Process Control: History

Process control is control technology as applied in the flowing process industries. These are the industries which manufacture homogeneous material products and services. The common industries in this category are oil, chemicals, electrical power, paper, mining and metals, cement, drugs, foods and beverages. A common characteristic of all of these industries is that their products can be made to flow. Thus, movement of these products can be carried out in pipes (or, at worst, heaped on conveyor belts) and controlled by valves or similarly simple devices. Generally the processing plants are large and controlled from a central location.

Processing plants are usually unique; thus the control strategies are unique. There is no vast design and servicing organization capable of maintaining a given plant as there is for mass-produced products like automobiles or even aircraft and military equipment. Thus, as a control discipline, process control is unique in that design production and servicing economies are achieved by selling the same control equipment for diverse applications, rather than by selling the same control application (e.g., automobile, aircraft) to diverse users. In such a situation the costs associated with the differences in application-the detailed control application design costs-loom large in determining the viability of the business. The incentives to generalize the hardware and the software are great but have to be balanced against the requirements of the application.

Because the processing technology is centered in fields remote from the measurement and control technology, a separate processing control manufacturing and servicing industry developed. The diversity of the processing industry eventually gave rise to a much smaller but equally diverse process control industry. There are process control companies based on the universal elements common to all process control, applying them to the special processing situations, and companies based on special processing industries or special services or elements of control. One understands the development of the process control industry in terms of the developments in the processing industries served, the economies of control design and implementation and the whole combination of measurements, computational technologies and operational attitudes making up process control. In this mix, control technology is a subordinated part.

1. The Processing Industries

Many of the processing industries date from the beginning of civilization; the processing of metals defined the ages of man. But for all their long history, the process industries, like other industries, were redefined by the Industrial Revolution. Before modern industrialization, most process products were made in batches like other handmade products. Manufacturing activities- sometimes grouped many craftsmen under one roof and subdivided production so that workers would specialize in parts of the effort. However, industrialization of these industries, in a modern sense, awaited development of production machinery, mass-production-oriented processes and mass markets. These interrelated developments led in turn to the modern continuous processes-the process industry equivalent of the transfer line of conventional mass production.

Both in control and in processing, the industries continue to distinguish between the earlier, more labor intensive batch processing (often used now where small lots or special handling are required) and the generally more capital-intensive continuous plant. Many of the well-known developments in the metals industries represent adaptations of batch processing to economic large-scale production. But rolling mills and the more recent casting processes are continuous. The invention of the Fourdrinier machine in France in 1799 transferred paper production from a batch mode to a continuous one. As with other industrial and processing inventions of the period, this invention first saw commercial use in England. Until the evolution of the German coal tar chemical industry (following the discovery of the first coal tar dye by Perkins, an Englishman), the major chemical industry developments took place in England and Scotland.

In terms of control history, the petroleum-based industries are, in a sense, archetypal for two reasons: first, their materials tend to be more fluid; and second, the dominant role of distillation and other separation processes has made possible the production of low-cost, high-purity feedstocks. The use of pure feedstocks is, in the process industries, the counterpart of the use of interchangeable parts in the discrete-products manufacturing industries. It makes possible predictable production relations and the effective use of modern, accurate and often nonlinear control models. This must clearly contrast with the earlier manufacture of such things as leather and glue from animal residues. In present-day process control, a distinction can be made between processes for which feeds and process relations are well-defined formally (e.g., chemicals, power) and processes for which feedstocks are highly variable and relations are ill-defined (e.g., paper, foods).

Because of the size and complexity of process plants, formal detailed understanding came late and piecemeal. Chemical engineering was the last of the traditional, hard-technology-based, engineering disciplines to develop, becoming independently recognized between 1910 and 1930. The nineteenth century chemical industry was more naturally the domain of mechanical engineering, based as it was on grinding and heating of rock and mineral feedstocks. In this manner, developments in a complex, poorly understood technology depended more on the ability to respond to opportunities, to achieve workable solutions to problems and to sway people than on formal or even accurate technology. For this reason, the process control industry started from individual, invented solutions to particular problems, often commissioned by an end user; the basic general purpose objects of process control-recorders, controllers and diaphragm actuator valves-usually started life as solutions to particular problems. Later sales efforts generalized the functions.

