A Brief History of Automatic Control

Stuart Bennett

Automatic feedback control systems have been known and used for more than 2000 years; some of the earliest examples are water clocks described by Vitruvius and attributed to Ktesibios (circa 270 B.C.). Some three hundred years later, Heron of Alexandria described a range of automata which employed a variety of feedback mechanisms. The word "feedback" is a 20th century neologism introduced in the 1920s by radio engineers to describe parasitic, positive feeding back of the signal from the output of an amplifier to the input circuit. It has entered into common usage in the English-speaking world during the latter half of the century.

Automatic feedback is found in a wide range of systems; Rufus Oldenburger, in 1978, when recalling the foundation of IFAC, commented on both the name and the breadth of the subject: "I felt that the expression 'automatic control' covered all systems, because all systems involve variables, and one is concerned with keeping these variables at constant or given varying values. This amounts to concern about control of these variables even though no actual automatic control devices may be intentionally or otherwise incorporated in these systems. I was thinking of biological, economic, political as well as engineering systems so that I pictured the scope of IFAC as a very broad one."

This diversity poses difficulties for historians of the subject (and for editors of control journals), and this article does not attempt to cover all application areas.

The history of automatic control divides conveniently into four main periods as follows:

- Early Control: To 1900
- The Pre-Classical Period: 1900-1940
- The Classical Period: 1935-1960
- Modern Control: Post-1955

This article is concerned with the first three of the above; other articles in this issue deal with the more recent period.

Early Control: To 1900

Knowledge of the control systems of the Hellenic period was preserved within the Islamic culture that was rediscovered in the West toward the end of the Renaissance. New inventions and applications of old principles began to appear during the 18th century—for example, René-Antoine Ferchault de Réamur (1683-1757) proposed several automatic devices for controlling the temperature of incubators. These were based on an invention of Cornelius Drebbel (1572-1663). The temperature was measured by the expansion of a liquid held in a vessel connected to a U-tube containing mercury. A float in the mercury operated an arm which, through a mechanical linkage, controlled the draft to a furnace and hence the rate of combustion and heat output. Improved temperature control systems were devised by Bonnemain (circa 1743-1828), who based his sensor and actuator on the differential expansion of different metals. During the 19th century an extensive range of thermostatic devices were invented, manufactured, and sold. These devices were, predominantly, direct-acting controllers; that is, the power required to operate the control actuator was drawn from the measuring system.

The most significant control development during the 18th century was the steam engine governor. The origins of this device lie in the lift-tenter mechanism which was used to control the gap between the grinding-stones in both wind and water mills. Matthew Boulton (1728-1809) described the lift-tenter in a letter (dated May 28, 1788) to his partner, James Watt (1736-1819), who realized it could be adapted to govern the speed of the rotary steam engine. The first design was produced in November 1788, and a governor was first used early in 1789. The original Watt governor had several disadvantages: it provided only proportional control and hence exact control of speed at only one operating condition (this led to comments that it was "a moderator, not a controller"); it could operate only over a small speed range; and it required careful maintenance.

The first 70 years of the 19th century saw extensive efforts to improve on the Watt governor, and thousands of governor patents were granted throughout the world. Many were for mechanisms designed to avoid the offset inherent in the Watt governor. Typical of such mechanisms were the governors patented by William Siemens (1823-1883) in 1846 and 1853, which substituted integral action for proportional action and hence produced "floating" controllers with no fixed set point. Practical improvements came with the loaded governor of Charles T. Porter (1858): his governor could be run at much higher speeds, and hence greater forces could be developed to operate an actuator. A little later Thomas Pickering (1862) and William Hartnell (1872) invented spring-loaded governors, which also operated at higher speeds than the Watt governor and which had the added advantage of smaller physical size than the Watt and Porter governors.

From the early years of the 19th century there were reports of problems caused by governors "hunting," and attempts to analyze the governor mechanism to determine the conditions for stable (non-hunting) operation were made. J.V. Poncelet (1788-1867) in 1826 and 1836, and G.B. Airy (1801-1892) in 1840 and 1851 produced papers that showed how dynamic motion of the governor could be described using differential equations, but both met difficulties when they attempted to determine the conditions for stable behavior. Airy, in 1851, stated the conditions for stable operation, but his report is so terse that it is not possible to determine how he arrived at these conditions. In 1868, James Clerk Maxwell (1831-1879) published his now-famous paper entitled "On Governors." In it he described how to derive the linear differential equations for various governor mechanisms. At this time mathematicians and physicists knew that the

---

The author is with the Department of Automatic Control & Systems Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, U.K., telephone: +44 (0)114 282 5230, email: s.bennett@sheffield.ac.uk.

0272-1708/96/$05.00©1996IEEE

stability of a dynamic system was determined by the location of the roots of the characteristic equation, and that a system became unstable when the real part of a complex root became positive; the problem was how to determine the location of the real parts of the complex roots without finding the roots of the equation. Maxwell showed, for second-, third-, and fourth-order systems, that by examining the coefficients of the differential equations the stability of the system could be determined. He was able to give the necessary and sufficient conditions only for equations up to fourth order; for fifth-order equations he gave two necessary conditions. Maxwell's paper, now seen as significant, was little noticed at the time, and it was not until the early years of this century that the work began to be assimilated as engineering knowledge.

The problem formulated by Maxwell was taken up by Edward J. Routh (1831-1907), whose first results were published in 1874. In 1877 he produced an extended treatise on the "Stability of Motion" in which, drawing on the work of Augustin-Louis Cauchy (1789-1857) and Charles Sturm (1803-1855), he expounded what we now know as the Routh-Hurwitz stability criteria. In 1895, the Swiss mathematician Adolf Hurwitz (1859-1919) derived the criteria independently (basing his work on some results of C. Hermite). He had been asked for help with the mathematical problem by his colleague Aurel Boleslaw Stodola (1859-1942), who was working on a turbine control problem.

