

Adaptive Control Around 1960

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This paper presents some of the developments of adaptive control during a 10-year period around 1960. This was a very fertile period when many ideas were developed that later proved useful. The motivation came from several sources—advances in control theory, demanding applications in flight control and process control, the desire to develop systems with learning capabilities, and problems related to decision-making under uncertainty.

There are several reasons for focusing on the period from the mid-1950s to the mid-1960s. Automatic control was well established as a discipline, and it was emerging as an essential tool for practically all engineers. Courses based on servomechanism theory were given to large groups of engineering students. There was a very dynamic development of control theory, and the fields of applications were expanding significantly. A number of useful ideas on adaptive control were proposed: the model reference adaptive system, the self-tuning regulator, extremal control, dual control, and neural networks. It would, however, take many years before the ideas were well understood and useful practical control systems were in operation. There was also a significant interest in cybernetics in that time; see [24] and [2].

This article deals almost exclusively with development in the Western world, the reason being that much material from that region is easily accessible. There were undoubtedly significant developments in other parts of the world that also deserve treatment to get a balanced perspective.

Interest in adaptive control grew significantly in the mid-1950s. Flight control was a strong driving force. There was also interest in process control, particularly because of the emerging interest in computer-controlled systems. There are several sources of information from this period. An overview of the state of the art at the beginning of the period is found in the survey paper [1]. Much interesting material arising from the work in flight control is found in the proceedings of the Self Adaptive Flight Control Systems Symposium held at the Wright Air Development Center, Jan. 13-14, 1959 (see [12]). Many adaptive schemes were presented at that meeting, particularly model reference adaptive systems, which proved to be of lasting value. Part of the material from the symposium is also available in the book [16]. Several participants of the Wright Patterson symposium also contributed to the Symposium on Adaptive Control Systems held in Garden City, Long Island, in October 1960 (see [7]). This proceedings also contain other interesting papers, e.g., a paper by Widrow that uses neural networks for adaptive control. This paper was inspired by early work on adaptive filtering

by Gabor (see [11]). There were also sessions on adaptive control at the first IFAC World Congress in Moscow, 1960, and at subsequent congresses. When the IEEE conference on Decision and Control started in 1962 it also included a Symposium on Adaptive Processes, which continued through the 20th CDC in 1981. There were two IFAC symposia on the Theory of Self-Adaptive Control Systems, the first in Rome in 1962 and the second in Teddington in 1965. The proceedings from the last symposium was published in book form (see [13]).

Process control was another source of inspiration. The first use of digital computers for process control was the TRW installation at the Texaco refinery at Port Arthur. This work started in March 1956, and the system went on-line in March 1959. There was much discussion of the best way of using digital computers for control. An important contribution to adaptive control was given in [14], which is the origin of the self-tuning regulator.

Yet another source of inspiration came from the development of dynamic programming [4]. The book [5] shows how dynamic programming can be used in adaptive control. This work also inspired the work by Feldbaum, who observed that in the presence of uncertainties, control “should be directing as well as investigating.” The catchword “dual control” was coined to capture this property [9].

The Brave Era

The title for this section derives from the cowboy attitude toward control systems development at the time. There was a very short path from idea to flight test, with very little theoretical analysis in between. Supersonic flight posed new challenges for flight control, and control systems for ballistic missiles emerged as an important topic in the post-Sputnik era. Interesting insights into these problems, which strongly influenced the development of adaptive control, are found in [12]. Among the introductory remarks by the chairman, we find the following introductory statement by Maj. Gen. L.I. Davis:

“My interest, of course, stems from the very fundamental relationships that exist in all our military weapon systems. I like to use the analogy of the three-legged milking stool, with the seat representing the warhead: one leg representing aerodynamics; another leg, propulsion systems; and the third leg representing guidance and control. Without any of these legs you don’t have an effective military weapon.”

The need for an integrated view of control can hardly be expressed in a better way. A little later he comments on the amount of effort spent on aerodynamics and propulsion, then remarks:

“It is my feeling that we don’t have a corresponding amount of effort on this other leg of the stool representing guidance and control including the adaptive control system.”

