Int. J. of The Soc. of Mat. Eng. for Resources Vol. 1 No, 1 10~26 (1993)

Plenary Lecture

Control Engineering as an Integrating Discipline from the 17 th to the 21 st Century

by

Brian D. O. Anderson †

Abstract

Control engineering is a discipline that has in part been driven by practice, in part by theory. The earliest drivers were applications problems in the field of time measurement, mills and steam engine speed control. Major control tasks included control with zero steady state error, and achieving fast response to a step change, without instability or excessive overshoot. Work late in the 19 th century provided the first formal solution to the stability problem, and an understanding of the value of integral control. A seventh order water turbine system had been successfully, and scientifically, controlled, by 1900.

In the first half of the 20 th century, electronic amplifier design and then the second world war gave much impetus to the development of control engineering. The methods developed for design were predominantly graphical, and involved adjustment of only a few parameters. The role of high gain, proportional, integral and derivative control all became understood and control engineering ideas found applications throught chemical and mineral industries.

Theoretical developments in the second half of this century have been substantial. Many took some years to be translated into practice, such as LQG design, adaptive control and sampled data control. Aerospace applications requirements drove some of these developments, many of which are now finding their place also in materials processing and handling systems, as diverse as sugar cane mills and chemical process control.

Future developments will arise from applications pressure, and theoretical work. Applications pressure is strong in the areas of robotics, automobiles, discrete-event systems, environmental control ; replacement of existing nonadaptive by adaptive systems will be widespread. Theoretical developments will occur in many areas including nonlinear systems, robust control design and, perhaps, use of time-varying controllers for time-invariant plants.

1. Introduction

The earliest use of Control Engineering probably go back thousands of years, but for the purposes

Received September 5, 1991

† Department of Systems Engineering, Research School of Physical Sciences, Australian National University
GPO Box 4, Canberra ACT 2601, Australia

of this paper, when a starting point had to be defined, we have picked one in the 17 th Century. As explained below, there occured a significant application of Control Engineering at this time (although it was not regarded as such). At the other end of the scale, we have chosen to set a limit of the year 2000. Predictions of the future are notoriously unsafe, and the further one seeks to see, the less confident one can be of the outcome.

For the sake of presentation, but also in reflection of several historical trends, we have chosen to divide the period of the 17 th to the 21 st Century into four epochs. These four epochs of Control Engineering we have chosen to name as :

- Pre-Scientific Control (17th—19th Century)
- The Classical Period (1900—1955)
- the Period of Major Developments (1955—1990)
- The Future (1991—2000)

2. Pre-Scientific Control (17th—19th Century)

The period of Pre-Scientific Control was primarily driven by applications. The applications of course were associated with economic activities. Yet the resolution of the associated imperfectly understood control tasks brought with is a realization of the existence of at least two generic control problems, which one might even call control science problems. Towards the end of the 19 th Century, attempts were made to formally resolve these scientific problems. Let us begin however with a discussion of applications, and the drivng effect they had on the development of control. We nominate four :

- Time-measurement
- Windmills
- Steam engines
- Telescopes

The economic significance of the first three is unquestioned. The economic significance of the last is very little indeed, but as described in more detail below, the work on telescopes gave rise to a major scientific advance. The four applications areas, each of which is described further below, together resulted in at least two control problems being indentified, these being the problems of :

- Securing dynamic stability of a feedback system
- Securing zero steady state error given constant disturbances

Time-measurement Both for its intrinsic worth, and for its help in maintaining accurate navigation for ships at sea, the accurate measurement of time was highly valued. Most clocks of the period relied on the motion of a pendulum. The great 17 th Century physicist Huygens, perhaps better known for his contributions to the theory of light, turned his mind to the question of improving the accuracy of time measurement of the devices of his day. He conceived of the idea of arranging for the pendulum whose period governed the basic advance of the clock hands to become longer when it speeded up. The details of how this is done are rather intricate, and therefore will not be described fully here. For further details see [2]. The crucial concept he employed was to use a conical pendulum, see Fig. 1. *KH* is a vertical axis, *DBGF* forms a plane, and *AB* is carefully designed curved surface. When the pendulum moves, *GF* traces out a conical surface. The effective length of the pendulum is governed by the point where BF is tangential to the surface *AB*, and the

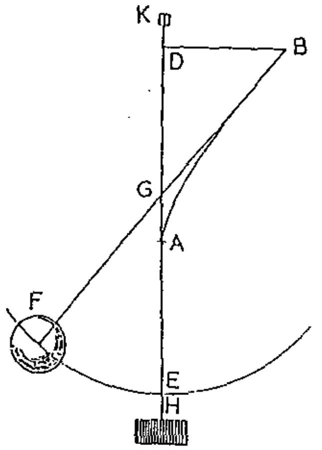

Fig. 1 Part of the conical Pendulum geometry.

