ChE laboratory

INCORPORATION OF PROCESS CONTROL COMPUTERS IN THE UNDERGRADUATE LABORATORY

A Case Study

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THE REBUILDING of our undergraduate unit operations laboratory was a substantial project and required the concerted effort of several individuals. To understand the process, it is first necessary to realize the state of our undergraduate laboratory before we began the conversion (*Background*). A plan for transforming the laboratory (incorporating state-of-the-art computers) was created, and a method for accomplishing the goals was developed (*Implementation*). The eventual capabilities were dictated by the choice of the computer systems to be used in the laboratory, and this will be briefly discussed (*Computer Capabilities*). A major aspect of the change was a realization that both the existing philosophy of the laboratory and the nature of the experiments needed to be modified; further, new experimental approaches would be available with the enhanced capabilities (*Course Content*). The next-to-last section will discuss the problems that occurred and our perception of the process (*Discussion*). We have continuing plans to modernize and update the laboratory to reflect current and developing "state of the art" in personal computers and their application to the measurement and control of chemical engineering processes. They will be discussed in the last section (*Future Plans*). The last two brief sections include an overview of the process (*Final Comments*) and *Acknowledgements* of the myriad of people that made this whole process possible.

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BACKGROUND

Seven years ago, when I came to the University of Massachusetts, the undergraduate laboratory was no more advanced than the ones I had been exposed to in my undergraduate education. It had been built in the 1950s and, without substantial state funds available for modernization, was essentially unaltered. The limited funding provided through the years had been used for maintenance of the existing equipment. At one time, our undergraduate chemical engineering laboratory course spanned three years and involved one credit hour each semester. A sequence of several small experiments was involved, *e.g.*, calibration of a thermocouple. Prior to that the laboratory had been run during several summer weeks between the junior and senior years, as a summer camp for chemical engineering undergraduates.

The laboratory can provide a method of testing and understanding the complexities of the concepts learned in class. This should occur after, or concurrent with, the class. Therefore, the laboratory was concentrated into two three-credit courses in the senior year. The focus in the fall semester was on thermodynamics and transport, and the focus in the spring semester was on kinetics and control. We also had been conducting a "senior seminar" course that gave the students an opportunity to choose a general interest topic and present a talk to the other students.

A group of the faculty met and decided that the laboratory should be restructured. The first steps were organizational. Out-of-date experiments were dropped, and other experiments were combined into larger experimental projects. As an example, an experiment to measure the VLE diagram was combined with distillation to reflect the design of a separation based on a mixture of components for which the vapor liquid equilibria were "unknown." The "senior seminar" was incorporated into the course. The students were required to orally present a proposal of their intended experiments prior to going into the laboratory and then to orally report on the results after they had finished. Written expression was also emphasized as the students were required to write a one-page proposal and a concise (less than ten-page) report.

Our primary concern was that the laboratory did not reflect the "state-of-the-art" use of digital computers in the acquisition of experimental data and did not foster the ability to efficiently design experiments and control the processes. A program (discussed below) was developed by which this goal might be realized. Catalyzing this proposal was the donation of modern process control computers, MACSYM-350®'s, from Analog Devices Corp., to the university. An undergraduate student, John Melanson, had used this system in our research in catalytic reaction engineering and found it was very easy to use and to interface with real experimental measurements.

IMPLEMENTATION

It was first necessary to plan the laboratory transformation. We initially proposed interfacing the computers over a three-year period. Two or three computers would be acquired each year and interfaced with two of the six or seven experiments conducted each semester in the laboratory. One or two computers would be set up in the student AIChE office to permit groups to write programs and to analyze data outside of the laboratory. Modest funding was requested for new experimental hardware (valves, transducers, *etc.*) which was to be augmented by funds from the university (generated by a new engineering school laboratory fee). The proposal was submitted to Analog Devices in the spring of 1983 and was accepted for the first year.

