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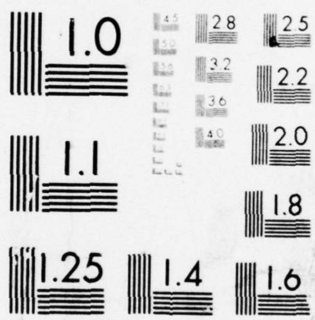

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This report is the final report covering a four year investigation into identification and control of real-time systems. The major results are summarized, the publications and presentations listed, and the present status of the participating students is included.

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FINAL REPORT

to

U.S. AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Bldg. 410, Bolling Air Force Base
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STUDIES IN OPTIMAL CONTROL, ESTIMATION, AND LINEAR SYSTEMS THEORY

Principal Investigator: Cecil L. Smith

Period Covered: 1 February 1973 - 31 August 1977

Louisiana State University
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Baton Rouge, Louisiana 70803

I. Introduction

This report summarizes the major results of our research program into the optimal control, estimation, and systems theory at Louisiana State University. As the papers resulting from this work are available in the scientific literature, detailed descriptions would be redundant.

Table of Contents

Abstract

This report is the final report covering a four year investigation into identification and control of real-time systems. The major results are summarized, the publications and presentations listed, and the present status of the participating students is included.

II. Synopsis of Major Accomplishments

2.1. The Effect of a Generalized "Numerator" Polynomial on Multivariable Control System Response

A time domain characterization of the numerator polynomials was given, a method for cancelling undesired zeros was presented, and it was determined how knowledge of the zeros of a system can aid in predicting and altering system response. One of the results appears to offer a strong tool in the area of multivariable feedback control. When the potential of this result was recognized, the subject of system zeros was set aside in favor of using the new result to develop methods for improving system response that has given very favorable results.

Consider the closed loop system

$$\dot{x}(t) = (A + BF)x(t) + BGv(t)$$

which results from applying linear state variable feedback

$$u(t) = Fx(t) + Gv(t)$$

to the open loop system

$$\dot{x}(t) = Ax(t) + Bu(t)$$

where $x(t)$ is an n component state vector and $u(t)$, $v(t)$ are m component input vectors.

It has been known for some time that the closed loop system can be assigned any self conjugate set of n eigenvalues as long as (A,B) is controllable ([B AB · · · A^{n-1}B] has independent rows). Equally well known is the fact that F is not unique for multivariable systems.

The theoretical result produced by research under this grant shows that the additional freedom reflected by the nonuniqueness of F can be used to choose among allowable closed loop eigenvectors for the case where the closed loop eigenvalues are distinct.

In a set-point control system the input is a vector of set-point values which remain constant except for isolated points in time (where set-point changes are made). The control system causes the output vector to take on the same value as the set-point vector after a transient period of time.

Ideally one would like for a set-point control system to be <u>decoupled</u> so that a change in only one component of the set-point vector causes a change in only one output component. Unfortunately, most systems are coupled: a change in one component of the set-point vector causes a transient disturbance in several (possibly all) of the components of the output vector. Moreover, most systems are such that this situation cannot be corrected by linear state variable feedback along.

Since decoupling by state feedback is generally not possible, the process of improving the response of a set-point control system has, in the past, consisted of the following steps:

1. Choose a set of desirable eigenvalues.
2. Compute F so that the closed loop system has the desired set of eigenvalues.
3. Compute G so that the closed loop systems maintains set-point control.

The method for computing F is generally based on an algorithm for single input systems which does not exploit in anyway the nonuniquenss of F.

Research conducted under this grant shows that it is possible to shape the transient response of a set-point control system by altering the closed loop eigenvectors without changing the closed loop eigenvalues. An algorithm has been developed which allows the designer to specify a set of weights (one for each component of the output vector) which reflects the relative importance of decreasing the presence of a given mode in each of the outputs. The algorithm finds a "good" allowable eigenvector for these weights, and then computes the feedback matrix which gives this closed loop eigenvector (without changing any closed loop eigenvalues). A Fortran program implementing the algorithm has been run successfully on several test cases. Using this program, the presence of a mode in the components of the output vector can be shaped by varying the weights.

2.2. Design of Sub-Optimal Controllers for Systems Excited by Unmeasured External Disturbances

The design of suboptimal feedback controllers for the regulator problem with no dynamics on the disturbance input place the most stringent demands on the control system. Representing the plant by a second order lag plus dead time transfer function, two design methods were considered:

1. An extension of discrete synthesis methods to continuous systems.
2. The results of the optimal output regulator problem which involves transformation of the transfer function into state variable form and solution of the matrix-Riccati equation.

For the second method, the control u in the quadratic performance index was replaced by $\dot{u}$ in order to force integral action into the controller.

Because it is not possible for a continuous controller to compensate for the dead-time, two methods were investigated for the approximation of the dead-time term:

1. First-order Taylor series expansion
2. First-order Padé approximation.

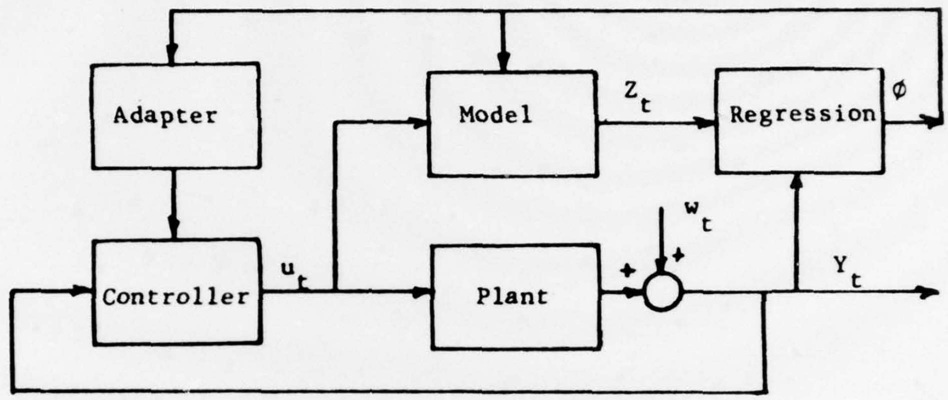
The second of these approximations introduces an extra derivative term when the output-regulator problem is considered.

