Facilitating Interdisciplinary Hands-on Learning using LabVIEW*

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The College-wide Integrated Teaching and Learning (ITL) Program at the University of Colorado at Boulder's College of Engineering and Applied Science serves six departments and more than 2,400 undergraduate students. The ITL hands-on learning approach places a strong emphasis on enhancing engineering education through the integration of experiments that use computerized data acquisition, and incorporate the latest sensors and test and measurement equipment, to demonstrate the application of fundamental engineering concepts in a real-world context. Experiments are shared by several departments and used at multiple levels. Examples of these experiments are described with special focus on how LabVIEW is used to implement data acquisition strategies that include simple voltage measurements of a fluid flow system, digital processing of audio signals and dynamic feedback control of a classical mechanical oscillator.

THE RATIONALE FOR HANDS-ON LEARNING

THE MOTIVATION for change in engineering education at the University of Colorado at Boulder is driven by the understanding that traditional, strictly theoretical, engineering education does not engage or adequately educate engineering students. The small number of American students in the natural sciences, mathematics and engineering (SME), notably only 4.5% of 24 year-olds in the United States, is well documented [1]. Attrition from the SME fields is not due to the inferior abilities of the many students who select other fields, as is commonly argued [2]. Rather, it is a function of the learning environment common to the SME fields not matching the learning preferences of 95% of the population. The traditional 'read, observe, listen to the lecture and memorize' method of teaching in SME has been shown to inadequately promote conceptual understanding due to its failure to challenge students' own preconceptions [3, 4]. Even when educators attempt to present information in a clear and unambiguous manner, the reluctance of students to change their own preconceptions influences how much they understand [4]. The implication of this on teaching and learning engineering is that students' erroneous beliefs should be deliberately challenged with experiences that are difficult to ignore, discount or change. A strong theoretical background, supplemented with hands-on, active learning activities, together provide the student with such experiences. In an experiment on learning the mechanics of pulley systems, Ferguson and

Hegarty [5] found that college students who learned with hands-on equipment demonstrated a significantly improved ability to make real-world links and solve application problems, as compared to students who learned only with diagrams. Given that the engineering fields are founded in and perpetuated through the creation of innovative products, it is logical that engineering students should be taught in a manner that promotes inquisition and supports their ability to apply concepts and make real-world connections. To support this change in engineering education, the Integrated Teaching and Learning (ITL) Program was conceived to promote and support efforts to reinforce engineering theory with hands-on learning.

THE ITL PROGRAM EDUCATIONAL MISSION

The ITL Program [6] was developed in response to the desires of engineering faculty and students for an interdisciplinary, collaborative setting where fundamental theory is complemented by experience and examples. The Program focuses on preparing students to work in a team environment and to understand and experience the problem-solving process, thus better preparing graduates to enter the engineering work force.

To support these goals, the 34,500 sq. ft. Integrated Teaching and Learning Laboratory (ITLL) was created to serve all six departments in the College of Engineering and Applied Science as well as extensive K-12 outreach activities, providing an environment where interdisciplinary projects and experiments are encouraged and facilitated [6]. This approach allows for sharing

and consolidation of resources across departmental boundaries by studying engineering concepts in terms of common focus areas, including: applied mathematics and numerical analysis, electronics and microprocessors, measurement and instrumentation, controls, fluid mechanics and thermal science, materials and structures, manufacturing, and environmental engineering. The ITL Laboratory features extensive computer capability and a variety of laboratory resources and experimental hardware to facilitate hands-on exploration in these focus areas.

DATA ACQUISITION CAPABILITIES

At the heart of the ITLL are two large, open laboratory plazas, each containing 15 LabStations for data acquisition and analysis (Fig. 1). Individual experiments, called *modules*, rely on the data acquisition capabilities of the LabStations.

The LabStations [7] were custom designed by CU staff and students to be general enough to support most undergraduate engineering applications. A LabStation consists of two separate computer data acquisition and control workbenches paired into one physical location. There are 60 separate data acquisition stations in the ITLL lab plazas, each capable of supporting a team of three students. Each LabStation side contains a Hewlett Packard Pentium-based PC, equipped with a National Instruments (NI) data acquisition (DAQ) card and GPIB interface card, a suite of four NI SCXI signal conditioning modules and several HP desktop instruments interfaced to LabVIEW via GPIB. The LabStation design allows easy connection of signals and promotes student understanding of the data acquisition system. The equipment value alone in each of the 60 stations totals $14,800.

