FINAL SCIENTIFIC REPORT

CONTROL STRATEGIES FOR COMPLEX SYSTEMS FOR USE IN AEROSPACE AVIONICS

by

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I. Faculty Employed on Grant During Part of All of Five-Year Period

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II. Summary of Research Accomplishments

The research program was focused on investigating new methods of analysis, synthesis, and optimization of control systems particularly those which contain uncertain parameters and disturbance inputs. The objective was to develop methods to improve the performance of control systems by counteracting the effects of these random parameters and disturbance inputs. Several new methods which contribute to this objective were proposed and developed under this program. Among these new approaches are strategies for sensitivity adaptive feedback with estimation redistribution, sensitivity reducing compensators using observers, stochastic adaptive control of systems containing random parameters, control of singularly perturbed stochastic systems, trajectory optimization of singularly perturbed systems, time-scale decomposition in regulator design, and high gain feedback systems and variable structure systems.

The results obtained during the five-year period are fully documented in 38 journal articles, 30 conference papers presented at various international congresses and national meetings, and 18 technical reports of the Laboratory. Some of these results were briefly summarized in four Interim Scientific Reports submitted annually during the grant period. We briefly sketch below the major accomplishments with emphasis on results not reported previously.

A. Sensitivity Adaptive Feedback with Estimation Redistribution

We have developed an entirely new approach to the synthesis of a dynamic controller for systems containing unknown random parameters. For a given total cost of estimation, we allocate the individual costs according to the accuracy required to achieve a control objective. Greater accuracy of estimation generally implies greater cost. Moreover, parameters to which the state of the system are more sensitive require more accurate estimation than those whose effect on the state is less significant. We represent the total estimation cost by a quadratic form of the sensitivity functions, where the weighting matrix in the quadratic form is to be chosen so as to achieve an allocation of estimation effort which is optimal with respect to the primary objective function. The general problem is to choose the control and the sensitivity weighting matrix which minimize an objective function subject to a fixed budget for total estimation cost. The optimization is such that the parameters which affect the trajectory sensitivities the most are estimated with the most accuracy, and those which have only a small effect on the trajectory sensitivities are allocated smaller estimation accuracies. The specific procedure results in an open loop optimal feedback control which has dual effect. We call this strategy Sensitivity Adaptive Feedback with Estimation Redistribution (SAFER) control. Details are given in [A31,B23,B30,C8].

B. Sensitivity Reducing Compensators Using Observers

A desirable property of any control design is that it be insensitive to small variations in the parameters of the controlled plant. The mathematical model can only approximate the physical problem so that the assumed values of parameters for the design may be different from the actual parameter values upon implementation. Also, most systems suffer from some forms of unmeasurable or unpredictable variations due to the degeneration of physical components and adverse environmental effects. The potential benefits of using state feedback to improve sensitivity can be evaluated by comparing the sensitivity of the closed-loop design to a nominally equivalent open-loop control. The development of these concepts led to the definition of the comparison sensitivity operator which directly relates the open-loop and closed-loop sensitivities, and a sensitivity reduction criterion giving sufficient conditions for a particular feedback control law to guarantee sensitivity reduction in comparison to the open-loop control. We reported these results several years ago under previous AFOSR grants.

Necessary and sufficient conditions for satisfaction of this comparison sensitivity reduction criterion was derived for full state feedback control law [A38] by Kreindler, and more recently for output feedback controls using dynamic compensators [A38] by Naeije and Bosgra. In both instances sensitivity reduction is directly related to some optimal control. Implementing a full state feedback law using an observer to estimate the unmeasured states, where the state feedback gains satisfy the state sensitivity reduction design, will not in general satisfy the output sensitivity reduction criterion.

We have developed an extension of Naeije and Bosgra to the particular case of output feedback systems which use state observers to implement dynamic compensation of the plant. A comprehensive design procedure has been developed and its application through the use of an interactive software implementation has been carried out for a simple aircraft control example [A38,C18].

The design procedure using observers is an improvement over the design with arbitrary compensator dynamics for the following reasons. First, the design of the observer is well known and by placing the poles of the observer the designer is selecting poles of the overall feedback system. Second, the dynamic order of the reduced order observer is less than the maximal bound on the dynamic order of the compensator designed by the methods of Naeije and Bosgra. Finally, the use of observers leads to a useful interpretation of the sensitivity weighting matrix [A38]. Related sensitivity studies are given in [C12,C17].

C. Stochastic Adaptive Control of Systems Containing Random Parameters

We have developed a procedure for controller design for discrete-time stochastic systems containing random parameters. The structure of the dynamic estimator-controller is fixed but its parameters are adjustable to optimize the control objective. A performance index that is quadratic in both the state and the control over N periods is considered. This performance index is minimized with respect to the feedback control gain matrix, the estimation dynamics matrix, and the filter gain matrix. It is important to note that both the parameter estimation and the state estimation are performed so that a control objective is satisfied, in contrast with other approaches reported in the literature in which the parameters are estimated with a particular objective different from the objective of the control. The performance index is a mathematical expectation taken over the distribution in the noise disturbances, the initial state, and the parameter uncertainty. Minimization of this expectation has the interpretation of reducing the sensitivity of the standard criterion function with respect to fluctuations in parameter values. The procedure is described in [A22,B18,B25,C8].

