

## **A Virtual Instrumentation Based Engineering Experimentation Course**

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### **Abstract**

The modern engineering experimentation course must not only cover experimental techniques, transducers, signal processing, and data analysis, but must also include fundamental concepts in computer based data acquisition. Though this list of topics is large and each topic could be the subject of an entire course, a single course introducing all of this material has been developed in the Mechanical Engineering major at the U. S. Coast Guard Academy (USCGA). In this course, computer based data acquisition is taught as a series of incremental steps that lead the experimenter from being a novice to being capable of designing and executing their own experiment using computer based data acquisition. Virtual instrumentation based on National Instruments hardware and Lab VIEW software, has been central to the USCGA engineering experimentation course. Four experiments from the course are presented with the developmental model to illustrate how virtual instruments have been used to teach engineering experimentation.

### **Introduction**

A course in engineering experimentation is a fundamental component of all accredited Mechanical Engineering programs. The purpose of such a course is to instruct students on the process of collecting experimental data to investigate physical phenomena and test engineering hypotheses. With the exception of computer based data acquisition instruction in the course, the content of such courses is fairly standard<sup>1</sup>. These standard topics include experimental design and techniques, transducers, signal processing, and data analysis. The topic of computer based data acquisition is an essential component of modern engineering experimentation courses and its incorporation in the course can serve as the backbone to explore other course topics.

The engineering instructor's challenge is to find a method for covering this material in a classroom setting while simultaneously conducting meaningful laboratory experiments to complement the classroom instruction. As any researcher or lab director knows, executing a single data acquisition based experiment can be demanding. Managing an undergraduate lab full

of data acquisition based experiments has the potential to be excruciating. A careful selection of experiments, reliable experimental hardware, and dependable data acquisition

hardware/software can turn such a challenge into a rewarding experience for students and faculty alike. The key to success is a standard set of lab tools which allow and encourage student learning to be developmental and exploratory.

At the U.S. Coast Guard Academy, an engineering experimentation course in the Mechanical Engineering curriculum has been structured on computer based data acquisition labs. Data acquisition hardware is used in experiments that are primarily conducted using Lab VIEW driven virtual instruments. This three credit course is conducted with two hours of lecture and three hours of lab per week. The lecture component of the course is divided into three sections: the design of experiments, data analysis and signal processing, and transducers. Specific topics of the lecture portion of the course include statistical analysis, uncertainty analysis, experimental technique, signal processing methods, sampling, aliasing, bridge circuits, thermocouples, pressure, velocity and acceleration measurements, and strain gauges.

The laboratory portion of the course consists of 16 lab sessions where 10 different experiments are conducted over the course of the semester. Most of the labs are "bench top" experiments where students collect data demonstrating physical phenomena. The students must apply information from the lecture classes to demonstrate proficiency in the course topic and solve an engineering problem. All labs rely on computer based data acquisition using standard software routines developed by the course instructors.

By a gradual exposure to the hardware and software necessary for research quality data acquisition, the students learn data acquisition fundamentals while focusing on experimental techniques. Independent experiments where students define a thermal property to investigate, design an experiment to investigate that property, conduct the experiment, and analyze the results (including error analysis, are also conducted in the course. This capstone project requires all aspects of the course to be applied to the problem at hand. As an open-ended design exercise, the independent projects help integrate design across the engineering curriculum<sup>2</sup>.

Standardization of hardware and software executed as virtual instruments is essential to efficiently run these labs which rely on a variety of transducers to illustrate numerous engineering experimentation techniques. Augmented with minimal in-class instruction on data acquisition, the labs themselves become the tool that teaches computer based data acquisition, reduction, and analysis. This paper details the system requirements used in the USCGA Experimental Methods course, introduces a developmental model for computer based data acquisition instruction, and presents virtual instrument based experiments conducted in the course.

### **System Components**

A single lab section consists of 12 students guided by a single faculty member. Each group of students has their own data acquisition workstation, and students often bring in additional laptop computers as secondary terminals for concurrent data analysis. The data acquisition workstation operated by each group of students consists of the following component:

- Macintosh 650 Performa with 24 MB RAM.

- National Instruments NB-MIO-16 Multifunction I/O Board
- National Instruments SCXI-1100 Chassis
- National Instruments SCXI-1121 4-Channel Isolation Amplifier with Excitation
- National Instruments SCXI-1320 Terminal Block
- National Instruments SCXI-1321 Terminal Block
- National Instruments B-50 Connector Block
- National Instruments Lab VIEW Application Software

In part because this extensive list of equipment can be overwhelming at first sight, but more so because of the course's developmental treatment of data acquisition skills, students are exposed to select components during each lab period. For example, the students' first experience with data acquisition in the lab uses the NB-MIO-16 I/O Board and the B-50 Connector Block to collect data. This simple arrangement is structured to make data acquisition look "as easy as" connecting wires to a computer. Later labs use the NB-MIO-16 I/O Board with the appropriate SCXI components needed for each particular transducer. By then, the students begin to appreciate that data acquisition is much more than simply connecting wires to a computer.