We had decided to directly involve the undergraduate students in the transformation of the laboratory. Two students, Ann-Marie Baker (a junior) and John Dorgan (a sophomore), were given jobs in the Applications Group of Analog Devices during the summer of 1983. They returned to campus in August to begin the conversion. Other students were employed at the university during the summer (and on a continuing basis since then) to transform specific experiments and to develop new experiments.

The conversion . . . to computer data acquisition and process control involved . . . reorganization. Two and one-half weeks at the beginning of the fall semester are now set aside to introduce students to the computer systems.

We decided to make programming of the computers an integral part of the course. Teaching software was developed to instruct the students on the use of computers and on the specific version of BASIC (MACBASIC®) employed on these process control computers. Ten megabyte hard discs were acquired for each computer system, and the teaching and demonstration programs were loaded onto each system. The demonstration programs (described below) gave examples of all of the programming functions required for the course. A 25-inch color monitor (RGB input) was purchased for class instruction using on-screen display of the programs with color graphics. We found that classes of 25-30 could be conducted with the monitor.

A technician and an instructor in our department also became involved in the conversion. Each had been involved in computer applications and readily volunteered their services and expertise. Graduate students who had used these computer systems were used as teaching assistants for the course.

The first year was so successful that we decided to complete the transformation in two years instead of the three years originally proposed. At the end of the first year, a renewal proposal for the completion of the conversion was submitted to Analog Devices and, in view of our progress, was accepted. The retail price was $250,000 ($200,000 in computer hardware and $50,000 in experimental hardware).

COMPUTER CAPABILITIES

The capabilities of the computers used for the conversion are essential for transforming our undergraduate laboratory to primary computer data acquisition and control. We decided to take the "quantum leap" and use state-of-the-art process computers. The language used by the computers had to be easy to learn and readily adaptable to the measurement of flow, force, temperature, and composition. We decided to incorporate dynamic control as well as data acquisition into the course curriculum; therefore, the ability to perform simultaneous tasks ("multi-tasking") was important. The MACSYM® line of computers produced by Analog Devices was ideally suited for this task. Analog Devices is a corporation based on the conversion of analog to digital and digital to analog signals.

MACBASIC® is a "compiled basic" language that is analyzed line by line as the program is written. Syntax errors are noted immediately. "On screen" editing is used. Analog to digital to analog conversions and high resolution graphics (including color) are inherent in the language. This system seemed to be designed specifically for the operations required in the monitoring and control of a chemical engineering process. Hence it was not necessary to adapt the computer system for communication with the world of real chemical processes. As an example, Table 1 illustrates a first attempt at proportional-integral control. It illustrates the ease of reading voltage inputs (line 30) and setting output voltages (line 100), in spite of the simplicity of the control scheme. Decisions regarding control and/or alarms are made in the program. On/off inputs such as valves and switches are controlled or recorded with comparable digital input (DIN) and digital output (DOT) command syntax. A number of commands are available to define simultaneous tasks and to activate or suspend the tasks. This permits the programming of simultaneous control, of gathering and storage of data, of printing, and/or of plotting.

We wanted to allow for expansion and the measurement and control of as many as forty variables on a single process (on a distillation column, for example).

TABLE 1
Program for PI Control

	Command	Comment
10	INPUT "Setpoint, Gain, Integral Const. ?" SP,G,I	Choose setpoint, control gain and integral constant
20	zero timer, TOT = 0, PT = 0	Starts time clock, zero's integral
30	X = AIN (2,3,10)	Measures voltage on card 2, channel 3 with sensitivity 10
40	T = timer	Records time
50	ET = T - PT	Calculates elapsed time
60	E = SP-X	Calculates error
70	TOT = ET*E + TOT	The integral
80	If Abs (TOT)>10 then TOT = 10*TOT/Abs(TOT)	Preventing integral wind up
90	Y = G* (E + TOT / I)	Calculate new output voltage
100	AOT(3,1)=Y	Set channel 1 voltage on output card 3 at Y volts
110	PT = T	Saves time
120	GOTO 30	

Setting up the distillation column for a steady-state experiment. Distillation column is seen on the right as is the computer monitor depicting the schematic for the column with temperatures and flow rates being shown dramatically at the appropriate positions on the diagram.