In the introduction by Lt. P.C. Gregory, he mentions that the Air Force had been supporting work for three years, particularly mentioning two projects: a contract to flight-test the MIT system

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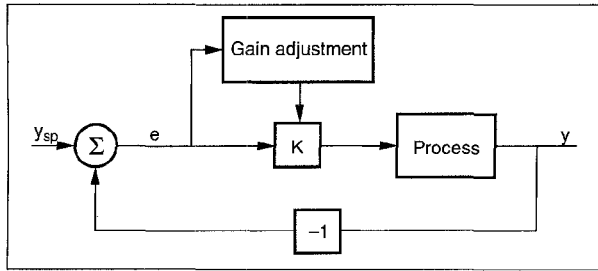


Fig. 1. Block diagram of the General Electric Adaptive system.

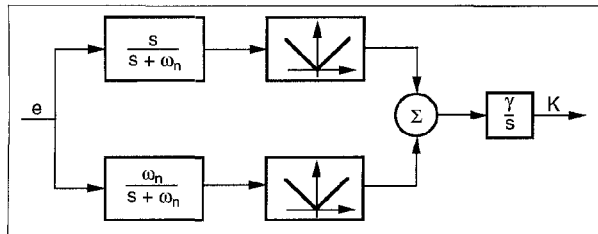


Fig. 2. Mechanism for adjusting the gain in the General Electric Adaptive system.

(a model reference adaptive control system) on an F-101A, and a future contract to flight-test a system developed by Honeywell. Several interesting systems were developed during this period. Two of them will be discussed below, while the model reference adaptive system will be discussed in a later section.

The General Electric System

This system was developed by General Electric ([15]), and is based on the idea of adjusting the gain so that the closed-loop system has the desired behavior. A block diagram of the system is shown in Fig. 1.

Only the loop gain is adjusted, based on the idea that for the classes of systems considered, a high gain leads to an oscillatory system and a low gain gives a sluggish performance. The actual mechanism used is shown in Fig. 2.

It attempts to adjust the gain so that the average energy of the error signal has equal energy above and below a critical frequency.

The Honeywell System

This system is described in [18]. It is inspired by the idea that a two-degree-of-freedom system with a high-gain feedback and a feedforward compensator is insensitive to plant variations. The design goal was to construct a system where the gain is always kept as high as possible. A block diagram of the system is shown in Fig. 3.

A key idea is to introduce a relay in the loop, creating a limit cycle oscillation. By choosing a proper filter, the frequency of the limit cycle is made higher than the desired loop gain. There is an additional loop that adjusts the amplitude of the relay. Using a dual input describing function analysis, it can be shown that the transmission of signals with frequencies much lower than the limit cycle will have a loop transfer function such that the amplitude margin is $a_m = 2$, independent of the gain of the process [3]. This is indeed a remarkable property.

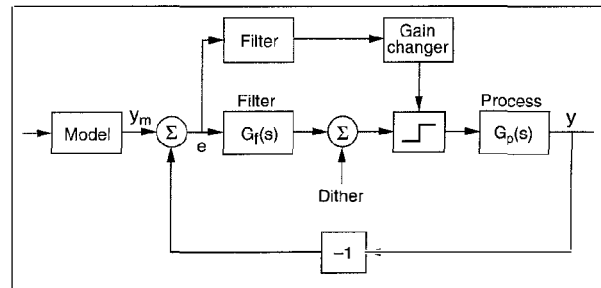


Fig. 3. Block diagram of a self-oscillating adaptive system (SOAS).

A limit cycle oscillation is always present in the system; it is therefore called a self-oscillating adaptive system (SOAS). The problem is to design the system so that this oscillation is acceptable. The oscillation can be influenced by the design of the filter and the gain changer. It is desirable to keep the amplitude of the relay small to have small amplitude of the limit cycle. The relay amplitude must, however, be large to have a fast response to command signals. The behavior of the system is illustrated in the simulation in Fig. 4.

The SOAS is an adaptive controller where perturbations are introduced intentionally to excite the system. The SOAS is one of the simplest systems with this property. Another possibility is to inject a sinusoidal signal of a given frequency. This is done in some recent systems for CD players.

