ChE laboratory

REAL-TIME COMPUTING IN THE UNIVERSITY

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The following papers were presented at the 1970 meeting at Ohio State University, as part of a symposium on Computer Control of ChE Lab Equipment.

WHAT IS THE ROLE of real-time computing in engineering education and research? Can it be the basis for effective industry-university cooperation? Are the costs justified?

The area of real-time computing is still so new in the university environment that these questions tend to generate discussion rather than answers based on documented studies. With the objective of contributing at least to the discussion, and hopefully to the answers of these questions, the following sections describe our real-time computing facilities in the Department of Chemical and Petroleum Engineering and outline some of the ways they have been utilized in education and research programs.

Probably the most distinguishing feature of the Data Acquisition, Control and Simulation (DACS) Centre, operated by the department, is the broad scope of the Centre's activities. The three digital and two analog computers operated by the Centre are utilized on a time-shared, essentially open-shop basis in undergraduate, graduate and continuing education courses and laboratories; in student assignment and thesis projects; in department research projects; and for service functions such as lab automation and program development.

Planning for the DACS Centre began in 1965-66, motivated primarily by the growing need to supply engineers with familiarity with real-time computer systems and to permit research and development in the various application areas. Program development started immediately, but equipment delivery was delayed until December, 1967, so that it could be installed in the Department's new facilities in Phase I of the new Engineering Centre. The department has fourteen full-time academic staff working in a wide variety of research areas. A typical graduating class would be 40 students and there are normally about 50 graduate students in residence. Therefore the computing facilities had to be designed to serve a large number of users and to handle a wide variety of continuously changing applications.

PRESENT FACILITIES OF the DACS Centre include an IBM 1800 digital computer, a DEC* 680 (PDP8I) communications system,, an EAI* 590 hybrid computing system, an AD* 32 PB analog computer and support equipment such as patchable digital logic units, recorders, etc.

Figure 1 summarizes the DACS Centre's facilities in block diagram form. They include most of the features common to real-time computer installations but with a configuration designed to meet the special needs of a university. Some of the factors leading to this configuration have been presented elsewhere.[16, 17]

The IBM 1800 with 48K of core storage and three 500K disk units operates under a multi-programming,

* DEC—Digital Equipment Corporation
* EAI—Electronics Associates Inc.
* AD—Applied Dynamics

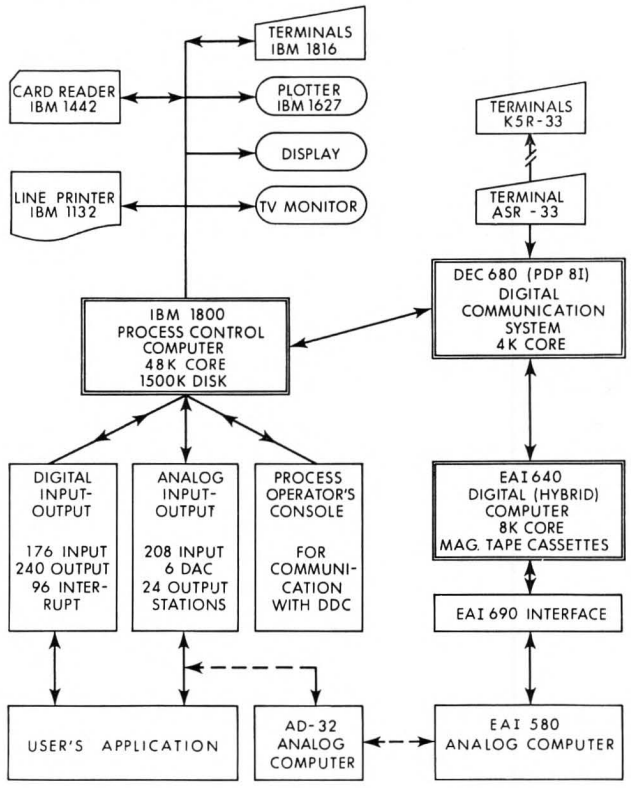
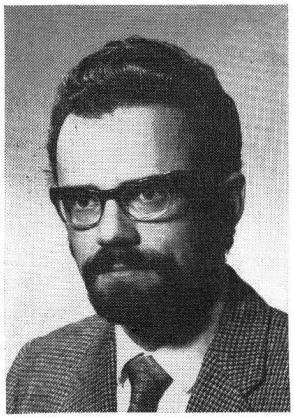


Fig. 1. DACS Centre computing hardware.



