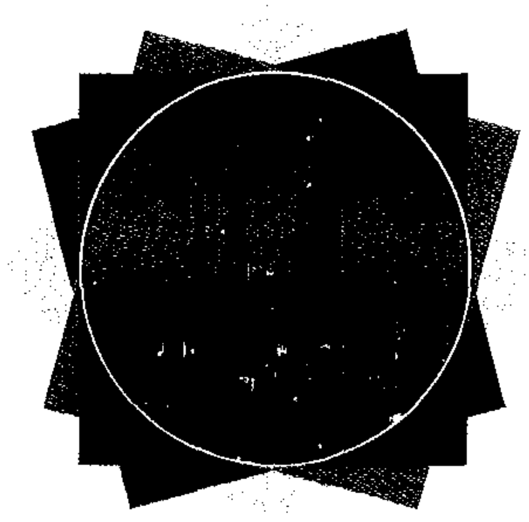

SPECIAL SECTION
Industrial Process Control

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By Michael J. Piovoso, Guest Editor

Process control has come a long way since the early 1900s. At the turn of the century, control was exercised primarily by process operators making manual adjustments. In the decades since, control theory and practice have evolved to the extent that, today, highly sophisticated control schemes make possible the efficient manufacture of a whole range of products. The three articles in this special section provide an introductory explanation of some of the technology that has made this evolution possible. Today's advanced controllers are model based, meaning that empirical models must be identified and formulated. The controllers incorporate and use these models to predict the future behavior of the system in what is called *model predictive control* (MPC). The first article addresses empirical modeling, the second is an introduction to MPC, and the third treats the special case in which a dynamic neural network model is the basis for prediction.

The second decade of the 20th century saw a rapid increase in the use of feedback regulation for boilers, electric motor speed control, steering of ships, and, for the process industries, temperature, pressure, and flow control. Elmer Sperry (1911) developed a controller for the steering of ships at sea. The controller was generated using intuition and by observing helmsmen, but it was essentially a proportional-integral-derivative (PID) controller, and it also had an automatic gain adjustment to account for changes in plant dynamics due to disturbances such as sea conditions. Another example is boiler control, which is multivariate in that both the water level and the steam pressure must be controlled. Nonetheless, the 1920s saw the introduction of control systems for boilers by several companies.

In 1922, Nicholas Minorsky (1885-1970) analyzed the stability of a controlled vehicle. In that work, he explicitly formulated the control law we now refer to as PID control. Minorsky also noted the way that helmsmen steered the ship and tried to capture that same behavior in his controller. At about the same time, Harold Black (1898-1983) noted that using negative feedback in a high-gain amplifier could reduce the signal distortion due to noise and component drift. This led to an improved understanding of the merits of negative feedback in controlling systems. Clesson E. Mason, a contemporary of Black's, developed a pneumatic version of the negative feedback amplifier. He used the negative feedback principle to linearize the highly nonlinear flapper valve amplifier (effec-

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tively an on-off device) invented by Edgar H. Bristol, founder of the Foxboro Company. This development simplified the incorporation of integral action into the controller. In 1931, Foxboro began to market the Stabilog pneumatic PI controller, which included linear amplification based on negative feedback.

In the 1940s, Hendrik Bode, who showed that there was a relationship between the characteristic gain and phase of a system, made a significant advance by introducing the concepts of phase and gain margins and gain-bandwidth limitation. During this period, manufacturers made significant improvements to pneumatic controllers. By 1940, the Taylor Instruments Fulscope and an upgraded Stabilog had field-adjustable PID controllers. In 1942, J.G. Ziegler and N.B. Nichols, who worked for Taylor Instruments, published an approach to tuning PID controllers that today is called the Ziegler-Nichols tuning rules. In the 1950s, Geraldine Coon, also of Taylor Instruments, extended the work of Ziegler and Nichols.

The Second World War brought a sense of urgency to the control community. The greatest need was for an automatic system to aim antiaircraft weapons. Mechanical, electrical, and electronics engineers joined together to work on this problem. The best features of the time-domain approach of the mechanical engineers and the frequency domain used by the electrical and electronics engineers were married to obtain a solution. At about the same time, George Brown and his students at MIT developed block diagrams that could be used to represent both mechanical and electrical systems. Albert Hall developed the transfer function using Laplace transforms, opening the way to a number of classical control system design approaches.

The modern control era began in the 1950s and was fueled by two developments: first, a recognition by governments of the need to guide and maneuver as well as track missiles and space vehicles; and second, the digital computer. The models for the ballistic objects were high-order, nonlinear differential equations. Engineers reformulated the differential equations into a set of coupled first-order equations leading to state-space models.

This modern period began with the work of Richard Bellman, who was with the Rand Corporation in the late 1940s and early 1950s. His research into the problem of allocating missiles to targets so as to inflict maximum damage led to his "principle of optimality" and to dynamic programming. In the late 1950s, Bellman worked on optimal control theory, seeking to formulate the problem in a way that dynamic programming might be used. This led to a formulation in which the optimization was viewed as a multistage decision process.

With the addition of constraints to the optimization problem, attention was refocused on the differential equations associated with the analysis and design of control systems. The optimization of a dynamical system subject to constraints was clearly related to the classical variational formulations of analytical mechanics due to Lagrange and Hamilton. Pontryagin (1956) developed his maximum principle, which proved to be the basis of optimal control theory.