The SOAS has been flight-tested in the F-94C, the F-101, and the X-15 aircraft and it is used in several missiles where the limit cycle oscillation is not as much of a drawback as in piloted aircrafts. The system has been tested in process control applications, but it is not widely used.

Model Reference Adaptive Control

Both Honeywell's and General Electric's systems were quite special systems where only the controller gains were adjusted. The model reference adaptive system is another more general way to solve the flight control problem. This system was presented in the paper [21], which was based on the report [22].

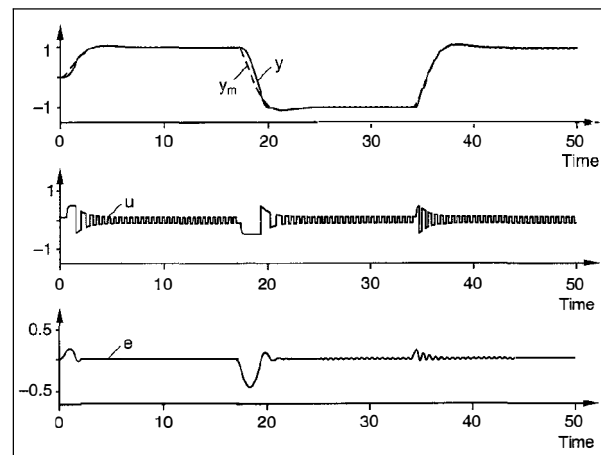


Fig. 4. Simulation of an SOAS with a lead network and a gain changer. The dashed line shows the desired response y_m from [3].

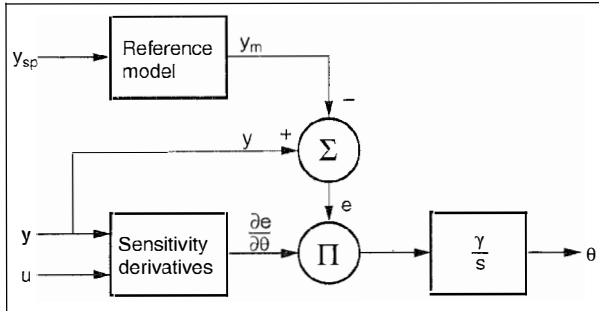


Fig. 5. Block diagram of the parameter adjustment mechanism in a model-reference adaptive system (MRAS).

This system is based on the idea of specifying the performance of a servo system by a model that gives the desired transfer function from command signal to process output. This was later called model following.

The parameter adjustment is based on the error e , which is the difference between the process output y and the model output y_m . An important contribution of Whitaker was a mechanism for parameter adjustment. His idea was simply to change the parameters by

$$\frac{d\theta}{dt} = -\gamma e \frac{\partial e}{\partial \theta}, \quad (1)$$

where $\partial e / \partial \theta$ is the sensitivity derivative. Because of difficulties in implementation, the following algorithm was also used:

$$\frac{d\theta}{dt} = -\gamma e \operatorname{sign} \left(\frac{\partial e}{\partial \theta} \right). \quad (2)$$

The principle of a model reference adaptive system is shown in Fig. 5. The model reference adaptive systems (MRAS) used in flight tests were implemented with analog techniques. The crucial operation was the multiplication followed by the integration to generate the controller gain θ . There were many practical problems with the tests because of difficulties with the hardware. The report [22] gives a good indication of the state of the art of the hardware. The following quote is a sample:

“Aside from the listing above, pot drift (all pots but pitch) was a constant source of trouble.”

The performance of the system is illustrated in Fig. 6, which is a sample of flight-test data.

The Stability Problem

Experiments and simulations of model reference adaptive systems indicated that there could be problems with instability, in particular if the adaptation gain, γ in Equation (1) were large. This observation inspired a lot of theoretical work on adaptive control systems. The paper [6] was a pioneering work where the stability problem was approached using Lyapunov theory. Much research was directed toward replacing the MIT-rule by other parameter adjustment rules where stability could be guaranteed. In [17] it was shown that stable systems could be obtained if all state variables are measured. For systems with output feedback, the problem could be solved only if the transfer function were strictly positive real. This observation established the connec-

tions with hyperstability theory. This was the beginning of very fruitful work on stability of adaptive control that culminated in the early 1980s. An account of this interesting work is outside the scope of this paper; see [3] for a technical discussion.