Generous individual, foundation and corporate sponsors, including the Hewlett Packard Company and National Instruments, contributed to the ITLL facility and equipment costs. One justification for LabStation cost is the heavily programmed use of the lab plazas, which are nearly 80% scheduled during normal business hours. The generality of the LabStation allows a different experiment to be used every 1–2 hours, thereby effectively maximizing available resources. During unscheduled times, and on nights and weekends, the lab plazas are occupied by students using the computers for homework, lab assignments and data analysis not requiring the module hardware.

THE LABVIEW SOFTWARE CHOICE

The LabStation hardware capabilities require a data acquisition software program to easily and

Fig. 1. A LabStation located in one of the ITLL lab plazas.

effectively communicate with the experiments. Before the opening of the ITL Laboratory in 1997, it was estimated that by the time engineering students graduated, they had to master more than 30 different software applications [8]. A deliberate choice was made to standardize the software packages in the ITLL to allow students to focus on specific course content rather than learning multiple software programs.

For data acquisition activities in the ITLL, LabVIEW was an obvious choice for many reasons including the advantages it offers for both the user and programmer. First, since the laboratory is equipped with National Instruments data acquisition hardware, the software/hardware interface is straightforward and seamless. Second, the graphical user interface (GUI) in a LabVIEW Virtual Instrument (VI) program is simple to develop and flexible to use. For the programmer, this means that time which would otherwise be spent developing a user interface can instead be used for functional programming. For LabVIEW users, it means that as they use different modules with different VIs, they will be presented with user interfaces that are consistent and predictable, thus reducing the time required to learn how to operate the software program. In addition, familiarity with LabVIEW as a user and availability of LabVIEW tutorial CDs allows those students to easily move towards developing programs for ITL experimental modules.

Another advantage of LabVIEW is the large built-in library of data acquisition and analysis functions that reduce the programmer's development time. Implementation of complex tools such as the fast Fourier transform (FFT), digital filtering, etc., becomes a simple matter of understanding and including a built-in LabVIEW sub-VI. These functions also provide the programmer with the flexibility to explore different approaches to performing data acquisition and analysis on ITL experimental modules.

Fig. 2. *Fluid Standpipe* module in use at a LabStation.

ITL EXPERIMENTAL MODULES

The ITLL currently supports more than 50 different modules that range in complexity from basic experiments demonstrating a single concept to advanced experiments encompassing several subject areas and requiring extensive hardware and software capabilities. The ITL Program supports the flexibility to integrate these modules into the curriculum in a variety of ways; including one-time use as a homework assignment to entire courses scheduling lecture and laboratory time in the ITLL semester long. Interdisciplinary use of modules is strongly encouraged and multiple departments frequently participate in the module development process. First a module is piloted in a single course, such as fluid mechanics, then faculty from other departments teaching fluid mechanics or other applicable focus areas like applied mathematics, modify the original hardware and documentation to develop a more diverse experiment. Some modules were purchased, while others were designed and built by CU faculty, staff and students. In addition, student participation is encouraged in the design and construction of experiments because it provides an invaluable level of hands-on learning that goes beyond using the experiment—to understanding the underlying concepts and the entire design/build process.

Three representative examples of interdisciplinary ITL modules, described below, demonstrate the range of complexity available and how the use of LabVIEW software facilitates student learning through experimentation. The first module is simple and little explanation of the LabVIEW programming is needed. The second module is more complex and diverse and currently uses three different LabVIEW programs, one of which is described in detail. The third module demonstrates one of the most complex ITL modules, requiring several LabVIEW VIs and sub-VIs, some of which are explained in detail. For further technical information and programming details, visit the ITLL website at http://itll.colorado.edu. The specific LabVIEW VIs discussed are available on the CD accompanying this journal.