In parallel, the processing industries and the process control industries developed as expressions of nineteenth century industrial opportunism. The development of the chemical industry evolved from stage to stage as uses were found for the wastes of earlier stages. More and more, the economics of the industry depended on effective total use of raw materials. But the synergism was commercial as well as technical. The British component of the Royal Dutch-Shell group originated as a trading company selling, among other things, decorative shells for Victorian living rooms and kerosene to the Japanese.

The major precursor of the oldest current English process control company-Kent Instruments Ltd-was a manufacturer of brackets for knife sharpeners. In the USA, two major valve manufacturers evolved from companies making steam pressure regulators: the precursor of the Fisher Controls Company was founded by the inventor of a fire-engine pump governor (designed after he participated in putting out a fire); and the Mason Company (now part of the Masoneilan Division of the McGraw-Edison Company) was founded by an inventor of steam-engine components. The largest independent manufacturer of process control equipment is the second of two companies started by the same family: the Bristol Company and the Foxboro Company originated out of a father's desire to establish a business with his sons. One of the first products of this venture was a type of staple for joining the ends of machine drive belts. These two companies split because an older brother with strong academic connections and a younger brother with strong mechanical intuitions were unable to work together-an early example of the academicpractitioner conflict in process control.

In this kind of environment, some history can be seen in patent records, but the actual practice-the time and conditions of actual application-is not recorded. Many practitioners, both in the processing industry and in the process control industry, were concerned about protecting secrecy and patentability. In both fields, ideas have been reinvented and litigated over. The complexity of the fields and economic interests of the participants have minimized opportunities for dispassionate observation of the technology and history.

2. The Elements of Process Control

Until the advent of the computer and the related modern analog control, the involvement of companies in the process control business could be characterized in terms of some variation of the definition: "measurement, indication, recording and control of temperature, pressure and flow." These activities and the corresponding measurements represented general-purpose activities which could be applied in many contexts to manage and automate the processing industries.

Looking at the practice of modern process control, that is, the distributed and centralized control of large plants by appropriate mixes of digital computers, localized controllers and manual control access consoles, one can identify a number of component features. Each of these corresponds to an evolving operational, organizational, conceptual or technical innovation, for which one may identify early economic incentives and milestones.

(a) Clearly, feedback control depends on ready availability of measurements, and practice of process control requires a diverse enough set of basic measurements to support reasonable control strategies for any processing objective likely to occur.

(b) Control requires actuators; the universality of the valve permitted process control to lead industry economically in automation and labor reduction.

(c) Most of the early measurement devices were mechanical devices directly linked to their final actuator or indicating pointer. As long as this marriage existed, integrated controls were impossible. Process control in its current form separates measurement devices from control devices.

(d) Integrated control of large plants depends on the development of strategies for transmitting data to a central control room and then to any desired control computing device. Initially the transmission strategy was based on the measurement technology. The economic separation of measurement and control technology from transmission technology was essential. In turn, transmission had limited value until standard signal media and levels evolved.

(e) The modern control system is based on combined computations freely linked by software or wired connections. The need for computation and the flexible connection of computation developed erratically, depending on the sophistication of process understanding. Different processing industries support quite different control strategies.

(f) The necessary process and process control understanding, as well as effective inventory and operational control, required effective recording of the operation early in the process control era.