Most of the inventions and applications of this period were concerned with the basic activities of controlling temperatures, pressures, liquid levels, and the speed of rotating machinery: the desire was for regulation and for stability. However, growth in the size of ships and naval guns, and introduction of new weapons such as torpedoes, resulted in the application of steam, hydraulic, and pneumatic power systems to operate position control mechanisms. In the United States, Britain, and France, engineers began to work on devising powered steering engines to assist the helmsman; on large ships the hydrodynamic forces on the rudder were such that large gear ratios between the helm and the rudder were required and hence moving the rudder took a long time. The first of powered steering engine, designed by Frederick Sickels in the U.S. (patented 1853) was an open-loop system. The first closed-loop steering engine (patented 1866) was designed by J. McFarlane Gray for Brunel's steamship the *Great Eastern.* In France, around the same time, Jean Joseph Farcot designed a range of steering engines and other closed-loop position control systems. He suggested naming his devices "servo-moteur" or "moteur asservi," hence our terms "servomechanisms" and "servomotors."

Further applications for control systems became apparent with the growth in knowledge of electricity and its applications. For example, arc lamps required the gap between the electrodes to be kept constant, and generally it was helpful to all users if either the voltage or the current of the electricity supply was kept constant. Electricity also provided additional tools—for measurement, for transmission and manipulation of signals, and for actuation—which engineers began to use. The electric relay, which provided high gain power amplification, and the spring biased solenoid, which provided (crude) proportional control action, were significant devices.

The Pre-Classical Period (1900-1935)

The early years of the 20th century saw the rapid and widespread application of feedback controllers for voltage, current, and frequency regulation; boiler control for steam generation; electric motor speed control; ship and aircraft steering and auto stabilization; and temperature, pressure, and flow control in the process industries. In the twenty years between 1909 and 1929, sales of instruments grew rapidly as Fig. 1 shows. The majority of the instruments sold were measuring, indicating, and recording devices, but toward the end of the period the sales of controllers began to increase. The range of devices designed, built, and manufactured was large; however, most were designed without any clear understanding of the dynamics both of the system to be controlled and of the measuring and actuating devices used for control. The majority of the applications were concerned with simple regulation, and in such cases this lack of understanding was not a serious problem. However, there were some complex mechanisms involving complicated control laws being developed—for example, the automatic ship-steering mechanism devised by Elmer Sperry (1911) that incorporated PID control and automatic gain adjustment to compensate for the disturbances caused when the sea conditions changed. Another example is the electricity supply companies concerned about achieving economic operation of steam-generating boilers. Boiler control is of course a multivariable problem in that both water level and steam pressure have to be controlled, and for efficient combustion the draught to the boiler has also to be controlled. During the 1920s several instrument companies develop complete boiler control systems.

As control devices and systems began to be used in many different areas of engineering, two major problems became apparent: (1) there was a lack of theoretical understanding with

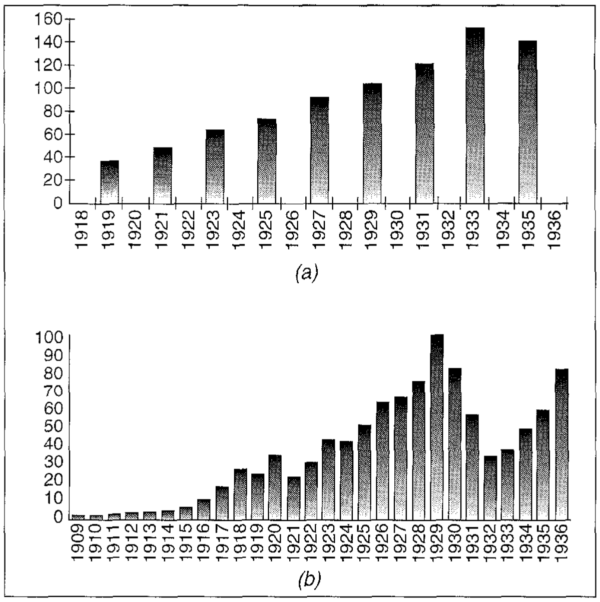


Fig. 1. (a) Ratio of instrument to machinery sales in the United States, 1918 to 1936 (1921 = 100). (b) Index of instrument sales in the United States, 1909 to 1936 (1921 = 100).

no common language in which to discuss problems, and (2) there were no simple, easily applied analysis and design methods. The only available analysis tool was the differential equation and the application of the still not widely known Routh-Hurwitz stability test. This is a laborious process, dependent on being able to obtain values for the parameters, and one that gives no guidance to the designer on the degree of stability, or what to do to make the system stable.

As applications multiplied, engineers became puzzled and confused: controllers that worked satisfactorily for one application, or for one set of conditions, were unsatisfactory when applied to different systems or different conditions; problems arose when a change in one part of the system (process, controller, measuring system, or actuator) resulted in a change in the major time constant of that part. This frequently caused instability in what had previously been, or seemed to have been, a stable system. Some acute observers, for example Elmer Sperry and Morris E. Leeds, noted that the best human operators did not use an on-off approach to control but used both anticipation, backing off the power as the controlled variable approached the set-point, and small, slow adjustments when the error persisted. Sperry tried to incorporate these ideas into his devices, and for many years Leeds resisted attaching simple on-off control outputs to his recorders because he realized that this would not provide good control.

In 1922, Nicholas Minorsky (1885-1970) presented a clear analysis of the control involved in position control systems and formulated a control law that we now refer to as three-term or PID control. He arrived at his law by observing the way in which a helmsman steered a ship. This work did not become widely known until the late 1930s, after Minorsky had contributed a series of articles to *The Engineer*. But even if designers had been aware of Minorsky's work they would still have lacked suitable linear, stable, amplification devices to convert the low power signals obtained from measuring instruments to a power level suitable to operate a control actuator. Slide and spool valves developed during the early part of the 20th century were beginning to provide the solution for hydro-mechanical systems, although valve overlap that resulted in dead space and stiction were problems that had to be overcome. However, there was an impasse with respect to amplifiers for electronic and pneumatic systems. As early as 1920 the amplification problem was proving a serious obstacle to the further development of long-distance telephony. Improvements in cable design and the use of impedance loading had extended the distance over which telephone transmissions could take place without amplification, yet the transcontinental service in the U.S. was dependent on amplification. Telephone repeaters based on electronic amplification of the signal were used around 1920, but the distortion they introduced limited the number that could be used in series. Expansion of traffic on the network was also causing problems since it necessitated an increase in bandwidth of the lines with the consequent increase in transmission loss. Harold Stephen Black (1898-1983) began work on this problem in the early 1920s. He realized that if some of the amplification of a high-gain amplifier were sacrificed by feeding back part of the output signal, the distortion due to noise and component drift could be reduced. On August 2, 1927, he sketched a circuit for a negative feedback amplifier. Following extensive development work, full-scale practical trials were carried out in 1930, and the amplifier began to be used within AT&T in 1931. Information about the amplifier was not published in the open literature until 1934. In developing the practical amplifier and in understanding its behavior, Black was assisted by Harry Nyquist (1889-1976), whose paper "Regeneration Theory" laid down the foundations of the so-called Nyquist analysis and was published in 1932.