Lab activities for the Experimental Methods course include an introduction to first and second order systems, calibration, error propagation, uncertainty analysis, torsional vibration, thermal time response, frequency response, and independent projects. Before shifting to a virtual instrumentation basis for this course, the lab activities tended to center on data collection, with most of the analysis and understanding of the course topics accomplished "off-line" (i.e. outside the lab and usually during the lab write-up process). The conversion to virtual instruments in the lab has allowed the students to focus on content and not be distracted by process. For example, each lab activity is based on a Lab VIEW virtual instrument (written by the course instructor), where the student can easily activate switches to begin the process of collecting data as soon as they walk into the lab. Having the data collected, there is ample time to explore the origin of the data and investigate how the collected data is related to the physical phenomenon being explored.

This initial emphasis on treating data acquisition "as easy as" connecting wires to a computer and clicking the start button on a virtual instrument demonstrates the utility of data acquisition as a means to an end, that is to simply collect data. By intentionally avoiding the process of data acquisition in the early labs of the semester, the lab focus is kept on the course topics of transducers and system behavior. Later in the semester, these results of data acquisition are the motivation to study how they were obtained, namely the process of data acquisition. Virtual instruments are essential for this instruction sequencing, in part due to the standardization of lab procedures that is possible when using virtual instruments.

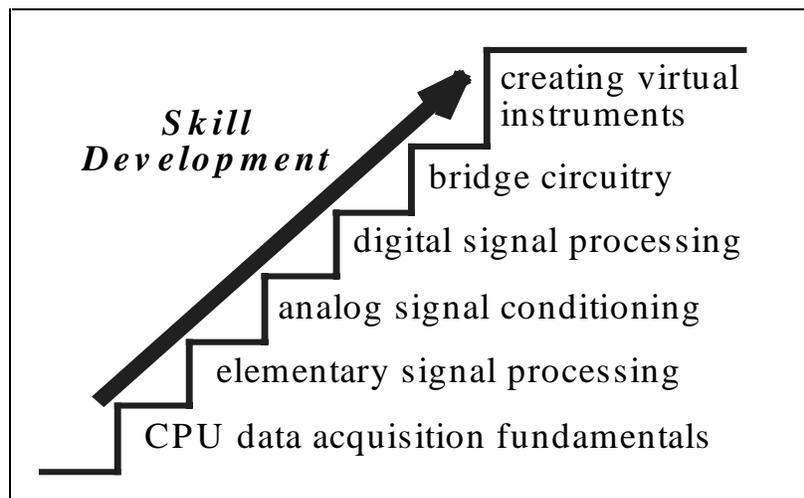
As an example of this process, the vibration of a beam is the physical phenomenon explored in one lab. Students know that the beam vibrates, for they see it and hear it, and the virtual instrument allows them to immediately see the vibrations as a data plot on the computer screen. The lab then progresses to explore the particular sensor that is used to "see" this vibration (in this case a strain gauge) and the circuitry (Wheatstone bridge) needed to power this transducer. Besides being a platform to display and collect data, the virtual instrument used in this lab includes a low pass filter to remove signal noise and user specified parameters needed for the volts to strain conversion (using a Lab VIEW sub-VI). The sampling speed and number of

samples to be collected are routinely included in the virtual instruments to allow students the chance to explore issues associated with these parameters, such as resolution and data file size. Later in the course, the same beam system and VI are used to investigate the effects of low pass filters, and the students build on their earlier experience. In this scenario, the “results” of the experiment are immediately seen and these results motivate the “how” and “why” investigation of the phenomenon.

### **Developmental Instruction with Virtual Instruments**

Careful sequencing of lecture topics and laboratory experiments is needed to ensure the students are prepared for the lab activities and that the lab activities augment the class lectures. Like most lab based courses, the course topics and lab experiences are a linked progression that build on previous material. This same form of developmental instruction has been adopted as the framework for teaching data acquisition fundamentals in the course. Data acquisition is viewed as the means to accomplish the ends, and as such, data acquisition is treated as a tool to complement instruction in experimental method techniques. Throughout this development of data acquisition skills, virtual instruments are the conduit for conducting the experiments and serve as a familiar interface in the weekly labs.