Ironically the solution to the flight control problem was given by gain scheduling and not by adaptive control [20]. The self-oscillating adaptive control system has, however, been used in several missiles.

The Self-Tuning Regulator

While the model reference adaptive system was inspired by flight control, the inspiration for the self-tuning regulator (STR) came from process control. DuPont had joint studies with IBM aimed at computerized process control. Kalman worked for a short time at the Engineering Research Laboratory at DuPont. During this time he started work that led to the paper [14], which is the origin of the self-tuning regulator. Citing from the abstract of this paper:

“This paper examines the problem of building a machine which adjusts itself automatically to control an arbitrary dynamic process.”

The controller proposed by Kalman can be characterized in the following way:

- The dynamic characteristics of the process are characterized by the discrete time model

$$\sum_{i=0}^n b_i c_{k-i} = \sum_{i=0}^n a_i m_{k-i},$$

where m is the control variable and c the measured variable.

- The parameters of the model are determined by least squares at each sampling interval.
- The choice of the optimal controller is largely arbitrary, depending on what aspect of the response is to be optimized. The determination of the coefficient of the controller is a routine matter if the coefficients of the pulse-transfer function are known.

In the paper Kalman also describes a special-purpose hybrid computer that was built at Columbia University to implement the controller for systems of second order (essentially an analog computer with periodic switching between operate and hold). The following quote from the paper gives an interesting view on the development of digital computing:

“As soon as the operations discussed in the foregoing sections have been reduced to a set of numerical calculations (see Appendix) the machine has been synthesized in principle. This means that any general-purpose digital computer can be programmed to act as the self-optimizing machine. In practical applications, however, a general-purpose digital computer is an expensive, bulky, extremely complex, and somewhat awkward piece of equipment. Moreover, the computational capabilities (speed, storage capacity, accuracy) of even the smaller commercially available general-purpose digital computers are considerably in excess of what is demanded in performing the computations listed in the Appendix. For these reasons, a small special-purpose computer was constructed.”

Much work on the self-tuning regulator was done in the 1970s and 1980s. It turns out that the regulator has many unexpected