This work provided a practical device—the negative feedback amplifier—and led to a deeper understanding of the benefits of negative feedback in systems. It also, eventually, led to a method of analyzing and designing control systems which did not require the derivation and manipulation of differential equations, and for which experimental data—the measured frequency response—could be combined with calculated data; from the combined response the degree of stability of the system could be estimated and a picture of changes necessary to improve the performance could be deduced.

Contemporaneously with Black's work, Clesson E. Mason of the Foxboro Company developed a pneumatic negative feedback amplifier. Edgar H. Bristol, one of the founders of the Foxboro Company, had invented the flapper-nozzle amplifier in 1914. The early versions of the flapper-nozzle amplifier were highly non-linear (effectively on-off behavior), and during the 1920s extensive modifications had only succeeded in increasing its linear range to about 7% of full range. In 1928, Mason began experimenting with feeding back part of the output movement of the amplifier, and in 1930 produced a feedback circuit that linearized the valve operation. This circuit enabled integral (or reset) action to be easily introduced into the behavior of the system. In 1931, the Foxboro Company began selling the Stabilog pneumatic controller which incorporated both linear amplification (based on the negative feedback principle) and integral (reset) action (Fig. 2). There was some initial market resistance to this device, on the grounds of cost and because its behavior was not understood. Foxboro responded by producing, in 1932, a bulletin explaining the principles of the system in clear and simple terms and stressing how the behavior was different from what it termed "narrow-band" controllers, that is, those with limited linear range.

The electronic negative feedback amplifier and the pneumatic controller were the outcomes of work on industrial problems. During the same period, extensive work was being carried out on analog calculating machines under the direction of Vanevar Bush at the Massachusetts Institute of Technology. This work resulted in the differential analyzer, which provided a means of simulating the behavior of dynamic systems and of obtaining numerical solutions to differential equations. It also led to the study and design of a high-performance servomechanism by Harold Locke Hazen (1901-1980) and his students. In addition to designing a servo system, Hazen also undertook the first major theoretical study of servomechanisms. His papers, published in 1934, provided the starting point for the next generation of control system specialists.

The Classical Period: 1935-1950

During the period 1935-1940, advances in understanding of control system analysis and design were made independently by several groups in several countries. The best known and most influential work came from three groups working in the U.S. The development in Europe and in Russia during this period followed a somewhat different path deriving from Vyschnegradsky's work in

Russia and then Barkhausen's work in Germany, followed by developments due to Cremer, Leonhard, and Mikhailov.

AT&T continued with its attempts to find ways of extending the bandwidth of its communication systems, and upon obtaining good frequency response characteristics. The ideal which they were seeking was a constant gain over a wide bandwidth with a sharp cut-off and with a small phase lag. Engineers in the Bell Telephone Laboratories worked extensively on this problem, but found that if they achieved the desired gain characteristic then the phase lag was too large. In 1940, Hendrik Bode, who had been studying extensions to the frequency-domain design method, showed that no definite and universal attenuation and phase shift relationship for a physical structure exists, but that there is a relationship between a given attenuation characteristic and the minimum phase shift that can be associated with it. In the same paper he adopted the point (-1,0) as the critical point rather than the point (+1,0) used by Nyquist, and he introduced the concept of gain and phase margins, and the gain-bandwidth limitation. Full details of Bode's work appeared in 1945 in his book *Network Analysis and Feedback Amplifier Design*.

The second important group, mechanical engineers and physicists working in the process industries in the U.S., encouraged by Ed S. Smith of the Builders Iron Foundry Company, began systematically developing a theoretical understanding of the control systems they used. They sought to establish a common terminology and tried to develop design methods. They persuaded the American Society of Mechanical Engineers to form an Industrial Instruments and Regulators Committee in 1936, thus becoming the first major professional body to form a section specifically to deal with automatic control. Several members of this loose grouping were aware of developments in Germany and in England. During this period the manufacturers of pneumatic controllers continued to improve and develop their instruments, and by 1940 field-adjustable instruments with PID control were available—for example, an improved version of the Stabilog and the Taylor Fulscope. In 1942, J.G. Ziegler and N.B. Nichols of the Taylor Instrument Companies published papers describing how to find the optimum settings for PI and PID control—the so called Ziegler-Nichols tuning rules. These were extended in the mid-1950s by Geraldine Coon (Taylor Instrument).

The third group was located in the Electrical Engineering Department of MIT and was led by Harold L. Hazen and Gordon S. Brown. They used time-domain methods based on operator techniques, began to develop the use of block diagrams, and used the differential analyzer to simulate control systems. Scholarly interchanges between MIT and the University of Manchester led to a differential analyzer being built at Manchester University and, in 1936, Douglas Hartree and Arthur Porter assisted A. Callender of ICI to use the machine to simulate an industrial control system and to derive design charts for the system.

The advent of the second world war concentrated control system work on a few specific problems. The most important of these was the aiming of anti-aircraft guns. This is a complex problem that involves the detection of the position of the airplane, calculation of its future position, and the precise control of the movement of a heavy gun. The operation required up to 14 people to carry out complicated observation and tracking tasks in a coordinated way. The design of an adequate servomechanism to control the gun position was a difficult task. It also became clear during 1941 that the cumbersome system of relaying manually the information obtained from radar devices to the gun controllers was not adequate to combat the threat of fast aircraft and that there was a need to develop a system in which an automatic tracking radar system was directly linked to the gun director, which was in turn linked to the gun position controller.

