

LabVIEW™ Facilitates Interdisciplinary Team Projects in Graduate Biomedical Engineering Courses*

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The Master of Science Biomedical Engineering Program at California State University uses class team projects to provide students with practice in interdisciplinary team problem solving. LabVIEW, with its rapid prototyping and interactive capabilities, provides valuable support for these projects. The use of LabVIEW in these class projects has attracted medical and industrial collaborators, and has made possible the successful completion of projects within a semester or just a few weeks that previously would not have been considered feasible, and has led to master's theses and research and development activities.

INTRODUCTION

THE MASTER OF SCIENCE (MS) Biomedical Engineering (BME) Program at California State University, Sacramento (CSUS) prepares graduates to apply engineering to the solution of problems in biology and medicine. As is true for engineers of all types, BMEs must be able to communicate effectively and to work productively with others, in addition to having a solid technical foundation. Communication and team skills are especially important for BMEs, because they must collaborate with biologists, medical doctors and nurses, and other life science and health care specialists with backgrounds very different from engineering. The CSUS BME Program gives students practice in interdisciplinary team problem solving via graduate class projects. We have found that virtual instrument (VI) workstations utilizing LabVIEW (Laboratory Virtual Instrument Engineering Workbench) software (National Instruments, Austin, Texas, USA) [1, 2] provide valuable support for these class projects. This paper describes our experience with using LabVIEW for these interdisciplinary graduate BME class projects.

CSUS BME VI LABORATORY

In 1995, the CSUS BME Program established a Virtual Instrument (VI) Laboratory, through a \$155,000 Whitaker Foundation grant. The

CSUS BME VI Lab consists of Power Macintosh 8100/100 desktop computers (Apple Computers) with 14-inch color monitors and color printers. Each computer contains an NB-MIO-16 data acquisition board (National Instruments) with a 12-bit analog-to-digital converter and 16 analog inputs, two 12-bit digital-to-analog converters with voltage outputs, eight lines of digital input/output, and three 16-bit counter/timer channels for timing input/output. Version 5.0 of LabVIEW is installed in each computer. Twelve of these computers are networked together, and additional 8100/100s and a PowerBook 5300c laptop computer with a DAQCard-700 PCMCIA card (National Instruments) are available for use outside the laboratory.

LabVIEW facilitates rapid prototyping of systems and user/system interfaces for biomedical data acquisition, processing, display, and storage and retrieval of results through its instrument-oriented, graphical programming language, large libraries of input/output and computational components, numerous example VIs, on-line help, and multiple debugging tools. An additional benefit is that VIs can be designed in modules and with hierarchical structures of VIs calling sub-VIs.

INTERDISCIPLINARY CLASS TEAM PROJECTS

The CSUS BME Program provides students with the opportunity to practice interdisciplinary team problem-solving through graduate course projects. These projects provide the students with

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experience in interdisciplinary collaboration with clinical and industrial experts on problem definition, system design, human factors, prototype implementation, design of protocols for performance testing, analysis of results, documentation, and presentation. We have successfully tried two formats for these projects—the semester-long class project and the three-to-four-week laboratory. The two formats are similar, with smaller projects chosen for the multi-week laboratory format.

For an interdisciplinary class project, a BME academic coordinator collaborates in instruction with clinical or industrial experts. The experts meet with the class and present background information and describe the clinical or industrial needs. The students and instructors together define the problem, develop solution strategies, prepare human subjects proposals, collect data, design and implement system prototypes, develop and carry out assessment procedures, etc. The students and instructors jointly accumulate resource materials into a class reference library and share in the presentation of background topics. Students organize into work teams, and these teams make periodic presentations to the class on their progress. Each student keeps a log of class activities and submits a copy weekly to the academic coordinator. Each student also submits formal reports at appropriate times during the semester—for example, at the end of problem definition, prototype design and implementation, and prototype assessment. At the end of the semester, the students make formal presentations to guests from the local medical and industrial communities. The students are evaluated on the basis of their weekly logs and their reports and presentations.

We have found that the CSUS BME VI Lab provides valuable support for these interdisciplinary class team projects. Thanks to LabVIEW's capability for rapid, flexible, modular prototyping of a wide variety of systems, we have been able to successfully complete semester-long and multi-week BME projects that we would not even have attempted previously. Some examples of both types of these projects follow.

EXAMPLES OF SEMESTER-LONG LabVIEW-BASED PROJECTS

LabVIEW-based cardiorespiratory monitor

We tried our first LabVIEW-based BME class project in the spring, 1995, semester in our graduate course BME 220, Advanced Topics in Medical Instrument Design. The BME instructor (Smith) gave the students a thin, flexible 3-cm × 10-cm polyvinylidene fluoride (PVDF) piezofilm sensor that generates an electrical charge separation between electrodes printed on opposite sides of the film when the sensor is bent, stretched, or compressed [3]. The semester project was for the students to design and implement a cardiorespiratory monitor VI that would use this PVDF sensor

affixed to a patient's chest to monitor the patient's heart rate and respiratory rate [4, 5].

Through interviews with clinicians and literature and Internet searches, the students decided to focus on monitoring applications in convalescent homes and for at-home infants. Biomedical engineers from local industry and medical experts from the University of California, Davis Medical Center (UCDMC) in Sacramento provided the class with guidance on medical instrument design and human factors issues [6]. The class learned about the mechanical and electrical properties of the sensor and designed and built sensor interface electronics. The class also developed and submitted a proposal to the CSUS Committee for the Protection of Human Subjects to record physiological data from one another. Once their proposal was approved, the students made simultaneous recordings on a multi-channel FM instrumentation tape recorder of the PVDF sensor output, electrocardiogram (ECG), and respiratory flow from six class members during various conditions of rest and physical activity, such as walking in place and exercising on a 'stair stepper'. They recorded the ECG and respiratory flow as their 'gold standard' references to compare with the heart and respiratory information extracted from the PVDF sensor.