There are eight card slots on the MACSYM® mainframe and each slot can take up to 16 differential or 32 single ended inputs, or four voltage outputs. Another twenty card slots are provided with the "200" front end.

A further consideration was the availability of service within twenty-four hours. Analog Devices is located in Norwood, Massachusetts, and their service hotline never failed to respond immediately.

COURSE CONTENT

The conversion of our laboratory to computer data acquisition and process control involved a reorganization of the course. Two and one-half weeks at the beginning of the fall semester are now set aside to introduce the students to the computer systems. Simple test benches are set up for each computer to provide voltage inputs and the display of voltage (analog) output signals. The students are divided into groups of two and are given three sets of homework during the period in order to demonstrate their mastery of the basic computer language. Five computer systems are set up and available each afternoon for the students. Teaching assistants are also available to assist in the programming.

Five or six experiments are required each semester. In the spring, the students are required to perform four experiments and to choose one from two additional experiments. The selection of experiments

TABLE 2
Laboratory Experiments

Experiment	*Equipment*	*3-Hr periods required*	*Computer Interfaced*
FALL SEMESTER			
Vapor/liquid equilibrium and distillation	Equilibrium still and gas chromatograph and 20', 13 plate, SS column	1+3	Temp. on each tray and 12 other points on the column; all flow rates; reboiler level
Concentric pipe heat exchangers	16' steam-water and 40' water-water co- or counter-current heat exch. network	3	Temperatures at 24 points in the network; all flow rates
Fluid flow through pipes and fittings	120' pipe network of different sizes with bends and fittings	3	Flow rate over a broad range; ΔP at 20 points; E & I for the water pump
Unsteady state heat transfer	Objects of different sizes and shapes immersed in water	2	None yet but all temperatures possible
Compressibility of gases and gas mixtures	Interconnected ballast volumes and pressure gages	2	None
SPRING SEMESTER			
Control of distillation	See above	3	As above with control of steam, reflux and feed flows
PID control of flow	Flow valve with transducer	2	Control valve and flow
Methanation	Catalytic PFR with on-line CO analysis	3	Control of all flows; reactor oven; analyzer
Water cooling tower	16' counter-current packed column	2	None
Saponification reactor	Liquid-liquid CSTR	3	Temperature; flow rates; up and down stream PH's
Diffusion	Capillary-column GC	3	Temperature; flow; concentration at 10Hz

TABLE 3
Computer Programs Provided on Each System

Name	*Purpose*	*Description*
Temptest	Data Measurement	*Conversion of a series of 16 thermocouples to a displayed list of temperatures (updated every second)*
DTMX	Data Manipulation	*Use of matrix to store data, to transfer to disc and to print out tables*
Datman	Multi-tasked data handling	*Simultaneous collection, storage, display, and printing of multiple analog inputs*
Pltmx	On-Screen and 8 color plotting	*Use of plotting graphics from data matrix "on screen" and, if chosen, with plotter (X vs Y or X vs time)*
AIN-OUT	Setting outputs based on inputs	*On/off decisions, alarms, and proportional control based on measured analog inputs*
Condem	Demonstration of PID control	*Setting of control constants and on-line screen plotting of set point, measured input and output*
Conplot	Dynamic PID control	*Multi-tasked control with data matrix storage and 8-color plotting...run dynamically*
"LAB"	Specific	*Basic programs for heat exchanger, distillation, methanation, saponification, and diffusion...includes flow diagrams*

varies as the updating of the experiments is done on a continuing basis. During each break between semesters, groups of three students are involved in designing new experiments and in updating earlier experiments. This is a "modest" effort to keep the laboratory program dynamic.