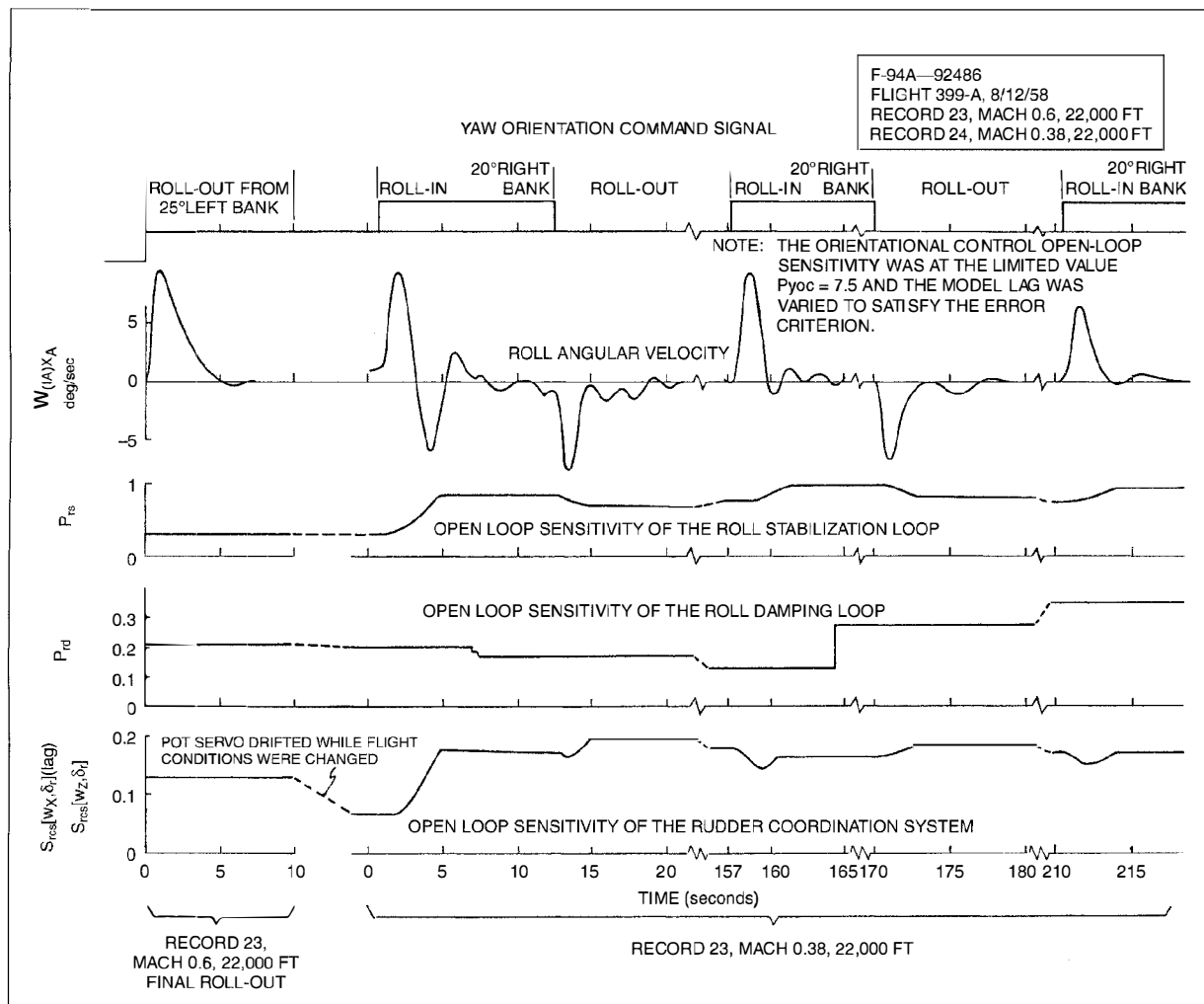


Fig. 6. Results of flight tests of a MRAS, from [22].

properties. A discussion of this is outside the scope of this paper; see [3].

Optimization

Natural laws can often be expressed very compactly as solutions to optimization problems. Many problems of automatic control can also be formulated as optimization problems. Draper and Li investigated the problem of driving an internal combustion engine under optimal conditions. They developed a self-optimizing controller that would drive the system toward optimal working conditions. In their approach, the system was considered as a static system. The controller was successfully flight-tested [8]. This was the beginning of the field of extremal control. Widrow also used an optimization scheme to train his neural networks [23].

Parameter uncertainty does not enter explicitly into the discussion of STR and MRAS, although uncertainty is a key ingredient in adaptive systems. There are also problems resembling the adaptive control problem in economics and operations research. In these fields the problems are often called decision-

making under uncertainty. The idea to neglect uncertainty and treat estimates as if they are true values was labeled the *certainty equivalence principle* in [19]. It became standard practice in early work on adaptive control to use certainty equivalence and to treat estimates as if they were the true values.

Use of optimization is often a powerful way to solve problems. It was an interesting challenge to formulate optimization problems that would lead to adaptive controllers. A major step forward in this direction was made with Bellman's development of dynamic programming [4]. The application to adaptive control is discussed in the book [5]. A key result is that the Hamilton-Jacobi equation in optimal control is replaced by a more general equation, called the Bellman equation. One example that focuses on uncertainty, but largely neglects dynamics, is the two-armed bandit problem. This consists of a slot machine with two arms, with different probability of success for the different arms. The control problem is to make as much profit as possible in the long run. Experimentation is clearly necessary to find out which arm to use; there is, however, a cost involved in using the arm with a

lower average outcome. The problem of using medical drugs has a similar structure.

Feldbaum came up with some very interesting ideas when investigating adaptive control using dynamic programming; see [9] and [10]. When investigating specific problems he found that when controlling an uncertain system the control actions have a dual purpose. They should drive the system in the desired direction, but they should also drive the system in such a way that we obtain better information about a system. A controller that balances these tasks in an optimal way was called a dual controller. Dual controllers can be obtained by applying dynamic programming, but the Bellman equation easily becomes intractable even for numerical solution. One of the difficulties is the high dimension of the state space.