For the last part of the course, class teams used LabVIEW to construct cardiorespiratory monitor VIs for different patient settings and as research tools to compare the cardiac and respiratory information extracted from the PVDF sensor with the ECG and respiratory flow recordings. In these VIs, LabVIEW digital filters first separated out the lower frequency respiratory information and the higher frequency heart information in the PVDF signal. The software then detected each breath cycle and computed and displayed respiratory rate and similarly detected each heart cycle and found heart rate. The teams benefitted by being able to share subVIs. Figure 1 shows the front panel of one of the team's cardiorespiratory monitor VIs, and Figure 2 shows the corresponding VI block diagram. Though the VI requires revision and correction before the monitor is suitable for actual use, the block diagram illustrates the level of programming skill that the students were able to attain with LabVIEW in just a few weeks.

LabVIEW control of the MicroScan's autoSCAN-4

We tried a second, semester-long class project in the spring of 1997 in collaboration with Dade Behring MicroScan of West Sacramento, California, supervised by two of the authors (Smith and Williams). Dade Behring MicroScan manufactures automated instruments to identify the bacteria causing a patient's infection and to determine the best antibiotic and dose for treatment [7, 8].

To begin the semester, scientists and engineers from MicroScan introduced the class to the microbiology of bacteria and methods for their

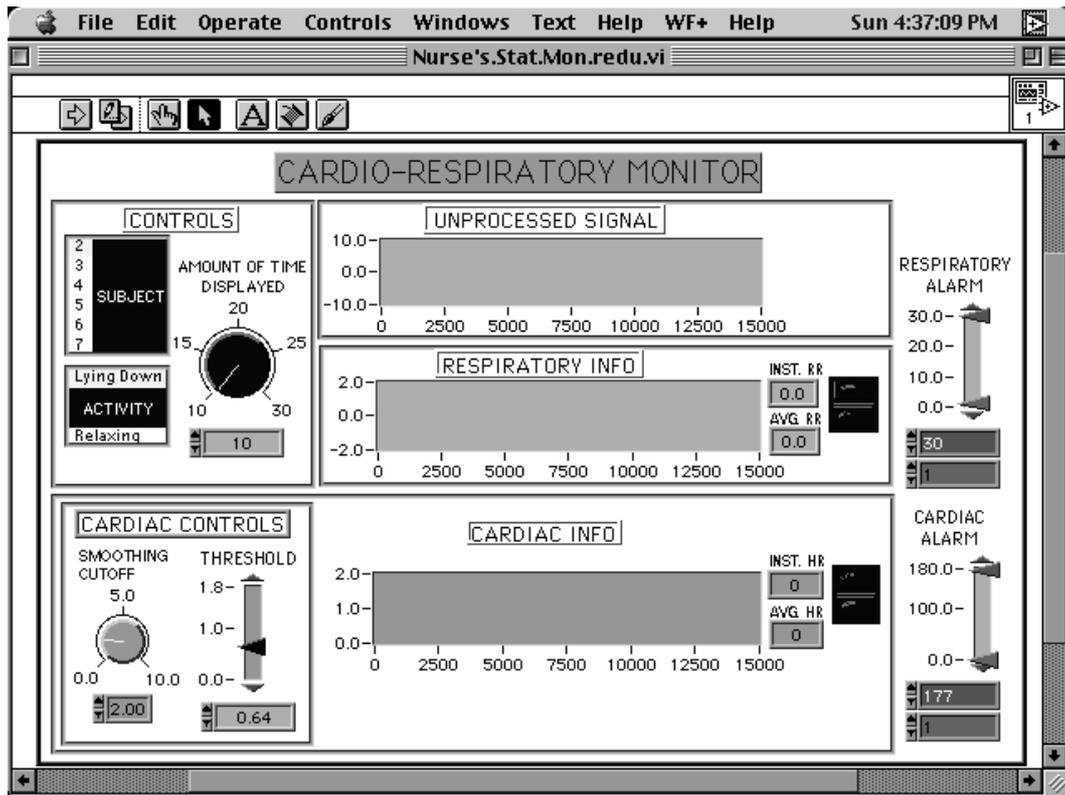


Fig. 1. The front panel of a cardiorespiratory monitor VI designed by a BME 220 class team.