A SIMPLE FLUID MECHANICS EXAMPLE

The *Fluid Standpipe* module (Fig. 2) is a simple water recirculating system that investigates the frictional resistance in different sizes of plastic tube using two first-order differential equations [9]. Water is pumped from a holding tank, through an electromechanical valve, and up several feet to the top of a standpipe. A column of water collects in the standpipe as it empties through several coils of tubing and returns back into the holding tank to complete the closed system. A schematic of the module is shown in Fig. 3.

Students use LabVIEW to control the valve and therefore the water flow in the system. As the flow rate is increased, the frictional resistance to flow in the tube increases (approximately proportional to the square of the flow rate) and consequently a higher level of water accumulates in the standpipe. Students use the data acquired by LabVIEW to experimentally determine the friction factor in the tube and then use this calculation to predict future behavior. Students model the system using two first-order differential equations based on the conservation of mass and the conservation of momentum of the fluid flow through the system.

The module is applicable in a variety of focus areas: applied mathematics, numerical analysis, controls and fluid mechanics. In these focus areas, the module has been used in multiple chemical engineering courses studying controls, statistics and fluid mechanics, as well as a
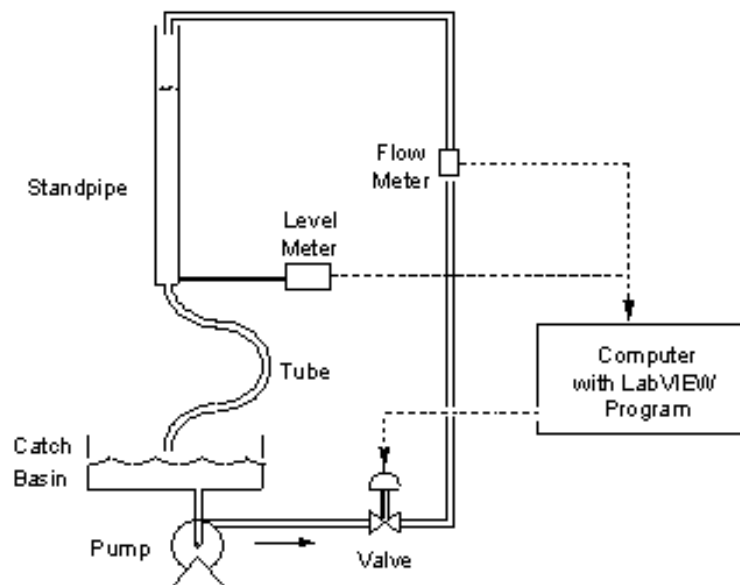

Fig. 3. *Fluid Standpipe* module schematic [9].

college-wide differential equations course. The use of this module has been so successful that replication of two more is in progress. The hardware and student labor costs total approximately $3000 per module.

LabVIEW programming details

The Fluids VI (Fig. 4) allows students to set the water flow rate by controlling the voltage sent to the valve.

The program reads the water level, as measured by a pressure transducer, and the water flow rate from a flow meter. LabVIEW plots the water flow rate (upper graph) and the water level (lower graph) in real time. The LabVIEW program offers several advantages, one being that the immediate display of the data on the LabVIEW screen allows the students to easily determine when the system has reached steady state. LabVIEW also saves the data to a text file for subsequent mathematical analysis with Microsoft Excel or MATLAB.

A MODERATELY COMPLEX FREQUENCY ANALYSIS OF SOUNDS EXAMPLE

The *Digital Sampling of Audio Signals* module (Fig. 5) illustrates digital sampling concepts and explores complex Fourier theory and second-order vibration equations. Sounds to be analyzed come from several sources, including a function generator, an electric guitar and amplifier, a microphone, a drum and the computer's CD-ROM output.

This module generates much student interest as they analyze a variety of sounds, such as their own voice, their favorite CD or a musical instrument they designed in a first-year design project class. Students can use this module to investigate the frequency content in sounds, Nyquist frequency, and how sampling rate and the number of samples affects data collection.

This module can be used to study concepts in a variety of focus areas including applied mathematics, numerical analysis and electronics. The applications have been so broad that currently three different LabVIEW programs have been developed for use with this hardware. The three LabVIEW programs focus on various aspects and all three are general enough to allow students to change the parameters to accommodate a variety of input sound signals.