Conclusions

Adaptive control was in a very interesting development in the mid-1960s. Many ideas such as extremal control, MRAS, STR, dual control, and neural networks, were born. It would take about two decades before the problems associated with adaptive control were reasonably well understood and adaptive techniques were finding use in industry. There are many reasons for the delay. The problems to be solved were difficult, funding for flight control dropped sharply because of accidents in flight tests, and new hardware was required for efficient implementation. A simple model reference adaptive controller for adjusting one parameter can be implemented with two multipliers and an integrator; see Equation (1). The difficulties with the analog systems are well evidenced in the experience with the early MRAS. There were also difficulties with the digital implementation. In the 1960s digital computing was only available in small quantities. The development of digital control and the microprocessor were required for good implementations.

It is interesting to observe that the IEEE Conference on Decision and Control included a symposium on Adaptive Processes as an integral part from its beginning until 1981. The IFAC symposium on the Theory of Self-Adaptive Control was discontinued after 1965. It reappeared when the Theory Committee of IFAC created a working group on adaptive control chaired by Prof. Landau in 1981. Of several initiatives, one attempt was to bring together the communities of control and signal processing. A series of workshops on adaptive systems in control and signal processing were planned. The first was held in San Francisco in 1983, followed by meetings in Lund 1986, Glasgow 1989, Grenoble 1992, and Budapest 1995. Because of the interest the meetings were upgraded to symposia starting with the Glasgow 1989 meeting. One may speculate about the reason for the 18-year gap in symposia from 1965 to 1983. In my opinion, this reflects the fact that much groundwork was needed to put adaptive control on a firm base. Substantial work in system identification and nonlinear control was required to understand adaptive systems better. Work on adaptive control was reported in the regular control meetings, CDC, ACC, and IFAC Congresses. There were also many papers on adaptive control in the IFAC Symposia on Identification and System Parameter Estimation. The first meeting in this series was held in Prague in 1967, and they have been held regularly every third year since that time.

Much work was required to develop a good theoretical understanding of adaptive control. The stability problem was an important challenge that led to interesting developments in sta-

bility theory. The development of the STR required much insight into the identification problem with issues related to parameterization and excitation. The role of simplified models and the robustness to neglected dynamics were other questions that have also arisen. Averaging theory, which is based on the observation that there are two loops in an adaptive system, a fast ordinary feedback and a slow parameter adjustment loop, turned out to be a key tool for understanding the behavior of adaptive systems.

Today we have a reasonably good understanding of the MRAS and the STR, but we do not understand questions such as limitations of adaptation rates. The dual control formulation is very attractive, but the computations required to solve the Bellman equations are overwhelming. It would be highly desirable to have a reasonably simple approximation. Most theoretical work has been based on linear design techniques, although recently there have been attempts to use nonlinear design techniques.

Adaptive techniques are starting to have industrial impact. A variety of techniques such as gain scheduling, MRAS and STR are used in different ways. Automatic tuning is widely used; virtually all new single-loop controllers have some form of automatic tuning. Automatic tuning can also be used to build gain schedules semiautomatically. Continuous adaptation is also used. The techniques appear in tuning devices, in single loop controllers, in distributed systems for process control, and in controllers for special applications.

There are many things we can learn from the early work. One is the style of presentation. In [12] the introduction to sessions and the discussions are included, giving interesting insight on ideas and attitudes. Reading this makes a good case to have at least some proceedings which includes discussions and more informal material. The World Wide Web may be a good forum to present such material today.

We can also learn about research problems. In retrospect, it appears that in view of the applications it would have been useful to start working on automatic tuning much earlier. It is also surprising that there is comparatively little work on such an important topic as gain scheduling. It is also clear that the mode of operation during the brave period, when there was a strong coupling between generation of ideas and their test on real systems, was very stimulating.