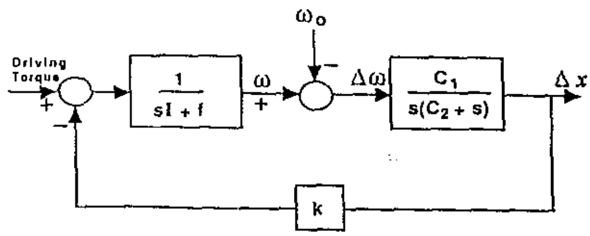

Fig. 2 Modern viewpoint of Huygens conical pendulum.

faster the pendulum swings, and thus the higher is the point F above the point E, the longer is the effective length of the pendulum, and thus the lower the natural frequency. In control systems terms, Fig. 2 can be regarded as a representation of what is happening. The frequency ω_0 is a consequence of the mechanical design, and particularly the design of the curved surface AB, and the frequency ω is the instantaneous angular frequency of the pendulum. The presence of the integrator in the loop ensures that in steady state, the error between ω and ω_0 must go to zero. Evidently, Huygens was addressing the problem of *securing steady state error in the presence of disturbances.*

Windmills A second major application was drawn from the area of windmills. It was necessary for windmills, the prime purpose of which was to crush grain, to be controllable in several respects. First, it was important to be able to turn the massive windmill structure to make its sails face the wind. The solution to this was to use auxiliary sails (a fantail) at right angles to the main sails, with the power developed in the fantail being used to drive the whole main structure around to its correct orientation (see Fig. 3 and Fig. 4). This is an extremely simple set-up in terms of the control science involved. Other uses of control in windmills included :

- Using a centrifugal governor employing fly-balls to control the speed of the windmill sails. With speed-up of the governor, the fly-balls would rise, inducing partial furling of the sails and then a decrease in speed.
- Using a governor to adjust a gap between the crushing stones.
- Using a governor to adjust the rate of grain supply to the stones.

Some elements of a multi-variable design problem can even be discerned here.

Speed control in steam engines The next major advance involved the adaptation of fly-ball governors which had been used on windmills to steam engines. This was a practical technology, full of art, which reached its zenith in the United Kingdom, the home of the steam engine. By the mid 19 th Century, there were between 50,000 and 100,000 Watt governors in use in Great Britain. All these governors had an adjustment capability, and the extensive experience of their operation soon highlighted a fundamental trade-off. *Offset error, ie, error between desired speed and actual speed,*

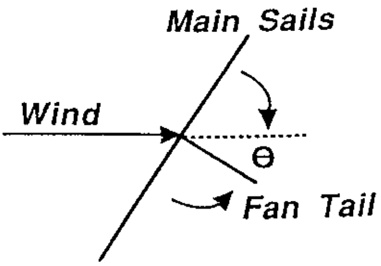

Fig. 3 Angular alignments of wind, main sails and fantail.

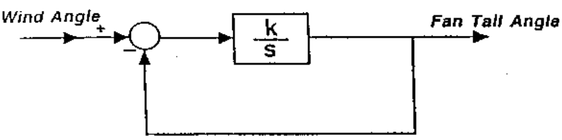

Fig. 4 Modern viewpoint of fantail action.

could only be reduced at the expense of increased overshoot in responding to a step change in level. These days of course, we see much of control engineering, particularly classical control, as embodying the task of picking the right trade-off point between a number of conflicting phenomena. It was the use of Watt governors that first highlighted this trade-off aspect of control engineering.

A rough explanation in control engineering terms is provided by noting that the centrifugal fly-ball governor has a transfer function $k/(c_0 + s^2)$. The design could be modified to secure integral action, thus offering a zero offset error in the steady state response to a step change, in which case the effective transfer function became k/s^2. But now the double, rather than the single, pole at the origin brings with it the likelihood of a stability problem.

Telescopes The fourth major applications area, but as noted above not one driven by economical considerations, was associated with the telescope. Telescopes in Britain in the 19 th Century came under a personage known as the Astronomer Royal, Airy by name. (he was actually the father-in-law on Routh, famous for a later major contribution to control.) Airy was a major scientific figure of his age, with some 500 papers and 11 books to his credit. His contributions are still recognized today in area like mechanical engineering. His particular problem with telescopes was to rotate them at a uniform rate, so that once a telescope was aligned with a heavenly body, it would automatically track the apparent motion of that heavenly body across the sky. The technology he proposed to use was the fly-ball governor, and he quickly became aware of the trade-off which had to be faced between low offset error and tendency to instability. ***He then set out to obtain a scientific understanding of the instability.*** To do this, he brought to bear his considerable knowledge of celestial mechanics to model mathematically the phenomenon he was observing, and this led him [4] to the following equation :

$$\left[\frac{d\theta}{dt}\right]^2 + \frac{a}{\sin^2\theta} - \frac{2q}{b}\cos\theta = c \qquad (1)$$

Even today, with a sophisticated knowledge of control, we might find this equation some what overpowering, and certainly so in terms of its non-linearity. Be that as it may, Airy was able to

- Describe the instability phenomenon with this equation
- Explain how the dynamics could systematically be adjusted (i. e. the knobs set) so as to ensure stability.

Not only was this a considerable tour de force in the scientific sense, but it was the first illustration that ***a control problem was susceptible to analysis via a differential equation.*** Indeed, more than

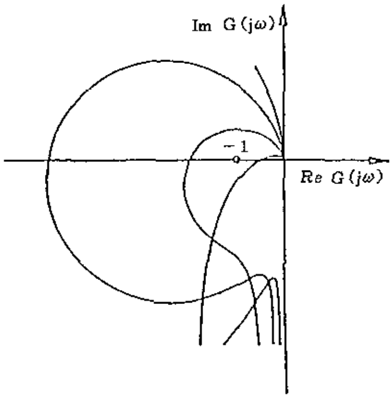

Fig. 5 Nyquist loci for Airy's telescope control with various damping coefficient values.