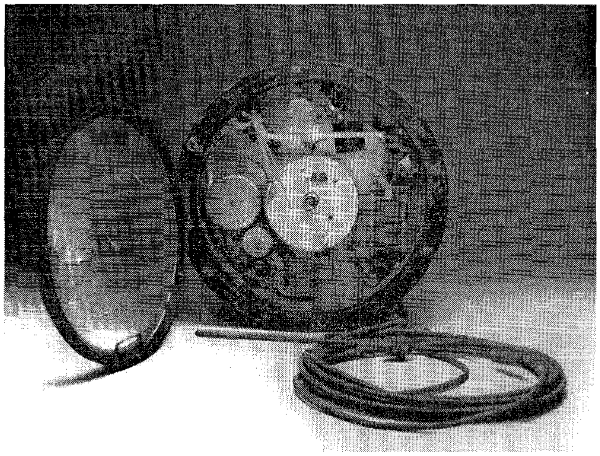


Fig. 2. Internal view of the Foxboro Stabilog circa 1936.

Work on this "systems" problem brought together mechanical, electrical, and electronic engineers, and an outcome of this cross-fertilization of ideas was a recognition that neither the frequency response approach used by the communication engineers nor the time domain approach favored by the mechanical engineers were, separately, effective design approaches for servomechanisms. What was required was an approach that used the best features of each.

Work by Gordon S. Brown and his students at MIT showed how many mechanical and electrical systems could be represented and manipulated using block diagrams. Albert C. Hall showed, in 1943, that by treating the blocks as transfer functions (he used the Laplace transform approach) the system transfer locus could be drawn, and hence the Nyquist test for stability could be used. More importantly the gain and phase margin could be determined, and he introduced the use of M and N circles which enable estimates of the closed loop time domain behavior to be made. Another group working the so called Radiation Laboratory at MIT (this laboratory was concerned with developing radar systems for the detection and tracking of aircraft) designed the SCR-584 radar system, which, linked with the M9 director, was deployed in southeast England and had a high success rate against V1 rockets. The M9 director was designed by a group led by Bode and including Blackman, C.A. Lovell, and Claude Shannon, working in the Bell Telephone Laboratory. Out of the work on the SCR-584 came the Nichols chart design method, work by R.S. Phillips on noise in servomechanisms, and W. Hurewicz's work on sampled data systems. After the war, details of the work were published in the seminal book *Theory of Servomechanisms*.

The Radiation Laboratory group used phase advance circuits in the forward loop to modify the performance of their control system. Several other workers, particularly in the U.K., used minor loop feedback to modify system response and hence found the Nyquist approach difficult. In 1942, A.L. "John" Whiteley of the British Thomson Houston Company proposed an approach based on plotting the inverse functions on a Nyquist diagram; in the same year H.T. Marcy (Kellog Company) independently proposed a similar method.

The problems raised by anti-aircraft control were system design problems in that several different units, often designed and manufactured by different groups, had to be integrated; the overall performance was dependent not so much on the performance of the individual units but on how well they worked together. Difficulties experienced in getting units to work together led to a deeper understanding of bandwidth, noise, and non-linearities in systems. By the end of the war people such as Arnold Tustin (1899-1994) in England and R.S. Phillips, W. Hurewicz, L. McColl, N. Minorsky, and George Stibbitz in the U.S. were concentrating on nonlinear and sampled data systems.

The other major development to emerge from the fire control work during the war was the study of stochastic systems: Norbert Wiener (1894-1964) wished to contribute to the war effort and proposed tackling the problem of predicting the future position of an aircraft. His proposal was based on the work he had done in the 1920s on generalized harmonic analysis (Wiener, 1931). He worked with John Bigelow on implementing his prediction system, and they succeeded in developing an electronic system for prediction. Wiener was disappointed that in the end his system was only able to achieve a marginal improvement (less than 10%) over the system developed empirically by the Bell Telephone Laboratory. The work did lead to Wiener producing the report "The Extrapolation, Interpolation and Smoothing of Stationary Time Series with Engineering Applications" (OSRD Report 370, February 1, 1942), known as "the yellow peril" because of its yellow covers and the formidable difficulty of its mathematics. It was eventually published in the open literature in 1949.

By the end of the war the classical control techniques—with the exception of the root locus design method of Walter Evans (1948, 1950)—had been established. The design methodologies were for linear single-input systems—that is, systems that can be described by linear differential equations with constant coefficients and that have a single control input. The frequency response techniques, based on the use of Nyquist, Bode, Nichols, and Inverse Nyquist charts, assessed performance in terms of bandwidth, resonance, and gain and phase margins and provided a graphical, pictorial view of the system behavior. The alternative approach based on the solution of the differential equations using Laplace transform techniques expressed performance in terms of rise time, percentage overshoot, steady-state error, and damping. Many engineers preferred the latter approach because the performance was expressed in "real" terms, that is, the time behavior of the system. The disadvantage, of course, is that until the development of the root locus method there was no simple and easy way in which the designer could relate parameter changes to time behavior changes.

The achievements of the classical era began to be consolidated and disseminated in books published during the 1940s and early 1950s. The first book dedicated to control systems was Ed S. Smith's *Automatic Control Engineering,* published in 1942; however, this book had a pre-war feel to it and it did not reflect the changes in approach that were developing from the wartime work. The later books, Bode's book (referred to above) and Leroy MacColl's *Fundamental Theory of Servomechanisms,* began to set out the new approaches. Encouraged by the British government, the Institution of Electronic Engineers held a conference in London in 1946 on radar, and the interest shown in the papers relating to servomechanisms resulted in a further conference devoted to control held in 1947. In the United States the government agreed to continue paying key people for a period of six months after the end of the war to enable them to write up their work. One outcome was the Radiation Laboratory Series of books, including *Theory of Servomechanism.*

The conference on "Automatic Control" held in July 1951 at Cranfield, England, and the "Frequency Response Symposium" held in December 1953 in New York marked the beginnings of the transition period leading to modern control theory. The first of these, organized by the Department of Scientific and Industrial Research, with the assistance of the IEE and the IMechE, was the first major international conference on automatic control. Arnold Tustin chaired the organizing committee, and 33 papers were presented, 16 of which dealt with problems of noise, non-linearity or sampling systems. There were also sessions on analog computing and the analysis of the behavior of economic systems (this latter reflecting both the particular interest of Arnold Tustin and the growing interest in applications of feedback theory).