The developmental model for teaching data acquisition is presented in Figure One. Over the lab series, data acquisition techniques, including both hardware and software components, increase in their degree of sophistication. At the entry level of the developmental process, students begin the course with the conception that a computer is primarily a tool to analyze experimental data that was manually collected and keyed into the computer. At the other end of the developmental process, students become comfortable using the computer, including data acquisition hardware and software, as a composite tool for collecting, processing, analyzing and documenting experimental data. Over a series of steps, they learn that data acquisition is much more than simply connecting wires to a computer to collect voltages. They learn the signals can be enhanced using analog and/or digital techniques, converted to represent other physical parameters, analyzed, displayed, and stored. If needed, signals can even be exported from the computer to power transducers or other actuators.



## **Figure One: The gradual development of data acquisition skills using virtual instruments.**

This progression of data acquisition skills is dependent on virtual instrumentation. The students start off with a simple virtual instrument to collect data with the NB-MIO-16 I/O Board. They progress to the point where they can select the data acquisition hardware needed for specific transducers, determine the required digital signal processing to enhance the signal, and, in some cases, create their own virtual instruments. As various transducers are introduced in the lab, each with its own operating requirements and output specifications, the instructor written virtual instruments serve as a common interface to collect data from each transducer. In the same fashion that a particular physical parameter can be best measured with a specific transducer, the students understand that there are optimum hardware components and software routines to collect and process data from each sensor.

The sequential exposure to more sophisticated data acquisition topics throughout the course is complemented with exposure to the hardware associated with data acquisition. For example, the SCXI-1121/1320 is first presented as a "black-box" needed for data acquisition. Once the students experience the benefits of the "black box," layers on the black box are peeled away in subsequent labs. The first time a student uses the SCXI-1121/1320 combination, they merely need to click software buttons to collect data. The next lab, the cover of the 1320 will be removed, the student will see the internal components of the 1320, and they must connect transducer leads to the terminals. In a following lab, the SCXI-1121 will need to be configured for the experiment at hand and the students work with the amplifier's schematic to manually set filters, gains, and bridge connections. Thus, they move from using the hardware as a "black box" to understanding its functions and configuring the hardware for a particular experiment.

### **Virtual Instrumentation Based Experiments**

Most of the laboratory apparatus are tabletop components that address a single physical phenomenon. These apparatus are outfitted with transducers to measure force, strain, displacement, pressure, temperature and other parameters. For example a torsional pendulum used in the first lab. The pendulum consists of a torsional spring with one end attached to a circular disk (which adds rotational inertia) and the other end attached to a rotational forcing function. An electromagnetic coil on the base induces viscous damping on the inertia disk. A linear variable differential transformer (LVDT) is attached to the linear mechanism that creates the rotational forcing function and a rotary variable differential transformer (RVDT) is mounted to the inertia disk. With these indicators, the displacement of the inertia disk and forced disk can be measured to examine the harmonic motion of second order system under various damping conditions. A lab exercise for this apparatus is to create a calibration curve that relates the RVDT output (in volts) to the dial indicator (in radians) position of the inertia disk. This same apparatus is used to investigate measurement uncertainties in a later lab.

Prior to using virtual instruments in the course, all data would be manually collected, tabulated, and then processed. With virtual instruments, the student can walk into the lab, be introduced to the apparatus and the virtual instrument, and immediately begin collecting data. This process allows the topic of the lab, in this case calibration techniques or uncertainty analysis, to be the central theme of the lab and avoids the time loss with manual measurements. For most labs in the course, students do not create their own virtual instrument, but rather use a common

interface designed by the instructors. This approach is needed to keep the labs focused on the course topics, rather than a specific data acquisition programming language. Students are exposed to Lab VIEW graphical programming during the course, but this process is gradual. A progressive exposure to creating virtual instruments offers the best students the ability to create their own virtual instruments, and several have done so for course and capstone design projects. Four lab activities are presented to illustrate the development of data acquisition skills during the course.

The lab sequence begins with the torsional pendulum apparatus described above. The measured signal for this lab is the output of the RVDT and the LVDT which indicate the position of the inertia disk and the forcing disk. Since these signals are in the +/- 2 V range, adequate results can be obtained using the NB-MIO-16 I/O Board with the B-50 connector block. In this simple arrangement, the transducer is “wired” directly to the computer. As indicated in Figure Two, the virtual instrument for this lab consists of sliding bars for the sampling speed and sample duration, a display of the sampled voltage and a low-pass filtered version of the voltage, and cursor controls. In the lab, students see the oscillatory voltage output as the disks rotate, and they calibrate the output voltage with the angular position of the disks. The cursor controls on the VI allow the students to easily “pick off” time and voltage values from the display, from which the calibration coefficient and period are determined. Once the basics of working with the VI are introduced and the linear calibration coefficient and offset determined, these values are entered into a second VI that instantly converts the sampled voltage signal and displays the displacement as a radial position.