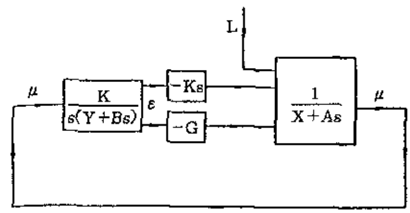

Fig. 6 Block diagram representation of one governor system analysed by Maxwell.

this was true : ***Control design could be regarded as adjusting coefficients in a differential equation to secure properties for its solutions.*** Fig. 5 shows various Nyquist loci for Airy's system, with various values of damping coefficient. Of course, Airy did not use Nyquist loci to analyse his system, and the figure is associated with a linearization of the basic equation.

Another great scientist/engineer of the day was J.C.Maxwell, and he attempted a systematic analysis of governor stability [5], having previously analysed the stability of the rings of the planet Saturn, which is defined by a fourth order system. His analysis of governor stability led him to consider a number of third order equations. A block diagram illustrating one of these systems is shown in Fig. 6. Maxwell also set himself the task of establishing criteria for stability of higher order system, but the problem defeated him. Given his great powers, one must wonder whether or not he devoted his full energies to the problem.

The stability problem in mathematical terms The problem which defeated Maxwell can be posed in mathematical terms as follows. Given a polynomial

$$p(s) = s^n + a_1 s^{n-1} + \cdots + a_n \qquad (2)$$

When dose this polynomial have all its roots with negative real parts ? This problem goes to the heart of one of the scientific problems of control. It is interesting to reflect on three different solutions which were presented to this problem. The solutions appeared as a result of three streams of work, which all seem to be independent one another.

The first stream of work was essentially that of French mathematicians, unpublished work of Cauchy (1831), Sturm [7] (1836) and Hermite [8] (1856). Hermite's paper actually gave a nice solution of the stability problem, nice in the sense that there was a closed form procedure for manipulating the coefficients a_i of $p(s)$ to give a yes/no answer to the question on the roots. Certainly, the roots did not have to be found, and of course for high order polynomials, the methods for finding the roots were at best primitive. Hermite's work was published in French, and was uninterpreted by engineers.

Maxwell in particular did not know of Hermite's work, and conducted some of his work on stability after Hermite had published his work. It was not till 1877 that E.J.Routh in England,

$$
\begin{array}{llllll}
1 & a_2 & a_4 & a_6 & \cdot & \cdot \\
a_1 & a_3 & a_5 & a_7 & \cdot & \cdot \\
b_1 = \dfrac{a_1 a_2 - a_3}{a_1} & b_2 = \dfrac{a_1 a_4 - a_5}{a_1} & b_3 = \dfrac{a_1 a_6 - a_7}{a_1} & b_4 & \cdot & \cdot \\
c_1 = \dfrac{b_1 a_3 - a_1 b_2}{b_1} & c_2 = \dfrac{b_1 a_5 - a_1 b_3}{b_1} & \cdot & \cdot & & \\
\cdot & & & & & \\
\cdot & & & & &
\end{array}
$$

Fig. 7 Routh table.

drawing on the work of Cauchy, Sturm, Maxwell and his father-in-law Airy published a solution to the problem, embracing the Routh table [9]. The Routh table requires one to manipulate the coefficients a_i in a systematic way, and to check for the positivity of the leading entries of the table. Positivity of the entries is equivalent to stability Fig. 7 illustrates the construction of the Routh table.

Stream three in the stability problem was associated largely with Swiss scientists and engineers. The two most important names are Stodola and Hurwitz, who worked right at the end of the 19th Century. Stodola was arguably the first control engineering academic, although he drew on the work of a Russian Vishnegradsky, who chose of water turbines, the equation descriptions of which ranged in order from three to seven. He recognized the nature of the stability problem and turned to his mathematician friend Hurwitz for advice, as a result of which Hurwitz developed the so-called Hurwitz criterion, which requires the checking for positivity of a number of determinants, easily constructed from the a_i [10]. In fact, the polynomial $p(s)$ has all its roots in the left half plane if and only if the following determinantal conditions are satisfied :

$$
a_1 > 0 \,;\; \begin{vmatrix} a_1 & a_3 \\ 1 & a_2 \end{vmatrix} > 0 \,;\; \begin{vmatrix} a_1 & a_3 & a_5 \\ 1 & a_2 & a_4 \\ 0 & a_1 & a_3 \end{vmatrix} > 0 \,;\; \begin{vmatrix} a_1 & a_3 & a_5 & a_7 \\ 1 & a_2 & a_4 & a_6 \\ 0 & a_1 & a_3 & a_5 \\ 0 & 0 & a_2 & a_4 \end{vmatrix} > 0 \cdots \qquad (3)
$$

In summary then, by the end of the 19th Century, one had seen two control science problems arise out of control applications problems, and in the case of the stability problem when posed with differential equations, a solution had been identified.

3. The Classical period (1900—1955)

In this section of the paper, we shall indicate very briefly indeed a number of advances which occured in the Classical Period, and then focus on several. We shall then indicate some of the shortcomings.

There were two major driving forces for control during the Classical Period. One driving force was indirect, and that was electronic amplifier design. A great many control advances came about because people were trying to understand not how to design a control system, but how to design an electronic amplifier when the active element in the amplifier, at that time a vacuum tube, could have characteristic which varied very substantially over the useful life of the device. It was probably not until World War II that control applications needs became the real driving force for the development of control.

