Award Lecture . . .

PROCESS CONTROL

— *From the Classical to the Postmodern Era* —

Professor Thomas F. Edgar presented this, the Thirty-Fourth Annual Union Carbide Lecture Award of the Chemical Engineering Division of ASEE at its annual meeting in June of 1996. The purpose of the award is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice.

Professor Edgar is the George T. and Gladys H. Abell Chair in Chemical Engineering at the University of Texas, Austin. He received his BS in chemical engineering from the University of Kansas and his PhD from Princeton University.

For the past twenty-five years, Professor Edgar has concentrated his academic work in process modeling, control, and optimization. He has published over 200 articles and book chapters in the above fields applied to separations, chemical reactors, coal combustion and gasification, and microelectronics manufacturing. He has supervised the thesis research of over 41 MS and 43 PhD students.

In the field of process control, Professor Edgar's work has focused on multivariable control and adaptive control. He has made important contributions to the modeling and control of linear and nonlinear systems and pioneered the use of nonlinear programming in controller design and data reconciliation, based on the combined use of collocation and optimization. This eventually led to experimental demonstrations of new model-predictive control algorithms on a commercial-scale packed-bed distillation column and rapid thermal processing in microelectronics manufacturing.

Professor Edgar has served in many national professional capacities over the years and is presently President of AIChE. He was founding general editor of the technical journal, *In Situ,* and has participated on six editorial boards and five university advisory committees. He has coauthored several textbooks, one of which, *Process Dynamics and Control* received the 1990 ASEE Meriam-Wiley Award as the top engineering textbook.

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Perhaps the most significant technological change during the last forty years has been the development of digital computers. Staggering improvements have occurred in computer speed and efficiency since computers were first commercialized in this century. They have evolved from large mainframe machines consulted only by scientific or engineering specialists to desktop microcomputers employed by a wide cross-section of the population. In fact, computing is now imbedded in many household devices and automobiles; today's video camera contains more computing power than the IBM 360 computer did forty years ago. The computer also performs an active role in management and operation without human intervention, also called "computer control." There are an estimated ten billion microprocessors and microcontrollers currently in the world—and that number is rapidly growing. Indeed, the industrial society has now become an information society where computers influence every facet of life and are the basis for economic well-being, as envisioned by John Naisbitt in *Megatrends.*[1]

Process control generally refers to the application of the principles of automatic control to industrial processes, spanning areas such as chemicals, refining, pulp and paper, metals, and microelectronics manufacturing. If one examines the evolution of process control since the third century B.C. to the present, some interesting parallels between important periods of world history and developments in process control can be noted. Table 1 lists the major epochs in this field, along with approximate dates.

The "Ancient History" of process control spans over 2000 years' use of automatic control and ends with the development and application of so-called classical control theory (the "Classical Era"). After a period of retrenchment in the 1970s (the "Dark and Middle Ages" of process control), a revival of interest occurred, spurred on by the digital revolution of the late 1970s and its application to process control. The digital revolution is somewhat analogous to the Industrial Revolution in the 1700s. This led to new-found optimism (the "Renaissance") on how R&D results in industry and academia could be translated into commercial success. While much progress in this area has been made in the past fifteen years, future improvements are limited by a lack of understanding of the behavior of industrial plants. In the "Postmodern Era," the ability to perform mathematical modeling in the context of process control (model-based control) will determine the ultimate success of this new paradigm of automation. Advances in information technology will also facilitate the merging of software for process management, process operations/design, and process control into extremely powerful, coordinated tools.

Ancient and Classical Eras

The principle of feedback served as the basis for many primitive feedback control systems (see Figure 1). In ancient times (third century, B.C.), mechanical controls were used to regulate such things as oil lamp flow, water clocks, and the water level in a reservoir by adjusting the inflow until the desired liquid level was reached.[3] The same concept was employed in the water tank of the modern flush toilet, purportedly invented by Thomas Crapper during England's Victorian era.