- In a mechanical engineering class, students use the Audio Frequency Response VI to analyze the frequency response characteristics of different stages of the guitar amplifier as the program sweeps through the audible frequency range on a GPIB-controlled HP function generator.
- In a partial differential equations course, students use the Spectrum Analyzer VI to compare measured frequency content in sounds, from a
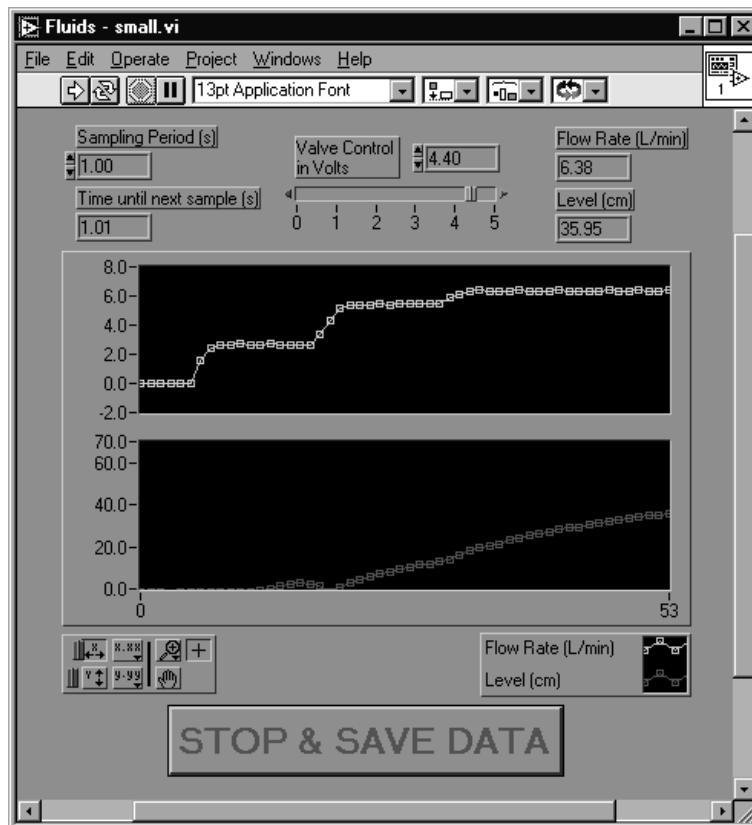

Fig. 4. Fluids VI.

Fig. 5. The *Digital Sampling of Audio Signals* module in use at a LabStation.

guitar string or a drum, to calculated wave equation solutions.

• The Digital Audio Simulator VI (discussed in greater detail below) is used extensively in applied mathematics and electrical engineering courses to investigate various aspects of digital audio recording and reproduction of analog signals.

This module evolved into a multi-functional sound analysis experiment through the collaboration of the mechanical, electrical and applied mathematics departments. In addition to its use by multiple engineering departments, the module is interesting and simple enough that it has been used in numerous K-12 outreach activities. The hardware costs were approximately $2700.

LabVIEW programming details

The Digital Audio Simulator VI (Fig. 6) displays the sampled data in chart format, and computes and displays the FFT of the waveform. In addition, the program reconstructs the signal from the sampled data and outputs the sound through headphones or speakers, allowing students to hear the results of the signal processing they have performed. Besides listening to the signal, students are able to view the signal before and after processing in both the time and frequency domains. After acquiring the original signal and processing it, students are able to use the LabVIEW program to zoom in on parts of the time waveforms and frequency spectra. This allows closer inspection of the effects of aliasing (unwanted peaks in the frequency spectrum),

slower sampling (less resolution in the time waveform), and output filtering (smoothing of the output signal).

Many parameters in a real-world digital audio system affect the quality of the final reproduced signal, including the anti-aliasing pre-filter frequency, the voltage resolution of the analog-to-digital converter, the sampling frequency, and the output filter frequency used to smooth the jumps in discrete voltage from the digital-to-analog converter. It is pedagogically convenient to vary these parameters while keeping the original input signal the same. Unfortunately, it is not practical to keep the original signal constant for a complex sound wave such as speech or music. The solution employed by the Digital Audio Simulator VI is to sample the original sound signal at a frequency that is high relative to the frequencies under investigation and *effectively treat this as the analog signal to be processed.* This sampled waveform is retained in the computer's memory while the students experiment with different ways of processing it. The analog anti-aliasing and output filters are simulated using digital filters, and changes in voltage resolution and sampling rate are simulated by using LabVIEW to modify the voltage and time resolution of the original sampled signal.