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time-sharing monitor and forms the heart of the system. The conventional data processing peripherals are shown at the top of Figure 1 and include a card reader/punch, a line printer, a digital plotter, typewritter units and provision for linkage to the University's IBM 360/67 computer. These facilities, under the control of the "non-process" operating system, comprise a conventional digital computer such as would be found in any small data processing centre. It has the ability, for example, to compile and execute FORTRAN programs.

The principal features that distinguish a real-time computer from a data processing unnit are:

- process input/output (I/O) equipment;
- real-time clocks; and a
- priority interrupt system.

As an oversimplification, the process I/O equipment shown at the bottom of Figure 1 permits the digital computer to gather, or send, information directly to a process or experimental installation in a manner analogous to use of a card reader or line printer. For example, thermocouples can be connected directly to the computer. Under program control the particular thermocouple of interest is "addressed" (i.e., connected to the computer by closing the appropriate multiplexer switch) and the voltage is amplified, sent to the analog-to-digital converter (ADC) and the equivalent digital value is stored in core. Once in core the value is fumnctionally indistinguishable from data obtained from more familiar sources, such as punched cards, and can be processed further by other computer programs. Digital values, generated by a user's computer program, can also be converted into an equivalent analog voltage, by using digital-to-analog (DAC) converters, and sent directly to conventional process instruments such as control valves. Digital input/output hardware can be used for opening or closing electrical switches and for connecting to other digital instruments. In general, through the provision of proper interface equipment, any electrical instrument or device can be read or actuated under control of statements in the user's computer program. Thus the user can use the computer to acquire any desired information from his equipment and/or to "automate" it by sending control instructions from the digital computer. However, the speed, data handling capability and computing power of the computer make it possible to go beyond mere "automation" and untake applications that are impossible by conventional means.

The second distinguishing feature, real-time clocks and timers, permits the user to have his program executed once, at a specific time of day, or repeatedly, at any specified interval. For example, our basic Direct Digital Control (DDC) program is executed every second and can also be used to acquire a series of data points from an experiment.

Hardware "interrupt" capability means that when a process event occurs, to which the user has assigned a higher priority than the program the computer is currently executing, the computer will transfer control to a program associated with the new event. When the high priority program is finished the computer returns to where it left off in the original job. Thus jobs are processed in the order of importance rather than the order received and the computer switches back and forth from one program to another in order to make efficient use (overlap operations) of different parts of the computer system. To the user it often appears that the computer is handling several jobs simultaneously.

In our experience five full time people are required to support the activities of the DACS Centre: three to maintain (and make the inevitable changes and additions to) the basic system and two to maintain the application program library and assist users.

TERMINAL SYSTEM

In a real-time application the computer must go to the user and not vice-versa. In our department, potential applications are scattered over all eight floors of the building and it is necessary that users be able to operate from these "remote" locations and not have to come to the main centre. Fortunately connections to the process I/O section of the computer are easily made by use of suitable shielded cable. Communications with the research personnel are handled through a DEC 680 communications system which permits up to 64 standard teletype units to be used at any one time (only six are in service at the moment).

The user has access to these terminals through standard FORTRAN statements and the system programs permit the user to enter information, at any time, through the keyboard of these termi-

nals and have it routed to the appropriate system program (e.g. DDC) or to a file for later use. The ability to "queue" (initiate execution of) a program from any terminal and to change parameters in system programs, such as DDC, gives the user the necessary flexibility and control.