The current list of experiments is shown in Table 2. Three experiments in the fall semester and five in the spring are interfaced with the computers. At least one experiment each semester does not involve computer data acquisition. The focus is on computer use as a tool to measure more variables more rapidly than was possible before. Further, the data can be stored instantaneously and decisions can be made to control the process variables and thereby the experiments. The emphasis of the laboratory performance is on chemical engineering principles and we are committed to retaining this perspective. The advantage is that computers are able to **dramatically** enhance the analyses on-line and thereby to permit changes and adjustments during the experiments.

The laboratory course is closely coordinated with the ongoing courses during the senior year. As an example, as the students learn PID control, Bode diagrams, cascade control, sensitivity analysis, or self-tuning regulators in their control course, these concepts are expected in their experimentation involving control. As mentioned above, each successive group performing experiments is required to go further than prior groups did. Oral reports from the groups are presented to the whole section (*i.e.*, those not in the laboratory conducting experiments). Students are encouraged to ask questions of other groups regarding experiments.

To facilitate the student's use of computers for data acquisition and control, a series of programs is provided which demonstrates all the techniques required for computer use. These are listed in Table 3. The programs are available on the 10MB Winchester disc attached to each system and they are discussed with the students in lecture sessions at the beginning of each semester. During the fall semester the emphasis is on proper techniques of data acquisition, management, and analysis. At the beginning of the spring semester this is augmented with lectures and demonstration programs on multi-tasking, on plotting, and on control. As the students become involved in the experimentation, they request assistance on programming at increasingly higher levels. The demonstration programs are employed (with encouragement and coaching) to develop the students' own approaches to their problems. The effect is synergistic. Basic data acquisition programs are provided for most of the computer-interfaced experiments. This provides flow diagrams for the specific systems and starts the students in the right direction. However, the students are informed that the use of these programs without substantial modification is unacceptable. Finally, a copy of the program that they used is appended to their final reports.

With a total of only 33 three-hour laboratory periods each semester, it is obvious that a rotating plan for the laboratory is needed. Fridays are set aside for make-up. For each experiment, each group must provide a proposal and a report in addition to the time spent in the laboratory. The assignments rotate, and each student in a group of two is responsible for at least two reports and two proposals each semester.

DISCUSSION

As we expected, we experienced several difficulties during the conversion. The first semester was assembled "on the fly" since the computers and all the flow transducers and valves arrived just one week before the first class. Each computer system was configured identically (this is crucial) as we scrambled to install the valves and transducers. Each student was given a formatted disc, and then the format command was removed from the operating systems in the laboratory. This was done after it was (painfully) discovered that the hard disc could be inadvertently formatted and thereby erased in this manner.

We soon realized that homework needed to be assigned during these first weeks in order to focus the student's practice on the computers. There is an activation energy with the use of a new computer system; however, after the initial reluctance, the learning process is autocatalytic.

The manual was not explicit in describing our specific needs. Several phone calls to Analog Devices revealed that bleed resistors from voltage low to ground were needed, and all the inputs had to be on common ground. We included capacitors across the inputs to decrease spurious noise. All the Foxboro transducers required 20-24 volt DC power. A high capacity DC power supply was requisitioned and was set up to service all the needs from a single switchable source. This worked well. Temperature measurements were handled through a sixteen channel, zero compensating subsystem. The example use software in the manual needed to be consulted to determine the proper configuration.

The MACSYM® system is very fast, and a certain amount of signal averaging is desirable. The students have to develop a perspective on the amount of data needed to perform each experiment; otherwise, they end up with reams of data and have difficulty extracting the pertinent portions. Proper experimental planning is essential, and this is emphasized.

Since we had obtained the computer system directly from Analog, there was no salesperson involved and the normal system-setup visit did not accompany the delivery. However, by learning to configure the systems "from scratch" and to set up the interfaces, we gained invaluable experience and insight. This has enabled us to correct problems and adjust the system parameters as needed. Almost all of our difficulties have occurred at the beginning of each semester when the computer systems are changed to new or different experiments.

