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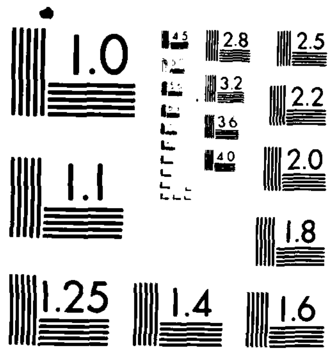

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Summary of European Feedback Control Research

Charles J. Holland

19 November 1985

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Feedback control will continue to be an important research area in Europe as well as internationally. This is not only because of applications in traditional areas, ranging from (perhaps mundane) boiler and industrial control to missile guidance, but because of newer applications areas in robotics and distributed systems such as flexible space structures. This report covers research on feedback control in The Netherlands, the UK, West Germany, and Sweden.

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CONTENTS

ACKNOWLEDGEMENTS

During my assignment as a liaison scientist in Europe, many researchers both here in Europe and in the US have given me considerable advice about problems on which to focus. I would like to thank them all. In particular, I would like to thank Dr. Gary Hewer, of the Naval Weapons Center, who continues to provide me with perspectives on how research advances can help satisfy future Navy performance requirements, especially in the area of missile control and guidance.

SUMMARY OF EUROPEAN FEEDBACK CONTROL RESEARCH

1 INTRODUCTION

Background

Feedback control will continue to be an important research area in Europe as well as internationally. This is not only because of applications in traditional areas, ranging from (perhaps mundane) boiler and industrial control to missile guidance, but also because of newer applications areas in robotics and distributed systems such as flexible space structures.

Increased performance requirements for US Navy weapons and vehicles will require improved, multivariable-control design analysis and synthesis techniques. Robustness techniques accommodating uncertainty based upon H^{∞} and semi-infinite programming methodologies offer hope for meeting these increased performance requirements. Successful implementation of these theoretical ideas will require the development of reliable numerical algorithms and computer-aided design procedures that incorporate these algorithms. Research in these directions is active both in Europe and in the US.

Objective

During the period July 1984 to November 1985 as a liaison scientist, I covered a wide range of activities in the mathematical and computer sciences. To support ONR Code 1111 research efforts in robust feedback control, a portion of my time was spent tracking European research in this and closely related areas. This report summarizes some of my findings; but this report does not duplicate all of my reporting on control activities. My *ESN* articles related to the general area of control are listed in Appendix A.

Scope

Research in control theory relates to the general area of control (and/or systems theory) and covers a wide range of topics. Key words include optimal control, modeling, estimation, filtering, guidance, feedback control, distributed control, classical control, and modern control. The research and application topics covered by each of these key words are not mutually exclusive and are subject to personal definition. In an attempt to define the scope of and motivation for this report, I will clarify my distinction between optimal control theory and feedback control theory.

In deterministic optimal control, known dynamics with unique performance criteria to be minimized or maximized are assumed. For example, computing a minimal time or minimal fuel trajectory for a spacecraft might fit into this category. These optimal control problems are not the focus of this report nor of my liaison activities. (However, one particular application of minimal time trajectory maneuvers for future agile aircraft was reported in *ESN* 39-3:115 [1985].)

For problems in feedback control, the focus of this report, the central issue is in accommodating uncertainty. Thus, the dynamics of the plant are not known precisely, and there is not a unique performance criterion to be minimized. For these problems, one desires to design a system that will be stable and have certain performance requirements over a range of possible operating conditions. These performance requirements are not rigid, and there are trade-offs.

This lack of a unique performance requirement leads to a proliferation of problem statements with associated solution methodologies. Most of these solution methodologies require some final engineering expertise and are not black-box solutions. Feedback control analysis and synthesis procedures for multivariable control problems can be considered in at least four categories:

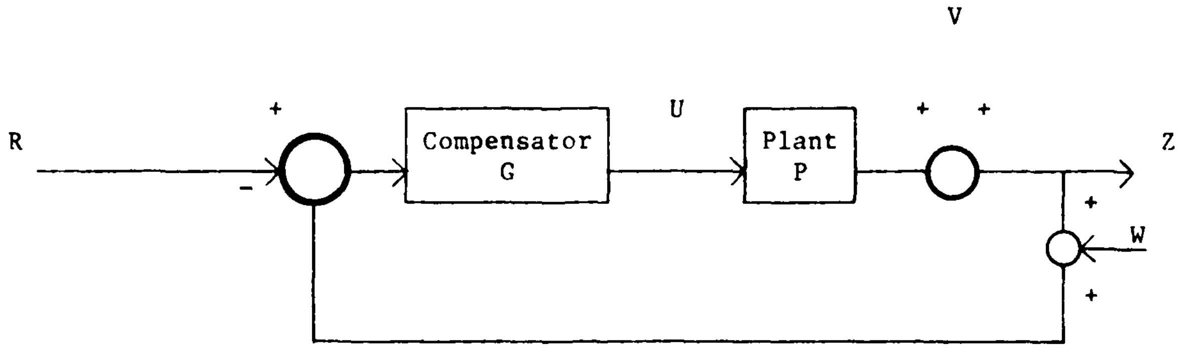

Figure 1. Single-input/single-output feedback system.

Control system robustness can be characterized in terms of the system functions S and T. For simplicity, assume that the plant transfer function P and the compensator transfer function G are rational and given by P = N/D and G = Y/X, where N, D, Y, X are polynomials in the Laplace transform variable S. Then,

$$S = \frac{DX}{DX+NY}, \quad T = \frac{NY}{DX+NY}.$$

The common denominator DX+NY of these two transfer functions is the closed-loop characteristic polynomial. If all the roots of this polynomial are in the left-half complex plane, the closed loop system is stable; otherwise, it is unstable. It will be assumed that for the nominal plant $P_0 = N_0/D_0$, the closed-loop system is stable.

In the case of robustness, it is in principle necessary to specify what kind of robustness is required. The most basic robustness requirement is stability robustness; this means that the control system remains stable under all possible perturbations. Kwakernaak has derived the following criterion: *Theorem.* A sufficient condition for the closed-loop system to remain stable is that

$$\left| S_0(iw) \frac{D(iw)-D_0(iw)}{D_0(iw)} + T_0(iw) \frac{N(iw)-N_0(iw)}{N_0(iw)} \right| < 1 \text{ for all frequencies } w.$$

This criterion involves the relative perturbation $(D-D_0)/D_0$ of the plant denominator, as well as the relative perturbation $(N-N_0)/N_0$ of the plant numerator. Also, the criterion depends on both the nominal sensitivity S_0 and the nominal complementarity sensitivity function T_0.

An immediate conclusion is that for all possible perturbations that satisfy

$$\left| \frac{(D(iw)-D_0(iw))/D_0(iw)}{V(iw)} \right|^2 + \left| \frac{(N(iw)-N_0(iw))/N_0(iw)}{W(iw)} \right|^2 < 1$$

for all w, where V and W are given frequency-dependent functions, then the closed-loop system remains stable for any admissible perturbation if

$$|V(iw)S_0(iw)|^2 + |W(iw)T_0(iw)|^2 < 1 \text{ for all } w.$$

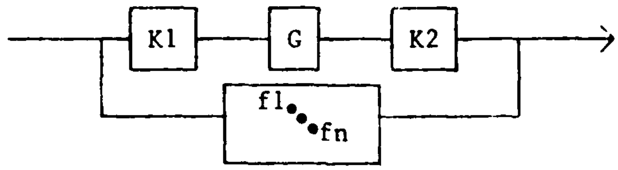

Figure 2. Inverse Nyquist Array.

Characteristic Locus Approach

Another method of category 1 is the characteristic locus method developed by A. MacFarlane of Cambridge University and I. Postlethwaite, now at Oxford University. Here, the design is based on manipulating the eigenvalues of the loop transformation (Postlethwaite and MacFarlane, 1979). The principal advantage of this approach is that it is intuitively appealing; the disadvantages are the sensitivity of the resulting eigenvalues (lack of robustness) and the difficulties in shaping the response over wide frequency ranges. Postlethwaite has moved his research interests to H^∞ optimization techniques, which are discussed below.