The wartime experience demonstrated the power of the frequency response approach to the design of feedback systems; it also revealed the weakness of any design method based on the assumption of linear, deterministic behavior. Real systems are non-linear; real measurements contain errors and are contaminated by noise; and in real systems both the process and the environment are uncertain. But what design techniques can be used that allow the designer to consider non-linear and non-deterministic behavior and to allow for measurement errors and noise? Also, the design problem changed from that of simply achieving a stable controller to that of achieving the "best" controller. But what is the "best" controller?

Ziegler and Nichols had shown how to choose the parameters of a given type of controller to obtain an "optimum" performance of a given control structure (PI, PID). Similarly, Whiteley's standard forms enabled designers to choose a particular performance for a range of systems. Work was done on evaluating a whole range of performance indicators including IAE, ISE, ITAE, and ITSE (Graham and Lathrop, 1953). Sterile arguments developed about which the performance indicator was the "best" until it was accepted that what was important was the choice of an appropriate performance indicator for a particular application. In addition to performance criteria based on minimizing some error function there was, for certain classes of system, interest in minimizing the time to reach a set-point (obvious applications are military target seeking servomechanisms and certain classes of machine tools). Donald McDondald's "Non-Linear Techniques for Improving Servo Performance" (1950) was followed during the 1950s by extensive work on the time-optimal problem relating to the single controlled variable with a saturating control. The problem was studied by Bushaw (1952) and by Bellman (1956). In a definitive paper J.P. LaSalle (1960) generalized all the previous results and showed that if optimal control exists it is unique and bang-bang. The progress made in this area is summarized in Oldenburger's book *Optimal Control* (1966).

The more difficult problem was how to choose the control structure that would give the best performance and how to define this "best" performance. To do this, a model of the plant was needed: either physical-mathematical balance equations of mass, energy, etc., in which the parameters are functions of the physical data of the process, or "black box" models based on experimental measurements—for example, frequency response in which the parameters are not directly related the physical data of the systems.

Work on developing frequency response ideas and design methods continued throughout the 1950s. Design methods for systems containing non-linearities were developed, as were the theoretical foundations of sampled-data systems. The teaching of servomechanisms and control theory spread, initially through special courses run for practicing engineers and graduate students and then through incorporation within the standard syllabus of many engineering courses.

Modern Control

Although the direction of some post-war work was influenced by the insights and new understandings developed during the war, the trajectory of development, Alistair J.G. MacFarlane (1979) argues, was largely determined by two factors: first, the problem that governments saw as important, the launching, maneuvering, guidance, and tracking of missiles and space vehicles; and second, by the advent of the digital computer. The first problem was essentially control of ballistic objects, and hence detailed physical models could be constructed in terms of differential equations, both linear and non-linear; also measuring instruments and other components of great accuracy and precision could be developed and used. Engineers working in the aerospace industries, following the example set by Poincaré, turned to formulating the general differential equations in terms of a set of first-order equations, and thus began the approach that became known as the "state-space" approach.

Between 1948 and 1952 Richard Bellman, working in the mathematics department of the RAND Corporation, studied the problem of determining the allocation of missiles to targets so as to inflict the maximum damage. This work led him to formulate the "principle of optimality" and to dynamic programming. The choice of name was, according to an account published in 1984, determined by political expediency. The research was supported by the Air Force but the then-Secretary of Defense had an aversion to the word *research* and it was assumed he would have an even greater aversion to mathematical research. *Dynamic* was, and still is, a word with positive connotations, and *programming* was thought to be more acceptable that *planning*. (Names are important, and looking back over 50 years it does seem that the use of the names *control engineering*, *automatic control*, and *systems engineering* have not achieved for our subject the recognition that might have been expected. Names such as *cybernetics* and *robotics* command a greater degree of public recognition and apparent understanding.)

In the latter part of the 1950s Bellman began working on optimal control theory, at first using the calculus of variations but later, because of the boundary value problem inherent in the calculus of variations approach, seeking to formulate deterministic optimization problems in a way in which they could be solved by using dynamic programming. His insight was to see that by applying a particular control policy the system would reach a region in state-space and there would be a specified amount of time left. Formulated in this way, the problem can be treated as a multistage decision making process. Working with Stuart Dreyfus, Bellman developed computer programs to produce numerical solutions to a range of problems, and the results were published in 1962. The principal difficulty with dynamic programming is the dimensionality problem, and even though we now have computing power far beyond anything available to Bellman and Dreyfus we still need to use approximations to handle complex systems.

As well as involving positional accuracy, performance requirements also involve constraints expressible as optimization requirements; for example, reaching a specified position in minimum time, or carrying out a set of maneuvers with minimum fuel consumption. Consequently, attention once again focused on the differential equation approach to the analysis and design of control systems. Dynamical problems that involve minimizing or maximizing some performance index have "an obvious and strong analogy with the classical variational formulations of analytical mechanics given by Lagrange and Hamilton." The generalization of Hamilton's approach to geometric optics by Pontryagin (1956), in the form of his maximum principle, laid the foundations of optimal control theory. This and Bellman's insight into the value and usefulness of the concept of state for the formulation and solution of many control and decision problems led to extensive and deep studies of mathematical problems of automatic control. And the growing availability of the digital computer during the late 1950s made a recursive algorithmic solution possible (as opposed to the search for a closed-form solution in the classical approach).