HYBRID COMPUTING SYSTEM

Both the EAI580 and the AD32PB analog computers are connected to the IBM1800 and are used to simulate processes for student labs and studies of direct digital control. This mode of operation is extremely convenient for developing and debugging control programs since all that is required to switch from control of the analog simulation, to control of the real process, is a change of input/output addresses and time scale.

The EAI590 hybrid computing system consists of the 580 analog computer, an EAI640 digital computer plus an interface and complete set of EAI system and hybrid computing support programs. The digital computer has 8K of core memory, high speed paper tape reader and punch, a cassette magnetic tape system, a KSR35 teletype and a data set for communication with the DEC680 and IBM1800. Although it will not operate in a time-sharing mode the EAI640 provides an independent system for single use applications in addition to its primary purpose of hybrid computation.

DACS CENTRE BUDGET

The IBM 1800 system is rented for approximately $8,000 per month but the DEC 680 communication system and the EAI 590 hybrid computing system were purchased. The equivalent capital costs are shown in Table 1.

TABLE 1
APPROXIMATE CAPITAL COSTS

IBM 1800	$325,000
DEC 680	30,000
EAI 590	135,000*

*Includes a grant of $37,000 from the National Research Council.

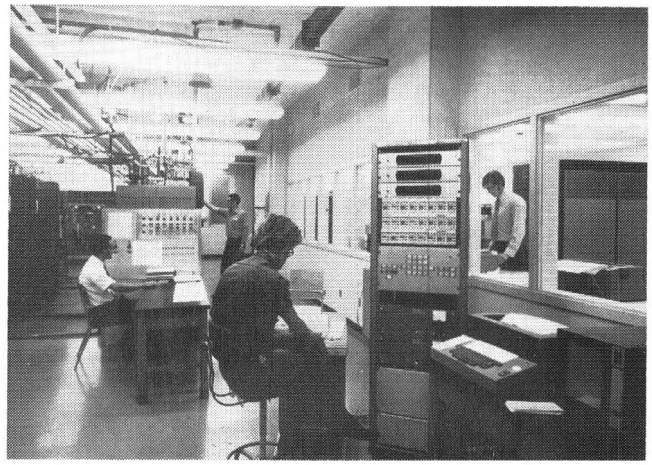
The annual operating costs of the Centre, including salaries of DACS Centre staff, is about $45,000. Thus the total cost of operating these facilities is quite high. It is justified about 50% by research and graduate student projects, 40% by undergraduate education and 10% by service functions.

EDUCATION

If any computer system is to be used effectively by relatively large numbers of people who are not computer specialists then the hardware must be readily accessible and the system software must be extensive enough that the user can concentrate on his application and not be distracted by the "mechanics" of using the computer. In our DACS Centre it was therefore decided that rather than allocating the system among users by "time-slicing" or by giving each user a "virtual computer," and leaving all the application programming to him, the DACS Centre would develop monitor programs to perform the most common data acquisition, control and service functions. The success of this approach has been demonstrated by experience.

Other than the instruction in computers and computing techniques which comes from "hands-on use," the most extensive educational application of the DACS Centre has been in the seven graduate courses in process dynamics and control offered by the department. The use of computing facilities differs from one course to another but can be divided into:

- Assistance with system design and analysis,
- Implementation of control techniques, and
- Demonstration of system structure and interaction.



COMPUTER CONTROL. The pilot-plant scale evaporator shown on the left is operated under control of the IBM 1800 digital computer visible on the right. The process operators console in the foreground is used to display results and/or to enter changes in process operating conditions.