In the late 1700s, about the time of the Industrial Revolution, there was a great deal of interest in controlling the speed of a rotating shaft in a machine. James Watt adapted some early ideas for controlling the speed of a grinding stone in a flour mill to develop the fly-ball governor for the Watt steam engine. The vertical position of balls in a cone measured the speed of rotation and mechanical levers adjusted the steam supply to the engine to increase or decrease the speed, using a version of proportional-integral control. As an historical note, to protest the mechanization of factories in England in the early 1800s, the Luddites actually destroyed many factories because of their belief that automation would eliminate many jobs.[2] The term "Luddites" is popularly used today to disparage people opposed to technological progress and to increased computerization of our society.

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TABLE 1
Major Epochs in Process Control

Ancient History	B.C. - 1920s
Classical Era	1920s - 1960s
Dark and Middle Ages	1970s
Industrial (Digital Revolution)	1980s - 1990s
Renaissance	1980s - 1990s
Postmodern Era	1990s - 2000s

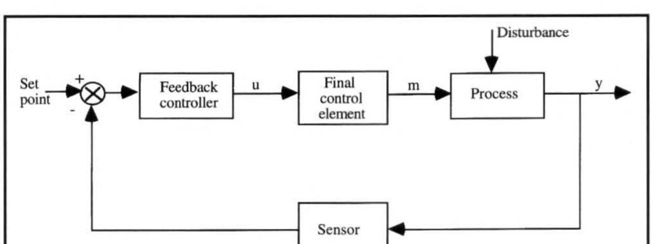

Figure 1. *Block diagram showing the principle of feedback and components of a feedback loop (u=controller output; m=manipulated variable; y=controlled variable).*

A theoretical understanding of feedback control came long after practical applications were introduced. The analysis of feedback controllers and the occurrence of instability arising from an improperly designed system aroused some academic interest in the late 1800s. But the main influence shaping feedback control theory was the work at Bell Laboratories on developing electronic amplifiers for long-distance telephoning in the 1920s.[3] The invention of the electronic feedback amplifier in 1927 solved the noise and distortion problems arising from successive re-amplification of the voice signal. A single-stage amplification was unsatisfactory, as anyone who has turned up the gain of a public address system discovers. The proportional-integral-derivative (PID) feedback controller gave a high-fidelity amplified signal

$$u(t) = K_c \left[e(t) + \frac{1}{\tau_I} \int_0^t e(t')dt' + \tau_D \frac{de}{dt} \right] \tag{1}$$

where e(t) is the error between the set point and the measured variable, u(t) is the controller output, K_c is the controller gain, τ_I the integral time, and τ_D the derivative time.

During the past fifty years, the PID controller has been the foundation for the practice of classical control. An important design question is how to "tune" the controller, *i.e.*, to select the values of K_c, τ_I, and τ_D that give satisfactory performance. This question has received considerable attention by both theoreticians and practitioners for the past seventy years.

Black and Bode of Bell Laboratories were the principal developers of the frequency response method for PID controller design during the 1920s and 1930s.[3] Pneumatic rather than electronic controllers based on Eq. (1) were introduced in the 1940s in chemical plants, since most of the instruments and control valves used air signals for their operation. Both types of analog controllers were adequate for many industrial applications, but they are in limited use today in most modern chemical plants.

Improved guidance and control of aircraft provided the next major transition in the evolution of control theory and practice. After World War II, primitive digital computers were needed to control airplanes and guided missiles rather than the analog or pneumatic device. The launchings of artificial earth satellites, beginning with Sputnik in 1957, were controlled by detailed analysis of differential equations that were used to model the space flight and landing of such vehicles.

During the 1950s and 1960s, optimization theory and stability analysis received new emphasis. The competition between the U.S. and U.S.S.R. for leadership in space brought control scientists and engineers to the forefront, involving such luminaries as Pontryagin and Lyapunov from the U.S.S.R., who helped develop the "maximum" principle. The U.S. scientists, not to be outdone, formulated the "minimum" principle, which merely involved a change in sign. This viewpoint was a departure from the earlier frequency-response approach because of its emphasis on the use of time domain analysis via differential equations. This approach was called "modern" control theory and provided a more sophisticated alternative to the "classical" control theory.

One of the key results from modern (or optimal) control theory was the Linear-Quadratic-Gaussian (LQG) control problem, the solution of which gave a multivariable feedback controller and a connection to classical control ideas. During the 1960s and 1970s, the modern and classical control camps continued to argue about the superiority of one approach over the other.

