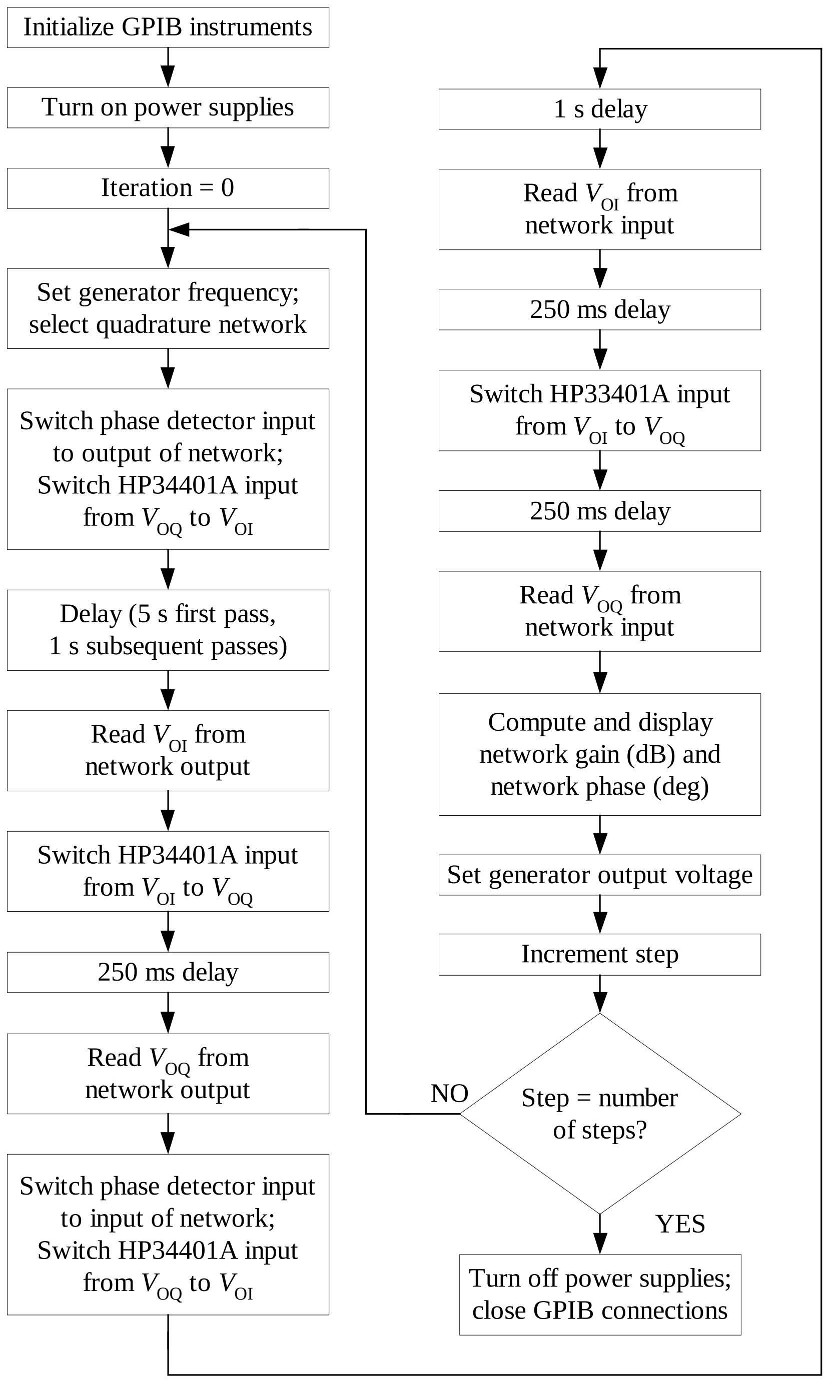

Fig. 5. Project TUNA software structure.

The TUNA user interface provides the user with four controls: start frequency, end frequency, number of frequency steps, and generator amplitude. The instrument displays the Bode plot of the voltage gain of the network under test with separate plots for magnitude and phase.

IV. Results

Figure 6 shows the frequency response of an active bandpass filter measured with the prototype TUNA instrument The frequency range was 50 Hz to 50 kHz. A separate sweep with a finer frequency step focusing on the response peak yields a maximal measured gain of 27.7 dB at 970 Hz and a bandwidth of 210 Hz. The theoretical maximal gain is 27.7 dB at 980 Hz and the theoretical bandwidth is 200 Hz. The instrument resolves phase in the range ±180 degrees, accounting for the abrupt phase crossover at the response peak.