Over the period 1900—1955, there were a number of theoretical advances, and recognition of applicability of analysis tools. These included :

- Formal recognition of the feedback concept
- System description via transfer functions and Fourier transforms
- The Nyquist criterion for stability
- The use of Bode diagrams and Nichols charts as a way of representing system behaviour
- The Routh test (actually available from 1877)
- The use of root locus as a tool for studying the effect of a design parameter variation
- An understanding of the benefits and costs of high loop gain
- The general recognition that much design was a matter of trade-offs

We shall say more about the Nyquist criterion and high loop gain below. Particular design ideas evolving in the period included :

- Position feedback
- Rate feedback
- Integral feedback with its implications for zero offset error
- PID controllers in effect a combination of position, rate and integral feedback
- Lead and lag compensation (and varieties thereof)
- General graphical procedures

The thinking at the end of this period, including discussion of the Nyquist criterion and high loop gain, is well reflected in [11].

Nyquist's contribution A truly outstanding development in the period was the Nyquist criterion. The Nyquist criterion represented a massive piece of lateral thinking, in that its starting point for the determination of stability was nothing like that used in the only other approach to stability available to that time, that is the approach based on differential equations. Instead, the Nyquist Criterion took as its starting point the availability of a system description obtained using physical measurements, ie. a frequency domain description of the system, and in fact one represented in particular graphical form. No differential equation was needed, and there was in fact no restriction to systems which could be described by an ordinary differential equation. Not only was the system description totally different to that which had been used before, but the way of describing the Nyquist test-involving as it does a topological property of a graph-together with a way of proving it-based on complex variable theory-represented a total departure from the past. To recall what the Nyquist criterion is, consider the setup of Fig. 8, in which P is notionally a plant and C a contoller. (many earlier treatments considered just one block, which we can think of as PC.) Suppose there is no unstable pole-zero cancellation between C and P. Then there is plotted in the complexplane as a function of ω the values of the loop transfer function $P(j\omega)\ C(j\omega)$, and one counts the number of encirclements of the point -1 made by the graph in the counter-clockwise direction, with the arrows on the graph pointing in the direction of increasing ω. See Fig. 9. If

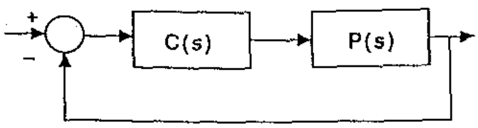

Fig. 8 Feedback system.

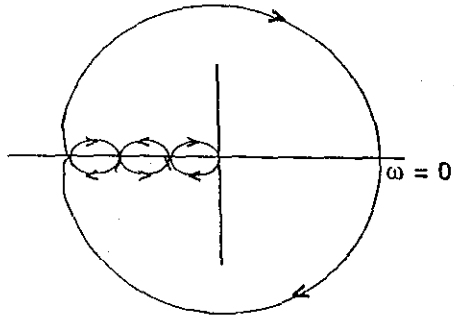

Fig. 9 Nyquist plot.

and only if the number of unstable poles of PC is equal to the number of encirclements of the -1 point, the closed loop is stable.

High Loop Gain Another one of the major areas in which conceptual understanding was reached during the Classical Control era concerned the trade-offs available through high loop gain. Consider Fig. 10. The loop gain is PC which is of course a frequency dependent gain. The output y is related to the input r, the disturbance d and the sensor noise n in accordance with

$$y = \frac{PC}{1+PC}\, r + \frac{1}{1+PC}\, d - \frac{PC}{1+PC}\, n \tag{4}$$

and the plant input u is related to r, d and n by

$$u = \frac{1}{P}\,\frac{PC}{1+PC}\,(r-d-n) \tag{5}$$

The positive effects of high loop gain were identified as

• The ability to suppress some effects of plant gain variation ; in today's jargon, this would be termed securing Robust Control, but the original concept was to secure insensitivity of overall performance to the gain variations of a vacuum tube in an electronic amplifier

• To reduce the effect seen at the output of additive disturbances, d. Reference to equation (4) above shows that the bigger PC is the smaller will be the contribution of d to the output y. The point of the feedback is to measure the changes in the output introduced by d and feed them back so as to exert a countervailing effect.

• Promote better tracking by the output of a reference input. Again, reference to equation

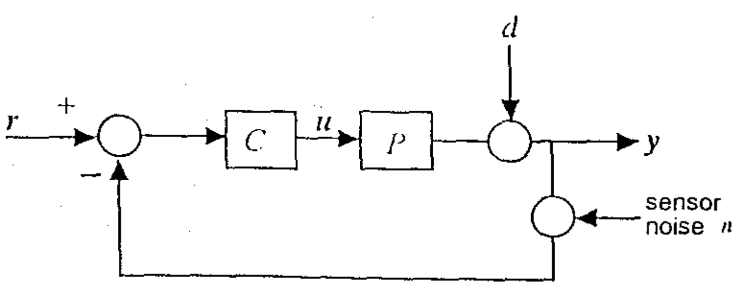

Fig. 10 Feedback system including disturbance and noise.

(4) shows that as PC becomes very large, y must become closer and closer to r, neglecting for the moment the effects of d and n.

High loop gain is not without is disadvantages, and in particular it can

- Induce high gain instability or ringing
- Worsen sensor noise problems
- Cause the plant input to saturate

In relation to this last point, consider the equation for u above, and suppose PC is made very large at a frequency which P has become small. Then, neglecting the effect of d and n, u will be approximately $P^{-1}r$, and thus a very large quantity ; of course, in the event of plant input saturation, the linear analysis giving rise to the above equations is no longer valid.