Dark and Middle Ages

The development of modern control theory was led in most part by aerospace engineers, electrical engineers, and applied mathematicians. While these control scientists felt that their new theories could be applied to any process, the chemical process industries and the field of chemical process control maintained a separate identity. Part of the reason for this was that chemical reactors and distillation columns were difficult to model using chemical engineering fundamentals, in contrast to the fairly accurate models that could be developed for communications networks and aerospace systems.

Another factor was the economic pressure felt by the process industries. Any move to use modern control theory in chemical plants required implementation by digital computers; improvements in product quality or throughput and the resulting increased profitability needed to be large enough to justify the capital expenditure, typically over one million dollars in the 1960s.

The first process control computer was constructed by Ramo-Wooldridge in 1957. Early tests using Direct Digital Control (DDC) were carried out in the Gulf Coast region by Texaco and Monsanto, but their results did not achieve the benefits suggested by the aerospace success.[4] The chemical industry resisted changing from reliable PID controllers, which worked well enough, were not terribly expensive, and were easy to understand. Why trade them for extremely expensive systems that were unreliable and required extensive research and development as well as highly trained personnel* for implementation?

The aerospace experience was not portable to the process industry for two reasons. First, in the case of satellites, large sums of government funds could be used to achieve success regardless of the economics, enabling very complicated control strategies to be implemented. Second, the aircraft industry had the advantage of being able to replicate successfully developed control systems on, for example, a thousand helicopters. But equipment such as chemical reactors and separations systems exhibit unique features from plant to plant, and while units are generically similar, they process different chemicals and have other idiosyncrasies. Development of accurate mathematical models for a given process could require extensive research. In addition, due to proprietary or competitive reasons, companies do not willingly share information on control systems or operating strategies. Because modern control theory generated controllers whose performance was quite sensitive to model inaccuracies, it was not a practical approach.

While there were a few plant installations that used advanced strategies such as feedforward control during the 1960s, it was clear that a significant gap between theory (mostly led by academicians) and industrial practice existed during the 1960s and 1970s. There was very little cooperation between the two groups. Industry used maxims such as "you can get 80% of the profit with 20% of the effort" and "what can go wrong will go wrong" (Murphy's feedback law). Once a plant was making a satisfactory product, any efforts to change the plant or to optimize the operating conditions were opposed. There was also a lack of funds and pilot facilities to test new ideas, so no hard evidence was developed to demonstrate the value of the new ideas (*i.e.*, which theories would be useful). One paper written by an industrial practitioner summed up a popular 1975 view: "The author has been reading the chemical process control literature for over 25 years, and in his opinion, the vast majority of papers contained little or no material useful in the daily practice of control engineering."

In defense of industry's viewpoint, successful implementation of control concepts was very difficult and required skills other than theoretical developments. It appears that very few practitioners in the control field were interested in or capable of working over a wide spectrum of theory and applications. One of the main criticisms of modern control theoreticians was that they made incorrect assumptions that did not reflect process realities. A lack of communication between theoreticians and the applications engineers was largely responsible for the so-called "gap" between theory

**Some cynics suggested that these control loops were PHD rather than PID.*

and practice. Applications engineers did not usually have the background, orientation, or interest to make the necessary mathematical extensions and to customize the theory for the problem to be solved. In a sense, process control researchers failed in their task to communicate important results that could be used in applications because they did not pose problems in an industrial context. Instead, they focused on problems such as the "linear absorber" and the famous industrial reaction $A \rightarrow B$.

Digital Revolution

Computers available in the 1960s typically cost over $1 million, had storage capacity of 32k, and were fairly unreliable in terms of component failure. Development of the microcomputer and the hundredfold increase in computer speed each decade ultimately caused a revolution in the practice of process control. The reductions in hardware cost of process control computers has been a significant incentive for implementing computer control and advanced control techniques, while the emergence of standard software packages and architecture has also facilitated applications in process control.

Early digital installations used for process control were not failure-proof and required a totally redundant system in case of component failure. In most cases, the backup system was the analog (pneumatic) system used before the introduction of computer control, which involved extra costs. Reliability improvements during the 1980s permitted use of digital redundancy. While there are still analog control systems in use today in chemical plants, no vendors are selling analog systems in today's market.