DESIGN AND ANALYSIS

In keeping with the policy of providing generalized programs which assist the user in handling common problems the department has developed two digital simulation programs, CSAP[14] and CSDAP,[15] which in addition to calculating the time domain response can also convert the clas-

sical block diagram and (Laplace) transfer function definition of a control system into an equivalent state-space (matrix) representation and provide design aids such as Bode, Nyquist, root locus plots, estimates of suitable controller constants, performance criteria such as sum of the absolute errors, etc. Both programs are "conversational" in operation and can display output on typewriters, display scopes, TV monitors and/or the digital plotter. Thus the user can define his own problem, apply different design and/or analysis techniques and then evaluate his result by analog, digital, hybrid or physical implementation. The opportunity to formulate one's own problem, the immediate feedback of results and the direct comparison of alternative methods are all powerful educational advantages.

We have also noted in a course dealing with optimization methods that a good program library and rapid turn around of computer jobs makes it possible for a class to get first hand experience on the relative advantages and pitfalls of different techniques.

As a generalization one could conclude that proper use of computers can reduce the extent to which students are distracted by the detail, or mechanics, of the method and provide him with the results quickly enough that he can relate them to his original selection or design decision. For example, calculation of "optimal" controller constants or operating conditions can be done while an experiment is in progress and applied immediately. (Improper use of computers can add to the "distracting detail" and/or turn design into a series of black box manipulations.)

LABORATORY IMPLEMENTATION

Computer control is demonstrated on specially constructed "trainers" or on pilot plant processes. These units can be operated with conventional industrial instruments and/or under computer supervisory, or direct digital control. The principal educational advantage of the computer is that the control configurations, the control modes and the control constants are all implemented by computer programs and are easily changed by the student. Thus instead of "cookbook" procedures to make the lab equipment do what it was designed to do the student has relatively unlimited opportunity to innovate and apply knowledge learned in the courses. (In some cases it has been observed that students are bewildered by the large choice of alternatives and would rather have a "cookbook" assignment!) The data acquisition and control monitor programs are powerful enough that students do not have to do any programming to implement data acquisition, limit checking, input data processing such as square root calculations or digital filtering, standard proportional-integral-derivative or nonlinear control algorithms, cascade control, etc. Service programs are also available to plot or list the experimental data.

In many cases, analog or hybrid simulation is extremely effective. The student can program the analog computer to solve the mathematical model he has developed based on a theoretical analysis or experimental testing. The same digital computer control programs and techniques as used on the physical experiment can then be used to control the simulated process and the results compared. This permits a very direct evaluation of the suitability of the model, the need for experimental tuning of parameters and the significance of physical assumptions. It also illustrates directly the relationship between terms in the model and components of the physical system. The convenience of hybrid computing can also be used to screen a number of alternatives so that only the most promising need be implemented on the physical system and the student can get more benefit out of his limited lab time.

SYSTEM STRUCTURE

Another advantage claimed for computer assisted instruction is that it allows the user to "see the forest in spite of the trees." That is, when each step in the design and analysis procedure is computerized the student, even though he might have some doubts about "how" some steps are implemented, he can learn "what" each step does and see its relation to the overall procedure. Thus he can experiment with, and evaluate, "system design techniques"—something which is generally too time consuming to do by hand. With proper design of the course material the various examples and assignments done throughout the term can be combined at the end of the term into an effective demonstration of the total design process and a review of the individual steps.

Many of the points brought out in the section on research applications also apply to student labs. Other practical points with respect to students labs are that the amount of "busy work" (i.e. data processing) can be reduced; it is more difficult for the student to "fake" data; and since the computer will not usually accept "vague" instructions his understanding of the application is well documented by the computer log. (We have noticed, however, that many students are very reluctant to try new options for fear of making errors and careful guidance must be given so they can learn without being embarrassed by their mistakes.)