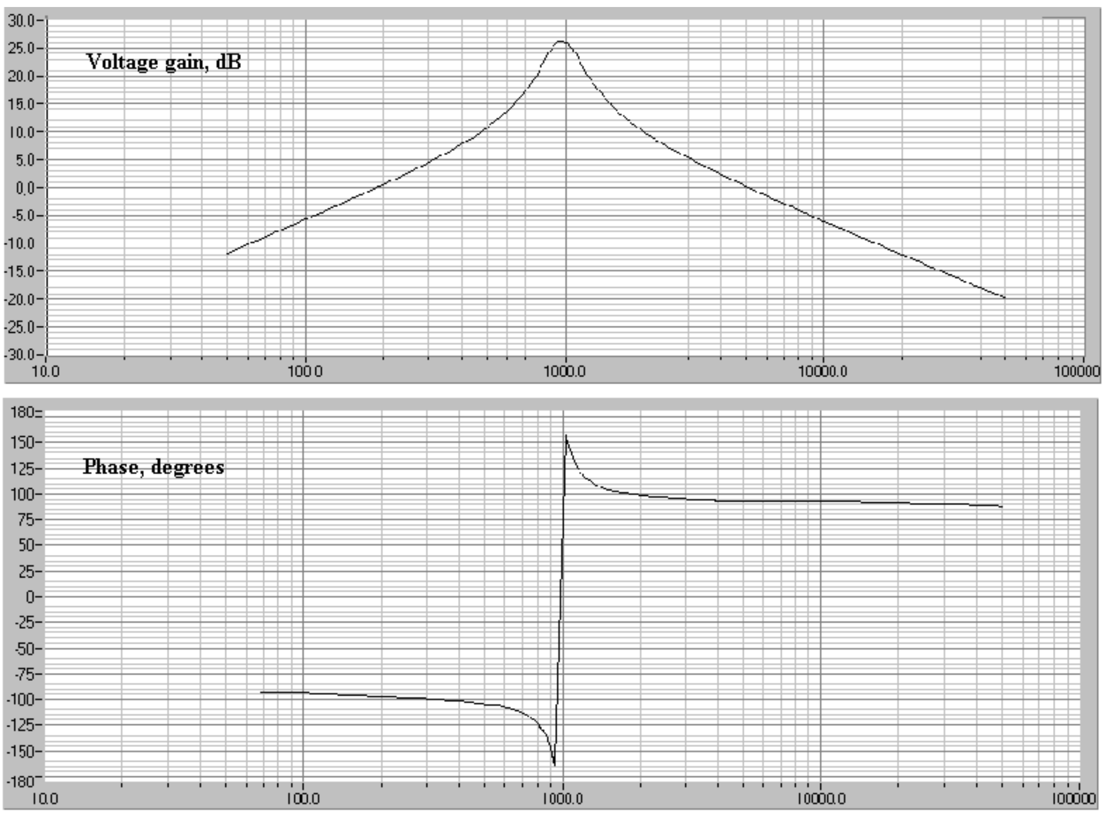

Fig. 6. Measured frequency response of an active bandpass filter obtained with the TUNA prototype with a frequency sweep from 50 Hz to 50 kHz. Text has been added to the *x*-*y* display areas. Virtual instrument controls are not shown.

The prototype instrument was successfully used in the active-filter laboratory in EENG 4409 to measure the responses of various two-pole lowpass, highpass, and bandpass filters. The TUNA prototype has been used to validate the frequency responses of various passive networks in an introductory experiment in EENG 3406 (Electronic Circuit Analysis I) and to verify the frequency response of an active 60 Hz bandpass filter used by mechanical engineering students in an experiment to measure the electrical power input to a fractional-HP universal motor.