An important hardware development pioneered during the 1970s by Honeywell was the distributed computer process control system (DCS) (see Figure 2). It is still dominant in the process industry and employs a hierarchy of computers, with a single microcomputer controlling 8 to 16 individual control loops.[5] More detailed calculations are performed using workstations that receive information from the lower-

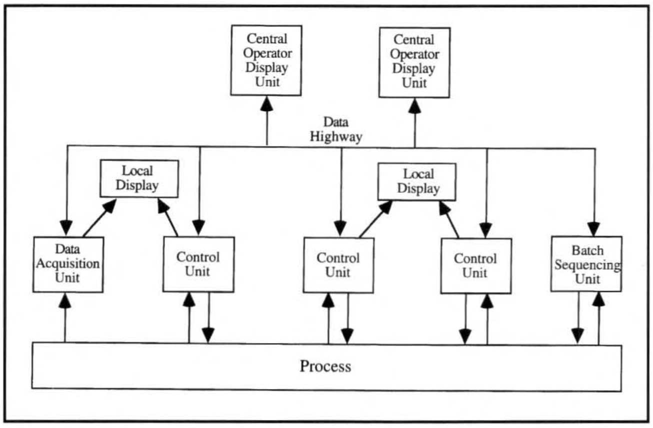

Figure 2. *A distributed digital instrumentation and control system.[5]*

level devices. Set points are sent from the higher level to the lower level. The advantages of this configuration are

- *Software can be located where calculations need to be made (computer limitations are usually not a problem)*
- *The system can be modularly designed, and failure at any one point in the network is not disastrous.*
- *The hierarchical design is compatible with different supervisory and regulatory functions and the need for database accessibility.*

Economic computer control allowed industry to address the issues of 1) increased profitability via control, and 2) environmental constraints and safety. Increased profitability in a plant via process control can be achieved by increased product throughput, increased yield of high-value products, decreased raw material costs, decreased energy consumption, extended equipment life, reduced plant shutdowns, and decreased production labor. A 1988 study by E.I. duPont de Nemours estimated that increased profits of $200 to $500 million dollars/year could be realized in their facilities through implementation of advanced control and optimizing operating conditions.

During the 1970s, steady-state optimization packages such as linear programming were used to determine set points in many refineries and chemical plants (supervisory control), and the increased profits were often used to justify the purchase of computer control systems. The quantum jump in oil and gas prices in the mid 1970s and early 1980s was another incentive for supervisory control (setpoint optimization). Chemical companies and refineries became heavily involved in energy conservation and energy management, often using optimization tools to reduce energy costs.

The effect of global competition on the chemical process industry caused a heightened awareness of the importance of product quality in affecting profitability. Process control began to be employed to ensure satisfactory product quality, and the subject of statistical process control was introduced as mandatory continuing education for process engineers.[6]

Because past hazardous waste disposal practices created a number of pressing environmental problems, the trend of increasingly more stringent environmental regulations began in this period. Chemical companies changed design and operating strategies (via process control) to minimize waste production because of the prohibition against discharge and/or disposal of toxic substances. New plants moved toward a "zero-discharge" concept, and protecting the safety of operating personnel took on heightened emphasis after the Three-Mile Island and Bhopal incidents. As plants grew more complex in terms of operations, interacting processes, and control loops, the use of computers to assist human operators became desirable. Computer-based expert systems, developed using artificial intelligence techniques, began to be employed for rapid decision making.

The increased sophistication of plant operations led to the concept of computer-integrated manufacturing (CIM), which is defined as a unified network of computer hardware and software systems that combines the business and process functions (such as administration, economic analysis, scheduling, design, control, operations, etc.). The system provides general access to a common data base and produces reports for managers, engineers, and operations so that optimum decisions can be made and executed in a timely and efficient manner. CIM is now recognized as an important tool for improving the competitiveness of the U.S. process industry, but it is not yet implemented in a significant number of plants. Cooperation among computer vendors is required to develop a satisfactory computer/communication/software system. Recently, several process control vendors have announced a field-based architecture to replace the historic DCS centric hub scheme. The architecture is largely PC based and includes intelligent field devices and modular software.

Renaissance

The digital revolution spurred a rebirth in the process control field in the 1980s, both in theory and practice, highlighted by a new spirit of cooperation between academia and industry. A new generation of model-based control theory emerged that is tailored to the successful operation of modern plants and addressing the "difficult" process characteristics encountered in chemical plants shown in Table 2.