CONTINUING EDUCATION

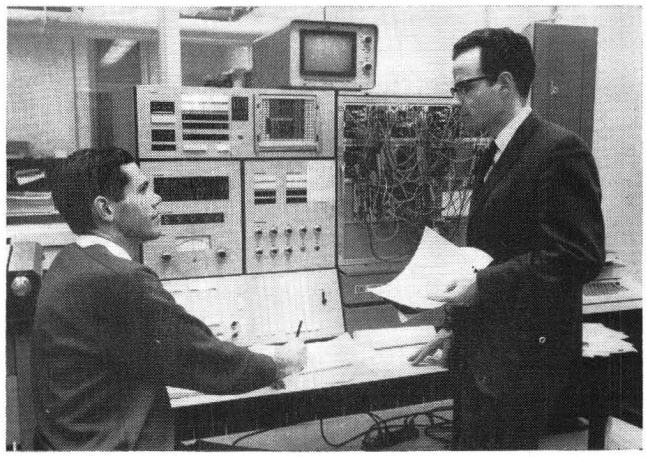
Finally, it is worthwhile to consider use of real-time computer systems in the areas of continuing education for engineers, demonstration of advanced techniques of interest to industry and as a basis for cooperative industry-university programs. Our Department has co-sponsored, e.g., with the Federal Department of Industry, seminars on computer applications, presented workshops and tours in conjunction with national meetings of technical societies and offered extension courses in the evening for the benefit of local engineers. These activities can be regarded as "public relations' or "professional service" but in many universities they are beginning to be regarded as an important basic function.

RESEARCH

It is impossible to deal with individual research projects in detail because most of them would require separate reports to adequately describe the work. However, it is possible to generalize about the types of research applications and some of the principal benefits of using real-time computers. Real-time computer applications within our Department can be categorized as:

1. Research projects in which the computer is an essential part;
2. Research projects which use the computer as an effective tool to assist with applications that could be, or were, run without a computer;
3. Research and development of computer hardware and software systems; and
4. Hybrid computation and digital simulation.

Most of the process dynamics and control studies fall into the first category. The computer has been used to succesfully implement multiloop[4], feedforward[4,5,6], inferential[4,5], multivariable-optimal-regulatory[7], optimal state-driving[8], non-interacting, and adaptive control techniques on the pilot plant equipment. Other studies include computer implemented process identification of pilot plant units with on-line display of results[9,10]; computer control of a nine inch, eight tray distillation column[11]; real-time checking and adjustment of process data so it is consistent with material and energy balance constraints[12], and the design/analysis of control systems[13,14,15]. A more complete list of research projects making use of the DACS Centre is found in appendices C and F of reference (1). Most of these applications and parallel studies of parameter and process identification are simply not practical without a real-time computer. It is hoped that the results of these studies will help to bridge the gap between theoretical developments and the practical applications of interest to industry.



HYBRID SIMULATION. Fisher and Bob Newell discuss simulation of the evaporator on the EAI580 analog computer. Bob has derived a state variable model of the evaporator and is evaluating optimal, multi-variable control by using his digital computer programs to control the simulated model. The same programs are also used to control the pilot-plant unit.

Other research projects in chemical and petroleum engineering make use of the computer for data acquisition, process monitoring, logging, data reduction and experimental documentation. Kinetic studies[2] make use of a computer controlled PE 621 infrared spectrophotometer and use the computer for acquisition of data from gas chromatograph analysers and other process instruments.[19] The computer is also used to monitor operation of an evaporator pilot plant so that it can be run 24 hr/day without any operator supervision.

Projects in category (3) are concerned primarily with application programs rather than

developing alternatives to the computer manufacturer's operating systems. Typical examples include the CSAP and CSDAP simulation programs mentioned earlier, and a generalized monitor system to supervise the execution of series of discrete events such as are found in plant start-ups and shutdowns, batch operations and system checkout. In general, these projects require a considerable degree of familiarity with the computer system as well as the application area and usually take longer than more "typical" thesis projects.

Hybrid computing is an area that has been widely reported in the literature. The interests of our Department are not to work extensively on the development of purely hybrid techniques or to get involved in that class of problems that are only practical if solved by hybrid techniques. Rather, the interests are directed toward student education and assisting research in other areas.