Michael Athans has placed the origin of what is now referred to as modern control theory as 1956, and in September of that year an international conference on automatic control, organized by the joint control committee of the VDI and VDE, was held in Heidelberg, Germany. During the conference a group of delegates agreed to form an international organization to promote progress in the field of automatic control. An organizing group—Broida (France), Chairman, Grebe (Germany), Letov (USSR), Nowacki (Poland), Oldenburger (U.S.) Welbourn (U.K.), with Ruppel (Germany) as Secretary—was charged with drawing up plans for an international federation. The organization, the International Federation of Automatic Control (IFAC), was officially formed at a meeting held in Paris on Sept. 11 and 12, 1957. Also chosen were attendee Harold Chestnut as the first president, with A.M. Letov and V. Broida elected as vice presidents, G. Ruppel as secretary, and G. Lehmann as treasurer. At this meeting the Russian delegate extended an invitation to hold the first conference in Moscow in 1960.

The Moscow Conference was an important and highly visible symbol of the change in direction that had been slowly developing during the 1950s, and it is fitting that at the conference Kalman presented a paper, "On the General Theory of Control Systems," that clearly showed that a deep and exact duality existed between the problems of multivariable feedback control and multivariable feedback filtering, hence ushering in a new treatment of the optimal control problem.

An important step was Kalman's treatment of the linear multivariable optimal control problem with a quadratic performance index, and in particular the provision of a synthesis procedure. Further impetus to the state-space approach was given with

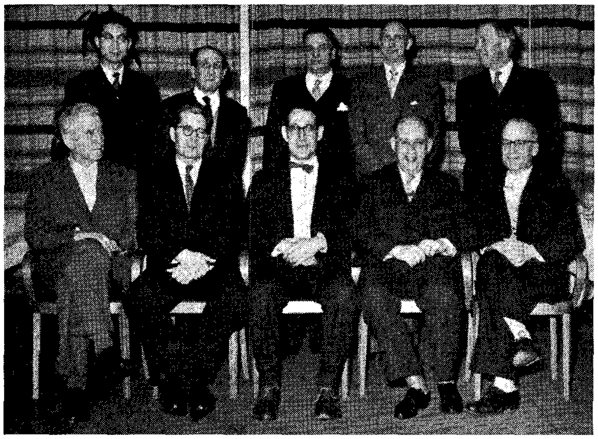


Fig. 3. The Executive Council of IFAC 1959 (reproduced from Automatica vol. 7, p. 55, 1971).

Kalman's work on the concepts of observability and controllability, and with Rosenbrock's idea of modal control, which led to extensive work on "pole shifting." A further important result was Wonham's proof that a sufficient condition for all the closed-loop characteristic frequencies of a controllable system to be arbitrarily allocatable under feedback is that all the states of the system are accessible.

The final triumph of time-response methods appeared to come when Kalman and Bucy attacked the filtering problem. Their work, as well as producing the Kalman-Bucy filter, demonstrated the basic role of feedback in filtering theory and the duality that existed between the multivariable control problem and multivariable feedback filtering. Following the Moscow conference, the state-space approach dominated the subject for almost two decades, leading Isaac Horowitz, who continued to work on frequency response ideas, to a feeling of isolation and to a lament written in 1984 that "modern Ph.D.s seem to have poor understanding of even such a fundamental concept of bandwidth and not the remotest idea of its central importance in feedback theory. It is amazing how many are unaware that the primary reason for feedback in control is uncertainty."

There was a rapid realization that the powerful optimal control methods could not be used on general industrial problems because accurate plant models were not available and in many cases not achievable. As Karl Astrom and P. Eykoff, writing in 1971, remarked, a strength of the classical frequency response approach is its "very powerful technique for systems identification, i.e., frequency analysis" through which transfer functions can be found accurately for use in the synthesis technique. In modern control the models used are "*parametric* models in terms of state equations," and this has led to interest in parameter estimation and related techniques.

Further problems arose in attempting to applying the state-space approach to industrial problems, one being the formulation of an appropriate performance index, not always obvious, and the other being the complexity of the controller resulting from the design method, for example, the incorporation of a Kalman-Bucy filter in the control systems results in the controller having a dynamic complexity equivalent to that of the plant being controlled. As a consequence there was a revival of interest in the frequency-response approach, and a systematic attack on the problems of developing frequency response methods for multivariable systems began in 1966 with a paper by Howard Rosenbrock.

Turning to MacFarlane's second influence on the development of modern control—the digital computer—we find that the main impact during the 1950s and 1960s was to support theoretical investigations and particularly (using Wonham's definition) synthesis. The design and implementation of practical systems were much more strongly influenced through "the replacement of electronic tubes by semiconductors such as diodes, transistors and thyristors in the fifties," as Gerecke commented, and the replacement of mechanical and electrical components by solid-state and microelectric devices. By the early 1960s the digital computer had been used on-line to collect data, for optimization and supervisory control (Monsanto Chemical Company, Luling, La., in 1960) and in a limited number of applications for direct digital control, for example, at an ICI plant at Fleetwood in the U.K. in 1962. However, its widespread use for on-line control did not occur until the early 1970s.

A leading advocate for the use of the digital computer in the process industries was Donald P. Eckman, who in the early 1950s persuaded several companies to support a research program based at the Case Institute of Technology, Cleveland, Ohio. The program, originally entitled "Process Automation," was renamed "Control of Complex Systems" because Eckman wished to distinguish what he was doing from the popular image of automation, meaning the mechanization of manufacturing and the displacement of labor. By the end of the decade Eckman was arguing in support of "Systems Engineering" with the idea that what industry needed was engineers with "a broad background [cutting] across conventional boundaries of the physical engineering and mathematical sciences" and with "an ability to approach problems analytically, to reduce physical systems to an appropriate mathematical model to which all the power of mathematical manipulation, extrapolation, and interpretation can be applied."

Conclusion

The conferences of 1951 and 1953, together with the publication of numerous textbooks; articles such as Tustin's in *Engineering* in 1950 and Brown's in *Scientific American* in 1951; and numerous articles on control topics in *Mechanical Engineering* during the early 1950s brought automatic control to the attention of engineers. The publication of Wiener's book *The Human Use of Human Beings* and a series of articles published in *Scientific American* in 1952 attracted the attention of a wider technical community. By the mid-1950s there was a growing general awareness of the potential of automatic control. Many books on the subject intended for the general reader were published, and the British government quietly encouraged a debate on the subject. The emphasis in these popular and semi-popular works was on automation in the sense of mechanization and remote control of production lines and other assembly processes. There was also great interest in the possibilities of numerical control of machine tools.