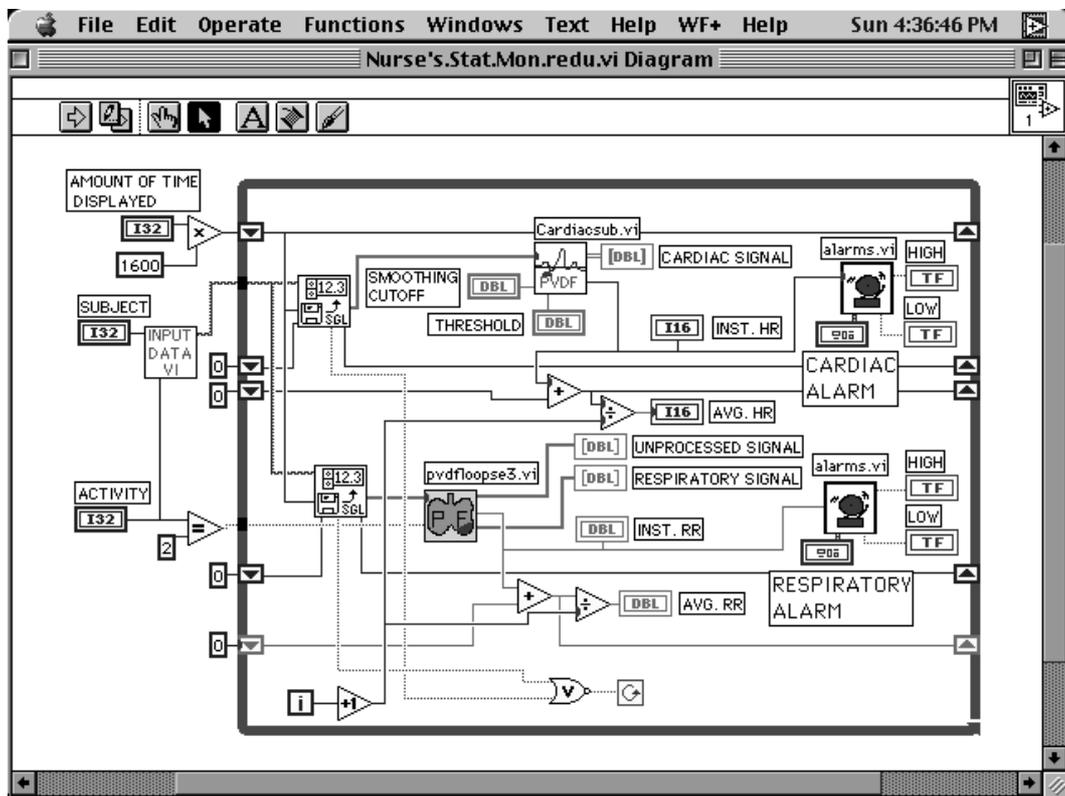


Fig. 2. The block diagram corresponding to the cardiorespiratory monitor VI front panel shown in Fig. 1.

identification and for determining their susceptibility to antibiotics. The students and instructors then decided as a project to use LabVIEW to develop a computer control and analysis VI to replace the on-board computer of MicroScan's autoSCAN-4, an automated system for bacterial identification and antibiotic susceptibility testing. This project was chosen to provide the students with insight into the autoSCAN-4's structure and functioning and the use of LabVIEW for instrument control and to provide MicroScan with the opportunity to learn about the capabilities of LabVIEW.

The autoSCAN-4 system measures bacterial growth and chemical test results in a 96-well microtiter sample tray. To make the measurements, a light source and color wheel and a set of optical fibers direct colored light up through the bottom of each well, and an array of photodiodes located above the tray reads the light intensity that passes through each well.

MicroScan loaned an autoSCAN-4 system to the class, and the students developed a VI that used serial port communication to control the position of the autoSCAN-4's color wheel and sample tray and digital commands to control the autoSCAN-4's internal multiplexing system in order to step through its array of 96 photodiodes. The VI then read the photodiode outputs via the LabVIEW-controlled analog-to-digital converter. The students utilized the graphics capabilities of

LabVIEW to create numerical, virtual LED, and color-scale computer monitor displays of the sample tray measurements that mimicked the layout of the original 96-well microtiter tray. Figure 3 shows the virtual LED microtiter tray display of the control and analysis VI for the autoSCAN-4 system. Figure 4 shows the VI block diagram.

LabVIEW monitor for real-time estimation of aortic root pressure waveform from radial artery pressure

In the spring of 1999, two of the authors (Smith and Anderson) supervised another semester-long class team project using LabVIEW. The focus was to improve the monitoring of critically ill and injured patients in the intensive care unit. Specifically, the class used LabVIEW to develop and evaluate an on-line monitor VI for estimating the patient's aortic root blood pressure waveform from the measurement of radial artery pressure. Such a monitor makes it possible to determine clinically useful information about the patient's heart and circulatory system from the measurement of radial artery pressure [9, 10].

To develop the VI, recordings were made of aortic root and radial artery pressures from patients, and the students analyzed these recordings to determine the mathematical transfer function between these two pressure sites. For real-time

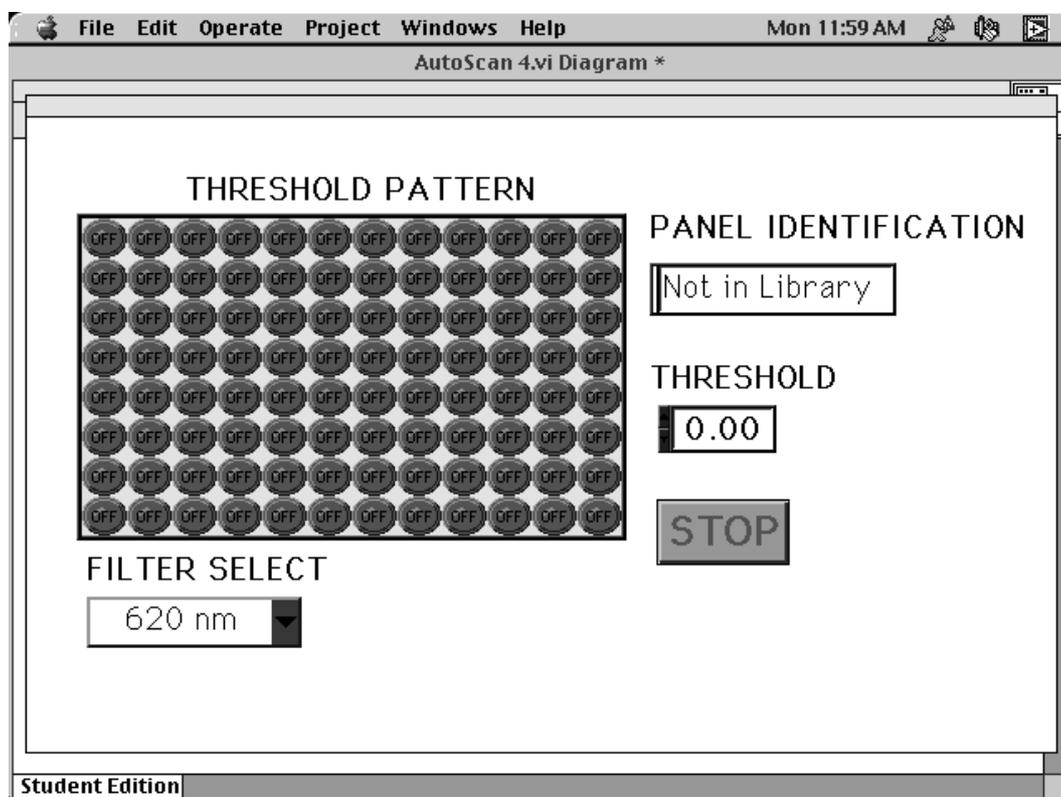


Fig. 3. The virtual LED microtiter tray display of the control and analysis VI for the MicroScan autoSCAN-4 system that was designed by a BME 220 class team.