One could sum up the overall design flavour of Classical Period by saying

- It was graphical
- Designers could only play at any one time with a limited number of parameters
- It was rule of thumb oriented (such and such a gain margin is desirable, such and such a phase margin is desirable, etc.)

The shortcomings were reasonably clear. Thus it was clearly a disadvantage that at any one time one conld only study the variation of a limited number of design parameters, and the extensive use of graphs for representing systems carried an inherent limitation. More broad criticisms included :

- The impossibility of systematic multivariable design
- The impossibility of design for time-varying systems
- The normal inability to perform optimization
- The inability to handle (other than on the most rudimentary basis) stochastic or noise problems.

There were some other developments in the Classical Period. Pre-figuring the computer age, a start had been made on the development of sampled data theory, but there were no text books by 1955. Attempts were made at handling non-linear systems by describing functions (a Procrustean approach and as such one for which is proved very hard to ever get adequate theoretical justification), and phase plane analysis (with its inherent limitation on the dimensionality of problems which could be considered). Relay control was also attempted, and actually used in the German V-weapons of World War II. Wiener filtering represented a major advance, the full exploitation of which had not occurred really by 1955.

4. The Period of Major Developments (1955—1990)

During the period 1955 to 1990, a number of subfields of control were developed very substantially, and new applications found. New viewpoints for description, analysis and synthesis of control systems were found, and it became necessary for control engineers to use new background tools. What were the driving forces during this period? For most of the period, the strongest driving forces were probably those associated with defence, and the cold war. Vast amounts of research work were supported by military or quasi-military agencies, and academics themselves played a significant role in setting the research agenda. Applications of control in civilian industries may have occured more as a result of fallout from the defence-driven work rather than because those industries themselves drove forward the development of control engineering.

Four subfields stand out from among the many which achieved major development during the three and a half decades. These are

- Sampled data control
- (LQG) Linear-Quadratic-Gaussian design including multivariable system design
- Adaptive control (including identification)
- Non-linear and time-varying systems

We will examine some particular issues below.

During the period too, the use of state-variable descriptions came to play a prominent role, and after early ideological discussions that sought to argue that it was better to describe a system in time-domain terms than frequency-domain terms or vice-versa, or better to describe it in state-variable terms than transfer function terms, or vice-versa, it became recognized that one should best work with a multiplicity of descriptions. Viewpoints were also conditioned by the availability of computers and subsequently the availability of very sophisticated design packages. These design packages today include extensive simulation capability, and capability for switching of system descriptions from one type to another.

To understand the textbooks, and in particular the sophisticated design packages, control engineers needed to learn some matrix algebra, needed to understand some properties of differential equations, and preferably needed to acquire some understanding of random processes.

In some succeeding paragraphs, we will highlight some particular problems which arose in three of the subfields mentioned above. They are problems with which the author has had a close personal association, and have been selected for this reason.

Sampled-data control The first problem is in the sampled-data control area. In sampled-data control, one seeks to avoid using a continuous-time controller, and rather one plans to use a discrete-time controller (together with a sampling element and hold element; an anti-aliasing filter is also normally used, but this is inessential for the present discussion). Quite frequently, it can be the case that a continuous-time controller is design and it is then to be replaced for the purposes of implementation by a discrete-time controller, see Fig. 11. The question then arises as to how the discrete-time controller $C_d(z)$ should be found from the continuous-time controller $C(s)$. Many methods can be found in textbooks for answering this question [12-13]. But it is wrong question. What is the right question? The right question is: How should $C_d(z)$ found from $C(s)$ and $P(s)$? Why is this right question? The answer is that we are seeking, in replacing a continuous-time controller by a discrete-time controller, to preserve as far as possible the closed-loop properties. These closed-loop properties depend on the plant $P(s)$ as well as the controller. It fllows that the plant has to affect the definition of what the best discrete-time controller is. This simple difference in viewpoint in a way goes to the heart of what distinguishes control from signal processing;

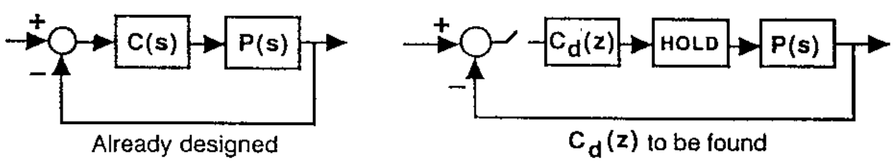

Fig. 11 Controller discretization.

all the time, it is closed-loop behaviour that is relevant, and not the behaviour of an entity by itself.

One of the first applications of "the right question" was to design of controllers for the Australia Telescope. Conventional, ie. text-book methods for the generation of a discrete-time controller from a continuous-time controller were found to fail with the Australia Telescope. The design engineers determined what the right question was, and then developed a way of solving is [14-15]. More recently, general theoretical tools have been developed for answering the right question [16-18].