Central to this debate were issues that many of the engineers and administrators involved in control system work during the war had anticipated—control systems had moved beyond feedback amplifiers and single-loop servomechanisms and had become concerned with large-scale, complex systems. Gordon

Brown and Duncan Campbell, in 1949, laid out clearly what they saw as the areas of application of control in the future:

"Improved automatic control ... is the co-ordinated design of plant, instruments, and control equipment. We have in mind more a philosophic evaluation of systems which might lead to the improvement of product quality, to better co-ordination of plant operation, to a clarification of the economics related to new plant design, and to the safe operation of plants in our composite social-industrial community. These general remarks are illustrated by mention that certain industries operating at large production might show appreciable increase in economy and quality on standard production items by improved automatic control. The conservation of raw materials used in a process often prompts reconsideration of control. The expenditure of power or energy in product manufacture is another important factor related to control. The protection of health of the population adjacent to large industrial areas against atmospheric poisoning and water-stream pollution is a sufficiently serious problem to keep us constantly alert for advances in the study and technique of automatic control, not only because of the human aspect but because of the economy aspect."

This they viewed as a long-term program with many technical and human problems that "may take a decade or more to resolve."

Since Brown and Campbell wrote these words, the penetration of control systems into everyday life has gone further than they perhaps expected. The complexity of what we now seek to control, the techniques that we have available, and the power of the technology—particularly the digital computer—place enormous responsibilities on us as engineers and as citizens.

Appendix: Books on Control Published Between 1940 and 1955

1942

Gardner, M.A., and Barnes, J.L., *Transients in Linear Systems*

Smith, E.S., *Automatic Control Engineering*

1943

Griffiths, R., *Thermostats and Temperature Regulating Instruments*

Hall, A.C., *The Analysis and Synthesis of Linear Servomechanisms*

1944

Oldenbourg, R.C., Sartorius, H., *Dynamik Selbsttätiges Regelungen*

Profos, P., *Vektorielle Regeltheorie*

VDI, *Regelungstechnik: Begriffe und Bezeichnungen*

1945

Bode, H.W., *Network Analysis and Feedback Amplifier Design*

Eckmann, Donald P., *The Principles of Industrial Process Control*

MacColl, L.A., *Fundamental Theory of Servomechanisms*

1946

Ahrendt, W.R., Taplin, J.F., *Automatic Regulation*

1947

James, H.J., Nichols, N.B., Phillips, R.S., *Theory of Servomechanisms*

Oppelt, W., *Grundgesetze der Regelung*

Lauer, H., Lesnik, R., Matson, L., *Servomechanism Fundamentals*

1948

Brown, G.S., and Campbell, D.P., *Principles of Servomechanisms*

Oldenbourg, R.C., Sartorius, *The Dynamics of Automatic Control*

Wiener, N., *Cybernetics: or Control and Communication in the Animal and the Machine*

1949

Shannon, C.E., Weaver, W., *The Mathematical Theory of Communication*

Wiener, N., *Extrapolation, Interpolation, and Smoothing of Stationary Time Series with Engineering Applications*

1950

Porter, A., *Introduction to Servomechanisms*

1951

Servomechanisms: Selected Government Research Reports

Ahrendt, W.R., Taplin, J.F., *Automatic Feedback Control*

Behar, M.F., *Handbook of Measurement and Control*

Chestnut, Harold, Mayer, R.W., *Servomechanisms and Regulating System Design Vol. I*

Farrington, G.H., *Fundamentals of Automatic Control*

Fett, G., *Feedback Control Systems*

Macmillan, R.H., *An Introduction to the Theory of Control in Mechanical Engineering*

1952

Tustin, A., *Direct Current Machines for Control Systems*

1953

Flugge-Lotz, I., *Discontinuous Automatic Control*

Haines, J.E., *Automatic Control of Heating and Air Conditioning*

Jones, R.W., *Electric Control Systems*

Nixon, F.E., *Principles of Automatic Control*

Thaler, R.J., Brown, R.G., *Servomechanism Analysis*

Tustin, A., *Mechanism of Economic Systems*

West, J.C., *Textbook of Servomechanisms*

1954

Ahrendt, W.R., *Servomechanism Practice*

Evans, W.R., *Control System Dynamics*

Fett, G.H., *Feedback Control Systems*

Izawa, K., *Introduction to Automatic Control*

La Joy, M.H., *Industrial Automatic Controls*

Oppelt, W., *Kleines Handbuch Technisches Regelvorgange*

Peters, J., *Einschwingvorgange, Gegenkopplung, Stabilitat*

Profos, P., *Vektorielle Regeltheorie* (2nd edition)

Soroka, W.W., *Analog Methods in Computation and Simulation*

Takahashi, Y., *The Theory of Automatic Control* (in Japanese)

Truxal, J.G., *Feedback Theory and Control System Synthesis*

Tsien, H.S., *Engineering Cybernetics*

Young, A.J., *Process Control*

Bruns, R.A., Saunders, R.M., *Analysis of Feedback Control Systems, Servomechanisms and Automatic Regulators*

1955

Chestnut, H., Mayer, R.W., *Servomechanisms and Regulating Systems Design vol. 2*

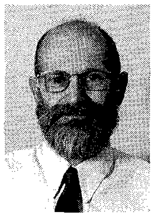
Thaler, G.J., *Elements of Servomechanisms*

Truxal, J.G., *Automatic Control System Synthesis*

Tsypkin, Y.Z., *Theory of Relay Control Systems* (in Russian),

Van Valkenburg, M.E., *Network Analysis*

Young, A.J., *An Introduction to Process Control Systems Design*



Stuart Bennett is a Senior Lecturer in the Department of Automatic Control & Systems Engineering at the University of Sheffield, UK. He teaches computer control and real-time software design. He has written extensively on the history of control engineering and is the author of two books on the subject, one covering the period 1800 to 1930 and the second covering the period 1930 to 1955. During 1988-89 he was a senior postdoctoral fellow at the National Museum of American History, Smithsonian Institution, Washington DC, where he worked on the history of process control.