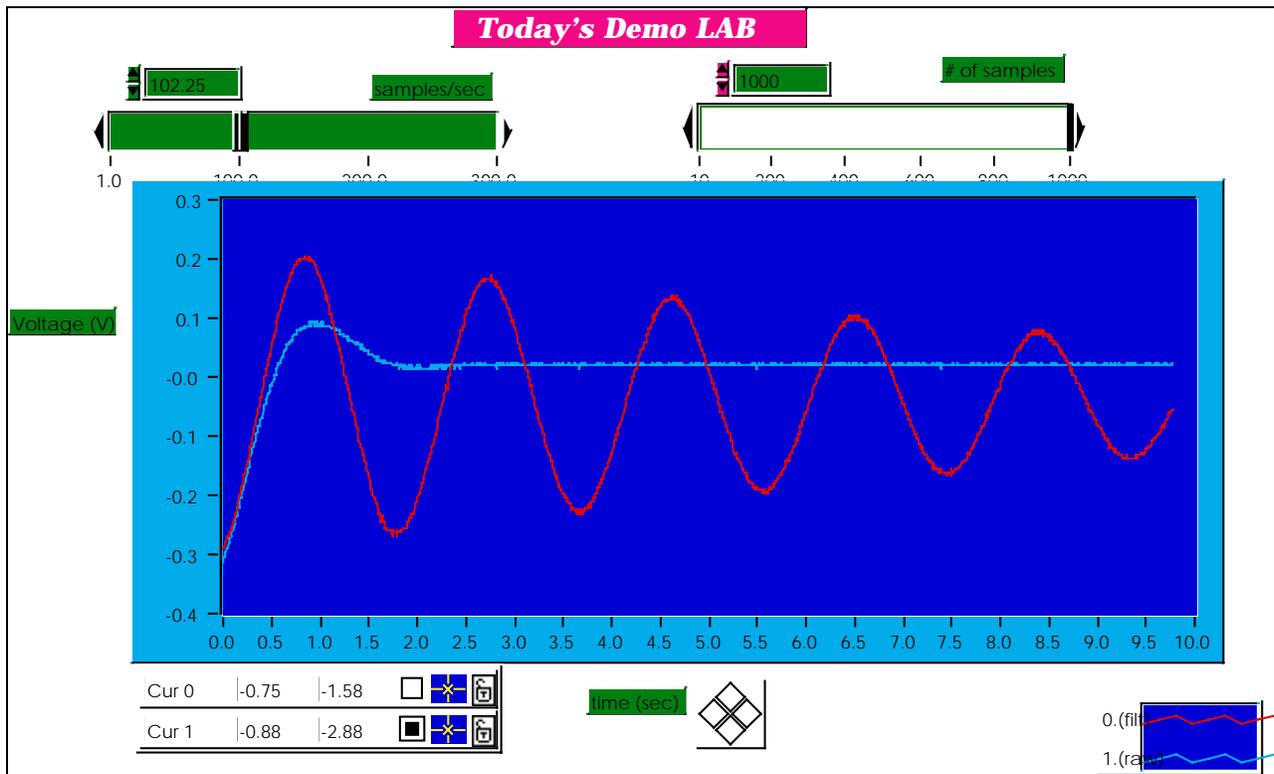
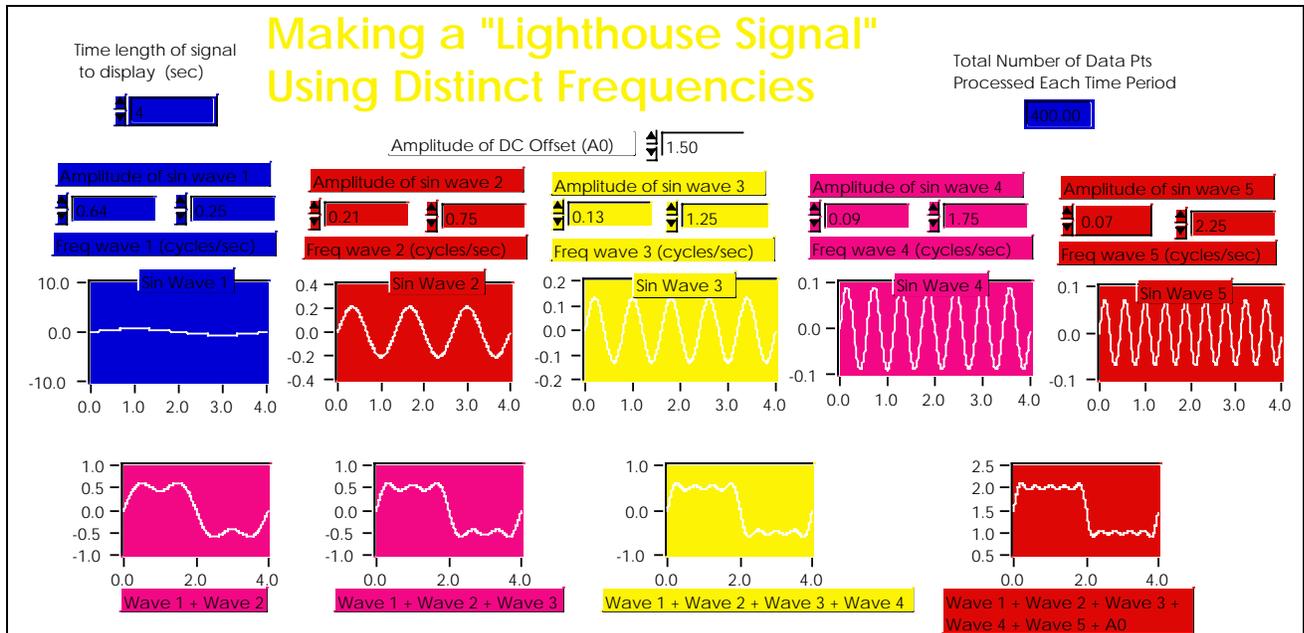