LQG design Our second example is drawn from the field of Linear-Quadratic-Gaussian design [19]. This design procedure allows treatment of high dimension multi-variable plants, with noise. For example, a pitch control system for a commercial aeroplane has two inputs (the flaps and the aileron settings) and two outputs (the attitude and the angilar velocity). The differential equations contain some 40 to 50 states, and there is a stochastic disturbance in the form of wind, for which a good model is available, as well as noise on the sensors. The key theoretical idea of Linear-Quadratic-Gaussian design is embodied in Fig. 12. The controller consists of a state estimator, which is a device for estimating the internal state of the system, in the case the aeroplane, together with a control law, which constructs values for the input based on the state estimate. The state estimator, or Kalman Filter, won for its originator the Kyoto prize in 1986. Linear-Quadratic-Gaussian design is a marvellous tool, which has required some time for people to understand. One of the difficult issues is how one should tune the software knobs, that is the design parameters. A second, and hitherto not fully resolved issue, is how one should design to obtain a controller which will cope with plant parameter variations. The third issue is that the design procedure in its raw form leads to a controller with the same complexity as the system, thus in the aeroplane example above, the controller would contain 40 to 50 states. This is in many situations simply unacceptable, and the question arises as to how a simple controller could be obtained.

One aircraft company with which the author has been associated several years ago indicated that an LQG design could be obtained efficiently, and which was statisfactory in all respects except for the order of the controller. Because the order of the controller was too high, an alternative design method had to be obtained yielding a simple controller. This design took 200 man-years and was obtained largely by trial and error. The importance of obtaining an algorithm which would allow systematic simplification of a complicated controller is evident. A survey of work on this problem is to be found in [20], and within the last year, the author and colleagues at ANU have

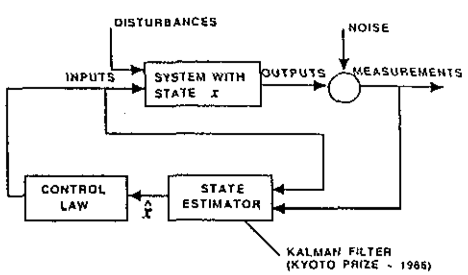

Fig. 12 Key theoretical idea of linear-quadratic-gaussian design.

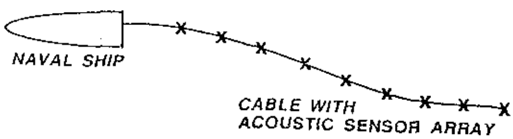

Fig. 13 Towed array.

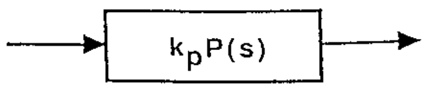

Fig. 14 Plant with unknown gain.

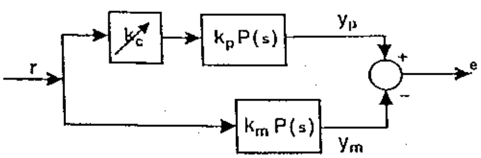

Fig. 15 System for learning k_p.

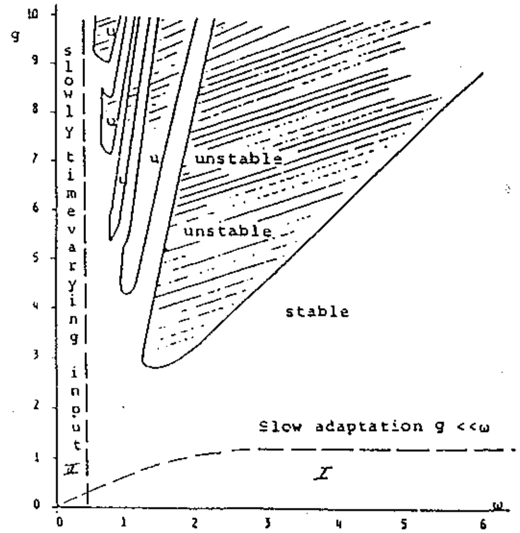

Fig. 16 Behhviour of MIT rule for differing gain and frequency.

written some commercial software which will be included in the premium CAD control systems package MATRIXx marketed by Integrated Systems Incorporated, to achieve model and controller reduction.

Kalman Filter The Kalman filter is not just a constituent of an LQG design, but an important and versatile tool in its own right. We give another application illustrating its use, [21-22]. Submarines can be searched for using a towed array of acoustic sensorsm see Fig. 13. Tha array is mounted on a cable, the motion of which is described by a fourth order nonlinear partial differential equations, with some random excitation due to currents etc. Accurate knowledge of array shape is necessary to obtain the advantage of having an array of acoustic sensors. By mounting compasses on the cable and using Kalman filter theory, an array shape estimator can be obtained.

Adaptive Control Another example is drawn from the field of adaptive control, and reminds us of the old maxim that there is nothing so practical as a good theory. One of the original questions of adaptive control, now some 30 years old, is depicted in Fig. 14. The plant $P(s)$ is known, but the gain k_p is not. We are faced with the question of designing a controller that learns k_p, either explicitly, or implicitly. An early approach to this problem was provided by MIT rule (refer to Fig. 14 and 15). In Fig. 15, k_m is a known gain, and it is clear that the error will be identically zero for all inputs r if and only if $k_c k_p = k_m$. The gain k_c is adjustable and Known, so that if an adjustment process can be found which results in e being identically equal to zero for all inputs, k_p will have been effectively identified. The MIT rule is a suggestion for a procedure for adjusting k_c, and is :

$$\dot{k}_c = -g\,[y_p - y_m]\,y_m \qquad (6)$$

In this equation, g is a positive gain (termed the adaptive gain), and $y_p - y_m$ will be recognized as the error e. Thus, if the error is identically zero, the gain k_c will remain constant. There is a heuristic justification of the MIT rule, but more important is the question of how it performs. Its