(g) Modern process control thinking is based on mathematical models. This development was late and continues to evolve for each industry only as formal process understanding is able to achieve the degree of accuracy and economic and operational relevance necessary to be a useful augmentation of the practitioner's understanding. Modelling attitudes evolved for reasons initially separate from control, and one can distinguish a number of quite different model roles:

(i) process design calculations,

(ii) mathematical calculations for billing,

(iii) mathematics to explain control effects (usually dated back to Maxwell and his steam engine governor analysis) (see Speed Regulation: History),

(iv) mathematics to compute, or justify, control tunings of standard controllers,

(v) linear, dynamic models used to design controllers matched in structure to the process, and

(vi) nonlinear models, based on process equations, to define control systems able to operate throughout the range of the process; these are a greater benefit to practical process control than are dynamic models.

(h) In parallel, the nature of connected control computation evolved from informal, fairly rigid combinations of cascaded controls, ratioing units and constraint controls into more diverse formally based control structures.

(i) The tools to impose human control over an automated system started as rough adjustments of devices (bending links, drilling holes and so on) and evolved to the modern CRT consoles.

(j) The introduction of the digital computer and later the microprocessor was significant, allowing new levels of automation and the recasting of earlier developments.

3. Specific Developments

It is axiomatic that control is impossible without measurements. The homogeneous fluid nature of process industry products meant that their state, quality, or quantity could be defined by simple measurements. Available early were the obvious measurements: pressure, temperature, fluid flow and level.

The invention of the Bourdon tube in 1852, and continual modifications to measure higher pressure, allowed the monitoring of pressure vessels and lines for safety and adequate pressure. Temperature could also be measured by enclosing a fluid in a bulb and using the Bourdon tube to measure the expansion of the fluid. In each of these cases, the Bourdon tube or spiral had to be mounted in a case with the tube fixed at one end and attached to an indicating or recording pen at the other. Thus the physical measurement was married to its end use. Any separation of measurement from end use implied a long line or pressurized process fluid, which could distort the measurement; unless compensated, and could leak.

Temperature could also be measured by thermocouple. One sees patented galvanometric instruments dating from this same period. At first these were used for high-temperature measurement, particularly in the metals industries. After World War I, the properties of metal under stress and temperature changes began to be understood. This led to establishment of temperature safety limits in power equipment. The precursors of the present-day process control divisions of Honeywell Inc., Republic Instrument Co., Leeds and Northrup Co. and Bailey Controls Co. developed a body of electrical measurement and computing controls, including electrically driven geared valves, from this thermocouple base for power station applications.: But here again, the separation of measurement from control would involve a long thermocouple line. These systems were limited to the power station, where the electrical spark explosion hazard did not exist.

Early flow measurements, such as those of gas flow, used some kind of filling-and-emptying displacement principle. Designers were aware of the possibility of measuring the pressure across a restriction shortly after Bernoulli's theorem was defined; informal use of the techniques dates back at least to Roman times. The invention of the venturi by Herschel in the late 1800s, the early studies by Kent Instruments Ltd in the early 1900s on gas flow and the gradual understanding of the relation between Reynolds number and the various coefficients were necessary to allow the universal use of the orifice-plate flowmeter.

There are patented chart recorders dating at least as far back as the second half of the nineteenth century, where the recorder and the sensor were married in the same case. With the introduction of round-the-clock operation of plants, recorders began to be used for monitoring when management was not around and checking the state of manual control. Many versions of planimeter were invented throughout the eighteenth century, so charts could be used to integrate records and bill from them as an alternative to the use of integrating displacement flowmeters (Sydenham 1979).

Valves tied to machinery were a natural part of the steam engine and the railway. Older manufacturers of control valves evolved naturally from manufacture of steam valves and pressure regulators, and various kinds of actuator-driven valves existed at least as early as 1900. But these were on-off control valves (at least as intended). The modern workhorse of process control is the diaphragm actuator control valve. This seems to have evolved in the mid 1920s as a result of the pioneering application work of Clesson "Doc" Mason as one of a group in the Foxboro Company's Tulsa, Oklahoma, office. "Doc" took valves provided by other manufacturers and replaced their flow plugs by handmade, hand-"tuned" plugs designed to allow effective throttled control.