Figure Two: Data acquisition fundamentals.

The lab introduces the hardware of data acquisition, discretization, sampling speed, and the virtual instrument interface. By the conclusion of the lab, students have developed a virtual instrument capable of sampling a signal and displaying the results in terms of the physical parameter that is measured. In the course of this first exposure to the hardware and software for data acquisition, they also see the effect of signal filtering as a motivation for future labs. By this experience, they see the value of the software, learn elementary functions, and begin to see some of the utilities of virtual instrumentation. The ease of use of the VI allows for exploration in the lab as they investigate the effects on the sinusoidal response as the system damping changes.

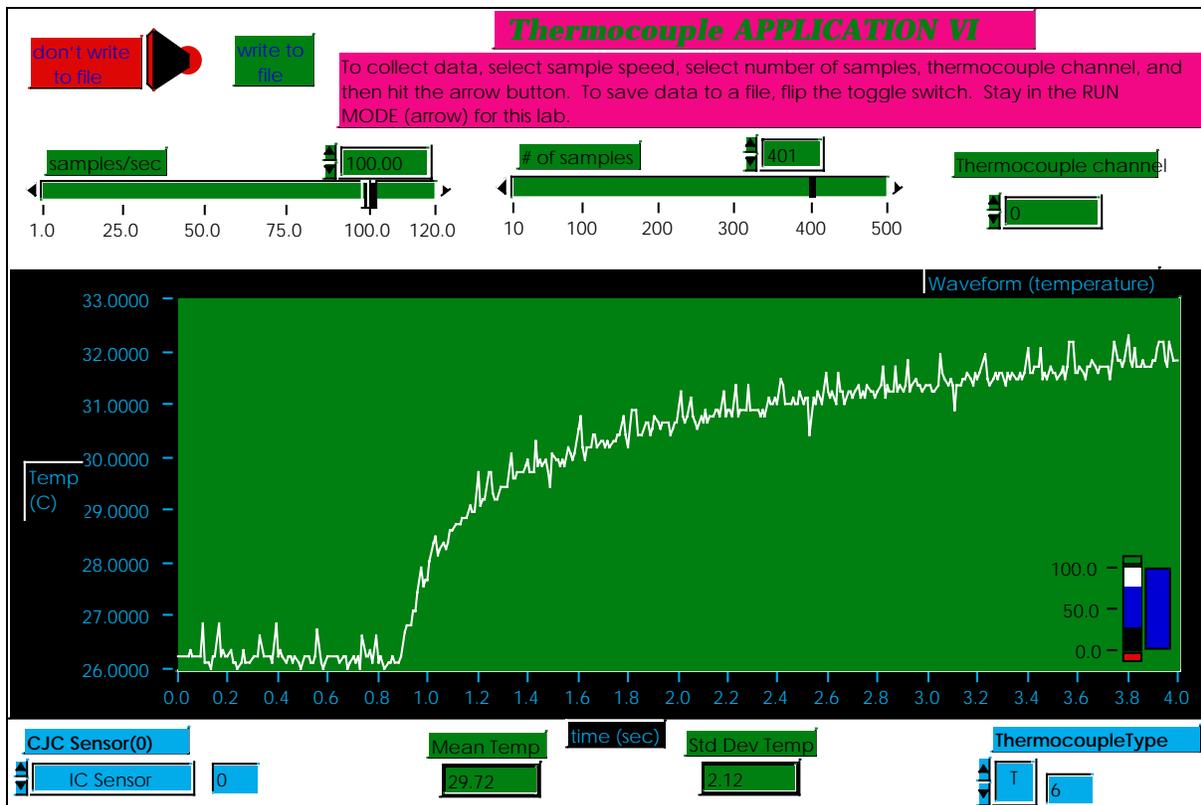
While the first lab introduced Lab VIEW and showcased data acquisition, this same hardware arrangement is used in a later lab to introduce the ability of a VI for analysis and to export voltage signals. As part of the frequency analysis portion of the course, students use two Lab VIEW VIs to explore the effect of sampling rate on Fourier analysis and the effect of noise on Fourier analysis. In this regard, they learn that the VI can help them understand signal processing topics as they witness aliasing and the problems associated with high signal to noise ratios. An application of Fourier analysis is presented in the lab as a scenario where they are assigned to a Coast Guard ship involved in covert activities. The scenario states that the commanding officer needs a light source which mimics a light house signal as a way to attract smugglers.