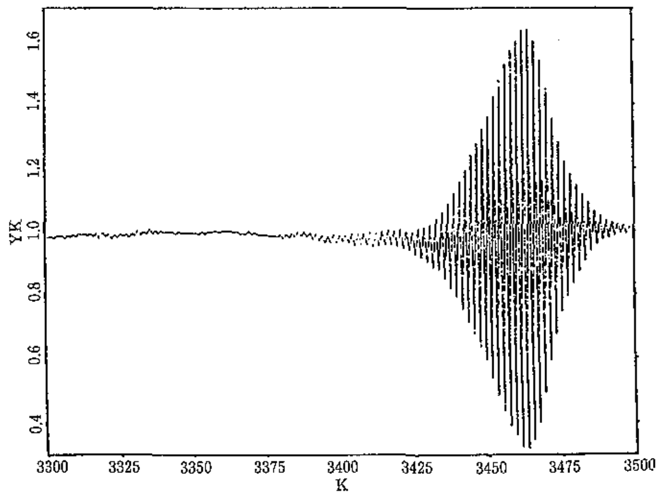

Fig. 17 Illustration of bursting in adaptive system with insufficient excitation.

performance can be reviewed for sinusoidal inputs r and for different levels of adaptive gain g and frequency, Fig. 16 sums up the situation. The very surprising result is that there are combinations *of gain and input frequency for which one has stability and their combinations for which one has* instability, without any clear pattern or apparent logic as to whether a given gain-frequency pair will be stable or unstable. If time delay is introduced in the plant, the situation is different again, with major changes to the regions. Workers were unable to explain why this happened, and because they were unable to explain why this happened, they were unable to predict the performance of the MIT rule and its derivatives in similar but different and sometimes more sophisticated situations. Because then there was no theory, there was effectively no use of adaptive control from 15 to 20 years. The subject went to sleep for many years, until new approaches to adaptive control were found : the theory for the MIT rule first became available around 1986, and then enabled consideration of many other adaptive schemes [25, 26].

The new approaches first referred to were not without their surprise. Round 1983, there were several reports of adaptive control implementations in which, after a very long period of satisfactory behaviour, eg. a week, osillatory behaviour apparently spontaneously occurred, but then died down again (see Fig. 17). This phenomenon became known as "bursting". Fortunately, a theoretical or scientific explanation for bursting was found without great difficulty, see [27]. The underlying cause is as follows. An adaptive controller usually attempts, implicitly or explicitly, to identify the plant to which it is connected. When a plant is subjected to a constant input (as was typical when bursting was encountered), it is impossible to identify more than one piece of imformation about the plant, viz its DC gain. Does this, the identifying part of the adaptive controller attempts to identify the whole plant, and that part of it identifying other than the DC gain is given in effect just by noise. Accordingly, the identifier is likely to be wrong about everything except the DC gain : errors in estimating the plant then lead to an inappropriate controller, and eventually instability. With instability, the signals entering the plant suddenly become richer, its

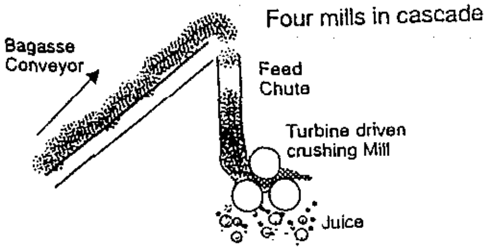

Fig. 18 Sugar cane crushing mill.

Fig. 19 Alumina calciner.

accurate identification becomes possible, the controller becomes correct, and stability is reencountered. The need to ensure proper excitation ("persistent excitation") when identifying a plant is now accepted as one of the standard requirements in any adaptive system, [26].

Adaptive control has now reached a certain stage of maturity, which means that applications are now becoming widespread.

Fig. 18 illustrates an application, with which colleagues of the auther have been involved, to a sugar mill crushing system. The system has effectively 2 inputs and 2 outputs, the inputs being the turbine governor setting and torque, with the turbine driving the crushing mill. The controlled signals are the feed chute height, and the chute aperture, which governs the feed rate to the crushers. Better extraction comes from better height control, and very sharp variations in the physical parameters of the feedstock of sugar cane occur. Adaptive generalised predictive control is possible for one loop, with fixed control for another loop.

An even more sophiscated application is provided by an aluminium calciner ([28]-see Fig. 19). The control variables are the discharge alumina temperature, which governs product quality ; the temperature fluctuation in the kiln, which governs the maintenance cost ; and the energy consumption. The controlling variables are the bauxite feed rate, the oil mass feed rate for the oil burner and the air mass feed rate for the burner. Besides the obvious measurements, the temperature at the bauxite gas can be obtainned. The system contains time lag, is multivariable, and only the crudest of physical models is available. Nevertheless, adaptive control using a Smith predictor achieves very effective results.

There is almost always a time lag between the generation of theory and its use and practice. Adaptive control has proved no exception, but the number of successful practical applications of the theory leave no doubt now as to its great usefulness as a particular control technology.

5. The Future (1991—2000)

The future will be driven by applications challenges, and the carrying forward of the current directions of theoretical development. There can be enormous argument about which are the most important applications challenges, and the author only tentatively lists some of these :

- **The Environment** : Legislation the world over is requiring industrial units to control their waste and legislation the world over is likely to increase demands for more efficient use of energy. Both these legislative thrusts translate themselves into a demand for effective application of control.