Both of the above techniques, while capable of producing satisfactory designs, have their limitations--especially in the area of robustness--as discussed above.

H^∞ Researchers

On several diverse fronts, UK researchers are playing a major role in applying minimum-norm interpolation methods to engineering control design. Professor I. Postlethwaite and coworkers (1985) at Oxford University have been working on the application of H^∞-optimization techniques for the design of robust feedback controllers. This is an area of much current research interest and stems from the work of Zames (1981).

Several researchers have considered separately the problems of minimizing the H^∞ norm (maximum singular value over frequency) of a weighted sensitivity matrix $S(s)$ to reduce the effect of disturbances on a feedback system and the problem of a weighted complementary matrix $T(s) = I-S(s)$ to reduce the effect of measurement noise. In realistic problems, there is a trade-off because both minimization problems cannot be accomplished separately. To account for this trade-off, Postlethwaite has formulated and solved a problem based on the minimization of a weighted combination of the sensitivity and complementary sensitivity function matrices. The solution is based on methods for minimizing the sensitivity function alone.

The problem considered by Postlethwaite is to minimize $||Z(jw)||_\infty$ ($j= -1$, $w =$ real frequency), where Z is the enlarged matrix $Z(jw) = [W_1(jw)S(jw)|W_2(jw)T(jw)]^T$ for appropriate weighting functions $W_1(jw)$ and $W_2(jw)$ over the set of stabilizing controllers. This choice for Z is motivated by the fact that he was unable to solve the "more natural" problem of minimizing $|| W_1(jw)S_1(jw)+W_2(jw)T(jw) ||_\infty$.

Postlethwaite has a conceptual algorithm for performing the minimization problem but no actual numerical experience.

At Cambridge University, Professor Keith Glover (1984) has been using norm-approximation techniques to formulate various engineering problems including feedback control, model reduction, etc. His approach is best illustrated with a model reduction problem. In many areas of engineering, high-order linear models are initially derived, and it is desirable to replace these with reduced-order models without incurring much error. For example, in filter design, it is sometimes possible to simply produce satisfactory high-order filters, and reduced-order filters would save in implementation.

In a different effort, Young has been investigating numerical algorithms to solve matrix versions of the N-P problem. In this matrix version, minimization occurs over the space $H^\infty(m\times n)$ of $m\times n$ matrices, each of whose entries is an analytic function in the unit disk. Some further definitions are needed to state the problem precisely. An $n\times n$ square matrix function $B(z)$ is said to be inner if B is in $H^\infty(n\times n)$ and $B(z)$ is unitary for each z on the boundary of the unit circle. Next the concept of norm is required. For G in $H^\infty(m\times n)$ and each z, let $|G(z)|$ denote the spectral norm of G--hence the largest singular value of G(z) denoted by $s_1(G(z))$--and let the H^∞ norm of G denoted by $||G||_\infty$ be the supremum of $s_1(G(z))$ over the unit disk. A matrix N-P problem is then the following: For F in $H^\infty(m\times n)$ and B, C inner functions of types $m\times m$ and $n\times n$, find G of the form $F+BH^\infty(n\times n)C$ such that $||G||_\infty$ is minimized.

Unfortunately, there are generally an infinite number of solutions to this minimization problem, and Young has considered additional conditions for the problem to have a unique minimizer. There are two reasons to do this. The first is that the added conditions might be physically relevant in the applications. The second is that the added conditions might lead to a numerically stable way of calculating an optimal solution to the original problem.

Young has obtained a formulation with a unique solution in the following manner. For each z, let $s_i(G(z))$ be the ith largest singular value of G(z), and let s(i) denote the supremum of $s_i(G(z))$ over the unit disk. Then, in the problem statement above, replace the $||G||_\infty$ minimization condition with the requirement that (s(1), s(2),...) be minimized lexicographically--this sequence has, at most, maximum (m,n) nonzero terms. Young has established that under reasonable conditions this new minimization problem has a unique minimum. Moreover, he has established that the minimizing G satisfies the property that $s_i(G(z))$ is a constant almost everywhere on the unit circle for each i. He shows that the minimizing element can be written explicitly in terms of singular values and vectors of a succession of Sarason-type operators. Young and his coworkers are currently working on efficient numerical schemes for implementing these ideas.