A COMPLEX REAL-TIME COMPUTER CONTROL EXAMPLE

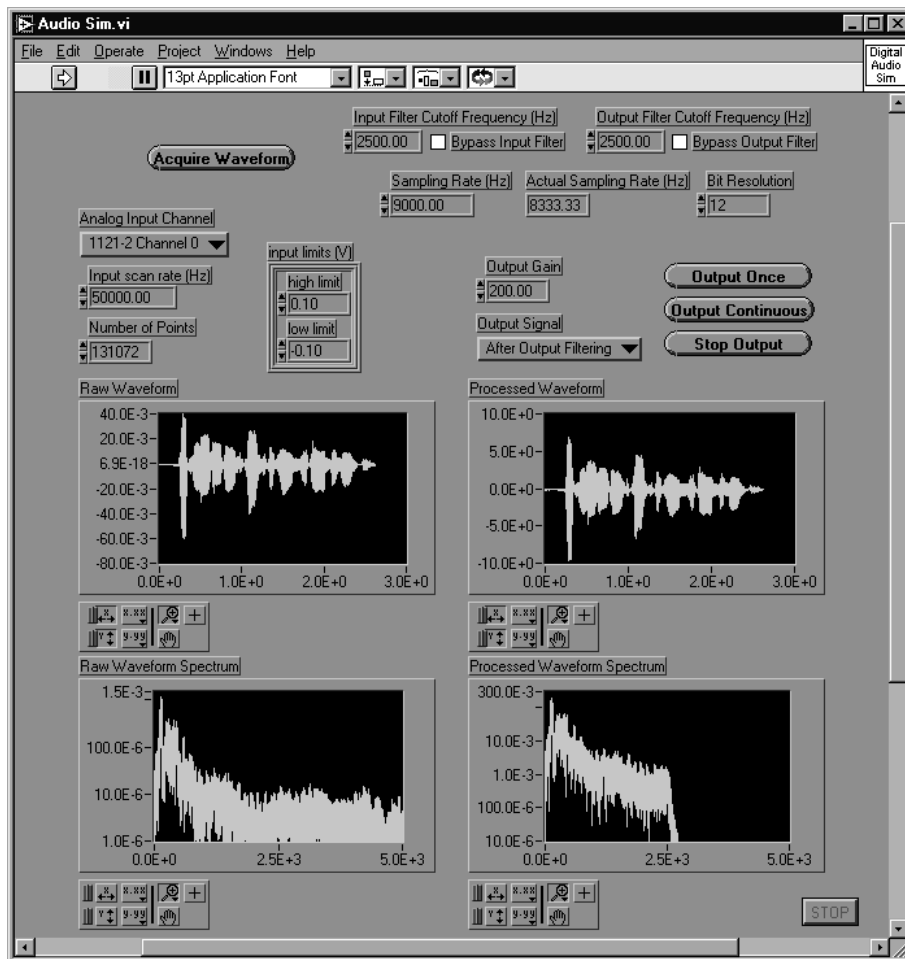The *Quarter Car* module is a replication of one wheel section of an active automobile suspension

Fig. 6. The Digital Audio Simulator VI.

system that demonstrates digital real-time control of a spring-mass-damper system described by second-order differential equations.

Physically, this module consists of a wheel connected to a mass by a spring (Fig. 7). A motor, rigidly attached to the mass, provides mechanical damping and controls the distance between the mass and wheel via a ball screw actuator. The wheel rides on an eccentric cylinder that provides a disturbance input to the system. Three sensors monitor the behavior of the system: a linear variable differential transformer (LVDT) measures the distance between the wheel and mass, a tachometer in the motor measures the velocity of the mass with respect to the wheel, and an accelerometer measures the vertical acceleration of the mass.