The Macbasic® language runs on a CCPM operating system, although DOS can be partitioned into the MACSYM® 120 systems. We have kept DOS off all the systems and religiously excluded any word processing software (or games) from the systems. These are powerful minicomputers, but their exclusive use for the laboratory needs to be maintained.

We initially attempted to prohibit students from sharing computer programs already developed for specific experiments, but this proved to be impractical. Subsequently, we encouraged the students to share their software, but required successive groups to do more and thereby improve on the prior experiments. We have found that at least four to five times as much data is gained by each group compared to our prior experience with the same experiment. As an example, prior running of the distillation column involved steady state measurements to compute plate-to-plate efficiencies. The students now start the system, investigate the dynamics, and develop elaborate control schemes to optimize the process.

The net results have been very dramatic. The technicians have developed programs to start up and check out the functions of each experiment. The students are stimulated to see how much they can extract from each laboratory. We noticed this soon after we started. Groups were asking to get into laboratory **an hour early** to get started! They often ask how to do various operations such as control, multi-tasking, or plotting before we instruct or require them to use these techniques. The most frequent questions start, "How can I . . .?" In addition to exercising their abilities in programming, they are developing a "feel" for chemical engineering processes and their state-of-the-art monitor and control. The whole process has been one of my most rewarding experiences in teaching.

FUTURE PLANS

The initial transformation of our undergraduate laboratory was first envisioned in 1983. Full implementation took several years. Since then we have continued to update and expand the available experiments. In particular, we realize the growing need for expertise in solids processing. A tray drier has been installed in the laboratory and is being interfaced with the computer systems. Further, we are expanding the separations/transport experimentation by adding a dynamic Taylor dispersion apparatus and a continuous membrane separation experiment. The first involves moment analysis of pulses in a capillary G.C. column. The second employs hollow fiber membranes to separate oxygen and nitrogen from the air. In both experiments temperature, flow rate, and composition are manipulated variables subject to monitor and control.

Since the availability and capabilities of computers has continued to change dramatically, we look at the latest state-of-the-art and the obvious directions in personal computers in order to plan for the next stage of development of our undergraduate chemical engineering laboratory. Further, Analog Devices has chosen to concentrate its effort on subsystems that are peripheral to the two major systems employed as personal computers (IBM and Apple). Indeed, this summer one of our students was employed at Analog Devices to develop the "drivers" for Macintosh SE® and MAC II® PC's to communicate with Analog's newest measurement and control systems (the 1050-1060 family of data aquisition subsystems). This seems to be the way to proceed with the abundance of PC's currently available. The computer driver would then be able to be changed and updated, retaining the A/D subsystems.

We look to the future and anticipate that we will begin a conversion to state-of-the-art personal computers with associated analog to digital to analog communication. This conversion will start next year and should be completed in three years. Ease of visualization (graphics) and a low activation energy for learning the specific system leads us to investigate the use of Apple Macintosh® II and SE systems for our future undergraduate chemical engineering laboratory. Multi-tasking has not yet become an integral part of either operating system; however, Apple seems to have recognized its significance in Multifinder®. For chemical engineering applications, **true multi-tasking** would be crucial as simultaneous monitor, display, and control of the processes are essential to a viable chemical engineering laboratory.

We have set up dedicated Apple Macintosh II and SE computers and the associated A/D and D/A systems. The use of these systems for the collection and control of analog inputs/outputs is being tested at this time in our reaction engineering laboratories. Our dialogue with Analog Devices continues as we and they investigate the use of their A/D/A based on Apple's Macintosh operating systems.