Bibliographic Note

The books and papers listed below have been used extensively in preparing this article; for details of other papers about the history of control see C.C. Bissell, "Secondary Sources for the History of Control Engineering: An Annotated Bibliography," *International Journal of Control*, vol. 54, 517-28, 1991 (an updated version of this paper is due to appear during 1996).

K.J. Astrom and P. Eykhoff, "System Identification—A Survey," *Automatica*, vol. 7, pp. 123-162, 1971.

M. Athans, "Perspectives in Modern Control Theory," in *Science, Technology, and the Modern Navy, Thirtieth Anniversary 1946-1976*, edited by Edward I. Solkovitz, Department of the Navy, Office of Naval Research, Arlington, Va., p. 143, 1976.

S. Bennett, "The Search for 'Uniform and Equable Motion': A Study of the Early Methods of Control of the Steam Engine," *International Journal of Control*, vol. 21, pp. 113-147, 1975.

S. Bennett, "The Emergence of a Discipline: Automatic Control 1940-1960," *Automatica*, vol. 12, pp. 113-121, 1976.

S. Bennett, *A History of Control Engineering 1800-1930*, Stevenage: Peter Peregrinus, 1979, reprinted 1986.

S. Bennett, "Nicolas Minorsky and the Automatic Steering of Ships," *IEEE Control Systems Magazine*, vol. 4, pp. 10-15, 1984.

S. Bennett, "Harold Hazen and the Theory and Design of Servomechanisms," *Int. J. of Control*, vol. 42, pp. 989-1012, 1985.

S. Bennett, "'The Industrial Instrument—Master of Industry, Servant of Management': Automatic Control in the Process Industries, 1900-1940," *Technology & Culture*, vol. 32, pp. 69-81, 1991.

S. Bennett, "The Development of Process Control Instruments 1900-1940," *Transactions of the Newcomen Society*, vol. 63, pp. 133-164, 1992.

S. Bennett, *A History of Control Engineering 1930-1955*, Stevenage: Peter Peregrinus, 1993.

C.C. Bissell, "Control Engineer and Much More: Aspects of the Work of Aurel Stodola," *Measurement and Control*, vol. 22, pp. 117-122, 1989.

C.C. Bissell, "Stodola, Hurwitz, and the Genesis of the Stability Criterion," *International Journal of Control*, vol. 50, pp. 2313-332, 1989.

G.S. Brown and D.P. Campbell, "Instrument Engineering: Its Growth and Promise in Process-Control Problems," Fall Meeting of Industrial Instruments and Regulators Division of ASME, September 1949. Published in Mechanical Engineering, vol. 72, pp. 124-7 and 136; discussion pp. 587-589, 1950.

M.S. Fagen, ed., A History of Engineering and Science in the Bell System: The Early Years (1875-1925), Murray Hill, NJ: Bell Telephone Laboratories, 1975.

A.T. Fuller, edition of E.J. Routh's *Stability of Motion*, Taylor & Francis, London, 1975.

E. Gerecke, "Theory and Mathematical Methods of Automatic Control Until 1963," *Automatica*, vol. 14, pp. 59-61, 1978.

I. Horowitz, "History of Personal Involvement in Feedback Control Theory," *Control Systems Magazine*, vol. 4, pp. 22-3, 1984.

T.P. Hughes, *Elmer Sperry: Inventor and Engineer*, Baltimore: Johns Hopkins Press, 1971.

R.E Kalman, "On the General Theory of Control Systems," *Proceedings of the First IFAC Congress in Moscow*, vol. 1, pp. 481-492, London, Butterworth, 1960.

A.V. Khramoi, *History of Automation in Russia Before 1917* (Moscow) (in Russian), 1956; English translation, Jerusalem, 1969.

I. Lefkowitz, "Don Eckman and His Impact on Process Control," *Control Systems Magazine*, vol. 4, pp. 32-3, 1984.

A.G.J. MacFarlane, "The Development of Frequency-Response Methods in Automatic Control," *IEEE Trans. on Automatic Control*, vol. AC-24, pp. 250-265, 1979. Reprinted in *Frequency-Response Methods in Control Systems*, New York, IEEE Press, 1979.

P.R. Masani, *Norbert Wiener 1894-1964*, Basel, Birkhauser, 1990.

O. Mayr, *The Origins of Feedback Control*, Cambridge, MA: MIT Press, 1970.

O. Mayr, "Yankee Practice and Engineering Theory: Charles T. Porter and the Dynamics of the High Speed Steam Engine," *Technology and Culture*, vol. 16, pp. 570-602, 1975.

O. Mayr, "Victorian Physicists and Speed Regulation: An Encounter Between Science and Technology," *Notes and Records of the Royal Society of London*, vol. 26, pp. 205-228, 1971.

O. Mayr, "James Clerk Maxwell and the Origins of Cybernetics," *Isis*, vol. 62, pp. 425-444, 1971.

D.C. McDonald, "Non-Linear Techniques for Improving Servo Performance," *Proc. Natl. Electronics Conf.*, vol. 6, pp. 400-21, 1950.

R. Oldenburger, "IFAC, from Idea to Birth," *Automatica*, vol. 14, pp. 53-55, 1978.

E.F. O'Neill, *A History of Engineering and Science in the Bell System: Transmission Technology (1925-1975)*, Murray Hill, NJ: AT&T Bell Laboratories, 1985.

I. Postlethwaite and A.G.J. MacFarlane, *A Complex Variable Approach to the Analysis of Linear Multivariable Feedback Systems*, Lecture Notes in Control and Information Systems, Springer, 1979.

K. Rörentrop, *Entwicklung der modernen Regleungstechnik*, Munich: Oldenbourg, 1971.

P.H. Sydenham, *Measuring Instruments: Tools of Knowledge and Control*, Stevenage: Peter Peregrinus, 1979.

N. Wiener, "Generalized Harmonic Analysis," *Acta Mathematica*, vol. 55, pp. 117-258, 1931.

N. Wiener, Extrapolation, *Interpolation and Smoothing of Stationary Time Series with Engineering Applications*, MIT Press, Cambridge, Mass., 1949.