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References

- [1] J.A. Aseltine, A.R. Mancini, and C.W. Sarture, "A Survey of Adaptive Control Systems," *IRE Transaction on Automatic Control*, PGAC-3, pp. 102-108, 1958.
- [2] W.R. Ashby, *Design for a Brain*. Chapman and Hall, London, 1960.
- [3] K.J. Åström and B. Wittenmark, *Adaptive Control*, Addison-Wesley, Reading, MA, 2nd ed., 1995.
- [4] R. Bellman, *Dynamic Programming*, Princeton University Press, Princeton, NJ, 1957.
- [5] R. Bellman, *Adaptive Control Processes—A Guided Tour*. Princeton University Press, Princeton, NJ, 1961.

- [6] R.L. Butchart and B. Shackcloth, "Synthesis of Model Reference Adaptive Control Systems by Lyapunov's Second Method," in *Proceedings 1965 IFAC Symposium on Adaptive Control*. Teddington, UK, 1965.
- [7] F.P. Caruthers and H. Levenstein, *Adaptive Control Systems*, Pergamon Press, London, 1963.
- [8] C.S. Draper and Y.T. Li, "Principles of Optimizing Control Systems and an Application to the Internal Combustion Engine," Technical Report ARG-TI, Aerophysics Research Group, Aeronautical Engr. Dept., MIT, 1955.
- [9] A.A. Feldbaum, "Dual Control Theory 1," *Avtomatica i Telemekhanika*, 21:9, pp. 1240-1249, 1960.
- [10] A.A. Feldbaum, *Optimal Control Theory*, Academic Press, New York, 1965.
- [11] D. Gabor, W.P.L. Wilby, and R. Woodcock, "A Universal Non-Linear Filter, Predictor and Simulator Which Optimizes Itself by a Learning Process," *Proc. Inst. Elect. Engrs.*, 108, Part B, p. 1061, 1959.
- [12] P.C. Gregory, ed., *Proc. Self Adaptive Flight Control Symposium*, Wright Air Development Center, Wright Patterson Air Force Base, OH, 1959.
- [13] P.H. Hammond, ed., "Theory of Self-Adaptive Control Systems," *Proceedings of the Second IFAC Symposium on the Theory of Self-Adaptive Control Systems*, September 14-17, National Physical Laboratory, Teddington, England. Plenum Press, NY, 1966.
- [14] R.E. Kalman, "Design of a Self-Optimizing Control System," *Trans. ASME*, 80, pp. 468-478, 1958.
- [15] M.F. Marx, "Recent Adaptive Control Work at the General Electric Company," in Gregory, ed., *Proc. Self Adaptive Flight Control Symposium*, Wright Patterson AFB, OH, 1959. Wright Air Development Center.
- [16] E. Mishkin and L. Braun, *Adaptive Control Systems*, McGraw-Hill, New York, 1961.
- [17] P.C. Parks, "Lyapunov Redesign of Model Reference Adaptive Control Systems," *IEEE Transactions on Automatic Control*, AC-11, pp. 362-367, 1966.
- [18] O.H. Schuck, "Honeywell's History and Philosophy in the Adaptive Control Field," in Gregory, ed., *Proc. Self Adaptive Flight Control Symposium*, Wright Patterson AFB, Ohio, 1959. Wright Air Development Center.
- [19] H.A. Simon, "Dynamic Programming Under Uncertainty with a Quadratic Criterion Function," *Econometrica*, 24, pp. 74-81, 1956.
- [20] G. Stein, "Adaptive Flight Control: A Pragmatic View," in Narendra and Monopoli, eds., *Applications of Adaptive Control*, Academic Press, New York, 1980.
- [21] H.P. Whitaker, "Massachusetts Institute of Technology Presentation," in Gregory, ed., *Proc. Self Adaptive Flight Control Systems Symposium*, pp. 58-78, Wright Patterson AFB, Ohio, 1959, Wright Air Development Center.
- [22] H.P. Whitaker, J. Yamron, and A. Kezer, "Design of Model-Reference Adaptive Control Systems for Aircraft," Technical Report, Instrumentation Laboratory, Massachusetts Institute of Technology, Boston, MA, 1958.
- [23] B. Widrow, "A Statistical Theory of Adaptation," in Caruthers and Levenstein, eds., *Adaptive Control Systems*, Pergamon Press LTD, 1963.
- [24] N. Wiener, *Cybernetics—Or Control and Communication in the Animal and the Machine*, John Wiley & Sons Inc., New York, NY, 1957.



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