It was found that the second derivative term introduced by the Padé approximation contributes very little to the controller performance. In general, controllers designed by the optimal regulator method did not perform as well as those designed by the synthesis method.

In respect to the question of when to use the first derivative term in the controller, this research produced results that indicated that the mode would be beneficial only if the smaller time constant (in a second order lag plus dead time model) is larger than the dead time.

2.3. Model Reference Adaptive Control of Nonlinear Sampled Data Systems

The scheme under investigation in this project can be represented by the following diagram:



The model chosen is a second-order discrete model of the form:

$$Z_t = \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \phi_3 U_{t-1} + \phi_4 U_{t-2} \quad (1)$$

or, in vector form:

$$Z_t = \underline{\phi}\ \underline{x}_{t-1} \quad (2)$$

where $\underline{x}$ is the observation vector with components Y_{t-1}, Y_{t-2}, U_{t-1} and U_{t-2}. The reason for choosing a second-order model is that the controller is seldom designed to compensate for more than the two dominant modes, i.e., the two longest time constants. In addition, the accuracy of the measurement is seldom high enough to determine more than two modes. The model is discrete because the regression equations must be solved by a digital computer that must sample the measurements.

The regression method if the instrumental variable method in which the regression matrix is obtained by multiplying the output or measurement vector times an instrumental variable vector. It is highly desirable that the instrumental variable be highly correlated with the output, Y_t, and uncorrelated with the disturbance, w_t. In this work, the output of the model was used as the IV, resulting in recursive regression equations.

Multicolinearity effects and their sensitivity to the relationships between sample-time and plant time constants was studied. The effect of the initial estimate of $\underline{\underline{P}}_t$ on the speed of convergence was evaluated. The technique was shown to be superior to straight least-squares because it eliminates the bias caused by correlation between the output and the observation vector, X_t. The method was successfully tested in the tracking of the parameters of a time-variant plant, and in the self-tuning feedback control of a nonlinear plant. In such on-line applications this straight forward, yet effective, method is able to function reliably on a minimum of statistical information.

III. Publications and Presentations

1. Touchstone, A. T., and Corripio, A. B., "Adaptive Control Through Instrumental-Variable Estimation of Discrete Model Paramters", Instrumention in the Chemical and Petroleum Industries, Vol. 13, (Proceedings of the 1977 ISA Conference, Anaheim, Ca., May 2-5), 1977, pp. 57-64.

2. Martin, J., Corripio, A. B. and Smith, C. L., "Comparison of Tuning Methods for Temperature Control of a Chemical Reactor", Instrumentation in the Chemical and Petroleum Industries, Vol. 13, (Proceedings of the 1977 ISA Conference, Anaheim, CA, May 2-5), 1977, pp. 31-36.

3. Martin, J., Corripio, A. B., and Smith, C. L., "How to Select Controller Modes and Tuning Parameters from Simple Process Models", ISA Transactions, Vol. 15, No. 4, 1976, pp. 314-319.

4. Juantorena, R., Richardson, J. A., Corripio, A. B., and Smith, C. L., "Obtaining Consistent and Efficient Parameter Estimates Through the Modification of the Kalman Filter", Proceedings of the Fifth National Bureau for Economic Research Conference on Stochastic Control and Economics, Stanford, CA., May 26-28, 1976.

5. Touchstone, A. T., and Corripio, A. B., "Simulation of Adaptive Process Control Using Instrumental-Variable Regression Algorithm", Proceedings of the Seventh Annual Pittsburgh Conference on Modeling and Simulation, Pittsburgh, Pa., April 26-27, 1976, pp. 361-365.

6. Touchstone, A. T., and Corripio, A. B., "Process Identification Utilizing a Sequential Instrumental-Variable Regression Algorithm", presented at the Milwaukee Symposium on Automatic Computation and Control, Milwaukee, WI., April 22-24, 1976.

7. Martin, J., Corripio, A. B., and Smith, C. L., "Comparison of Tuning Methods for Temperature Control of a Chemical Reactor", ISA Transactions, Vol. 16, No. 4 (December 1977), pp. 53-58.

8. Moore, B. C., "On the Flexibility Offered by State Feedback in Multivariable System Beyond Closed Loop Eigenvalues Assignment", IEEE Decision and Control Conference, New Orleans, December 1973.

9. Moore, B. C., "A Time Domain Characterization of the Invariant Factor of a System Transfer Function", Proceedings of the 1974 JACC, p. 186.

10. Moore, B. C., "Zero Cancellation in Multivariable Systems", Proceedings of the 1973 IEEE Conference on Systems, Man, and Cybernetics, Boston, Mass.

IV. Research Participants

The education of specialists in the area of process control is an important result of the research program. The graduate students involved in the project are listed below:

Research Participants in AFOSR Grant 74-2680

Name	Status	Completion Date	Present Affiliation
R. Juantorena	PhD Student	1977	Exxon Chemical USA
K. Krivoshein	MS Student	1976	Dow Chemical USA
J. Martin, Jr.	PhD Student	1975	Exxon Chemical USA
A. Touchstone, Jr.	PhD Student	1975	Dow-Badische
D. M. Starks	MS Student		PhD Student-LSU
K. Kominek	MS Student		PhD Student-LSU

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