• **Automobiles** : Automobiles represent a mature technology, but the application of control in automobiles has been comparatively primitive. Engine control, braking control and suspension control represent three possibilities.

• **Robots** : Robots have already captured the attention of control engineers. They will continue to do so, as control engineers attempt to cope with flexibility in the robots, adaptive control problems associated with robot, maximization of speed, and the like.

• **Discrete-Event Systems** : What are the control problems for an airport with freight, passengers and planes arriving and departing in a stochastic fashion, with all sorts of costs applying to different stages of their activity ?

• **Adaptive Control** : There is enormous scope for the application of adaptive control systems insituations where at present non-adaptive control is used. To squeeze several percent improvement in productivity in a plant can translate to millions of dollars of savings in a year.

There are a number of exciting directions of theoretical development also. These include :

• The use of so-called H^{∞} control as a design tool. This shows as much promise as linear quadratic Gaussian design, it appears suited for similar problems, but at the same time, it does seem more closely tied to classical control ideas and the sorts of constraints that come up in classical control than does LQg design.

• Progress on time-delay systems, especially adaptive time-delay systems.

• Non-linear control. A very interesting survey of the applications of major new theoretical develpoments in non-linear control to the process control industry can be found in [29].

• Robust Control (An example is given below)

• Time-varying control for time invariant systems (an example is given below)

What is Robust control ? See Fig. 20. The plant is designed by $P(s;\alpha)$, because the transfer function of the plant depends on some parameter, typically a physical parameter α, which can vary during the course of the operation of plant. Thus α could be an air pressure, temperature, a dryness, a friction coefficient, etc, and may indeed be a vector, ie, the plant depends on several scalar physical parameters. Analysis is the first question that may be faced. Consider Fig. 21. One could formulate the question : Is it enough to check for stability at the parameter settings corresponding to points *A, B, C,* and *D* in order to conclude stability for the whole of the allowed parameter region ? More generally, one could ask : If a controller $C(s)$ gives adequate performance at *A, B, C* and *D*, will it give adequate performance for all allowed vales of the parameters ? And once the analysis problem is solved, the design problem comes up. How can one design a controller that will work satisfacorily for all allowed parameter settings ? (Before this actually, there comes the question : Can such a controller exist, or must one necessarily turn to an adaptive control approach to adequately control the plant?)

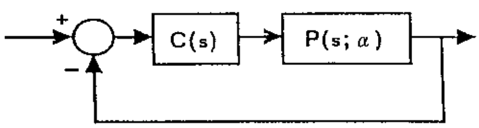

Fig. 20 Robust control.

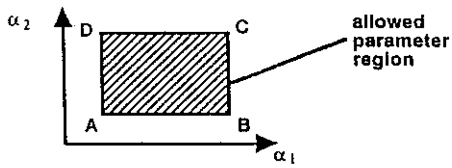

Fig. 21 Parameter variations.

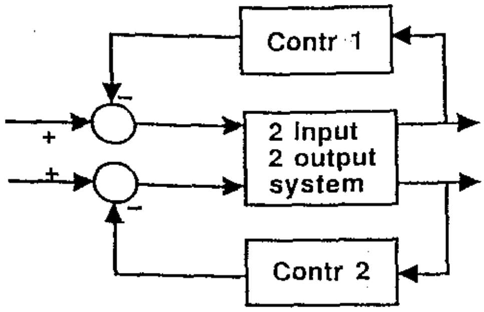

Fig. 22 Decentralized control.

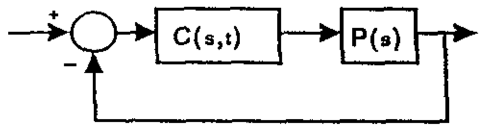

Fig. 23 Use of time-varying controller for a time-invariant plant.

The second example we give is tied to time-varying control. Consider the arrangement in Fig. 22. The example is artificial, but it is to make a particular point. The control structure in the figure is termed decentralized, because input 1 can only be affected through feedback from output 1 and input 2 can only be affected through feedback from output 2. Now it is a fact that there exist some 2 inputs, 2 output, linear time-invariant systems which cannot be stabilized by any choice of decentralized linear time-invariant controllers. *Nevertheless, such systems can be stabilized by decentralized linear controllers which are periodically time-varying,* [30]. The feedback controllers switch at periodic intervals between one transfer function and another transfer function.

This is a remarkable fact, because it shows that one can do strictly more with time-varying controllers than *one can with time-invariant controllers, even for a time-invariant plant.* It naturally then raises the question of what actually can be done in practice that is useful with time-varying controllers that cannot be done with time-invariant controllers, all for a time-invariant plant (see Fig. 23). Almost no answers are available to this question at the moment. One fact which can be achieve the same level of disturbance suppression, it is normally always possible to get a better gain margin with the time-variant controller than the time-invariant controller, [31]. But such an isolated statement is an enormous distance from a full understanding of the possibilities, and there is at this stage no cohesive design theory.

6. Conclusions

Control engineering has come a long way in four centuries. In most of that journey, it has been applications driven, and this will occur in the future. Nevertheless, it is quite clear from the significant theoretical work going on at the moment that the scientific content of control will develop also substantially in the future, and interact with the applications demands to solve problems more effectively than we have dreamt, and to solve problems that up to now we have not dreamt of being able to solve.

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