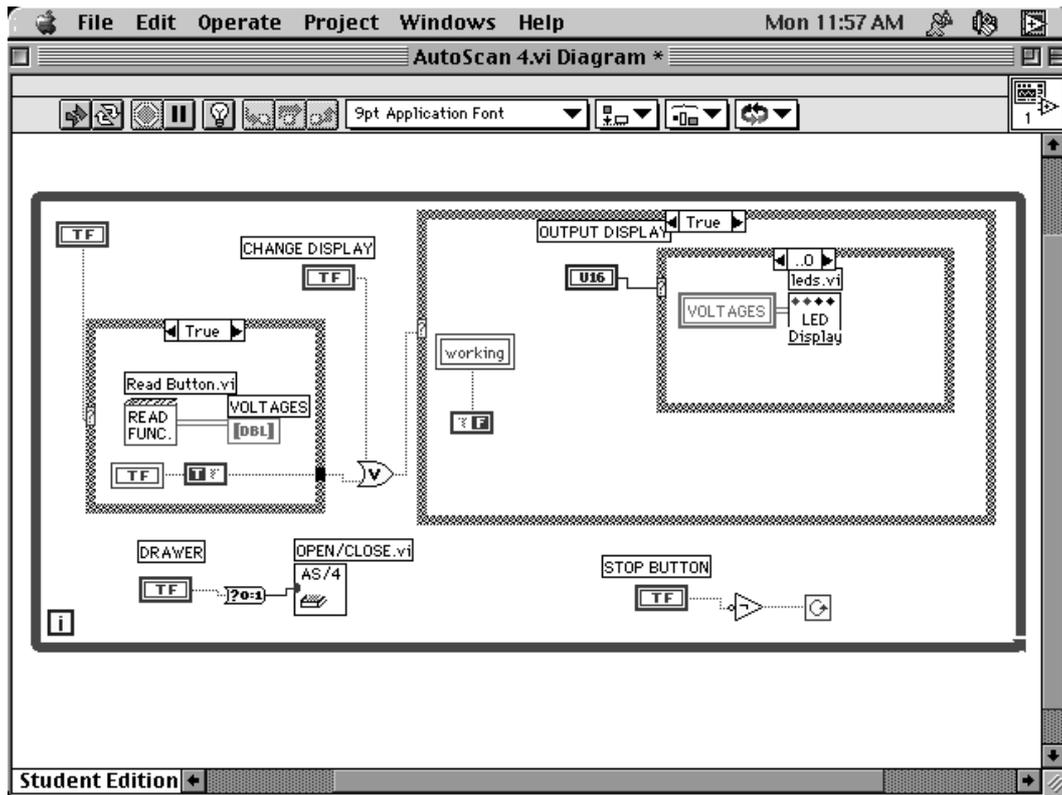


Fig. 4. The block diagram for the control and analysis VI for the MicroScan autoSCAN-4.

estimation of the aortic root pressure waveform, the students implement a real-time difference equation form of this transfer function in LabVIEW. They then evaluated this implementation by comparing its estimate of the aortic root pressure waveform with the actual recorded aortic root pressure waveform.

EXAMPLES OF MULTI-WEEK LabVIEW-BASED LABORATORY PROJECTS

LabVIEW to improve patient monitoring for the anesthesiologist

Another format we have tried for interdisciplinary team projects is the multiple-week laboratory in the graduate course BME 261, Human Factors in the Design of Medical and Assistive Technology. During the springs of 1996 and 1998, we carried out a total of three, four-week LabVIEW-based team laboratories.

In the first such laboratory, in 1996, one of the authors (Smith) and experts from the UCDMC Anesthesiology Department directed the class in an investigation of how to improve the display of patient monitoring information during surgery. The current one-sensor/one-display approach to presenting information can lead to interpretation and decision errors, especially in emergency situations [11]. The class used LabVIEW in the BME VI Lab to develop and test alternative anesthesiology monitor displays of seven physiologic variables,

three for the cardiovascular system (heart rate and systolic and diastolic blood pressures) and four for the respiratory system (respiratory rate, tidal volume, peak inspiratory pressure, and end-tidal carbon dioxide partial pressure). This laboratory project, described briefly below, is presented in more detail in Smith, Berguer, and Loeb [12].

The anesthesiology experts first introduced the class to the anesthesiologist's job, the instrumentation in the operating room, and human factors issues that affect the anesthesiologist's ability to properly use the instrumentation, especially in critical situations. Class teams then used LabVIEW to create and test three different types of displays—numerical, graphical, and integrated—of the physiological variables. Figure 5 shows the integrated display created by the students, with the variables related to the respiratory system on the left and the variables related to the cardiovascular system on the right. Deviations of patient variable values from normal are readily seen as changes in geometric shape. This figure illustrates the power and flexibility of LabVIEW's graphics capability. Figure 6 shows the corresponding VI block diagram.