The VI used in this lab is presented in Figure Three. The students determine the Fourier coefficients and frequencies, and then input their results into the VI. The progressive combined signal of their five sine waves is displayed in the VI, and they are able to witness the signal refinement as each sine wave is added to the series. The resultant digital signal is then converted to an analog voltage and exported on the NB-MIO-16 I/O Board and B-50 Connector. With an LED connected across the output channel leads on the B-50, the students “see” their solution in real time as the LED blinks as either the needed light house light pattern or some incorrect on/off signal. Through this lab, students begin to understand some of the signal processing capabilities of Lab VIEW and experience analog output from a data acquisition system.



**Figure Three: Using VI to teach Fourier Analysis.**

In a lab using thermocouples, students begin to understand that not all transducer outputs can be collected only using a +/- 10 V range data acquisition board, but rather that some transducers require signal conditioning applied before the data can be digitized and correctly used. Here, a series of thermocouples, each with a different insulation surrounding the thermocouple, are moved from an ice bath to a boiling water bath to study the each thermocouple's thermal response. The VI for this lab, illustrated in Figure Four, shows the system response for a thermocouple during a temperature transition. The VI includes an option to write data to a file which is accessed to determine the system's time constant. Also, simple statistics are computed in the VI, and a sub-VI converts the thermocouple voltages to temperatures.