By the late 1950s, several developments came out of the foundation provided by Bellman and Pontryagin. One of the most important of these was Kalman's work showing the connection between multivariate feedback control and multivariate filtering. Applying the design methodology called linear quadratic Gaussian control, he demonstrated that the states needed for an optimal control strategy could be estimated online using the so-called Kalman filter. His primary contribution was to tie the state estimation problem to state-space models. In doing so, Kalman introduced the concepts of observability and controllability of linear time-invariant systems. Kalman's contributions were among the most significant of the 20th century.

The 1970s were characterized by attempts to apply the ideas developed in the 1950s and 1960s to the chemical and process industries. Dale Seborg and others were very active in trying to promote these concepts. Several applications were demonstrated on experimental facilities at universities, but applications to manufacturing processes lagged. The obstacles were many, including the complexity of the algorithms, the computational requirements, and the uncertainty as to the robustness of the methods.

Around 1980, Charles Cutler and his colleagues at Shell Development Company successfully installed and demonstrated the capabilities of an optimal control strategy on a petrochemical facility. This MPC approach was based on an empirical model obtained by perturbing the process with a step change in the input. The time samples of the step response provided the model for doing prediction. This work was significant in that a methodology was formulated to apply optimal control concepts to industrial problems, and a major hurdle in gaining acceptance by the industrial community was cleared. The success of Cutler and others at Shell spurred a new wave of research in academia. From the 1980s until the mid-1990s, improvements were made in the model form and generation, use of constraints on both manipulated variables and controlled

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outputs, and making the solution more robust by guaranteeing stability. By the late 1990s, the technology had matured enough that several companies—Honeywell, Aspen Technologies, and others—were marketing products for implementing variations of the approach proposed by Cutler. Today, nearly all process industries apply MPC to their processes.

The 1980s also saw the growth of new technologies that were being harnessed for control purposes as well. There was renewed interest in neural networks for various types of application. They were particularly appealing because of their ability to capture nonlinearities. Work began on their application to process control, and several researchers demonstrated the utility of neural networks in controlling highly nonlinear systems. Some looked at the optimal control problem in the MPC framework, using a dynamic neural network for the model of the process. During the 1990s, neural networks found their way into commercial control applications, with Pavilion Technologies in Austin, Texas, being one of the leaders.

Rarely are first-principle models used for control. The models used in MPC are invariably empirical. Often, no first-principle model exists, and if one does, it generally involves nonlinear differential and algebraic equations with many parameters that must be estimated from process data. The parameter estimation problems can be more difficult than those of identifying the parameters of an empirical model. For most control applications, the benefit of using a first-principle model does not justify the problems associated with its generation and implementation. The proper identification of an empirical model for control is a critical element, however, in how well a control scheme will work. Work begun in the 1970s and continuing through the 1990s has resulted in a number of improved methodologies for the identification of models to be used for control.

The transition from theory to application for optimal control required the codevelopment of the computer. Almost from the first appearance of the computer, there was keen interest in applying the technology to the control of dynamic systems. Ragazzini, Franklin, and Zadeh all made major contributions in the 1950s. In 1960, TRW, an aerospace company, demonstrated the first successful use of a digital computer for process control on a polymerization unit at Texaco's Port Arthur plant in Texas. Besides cost, the early problems had to do with computer speed and reliability. With the early computers, addition and multiplication times were approximately 1 and 20 ms, respectively. The mean time between failures (MTBF) was on the order of 50-100 hours.

The development of the minicomputer in the mid-1960s marked a tremendous improvement in cost, speed, and reliability. Several companies began offering a process control computer. The typical word length was 8 or 16 bits, and it had 8-124K of RAM. An example is the CDC 1700, which had addition and multiplication times of 2 and 7 μs, respectively.

But it was the microcomputer, introduced in the mid-1970s, that had the greatest impact on process control. Prior to this, computer costs were in the $10,000-$100,000 range. By 1980, the cost was down to $500 for a computer with enough computing power and low-cost peripherals to do control. In addition, the reliability improved to the extent that one could consider using it in critical applications that had to run around the clock, and the speed was such that sophisticated control algorithms could be routinely applied.

Today, computers are no longer a barrier to implementing control strategies. Developments have been such that the theory of the 1950s through the 1990s is being routinely applied, and today MPC applications are commonplace. This special issue is devoted to demonstrating how the developments of the past 40 years have found their way into process control practice. It illustrates how much the state of the art has evolved over the past 100 years. It is this model-based technology that will be the steppingstone into the 21st century.

To identify the dynamic behavior of a plant, excitation inputs are required. Ideally, the excitations ought to be of minimum duration and amplitude so as to produce the smallest possible effect on the product. The first article, "An Integrated Identification and Control Design for Multivariable Process System Applications" by Rivera and Jun, discusses the design of such signals. It illustrates for the multiple-input, multiple-output case how a specific autoregressive with external input (ARX) model can serve for designing several different controller structures.

The second article, "Tutorial Overview of Model Predictive Control" by Rawlings, is excellent for gaining a basic understanding of MPC and provides a set of valuable references for those who wish more detail. The article covers the development of MPC for both linear and nonlinear models. For linear models, details are presented for computation of the steady-state target values, the infinite horizon and receding horizon regulation problems, and resolving any infeasibility that might exist.

The third article, "Nonlinear Model Predictive Control Using Neural Networks" by Piché, Sayyar-Rodsari, Johnson, and Gerules, covers the special case of MPC in which the dynamic model is a neural network. The practical aspects of model development are presented along with an application to an industrial polyethylene reactor and a simulated continuous stirred tank reactor.

In summary, I believe we have put together a collection of articles that cogently illustrate some of the progress in process control over the last 100 years. They are all well written and contain material that is relevant to the readership. I want to personally thank each of the authors for their contribution to *IEEE Control Systems Magazine*. I hope you enjoy the articles as much as I did.

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