TABLE 2
Process Characteristics That Must Be Treated By Advanced Control

- ☐ Time delays
- ☐ Nonminimum phase
- ☐ Disturbances
- ☐ Unmeasured variables
- ☐ Noise
- ☐ Time-varying parameters
- ☐ Nonlinearities
- ☐ Constraints
- ☐ Multivariable interactions

These advanced algorithms include model predictive control, robust control, and adaptive control,[8,9] where a mathematical model is explicit in developing a control strategy. Model predictive control (MPC) uses the notion that one can intelligently select the current and future control actions if a model is available to predict the process dynamic behavior (see Figure 3). A robust controller recognizes that the process characteristics can change over time and is designed so that it always gives satisfactory performance regardless of the severity of such changes.

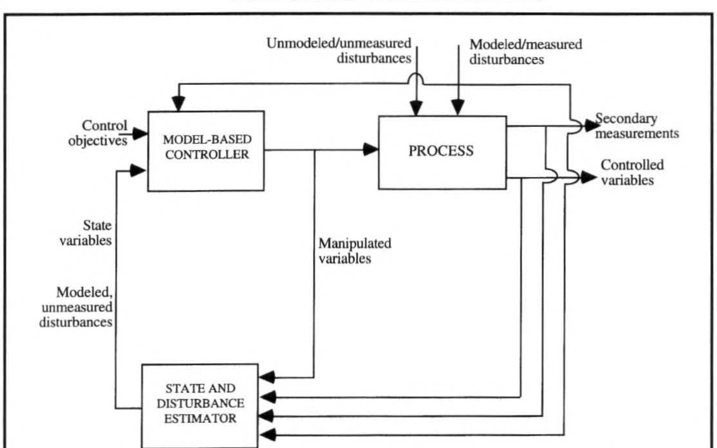

Figure 3. *Generalized block diagram for model predictive control.*

Adaptive control implies that the controller parameters should be adapted in real-time to yield optimal performance at all times; this is often done by comparing model predictions and on-line plant data and updating the process model parameters. Various model predictive controllers have become the most widely used type of multivariable control algorithm in chemical process industries. In MPC, control actions are obtained from on-line optimization (usually by solving a quadratic program, or QP), which handles process variable constraints. MPC also unifies treatment of load and setpoint changes via the use of disturbance models and the Kalman filter.

In contrast to the air of distrust and lack of cooperation between academia and industry during the 1970s, the process control community became quite active in forming research partnerships between academia and industry in the 1980s. At the present time, the largest research consortia in process modeling and control are at the University of Texas, University of Wisconsin, Lehigh University, University of Maryland, UC Santa Barbara, Purdue University, University of Tennessee, Texas Tech University, and MIT. When one also considers single-investigator projects supported by industry, it is likely that industrial support of process control research is comparable in scale to that provided by NSF (about $2.5 million), and the industrial percentage is growing due to such new NSF programs as GOALI.

Postmodern Era

The postmodern era of process control began around 1990. In today's vocabulary, the term "postmodern" has taken on a broader meaning than merely indicating a period of time; it is characterized by a multitude of voices and theories and a belief that there is no absolute truth but truth determined by the surrounding culture. A fragmentation of knowledge and authority results along with a decentralization of decision-making. While the ramifications of postmodernism are frequently debated in the arts and humanities, we have some similar phenomena occurring in science and engineering. There has been a proliferation of journals, proceedings, and papers, plus the advent of personal desktop publishing. The role of archival journals is changing as a greater premium is being placed on fast (electronic) publication of research results in a variety of science and engineering fields, reducing the dominance of peer-reviewed, selective journals.

Mathematical modeling as

applied today embodies a sort of post-modern philosophy. Many possible models may satisfactorily explain physical phenomena, and such models are at worst utilitarian (all models are wrong, but some are useful; it is much easier to prove a model is wrong than to prove it is right). One textbook example of matching models to data is Anscombe's quartet, where four data sets are all fitted by least squares to yield the simple algebraic model, $y = 3 + 0.5X$ (see Figure 4). More recently, the increased interest in artificial neural nets as an automatic modeling tool demonstrates the now-accepted relativism inherent in mathematical modeling.