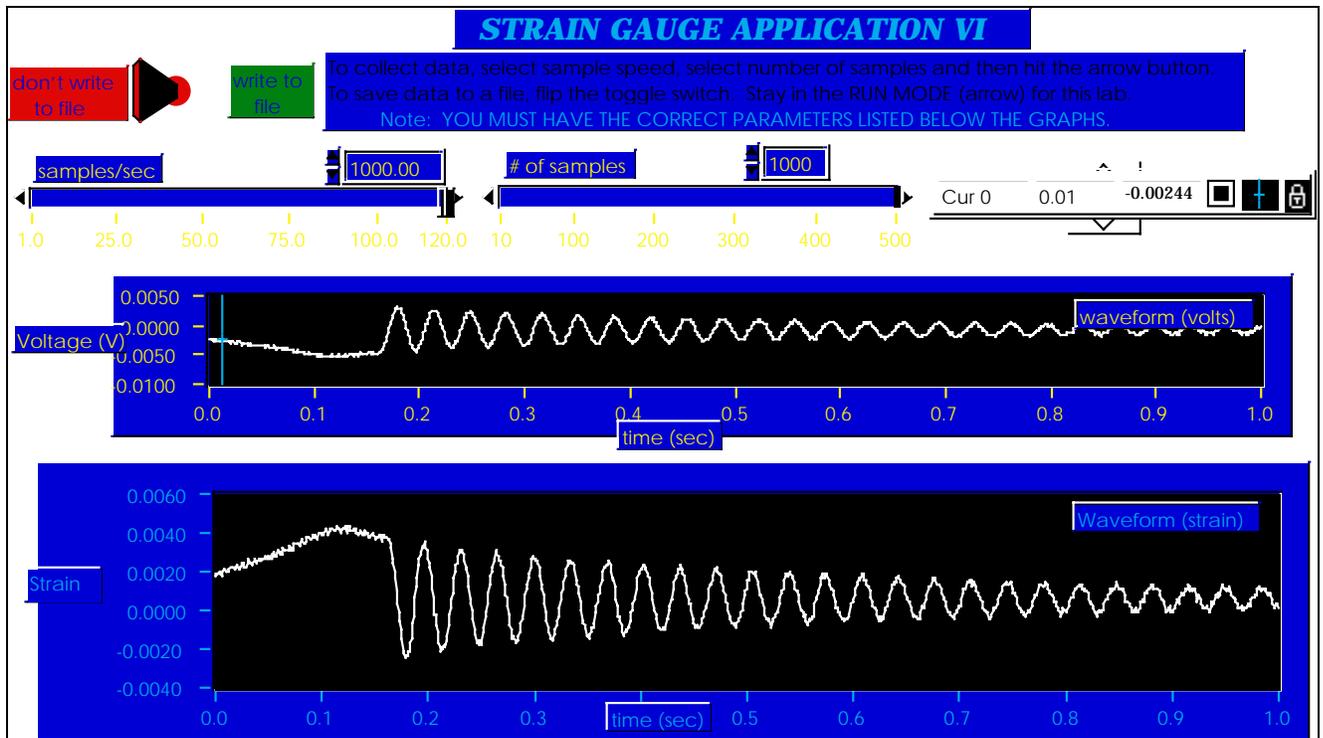


**Figure Four: Using the SCXI-1121/1320 and simple analysis.**

Because of the milli-volt range output of the thermocouples, the input signal must be amplified before it can be digitized. The SCXI-1121 Isolation Amplifier is used in conjunction with the SCXI-1320 Terminal Block (which includes a thermistor that serves as a reference junction temperature). Through this lab, students see that additional signal processing can be needed before a signal is ready to be digitized, and they work with the associated hardware to amplify the signal. This experience reinforces the resolution of the NB-MIO-16 I/O Board, stresses the need for amplification of low voltage signals, and presents advanced conversion techniques to convert a thermocouple voltage to a temperature. For the first time, students use the VI as a statistical tool and to direct data to storage devices.

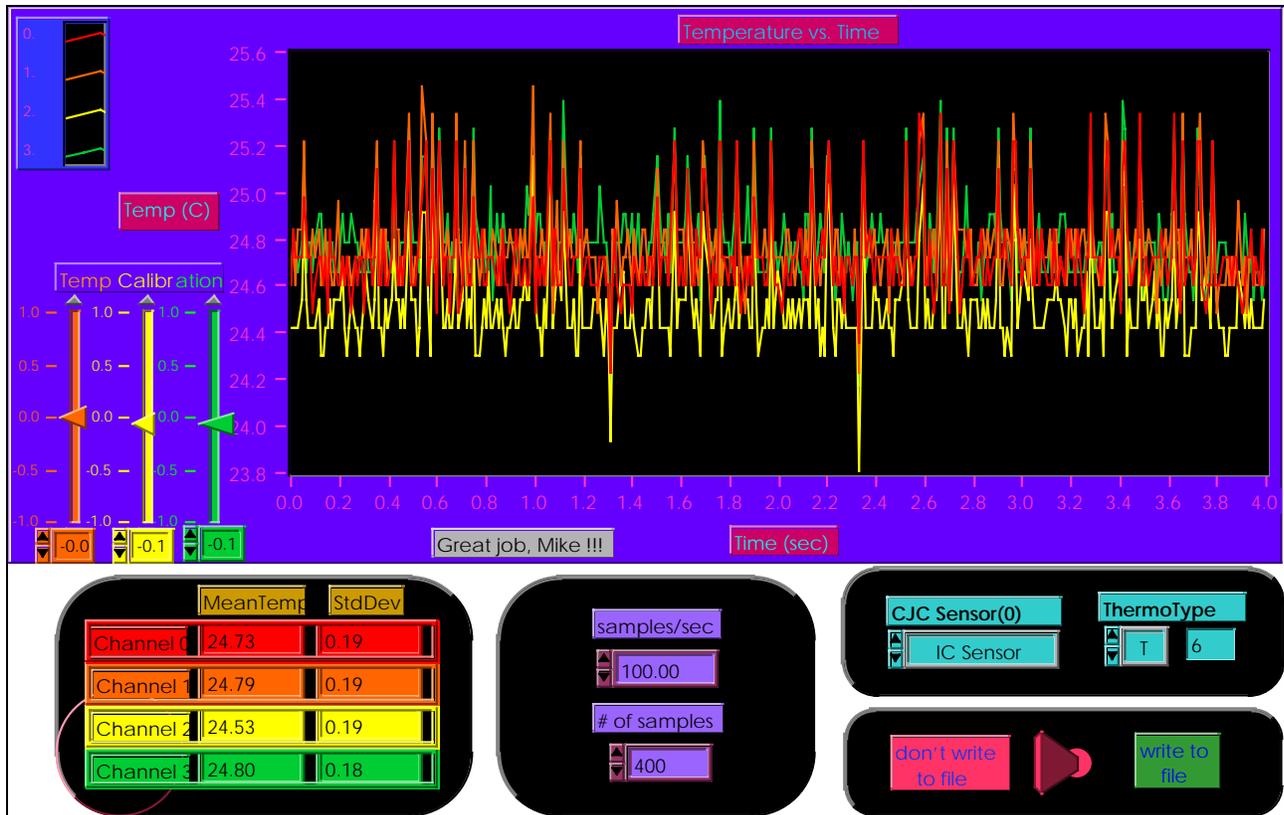
Additional data acquisition hardware and signal processing software are introduced in a lab where strain gauges are used to measure the displacement-strain relationship of an aluminum beam. In this lab, a single strain gauge is mounted on a 30 cm long aluminum beam. As the beam deflects, the data acquisition system monitors the strain in the beam. The SCXI-1121 is used in conjunction with the SCXI-1321 for this lab. The internal bridge circuitry of the SCXI-1121 is used with the nulling circuitry on the SCXI-1321 as a Wheatstone bridge for the strain gauge measurements. The external voltage source of the SCXI-1121 is used as the excitation voltage for the strain gauge and the quarter-bridge circuitry helps students understand the components of the Wheatstone bridge that are essential for many low voltage transducers. As with the thermocouple lab, an amplification gain of 2000 is used to bring the signal into a useful voltage range for the NB-MIO-16 I/O Board.