The class tested which display allowed a subject to determine most quickly that a patient was in difficulty and to most accurately diagnose the problem. Testing was performed using 5-min. scripts of variable values created by an anesthesiologist to simulate the occurrence of four types of critical events in the operating room, such as the

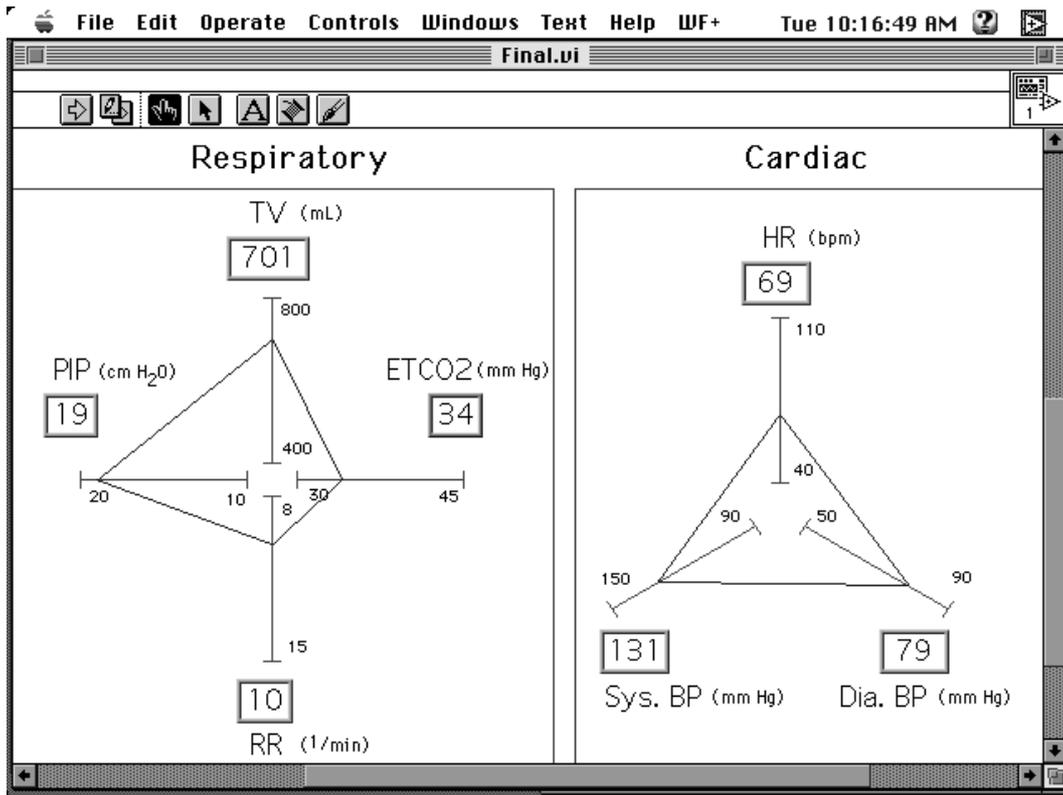


Fig. 5. The front panel of the integrated display of physiological variables designed by a BME 261 class team.

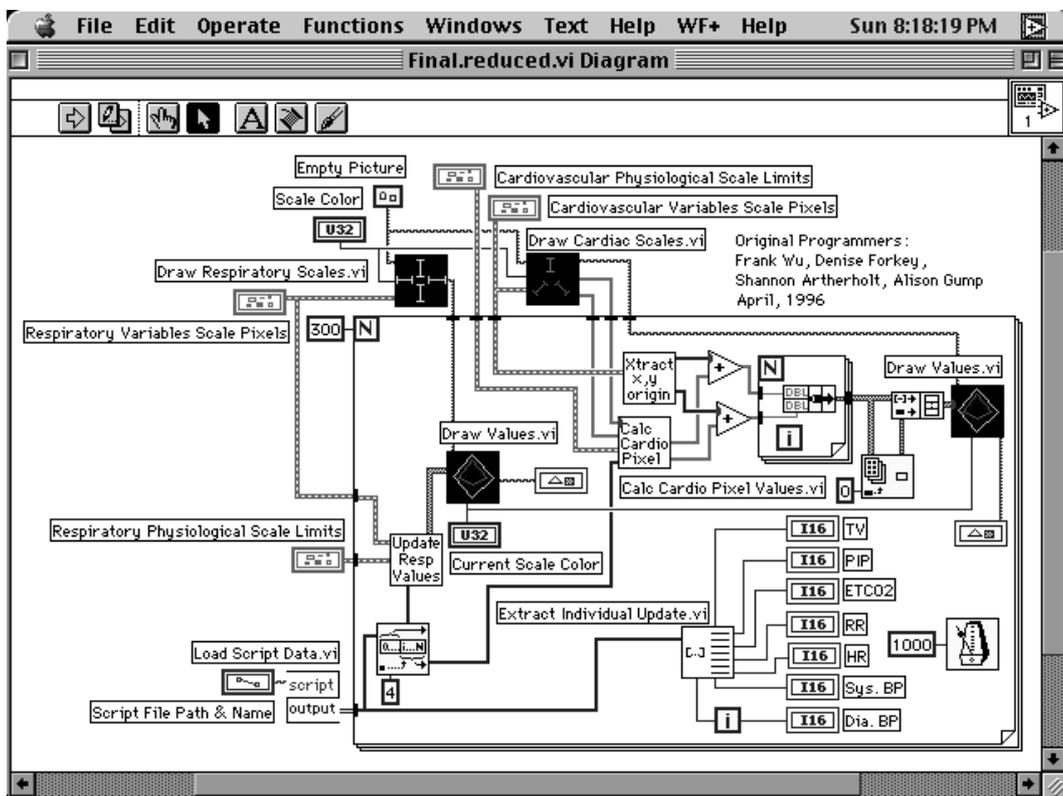


Fig. 6. The block diagram corresponding to the integrated display VI front panel shown in Fig. 5.

patient hemorrhaging or having an asthma attack. The class learned that experts performed better than novices when using the numerical and analog displays but that the experts and novices performed equally well with the integrated display.