The capability of using more sophisticated mathematical models in automation and control has grown during the past twenty years. Given the current state of the art in control and optimization theory, the major uncertainty in controller design is selection of the model and its level of detail and complexity. Once the model is actually chosen and verified, there are usually several methods available to compute a control strategy.

It is notable that industry has taken a leadership role in developing and implementing model predictive control methods with the involvement of companies such as Shell Oil, Texaco, ADERSA, Honeywell, Dot Products, Treiber Controls, Set Point, and DMC*.[9] The resulting proliferation of acronyms (see Table 3) is consistent with the "multitude of voices" attributed to the post-modern era.

There are still many questions to be answered regarding the connection between modeling and control. For example

- *What explicit modeling information is required to achieve a particular level of control performance?*
- *Even in the case of perfect models, what are the fundamental limitations on control performance?*
- *What are the trade-offs between modeling accuracy, control performance, and stability?*

Developing the answers to these questions is the subject of current research and curriculum changes.[10]

The success of MPC in solving large multivariable industrial control problems is impressive. Model predictive control of units with as many as ten inputs and ten outputs is already established in industrial practice. Computing power is not causing a critical bottleneck in process control, but larger MPC implementations and faster sample rates will probably accompany faster computing. Improved algorithms could easily have more impact than the improved hardware for the next several years. MPC will appear at the lowest level in the DCS, which will reduce the number of PID loops implemented. Nonlinear models and controllers are now employed in some applications.

Some of the new versions of MPC are incorporating model adaptation, but up to this time adaptive control has not had much impact. This is due to problems in keeping such loops operational, largely because of the sensitivity of multivariable adaptive controllers to model mismatch. On the other hand, there has been considerable success with adaptive PID controllers, which can be purchased for a small incremental cost over the standard non-adaptive PID controller from many instrument companies. Unfortunately, adaptive control algorithms are not readily available from DCS vendors.

In the factory of the future, the industrial environment where process control is carried out will be different than it is today. In fact, some forward-thinking companies believe that the operator in the factory of the future may need to be an engineer, as is the case in Europe. Because of greater

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* *Set Point and DMC were both recently acquired by AspenTech.*

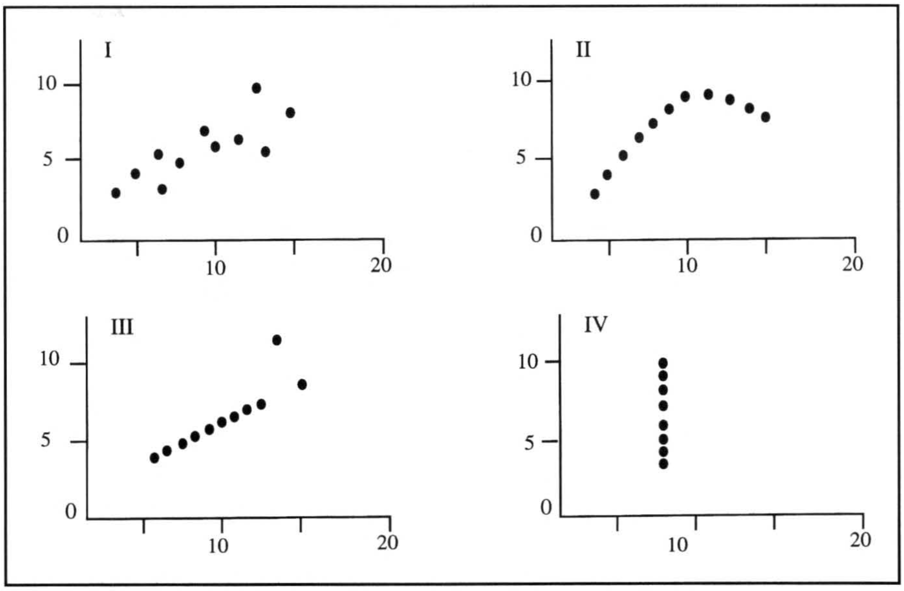

Figure 4. *A modeling paradox; Anscombe's Quartet ($y = 3 + 0.5X$).*

TABLE 3
Acronyms Used in Model Predictive Control

DMC	Dynamic Matrix Control
DMI	Dynamic Matrix Identification
GMC	Generic Model Control
IDCOM	Identification and Command
IMC	Internal Model Control
LDMC	DMC with Linear Programming
LQG	Linear-Quadratic-Gaussian
MPC	Model Predictive Control
NMPC	Nonlinear Model Predictive Control
QDMC	DMC with Quadratic Programming