Controls in conventional machinery were naturally designed as integral parts of the machinery. In process control on the other hand, the controllers were first integrated into the same case with the measurement device, indicator and recorder. The early controllers were on-off controllers. Initially the set point or reference for the controller was an uncalibrated screw or knob, included almost as an afterthought. Apparently the first controller with a calibrated reference or setpoint scale was a 1912 Foxboro design. As with measurements, these early controllers were implemented in several different technologies, notably electrical and pneumatic. Some of the early devices were powered by vacuum lines. In fact, the present-day 20-100 kPa (gauge) signal dates from efforts to operate vacuum driven devices "reversed." By the mid 1920s most processes now controlled were controlled with on-off controllers. This of course gave rise to unstable control and many accommodation strategies. A common one used a small on-off control valve with a manually set bypass valve, which was periodically reset to center the control valve.

People were aware that the stability problem came from the switched character of control and attempted to soften its effects in various ways, such as introducing lag into the loop or widening the on-off band (now called the proportional band) of the controls. The first use of proportional controllers employed permanently fixed gains rather than the easy modern adjustments. The previous work of Mason included some of the earliest proportional control applications, achieving adjustment by enlarging an air bleed hole in a diaphragm. These efforts gradually added integral and derivative control, although not by name.

Several papers of the 1930s began to analyze the dynamic behavior of control loops with these basic modes of control, notably the papers of Ivanoff (1934) and Callender et al. (1935-36) in the UK and of Mitereff (1935) in the USA. Comments of the time show a sophisticated interest in the problems. These papers did not attempt a general control methodology in a modern sense; instead they analyzed several fixed process and control structures. The use of a few standard process structures (e.g., dead-time, lag) continues to form one of the most effective ways of understanding process control feedback practice. In a more informal way these same concerns are echoed in a series of papers published by Mason (1933). Working with Mason, George Philbrick began in 1936 to develop his electronic simulator for process control studies and training (Mayr 1971). The strategy for tuning these additional modes of control and even the appropriate nomenclature were nevertheless conjectural. These issues came into focus with the publication of two papers by Ziegler and Nichols (1942, 1943) of the Taylor Instrument Company describing the results of systematic experimental studies.

The impracticality of producing exact a priori models means that the use of mathematical calculations to compute settings would be unusual even now. The use of mathematical models took a different direction in process control. Many of the measurements, such as flow based on differential pressure across a restriction, were known to require various kinds of computed compensation, particularly where a difference in measured value costs money (e.g., the case of measurements used for billing).

There are proposals and patents dating from the 1920s for many kinds of pneumatic and electronic computing devices for process control, notably many of the strategies for controlling power plants (the coordination of combustion control dates from the 1920s and 1930s). Most of these designs were based on logical or commonsense arguments rather than formal analysis. Nonlinear designs based on simplified process calculations are a more recent development dating from the late 1950s. The most successful of these designs are feedforward and decoupling, based on the most exactly known process relations: the material and energy balances. However, a precursor to these techniques — three-element level control, that is, the control of level in a tank by using feedforward of outlet flow combined with the output of the level control to set the set point of an inlet flow controller with a controlled inlet flow — dates from before 1930 and evolved as part of the power control systems just described.

Until the 1950s, transmission of the signal from sensor to controller tended to mean that the thermocouple leads or the pressure lines were extended from the plant back to the control room. There were papers in the early 1940s discussing pneumatic transmission effects, and pneumatic relays were incorporated into instruments before 1920. Modern distributed control required the evolution of standardized measurement transmitters and the standard signal media (the 20-100 kPa (gauge) or 4-20 mA signal, likely to be replaced increasingly by digital signals). To some extent the evolution of transmitters is a consequence of the availability of solid-state electronics developed in the 1950s. Field measurement and transmission remains an Achilles heel for process control. The field environment can be hard (corrosive or highly variable in temperature and humidity) on the field devices. Depending on the measurement technology, the measurements (and actuators) must not only be signalled but also powered. The most powerful systems technology is of course electrical, but it is associated with explosion hazard for some processes. These limitations require all kinds of inelegance in process control equipment and continue to motivate the search for better methods.