LabVIEW monitor of physical workload of video-endoscopic surgery

In a second four-week laboratory in 1996, also described in more detail in Smith, Berguer, and Loeb [12], two of the authors (Smith and Berguer) directed the class in an investigation of the physical effort required by the surgeon to perform video-endoscopic surgery (VES). In VES, the surgeon operates by means of long instruments inserted into the patient through skin ports and views the surgery field via a color video monitor. Though VES is less stressful than traditional open surgery on the patient, it imposes greater physical and mental demands on the surgeon. Ergonomic studies are needed to design improved surgical instrumentation and procedures [13–15].

The students first were introduced to the process of VES and the concepts of ergonomics and the design of surgical facilities and instrumentation. They then designed and carried out a study of the effect of wrist angle on the physical effort required to close a pistol-grip laparoscopic grasper against a calibrated spring. To estimate the physical effort, the students measured the surface electromyogram (EMG) from the thumb and forearm flexor and extensor muscles [16]. The students developed the necessary electronics and experimental apparatus and used LabVIEW in the BME VI Lab to create a three-channel EMG acquisition and analysis VI. The results of the study showed that, consistent with surgeons' experience, the effort to close the laparoscopic graspers increased as the wrist deviated away from its neutral position.

LabVIEW monitor of mental workload of video-endoscopic surgery

In a third four-week laboratory, in 1998, two of the authors (Smith and Berguer) guided the class to develop and test a LabVIEW VI for

measuring the surgeon's mental workload while performing VES. Figure 7 shows the overall approach taken by the class. One class team developed the electronics and VI software to measure skin conductance [17]. To test the usefulness of the Skin Conductance VI to measure mental workload, another class team developed a Task VI to create a graded series of levels of mental workload [18].

The Task VI presented random sequences of addition and subtraction problems of different levels of difficulty to subjects and scored the results. Specifically, the Task VI displayed a pair of randomly generated numbers and an add/subtract sign, and the subject had 6 s to enter the answer on the keyboard. The Task VI adjusted the number of digits of the numbers presented to produce five levels of mental workload, ranging from two single-digit numbers (Level 1), to two three-digit numbers (Level 5). A trial, lasting 150 s, consisted of five 30-s sets of five arithmetic problems each, one set at each of the five levels of difficulty. Each of eight subjects was tested for three trials. The Task VI saved a file of the sequence of workload levels, the arithmetic problems presented, the correct answers, the subject's answers, and the percent correct at each level. Figure 8 shows an arithmetic problem presented by the Task VI.

During testing, the Skin Conductance VI measured voltages proportional to skin current (Channel 0) and skin voltage (Channel 1) and computed skin conductance. The Skin Conductance VI received the sequence of levels of difficulty from the test VI through the BME VI Lab network, sorted the skin conductance values in order of increasing level of difficulty, and computed average skin conductance values for each level of difficulty. The Skin Conductance VI displayed plots of raw channel 0 and channel 1 voltages, unsorted and sorted skin conductance values, and average skin conductance value versus workload level and saved these arrays to the hard drive. Figure 9 shows a recording of skin conductance data during a 150-s trial.

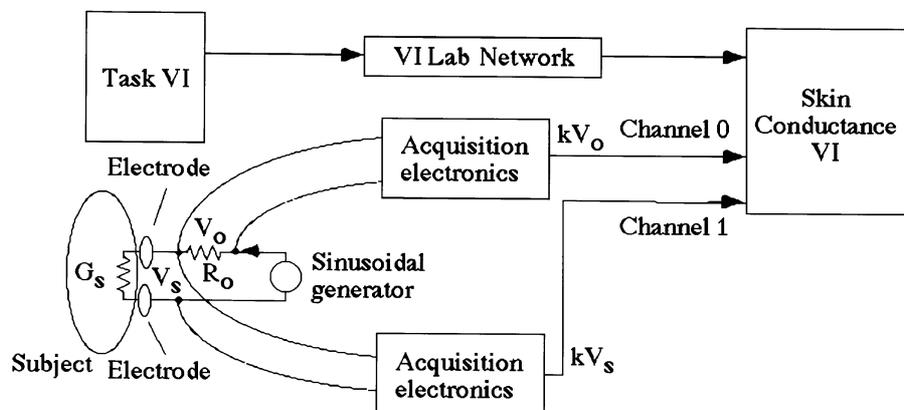


Fig. 7. The overall system developed by the BME 261 class to measure skin conductance and test it as an indicator of level of mental workload.