As evidenced by the foregoing, researchers are making a big push in the area of H^∞-based design procedures. Glover, Postlethwaite, and Young attended an ONR-sponsored workshop on Advances in Multivariable Control held at the Honeywell Corporation in Minneapolis in October 1984 (the proceedings were not published). The theme of this workshop was robust system design using H^∞ optimization. As a follow-on, the British Science and Engineering and Research Council and the Institute of Measurement and Control are planning a workshop at Oxford in March 1986 to introduce the potential developments of these techniques to UK industry as well as to other academics.

Control System Design via Semi-infinite Optimization

D. Mayne, of Imperial College, London, in collaboration with L. Polak (1984), of the University of California, Berkeley, have been working on the development of a control system design methodology via semi-infinite optimization techniques. Performance specifications for single-input/single-output design are sometimes given in the frequency domain such as gain and phase margins, as well as in the time domain, such as rise time and settling time. Multivariable design specifications are frequently given as bounds on the transfer function matrices. These specifications lead naturally to a nondifferentiable, infinitely constrained optimization problem in a finite design parameter x that represents the free compensator coefficients. This problem is called a semi-infinite optimization problem since the constraints are infinite in number (varying over time and frequency intervals) while the design parameter is finite-dimensional. Mayne and Polak have been working on reliable algorithms for solving these problems as well as incorporating them into the DELIGHT.MIMO scheme which is a direct approach, the plant is restricted to minimum phase. Kreisselmeier does not make that restriction. Instead, he assumes that the plant is of known order, that the unknown parameters lie in a given convex set, and that throughout this set there is no unstable pole-zero cancellation.

He describes a system as "stable" if bounded inputs produce bounded outputs. The proof of his result depends on a special nonminimal representation of the plant. In this representation, the closed loop system is rewritten as an exponentially stable system with the identification error appearing as a feedback term. This procedure established a link between the identification error and closed-loop-system stability. Then, global stability is established in a similar fashion, as in the model reference, adaptive control approach.

This is an interesting theoretical result. Nevertheless, all realistic systems are not linear time-invariant, and adaptive control schemes must be robust with respect to unmodeled dynamics and noise disturbance. There are still many interesting and difficult challenges for Kreisselmeier and others to confront before a totally satisfactory design methodology for adaptive control synthesis is developed.

5 SWEDEN

Except for the above discussion of Kresselmeier's work, I have dealt primarily with robust feedback control techniques for handling uncertainty, i.e., designing a controller with fixed structure to provide acceptable performance. An alternative method to handling plant uncertainty is by the use of adaptive techniques, i.e., adjusting controller parameter on-line to optimize system performance. For the last 20 years, the analysis and design of adaptive control systems has been the subject of extensive research. A recognized leader in this area is Professor Karl Åström of the University of Lund.

The use of adaptive control has been somewhat controversial. According to Åström (1983), this occurs because of the following contradictions:

- Adaptive control works very well in a particular application.
- Adaptive control can be made to look ridiculous (how an algorithm behaves in a particular simulation).
- There is not a proper theory that guarantees stability and convergence of the algorithm.

Part of this controversy arises because of the difference between theoretical and practical aspects. The theory deals with idealized saturations where all the conditions are under control. In the practical situations, there are all kinds of violations of the conditions of the theory. Åström concentrates on the latter area, especially for self-tuning regulators. While aware of and using the theoretical work, Åström's practical work is not done on a firm theoretical basis; it consists of ad hoc solutions that depend on a particular application. His algorithms are often verified by extensive experimentation and simulation. Based upon his research in and applications of adaptive control, Åström feels that the key points in practical adaptive control are:

- How to use prior information about the process.
- How to determine realistic specifications of the closed-loop system.
- How to make robust estimation.
- Unmodeled high frequency dynamics.
- Signal conditioning.
- Numerical problems.
- Start-up and bumpless transfer.
- Processor and actual nonlinearities.

APPENDIX B: ADDRESSES OF SCIENTISTS MENTIONED IN THIS REPORT

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