The VI for this lab is illustrated in Figure Five and shows the signal as a voltage and as a strain with this conversion accomplished using a Lab VIEW sub-VI. The option to save the data to a disk is included, as well as a slide bar to set the cut-off frequency for a low-pass digital filter (not indicated in the figure). This lab is effective as a means to teach transducer circuitry, reinforce the need for analog and digital signal processing, and as an analytical tool to convert voltages to strain. The exploratory nature of the lab is provided with this VI since it offers a “real time” view of the strain in the beam. As indicated in Figure Five, the damping in the beam can be compared to the damping witnessed with the torsional pendulum to illustrate a common behavior of mechanical systems.



**Figure Five: Using the SCXI-1121/1321 with digital filtering.**

For these labs, the VI was provided to the student as a tool to use while learning about transducers, signal processing, and experimental techniques. The only instruction on graphical programming provided in the lab was a short discussion on the wiring diagram for each VI and one assignment where students wrote VIs to sum a series of numbers and take the average of that result. The gradual exposure to the capabilities of Lab VIEW through the lab VIs and this limited instruction in graphical programming was sufficient to allow motivated students to write their own virtual instruments for independent research projects. One example of a student written VI is presented in Figure Six where four thermocouple channels are simultaneously sampled in a design project that investigated the thermal conductivity of a rod.



**Figure Six: Student written VI for four channel thermocouple data acquisition.**

### Observations

The standardization offered by virtual instruments was essential to develop data acquisition skills over a series of lab activities. While each lab introduced new transducers, new experimental techniques, new analysis methods, the Lab VIEW virtual instruments were a common interface in the labs. With the same VIs running on each workstation, students could accomplish the tasks needed to satisfy the lab goals and avoid getting bogged down in the mechanics of collecting data. The VIs kept the focus of the labs on the course topics and afforded the opportunity to concentrate on results during the lab period, rather than treat the lab as merely a time to collect data.

The common interface of virtual instruments was also useful to provide continuity as the data acquisition hardware increased in sophistication over the semester. Similar to the need to select a specific transducer to measure a specific physical parameter, through the lab experience the students learned that specific data acquisition hardware is needed to match transducer output specifications. That data acquisition hardware not only includes amplification, but also transducer excitation and bridge circuits. By slowly peeling away the layers on the data acquisition hardware, students were exposed to the internal configuration of the SCXI-1121 needed to set signal conditioning parameters.

A traditional course in experimental methods can benefit greatly by using virtual instruments. These devices allow instruction in data acquisition techniques, including hardware and signal processing methods, to be concurrent with instruction in transducers and engineering experimentation. The gradual development of data acquisition skills is achievable over a one semester course using carefully selected labs that cover the spectrum of transducers and data acquisition requirements. As evidenced by the ability of students to produce their own virtual instruments and configure the data acquisition hardware for specific transducers, students can progress, over the semester, from data acquisition novices to competent as engineering experiment practitioners.

## References

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