Not all of the original performance objectives were achieved in the prototype design. A minimum operating frequency of 1 Hz required the time constants of the phase detector's passive low-pass filters to be greater than approximately 600 ms. Such long time constants would have necessitated long dwell times at each frequency for the filter output voltages to reach their steady-state values. Changing the time constants of the low-pass filters depending upon the measurement frequency was considered but not implemented since it required more-complex switching circuits. The minimum operating frequency specification was accordingly raised to 10 Hz and filters with fixed time constants of 0.16 s were used. The maximum operating frequency goal was also not achieved; the quadrature network for use between 100 kHz and 1 MHz did not function as expected and it was decided to set this network's development design aside until the basic TUNA instrument was operational. Thus the operating frequency range of the TUNA instrument is presently 10 Hz to 100 kHz. The TUNA prototype incorporated two quadrature networks (one for 10 Hz to1 kHz and the other for 1 kHz to 100 kHz) although the control circuits allow as many as four quadrature networks.

Figure 7 shows the TUNA prototype instrument. Work is underway to construct permanent examples. It is planned to use four quadrature networks in these instruments with each covering a smaller frequency span than the 100:1 span of the prototype instrument. Complete schematics of the TUNA prototype hardware and the LabVIEW virtual instrument program are available.

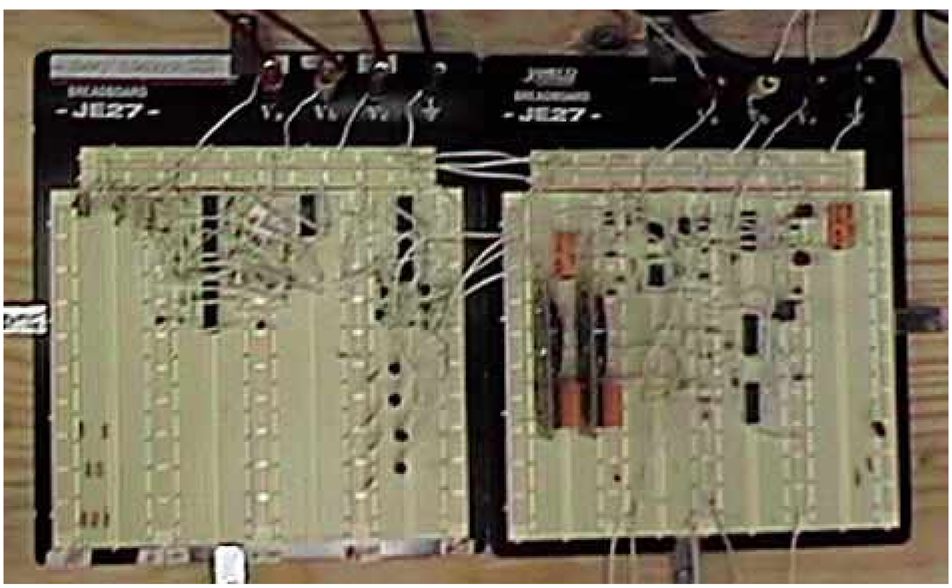

Fig. 7. TUNA prototype instrument. The left-hand prototyping board contains the 4-bit ADC and the control logic. The right-hand prototyping board contains the phase detector. The two quadrature networks are installed vertically to the phase-detector board.

Figure 8 shows the Project TUNA hardware installed at a laboratory bench in one of the electrical engineering laboratories at the University of Texas at Tyler. The small prototyping board visible in front of the TUNA hardware contains the bandpass filter under test which produced the frequency response shown in Fig. 6.