The motor serves two purposes in addition to being the source of mechanical damping. It can be controlled by LabVIEW to change the effective stiffness, damping and mass of the system by generating a torque proportional to position, velocity, and acceleration respectively. It can also control the relative position of the mass and wheel in response to a reference position waveform, such as a sine wave.

Students use this module to study concepts in the controls focus area, comparing human control to computer control and/or to investigate the behavior of a classical mechanical oscillator. The module has also been popular in K-12 summer activities, public demonstrations and various outreach activities. This module has been used in a senior-level mechanical engineering laboratory course, and is most extensively used in a junior-level aerospace control systems course. The development and hardware costs of this module totaled $6500.

LabVIEW programming details

A basic implementation of a control loop in LabVIEW, called the Basic Controller VI, is provided on the CD accompanying this article. This VI consists of a loop in which a single data point is acquired and passed to a control algorithm whose output is converted to an analog voltage. Using this technique, loop rate is limited to a few hundred Hz because the controller runs on the computer's CPU and competes with other processes running on the computer. If this loop rate is adequate, the control loop is simple to program and operates effectively. It is important to note that the loop rate will remain constant regardless of the processing time for the control
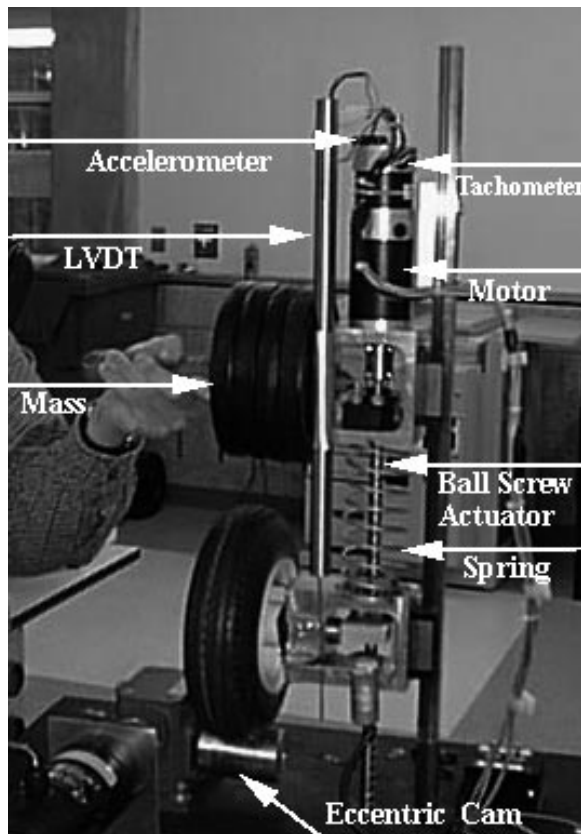
Fig. 7. *Quarter Car* module.

algorithm or the CPU time given to other processes. For higher speed feedback control, it is necessary to have a dedicated digital signal processing (DSP) board to run the control algorithm.

Students learn about control systems by performing a sequence of experiments with the *Quarter Car* module. To begin to understand how a computer controls a system, students try to control the suspension by hand. The LabVIEW front panel for the Human Control VI used in the first experiment is shown in Fig. 8. The chart on the left shows a reference position waveform that students try to track and the actual position measured by the LVDT.

The chart on the right shows future values of the waveform so that students can anticipate the force they need to apply to move the mass up and down. Features include: setting the reference position to vary slowly or quickly, turning off the future waveform display for an added challenge, and varying the simulated physical parameters.

In the second experiment, the PID VI implements a proportional-integral-derivative (PID) controller, allowing students to observe how effectively the computer tracks a reference position waveform as they vary the P, I and D gains. Also, the effective physical parameters can be varied to see how this affects the controller's response. Among other reference waveforms is a long-period square wave that allows students to observe the step response of the closed-loop system.

The third and fourth experiments both use the Control Systems Frequency Response VI. In both cases, the frequency response of the physical system is determined by using a sinusoidal reference and calculating the steady-state magnitude and phase of the measured response. In the third experiment, the frequency response of the system is quantitatively determined by applying a sinusoidal driving force that is stepped through the frequency range of interest. In this case, the instructor supplies the controller and only the plant's frequency response is measured. In the fourth experiment, students design their own controller and observe how well it works. The student uses the controller s/he has designed based on the results of the previous experiment and then measures the frequency response of the entire closed-loop system.