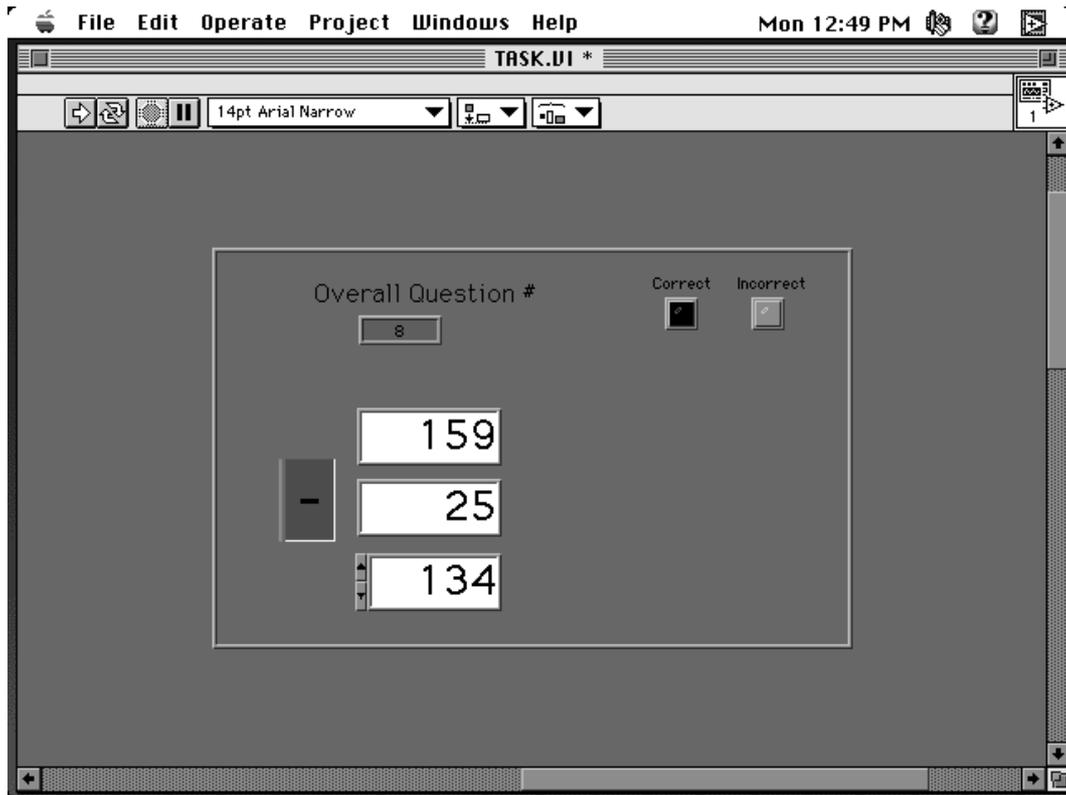


Fig. 8. An arithmetic problem presented by the Task VI developed by a BME 261 class team.

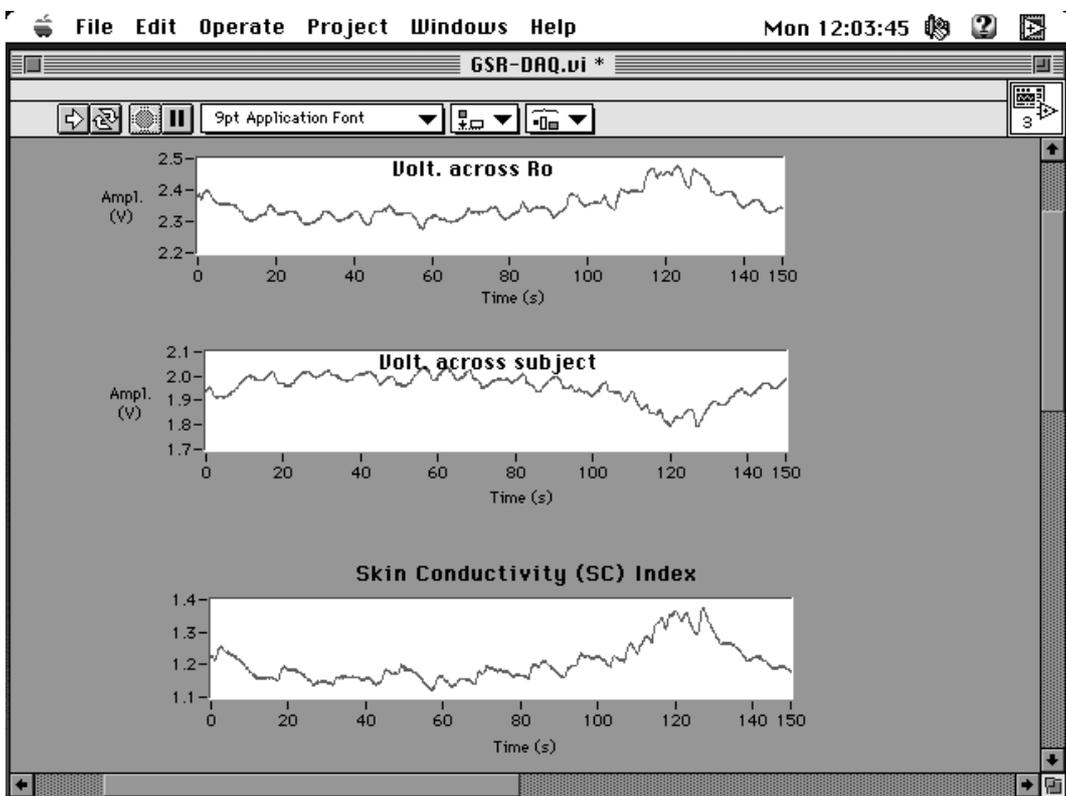


Fig. 9. The results of a 150-s trial recorded by the Skin Conductance VI developed by a BME 261 class team.

The results showed that an increase in skin conductance could be used to detect an increase in the level of difficulty of the arithmetic problems. The results of this laboratory suggest that skin conductance could be useful for monitoring the mental workload of surgeons during VES.

DISCUSSION

Our very first experience with LabVIEW in the spring of 1995 convinced us of its value for supporting interdisciplinary team projects in our graduate BME courses. The spring semester started at the beginning of February and continued through the third week in May. We expected to set up our new BME VI Lab in January, 1995, but the equipment did not arrive in time. Nevertheless, we started the students on the cardiorespiratory monitor project described above. The laboratory equipment finally arrived in mid-April, with only four weeks of the semester remaining. In this short time, the class assembled and learned how to use the computers, installed and learned LabVIEW, and built and tested cardiorespiratory monitor VIs. We were able to complete this project by the end of the semester only because of the rapid and powerful implementation and interactive capabilities of LabVIEW.