Award Lecture: Process Control

Continued from page 17

integration of the plant equipment, tighter quality specifications, and more emphasis on maximum profitability while maintaining safe operating conditions, the importance of process control will increase. Very sophisticated computer-based tools will be at the disposal of plant personnel. Controllers will be self-tuning, operating conditions will be optimized frequently, fault detection algorithms will deal with abnormal events, total plant control will be implemented using a hierarchical (distributed) multivariable strategy, and expert systems will help the plant engineer make intelligent decisions (those he or she can be trusted to make). Plant data will be analyzed continuously, reconciled by using material and energy balances and nonlinear programming, and unmeasured variables will be reconstructed using parameter estimation techniques. Digital instrumentation will be more reliable, will be self-calibrating, and composition measurements which were heretofore not available will be measured on-line. There are many industrial plants that have already incorporated several of these ideas, but no plant has reached the highest level of sophistication over the total spectrum of control activities.

Figure 5 illustrates a possible hierarchical CIM structure that could be used in merging business optimization with plant and process operations and control.[11] Each layer will have different models and time scales and includes checking the model against data obtained by the computer systems. Recent announcements by software vendors indicate that the combination of process simulation, optimization, and control into one software package will be a near-term reality. Aspentech's acquisition of Dynamic Matrix Control

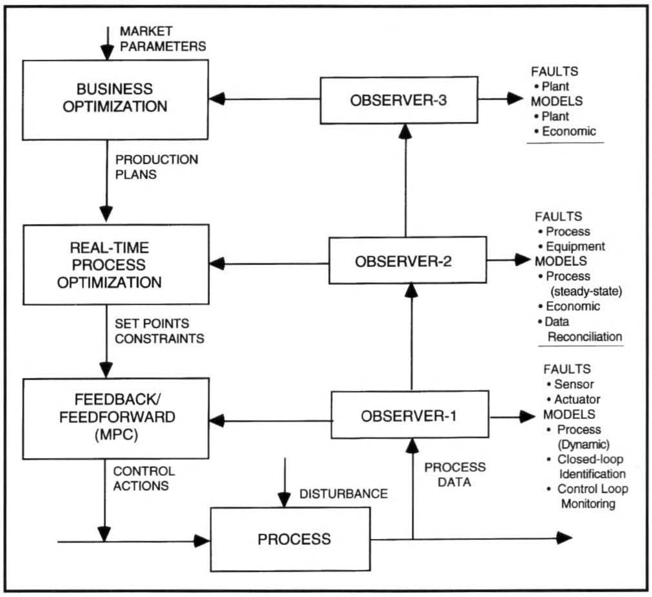

Figure 5. *Computer-integrated manufacturing: combining business and process operation using computer control (adapted from Stephanopoulos[11]).*

Corporation and Setpoint, Inc., represents a connection of off-line process engineering services to on-line control services. This would provide the ability to offer integrated technology with a set of consistent models across R&D, engineering, and production stages. An increased emphasis on rigorous dynamic models and the best control solutions will result from the acquisitions.

Similarly, Shell Oil Company and Simulation Sciences have signed an agreement to develop a new modeling software system called rigorous on-line modeling and equation-based optimization (ROMEO). Software users will be able to optimize plant-wide operations using real-time data and current economic objectives. The equation-based approach is expected to be faster than the sequential-modular (unit operation) methodology. "What if" real-time analysis and model-based soft sensors are also featured in ROMEO. The software can determine the location and cause of operating problems and provides a unified framework for data reconciliation and parameter estimation in real-time.

CONCLUSIONS

The rate of knowledge generation and demand for application of information technology will continue to grow exponentially well into the next century. Process control has become a relatively mature part of chemical engineering, but process control technology and the corresponding body of knowledge and applications are expected to continue their expansion. The Postmodern Era of process control promises to be an exciting one, merging process economics, design, operations, simulation, optimization, and control into a unified field of study.

How this will translate into the classroom is still unclear.[10] And what comes after the Postmodern Era?

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