There are many programming challenges associated with these experiments, but two deserve special mention. First, the controllers for the third and fourth experiments have arbitrary structure and thus the Control Calc sub-VI implements a controller with only the discrete-time coefficients as inputs. Second, since the students use MATLAB to develop their controllers, it was desired to
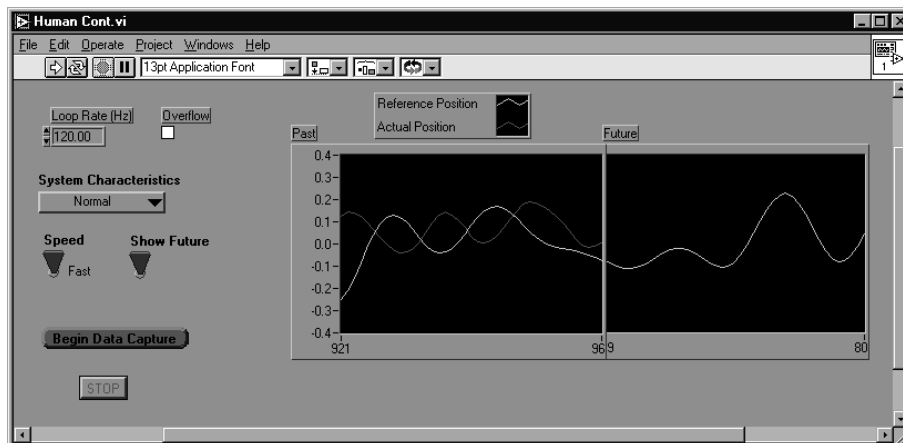

Fig. 8. Human Control VI.

import the controller parameters directly into LabVIEW rather than typing them in manually. This was accommodated by developing a set of data transfer VIs that use dynamic data exchange (DDE) to communicate directly with MATLAB.

STUDENT RESPONSE TO HANDS-ON LEARNING

Formal assessment of the value of hands-on learning at ITLL is in process, but already there is a large amount of anecdotal feedback from students about their experiences, including their work with the three modules described in this article. After using the *Fluid Standpipe* module, an electrical engineering junior said, 'For the first time I was able to actually see the mathematics in use. I finally understood the concept and importance of initial conditions.' Regarding the component of the *Digital Sampling of Audio Signals* module in which students investigate the frequency response of a guitar amplifier, a mechanical engineering senior commented 'It allowed me to turn something I could hear into something I could see and understand.' Another electrical engineering junior commented that, 'the concept of aliasing was always a difficult one for me to understand. I don't think I really understood it until after seeing and hearing its effect.' And lastly, in response to the *Quarter Car* module, a mechanical engineering senior stated that, 'this system was good for studying the classical mechanical oscillator equations we investigated for our senior lab experiment. We had some trouble with the hardware not giving us the controls results we expected, but we learned a lot about how control systems actually work.'

In addition, the ITL program has solicited feedback from students regarding their overall experience with hands-on learning in the ITL Laboratory. An end-of-the-semester survey elicited a strong positive response to the hands-on learning model. Commonly cited were: the effectiveness of hands-on exercises for developing a better understanding of theory; the opportunity to experience what real-world engineering is like; and the enjoyment of the educational experience that comes from *doing*. When asked why engineering education should support hands-on learning, a senior engineering student commented, 'It may be more difficult, but it's time well spent. Knowing a bunch of equations does not do you much good if you don't know how to apply them.'

CONCLUSIONS

The use of LabVIEW in the ITL Laboratory is an effective way of supporting the interdisciplinary, hands-on learning philosophy to which the ITL Program and College are committed. Having recently completed undergraduate and graduate degrees in engineering at CU themselves, the authors have witnessed, first-hand, a dramatic improvement in engineering education as a function of hands-on learning experiences. LabVIEW's ease of use, coupled with its flexibility and power, are significant advantages in the development of hands-on learning experiences. The flexibility of the ITLL LabStations and LabVIEW allows experimental module developers, including faculty, staff and students, to confidently turn their ideas into reality.

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