FINAL COMMENTS

Several aspects of the transformation might be discussed. The integration of computer based experimentation for one or two of the experiments, as compared with the transformation of the vast majority of the experiments at one time, is not recommended. There is an activation energy to learn and to teach a new computer language and the philosophy associated with digital acquisition and control. If the students gain this insight up front, they can focus on the actual experiments being conducted. Use of the computers becomes a tool by which they can function more efficiently in the laboratory. With only a few experiments, the computer and not the chemical engineering principles becomes the experiment.

It would be impossible to gain the same insight into experimentation by conducting "computer experiments" where all of the experiments are conducted against a "simulator" within a computer. I realize that this is a popular approach to teaching "experimental" work. However, this is not only naive, it is grossly unrealistic. If we are preparing our students to work in industry with real processes and materials, they must come to grips with the nature of experimentation. Throughout their education they are exposed to an idealization of real processes. The only place in our students' education where they are exposed to real, albeit simplified, engineering processes is in the laboratory. The real world is not dimensionless and represented by smooth curves. As they see the valves turn and the flow, pressure, temperature, and products change, they learn some of the limits to theory and the necessity of planning the experiments and making the appropriate measurements.

The undergraduate laboratory in chemical engineering can be a course that brings together the curriculum and allows the students to visualize the application of theories in their courses. If these experiments are interfaced with data acquisition and process control computers, and if they learn to use these to conduct the experiments, they can visualize the applications and learn to probe the more realistic aspects of real processes.

ACKNOWLEDGEMENTS

This whole process could not have been ac-

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*block under water, calculate **h** for the top and sides, and subtract to find **h** for the bottom. (Hopeless!)*

- *Did they measure the thickness at more than one point, and did they plot all their points? Or did they just average all their readings?*
- *Did they state that they tried to make their measurements with as little disturbance as possible (agitation will greatly increase **h**)? Did they discuss this and verify this with calculations?*
- *Did they choose a large enough reservoir of water so that the water temperature did not change significantly during the experiment?*
- *Did they choose to weigh the ice? (Not such a good method because the edges of the slab melt faster than the center.)*
- *In the weighing approach, if that was used, did they remove the slab for weighing? (Poor, because the extra agitation increases **h** drastically.) Or did they figure out how to weigh the slab in place? (Better.)*

Variations and Extensions

Many variations and extensions of this simple experiment can be used by the teacher throughout the years. For example:

- *Find **h** for vertical surfaces in water at different water temperatures.*
- *Find **h** for horizontal upfacing surfaces in water. (This is more difficult experimentally and is not recommended.)*
- *Repeat all the above for ice in air.*
- *Find the effect of fluid motion relative to the ice surface. For air, all one needs is a regular household fan and a pitot tube to study this.*

For the teacher, there is the inescapable temptation to ask the student to study a number of these factors, all in one experiment: upfacing, downfacing, vertical, effect of velocity and of ΔT, *etc.* Try to resist this as the lesson of this experiment can be learned just as well by studying one factor alone.

FINAL COMMENTS

What do students learn from this type of experiment?

- *They have to use their ingenuity and come up with their own way to answer the question.*
- *The best way of approaching the problem will not come to them right away, but only after they have thought up a number of schemes. This sort of exercise may give them an appreciation of the value of group discussion.*
- *They had to develop their own analysis and equations–no copying from books. This should give them a taste for doing original work.*
- *The laboratory course can be challenging, surprising, and interesting.*

We feel that there is a place for this type of laboratory experiment in the undergraduate program. □

AWARD LECTURE

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complished without the effort of several dedicated people. Professors R. L. Laurence and B. E. Ydstie helped with the initial proposal. Dr. Graham Sterling, Alan Ryan, Michael Hajjar, and the whole educational support committee from Analog Devices supported and assisted in our development of this laboratory. Their faith and vision were crucial to this project. Paul Grabin and Frank Pulaski were central to the setting up of the laboratory. We also acknowledge our undergraduate classes of 1985 and 1986. With their patience, assistance, and feedback, this major transformation was completed with a minimum of problems and an enhancement of the results. □