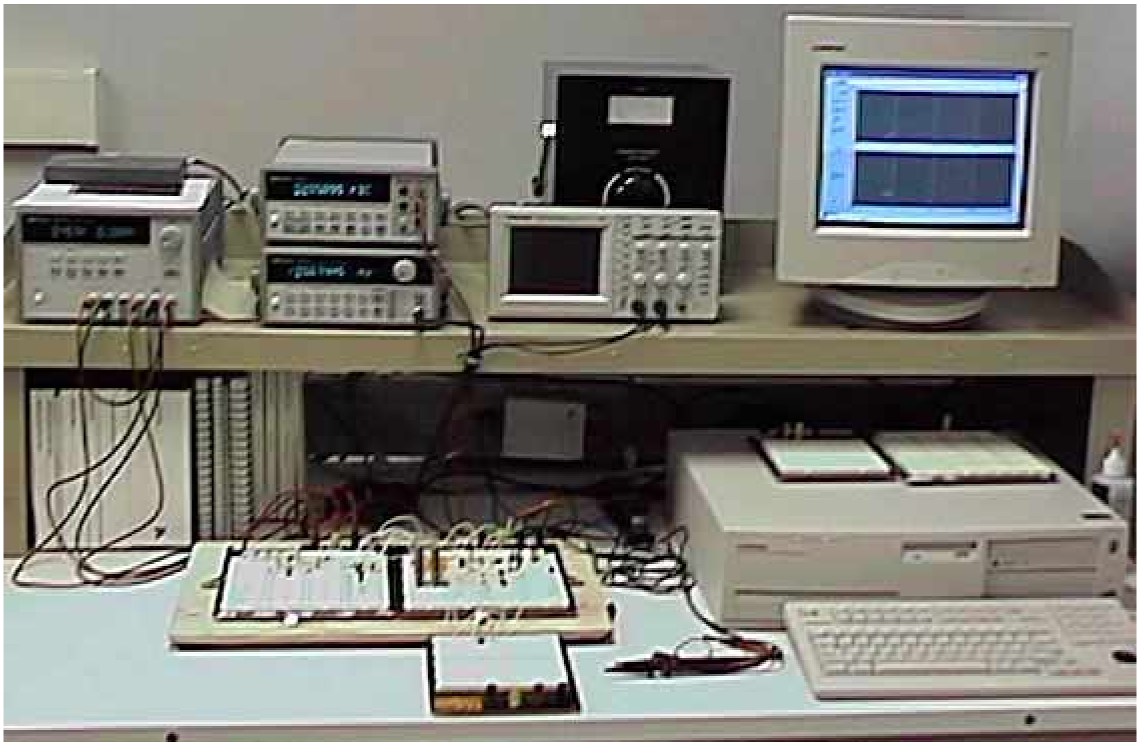

Fig. 8. Project TUNA hardware and GPIB-based test equipment. The equipment shown reflects the standard bench configuration for electrical engineering laboratories at the University of Texas at Tyler. The oscilloscope and autotransformer are not used with the TUNA instrument.

V. Lessons learned from Project TUNA

1. Students reported that Project TUNA was a positive experience. They especially were pleased that they were creating something permanent and useful to the electrical engineering program.
2. Students were exposed to the iterative design process as alternative solutions were explored. This was a salutary experience in that it challenged the preconceptions which they appeared to have that engineering design is a linear process without detours, false starts, or errors.
3. Project TUNA permitted enrichment of EENG 4409 with material on all-pass filters, analog-to-digital conversion, and phase-sensitive demodulation.
4. There may be some doubt, however, about how well that material was learned. Questions about phase-sensitive demodulation were included on the final examination, and as a whole the class did not perform well on these questions. They may not have anticipated that material from Project TUNA would appear on the exam.
5. Students gained experience in reading and understanding manufacturers' data sheets.
6. Students gained greater experience with computer-based virtual instrumentation. They had used virtual instruments in previous coursework but had no experience in developing them. Students found it very difficult to learn LabVIEW, and successful completion of the software

required extensive help from the instructor and re-use of portions of existing virtual-instrument programs. It was a significant mistake to postpone the start of software development until approximately two-thirds of the semester had passed. Hardware and software should have been developed concurrently.

VI. Conclusion and future developments

Development of a virtual instrument of significant software and hardware complexity was incorporated experimentally into a junior-level electronics course at the University of Texas at Tyler in the spring semester of 1999. The result was sufficiently successful that development of computer-based laboratory instrument projects will become a permanent part of the curriculum. A grant from the NSF to begin in 2000 (DUE-9952292) will fund further development and dissemination of computer-based laboratory instruments. Plans are being made to develop an impedance-measurement instrument, a sensor/transducer interface instrument (capable of supporting resistive, capacitive, and LVDT sensors), and an instrument for measurement of electrical parameters of operational amplifiers. Future developments are planned to use data-acquisition boards (National Instruments PCI-1200) instead of GPIB-based test equipment.

VII. Acknowedgements

Support for Project TUNA was provided by Dr. William Hoover, Chair of the Department of Electrical Engineering at the University of Texas at Tyler. Dr. Allen Barger developed the original curve-tracer instrument, of which some elements were incorporated into the TUNA software. The dedication and work of students Jason LaSalle, Lim Kau Teng, Gary Walker, Chris Cothran, and Cullen Huffhines made Project TUNA possible.

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