With LabVIEW, we successfully carried out the projects described above within a semester or in just a few weeks. Before LabVIEW, we would not even have considered attempting such projects as semester or multi-week class exercises. Without LabVIEW, the class projects tended to have a

relatively narrow focus, such as the development of electronics for the acquisition of a particular biosignal. With LabVIEW, the students have the educational benefit and satisfaction of working on projects of much broader scope, involving not only, say, biosignal acquisition, but also processing and display, control, and human factors issues.

Observers from the medical and industrial communities have been very impressed by what the students have been able to learn and accomplish in such a short time. In fact, Dade Behring MicroScan asked the students to repeat their presentations on LabVIEW applied to the auto-SCAN-4 after the semester was over. The success of LabVIEW in these class projects has stimulated additional collaborative projects with the local medical and industrial communities. The projects described above have led to eight BME master's theses, 14 papers and conference presentations, and five funded contracts that have paid for 12 student research positions.

The Whitaker Foundation grant used to establish the BME VI Laboratory provided the computers, printers, networking capability, software and licensing, software and hardware manuals, data acquisition boards, and National Instruments 5B-series backplanes and amplifier modules. Taking all these items into account, the cost per VI computer station in 1995 was \$8000 to \$9000.

We plan to continue our use of LabVIEW to support interdisciplinary class projects. In the future, we look forward to enhancing this support by adding motion control and IMAQ Vision image processing capabilities and utilizing LabVIEW's growing Internet features.

REFERENCES

1. C. J. Kalkman, LabVIEW: a software system for data acquisition, data analysis, and instrument control, *J. Clin. Monit.*, **11** (1995) pp. 51–58.
2. M. Santori, An instrument that isn't really, *IEEE Spectrum*, **27** (1990) pp. 36–39.
3. G. M. Sessler, Piezoelectricity in polyvinylidene fluoride, *J. Acoust. Soc. Am.*, **70** (1981) pp. 1596–1608.
4. M. N. Ansourian, J. H. Dripps, J. R. Jordan, G. J. Beattie and K. Boddy, A transducer for detecting foetal breathing movements using PVDF film, *Physiol. Meas.*, **14** (1993) pp. 365–372.
5. J. Silvola, New noninvasive piezoelectric transducer for recording of respiration, heart rate, and body movements, *Med. & Biol. Eng. & Comput.*, **27** (1989) pp. 423–424.
6. Human factors engineering guidelines and preferred practices for the design of medical devices (ANSI/AAMI HE48–1993), in *AAMI Standards and Recommended Practices, Volume 2S: Biomedical Equipment, Supplemental*, Arlington, VA: Association for the Advancement of Medical Instrumentation, (1994) pp. 883–978.
7. B. G. Clayland, C. Clayland, K. M. Tomfohrde and S. Wallace, Full spectrum automation for the clinical microbiology laboratory, *Am. Clin. Lab.*, **25** (1989) pp. 30–34.
8. A. McGregor, F. Schio, S. Beaton, V. Boulton, M. Perman and G. Gilbert, The MicroScan WalkAway diagnostic microbiology system—an evaluation, *Pathology*, **27** (1995) pp. 172–176.
9. M. Karamanoglu, M. F. O'Rourke, A. P. Avolio and R. P. Kelly, An analysis of the relationship between central aortic and peripheral upper limb pressure waves in man, *Eur. Heart J.*, **14** (1993) pp. 160–167.
10. H. Senzaki, C. H. Chen and D. A. Kass, Single-beat estimation of end-systolic pressure-volume relation in humans, *Circulation*, **10** (1996) pp. 2497–2506.
11. M. B. Weinger and C. E. Englund, Ergonomic and human factors affecting anesthetic vigilance and monitoring performance in the operating room environment, *Anesthesiology*, **73** (1990) pp. 995–1021.
12. W. D. Smith, R. Berguer and R. G. Loeb, Virtual instrumentation for human factors studies in surgery and anesthesia, *Lab. Robotics and Automation*, **10** (1998) pp. 99–105.
13. M. Patkin and L. Isabel, Ergonomics, engineering and surgery of endosurgical dissection, *J. R. Coll. Surg. Edin.*, **40** (1985) pp. 120–132.

14. F. Tendik, R. W. Jennings, G. Tharp and L. Stark, Sensing and manipulation problems in endoscopic surgery: experiment, analysis, and observations, *Presence*, **2** (1993) pp. 66–80.
15. R. Berguer, Ergonomics in the operating room [editorial], *Am. J. Surg.*, **171** (1996) pp. 385–386.
16. G. E. Loeb and C. Gans, *Electromyography for Experimentalists*, University of Chicago Press, Chicago (1986).
17. S. C. Jacobs, R. Friedman, J. D. Parker, G. H. Tofler, A. H. Jimenez, J. E. Muller, H. Benson and P. H. Stone, Use of skin conductance changes during mental stress testing as an index of autonomic arousal in cardiovascular research, *Am. Heart J.*, **128** (1994) pp. 1170–1177.
18. T. Kakizaki, Relationship between EEG amplitude and subjective rating of task strain during performance of a calculating task, *Eur. J. Appl. Physiol.*, **53** (1984) pp. 206–212.

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Gregory Brian Williams has a 22-year biomedical career in research and development at the interface of biology and instrumentation, following a BA in Microbiology, University of Montana, Ph.D. in Biology, University of Pittsburgh, and postdoctorate in Biomedical Engineering, Harvard-MIT division of Health Science and Technology. He has helped transfer technology from academic, government, and industrial labs to the marketplace in clinical and environmental microbiology, cancer biology, and toxicology. He currently is Group Manager of Advanced Development at Dade Behring MicroScan, a worldwide medical diagnostics company, overseeing new product concept generation and feasibility development. He originated, and now leads a project to commercialize, a new system for rapid clinical antibiotic susceptibility testing and microbial identification.

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