The natural culmination of all this evolution is the digital distributed control system. Probably the first real-time digital computer control installation was the Thompson Ramo Wooldridge RW300 installation at the Port Arthur Texas Co. plant in 1959. This installation involved true computer feedback control as well as alarms and logging of alarm conditions. A publication that year (Instrument Society of America 1959) listed 31 computer projects, each of which partly involved some kind of digital computer.

Within the interval 1956-62, pioneering computer control systems were installed in a number of plants. Initially it was difficult to assign a valid economic role to the computer. Early machines were used for data logging as well as control. The temptation was to pile many poorly understood control issues into a justification. It was argued that, above a certain number of loops, digital control was cheaper than analog control. Actually only the microprocessor began to bring the economics of the digital computer control onto a plane with analog control. Many of the early installations were economic failures; it took time to appreciate the values of digital control in increased flexibility, more elaborate higher-level control functions and more responsive man-machine interfacing.

4. The Future

The past trends mentioned in this article lead in several directions, some of which are constrained by hardware technology but many by software imagination.

(a) The field devices are our "feet of clay." Measurement technologies which require no powering and can be queried remotely without unsafe or unwieldy signal lines will be sought indefinitely. The conventional diaphragm actuator valve is also an ugly necessity, but hard to do without because the cost/ force ratio of the diaphragm actuator is so favorable.

(b) Higher-level forms of control will be sought. The academically interesting technologies of adaptation and optimization will of course find their home. However, from an industrial point of view these are specialized and secondary techniques. More important are higher levels of effective organizational and human control: effective inventory records and cost controls, effective scheduling of production and raw material orders, effective maintenance aids and effective man-machine interfacing.

(c) Automation of control design will proceed. Of course this will involve more intricate linear, nonlinear and multivariable algorithms, but the industrially more important developments will provide formal aids to the documentation of the control system and the relation between the system design and the commonsense process engineering objectives which motivated it.

See also: Production Control in Process Industries; Petrochemical Industry: Process Control

Bibliography

Bristol E H 1982 Process Control: An Application Theorist's View on Control. *IEEE Control Systems Mag*. 2(1), 3-8

Callender A, Hartree D R, Porter A 1935-1936 Time-lag in a control system. *Phil. Trans. R. Soc. London* 235, 415-44

Hardie D W F, Pratt J D 1966 *A History of the Modern British Chemical Industry*. Pergamon, Oxford

Instrument Society of America 1959 *Special Report on Process Computer Control*. ISA, Research Triangle Park, North Carolina

Ivanoff A 1934 Theoretical foundations of the automatic regulation of temperature. *J. Inst. Fuel* VII, 117-30

Mason C E 1933 Science of automatic control in refining I-IV. *World Petroleum* 4((6)-(9))

Mayr O 1971 *Feedback Mechanisms in the Historical Collections of the National Museum of History and Technology, Smithsonian Institution*. Smithsonian Institution Press, Washington DC

Mitereff S D 1935 Principles underlying the rational solution of automatic-control problems. *Trans. ASME* 57, 159-63; the discussion, (1936) 58, 55-65

Nichols N B 1977 Control revisited. *IEEE Conf. Decision and Control*. IEEE, New York, pp. 615-17

Sydenham P H 1979 *Measuring Instruments: Tools of Knowledge and Control.* Peter Peregrinus, Stevenage Ziegler J G, Nichols N B 1942 Optimum settings for automatic controllers. *Trans. ASME* 64, 759-68

Ziegler J G, Nichols N B 1943 Process lags in automatic control circuits. *Trans. ASME* 65, 433-44

E. H. Bristol