Specific advantages of the use of real-time computers include:

1. Increased quantity of research data due to faster operation or extended periods of operation. Some of our M.Sc. thesis projects now involve several times the amount of experimental data collected in earlier Ph.D. studies.
2. Increased quality, precision and reproductibility of data due to precisely implemented procedures, replicated runs, automatic recalibration, continuous monitoring of data during each experiment and elimination of random human errors and bias between different operators.
3. Broader experimental studies because the incremental effort required to extend the data acquisition and/or processing is often minimal.
4. Cooperation between different people because the computer acts as a standard "interface" so the experimentalist can implement the work of the theoretician and the data processing specialist can work with "real" data. Projects tend to become more interdisciplinary.
5. More continuity and carryover from one research student to the next because of computerized procedures.
6. Precise documentation (the program itself!) and standardized, tested, and approved methods for data reduction, presentation and interchange between groups.
7. Reduction of "busy work" and more challenge to the researcher to critically examine and improve both his techniques and his results. (From a student point of view the use of a computer makes many traditional areas of research more attractive as thesis projects.)
8. Permits design or evolution of projects int oareas that are not possible without a computer due to the speed of operation, the degree of control required or the amount of data that must be processed.
9. Computer facilities represent a much more "flexible" investment for the research dollar than special purpose instruments such as multi-channel recorders, etc. They can be pooled for large applications or reallocated to meet changing needs of smaller projects.

One tends to gloss over a long list of points such as those listed above but I am convinced that in many engineering research and development projects—particularly "mission-oriented" ones involving experimental work—it will become a question of computerize or get out. One clear cut example of this in the science field is an X-ray crystallography (18).

CONCLUSIONS

Real-time computing can make an important contribution to university education and research. Also as industry solves the practical problems and personnel training requirements associated with the installation of its first real time computers there is an increasing interest in areas such as "modern control theory," "information processing" and "systems engineering." In the future the emphasis will change, even more, from "automation" of existing procedures and processes, to developments which integrate computers into all phases of the research-development-production-management system. Thus there is an expanding opportunity for universities to "bridge the gap" and contribute more directly to the needs of industry and society.

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A Facility For

EDUCATION IN REAL-TIME COMPUTING

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OBJECTIVES

IN THE FALL OF 1968 it was decided to establish a facility for graduate and undergraduate education in real-time computing at the College of Engineering of The University of Oklahoma. This facility was to provide i) on-line data acquisition and processing capabilities for the undergraduate engineering laboratories; ii) "hands-on" experience in operation of real-time computers; iii) experience in hardware and software design for graduate and advanced undergraduate students; and iv) a facility for the rapid synthesis and check-out of complex digital logic circuits.

CONSTRAINTS

THE ENTIRE SYSTEM had to be purchased with $35,000 available as a one-shot investment from College of Engineering funds, plus whatever funding could be obtained from outside agencies. After the initial purchase, only limited funds—around $500 per year—would be available for system operation and maintenance. Thus, the computer system would have to be **reliable** and **easily maintainable** with local faculty and student effort. Also, since only a limited number of peripheral interfaces could be purchased, the system had to be **easy to interface**; then the bare-bones peripheral equipment could be purchased and interfaces built as student projects. Finally, the system had to have adequate **core memory** to support a minimal two-user **time-shared** monitor for on-line use in undergraduate laboratories.

EQUIPMENT

CONSIDERING THE ECONOMIC and performance constraints, we decided to purchase a Digital Equipment Corporation PDP-9/L computer with a basis cycle time of 1.5μsec, 8K of 18-bit word memory, and ASR-33 teletype input/output. In addition we bought as factory-installed options a 12-bit analog-to-digital (A/D) converter, capable of multiplexing up to 64 channels of analog data with 4 channels implemented, since we considered our experience to that point inadequate to construct these interfaces locally.

Through an NSF Instructional Scientific Equipment Grant[1] we obtained $17,500 to obtain additional peripheral equipment, including:

i) A DEC Multiple Teletype Interface with KSR-33 teletype;