We have also developed a new method of designing nonlinear control systems containing random parameters. An open-loop component establishes a satisfactory nominal trajectory, and a feedback component augments the control to minimize trajectory dispersion due to the random parameter changes. The optimization problem is similar to that for a deterministic regulator problem with incomplete state feedback. The feedback component can be expressed as the usual feedback if there is no parameter deviation from the nominal values plus a feedback term which is recognized as a conditional estimate of the parameter deviation. Thus the parameter estimation arises naturally from the control formulation. Details are given in [A4]. Related sensitivity results where random plant parameters are considered are given in [A1,A11,B1,B5].

D. Control of Singularly Perturbed Stochastic Systems

Properties of singularly perturbed systems with white noise input have been investigated and the optimal filter problem is solved in two time scales. The two filters yield estimates of slow-mode and fast mode states [A21]. The stochastic control problem is then formulated for linear singularly perturbed systems [A26,B22]. The meaning of fast variables is not always clear due to the white noise model used in the system representation. The problem has since been reformulated to allow the fast modes to serve as a model for well-defined variables in the stretched time-scale, with non-negligible contribution to the slow modes of the system. The new formulation is made possible by the introduction of additional scaling in different powers of the singular perturbation parameter appearing in several parts of the stochastic model and also in the quadratic performance index. Relative values of the powers have been obtained to yield meaningful fast and slow variables. Details are given in [A34].

E. Trajectory Optimization of Singularly Perturbed Systems

A large number of systems to be controlled, such as aircraft, missiles etc., can be realistically modeled as singularly perturbed systems, that is systems involving fast and slow dynamic phenomena. Calculation and implementation of optimal trajectories for such systems are hindered by difficult numerically "stiff" two point boundary value problems which often have to be solved in real time. In the singular perturbation method we have developed, the difficulties with the two-time-scale behavior of singularly perturbed systems are converted into a conceptual and computational advantage. The method permits separable trajectory optimization of a reduced order model representing the slow phenomena, and two "boundary layer regulators" controlling fast maneuvers at the trajectory ends.

We have established that the controllability properties of a singularly perturbed system are determined by the controllability properties of the slow and the fast subsystems. Then the time optimal control has been approximated by a "slow" and a "fast" control. The slow and the fast switchings are calculated separately, in their own time scales thus avoiding "stiffness" difficulties and reducing the order of the state and the adjoint equations [A6,A7,A27]. An iterative method for time-optimal control problems has been developed [A25,B16,B21,C7,C13].

F. Time-Scale Decomposition in Regulator Design

Singular perturbation methodology surveyed in [A20] has been developed for complete decomposition in the design of regulators for systems with fast and slow modes. In [A23,B19,C6] the linear regulator problem is solved using a two-stage design. A fundamental property of this new design is its insensitivity with respect to singular perturbation parameters. For a second order near optimum performance these parameters need not be known, while a first order approximation is still achievable when neither the parameters, nor the exact model of the fast subsystem are known. Among potential applications of this procedure are recent control problems in advanced helicopter design with widespread interacting modes.

Time-scale decomposition has been developed for the design of a class of nonlinear systems which are linear in the fast variables [A33,B20,C14]. A guaranteed region of asymptotic stability for the nonlinear model has been determined [A30]. Furthermore a near-optimum two time scale design has been developed in [A35,C16] applicable to some essentially nonlinear systems.

G. High Gain Feedback Systems and Variable Structure Systems

High gain feedback has been a classical tool for reduction of effects of disturbances, parameter variations and distortions. Although limited to single input-single output feedback systems, early investigations of structures permitting high gains, rules for root locus asymptotes and results on sensitivity and return difference have greatly deepened the intuition of control engineers in the 1950's. Recent developments in multivariable system theory have revived the interest in high gain feedback systems. Works on disturbance rejection, and parameter uncertainty either purposely introduce high gain feedback in the problem statement or they implicitly appear in the resulting feedback structures. Feedback implementations of linear optimal controls when only small penalties are made on the control variables result in loops with high gain.

Another class of feedback controls capable of reducing parameter sensitivities and rejecting disturbances is the so-called variable structure control. Basically, it is a feedback control discontinuous on some switching surface defined on the state space.

We have investigated the analysis and synthesis of these two classes of multivariable feedback systems, namely, high gain feedback systems and variable structure systems, subject to parameter variations and disturbances. When only some of the states variables are accessible in a high gain feedback system we introduce the idea of incorporating high gain feedback loops in observers. By allowing high gain feedback in the observer structure, the observation error dynamics enjoy the same insensitivity property inherent in high gain feedback systems. In place of high gain state feedback, the "high gain" observer states are fed back through the main high gain feedback loops. We investigated the behavior of this "two-high-gain-loops" feedback system. A practical alternative to examining the sensitivity of all the states of high gain feedback systems is to investigate only the sensitivity of the variables which are critical to performance degradation or have to meet certain design specifications. We call these variables, the regulated variables. We discover that there remain some degrees of freedom in the design of the high gain feedback matrices which can be utilized to enhance the insensitivity of high gain feedback systems. The number of degrees of freedom depends on the number of control variables, available measurements, disturbance inputs and regulated variables. A procedure is developed for the design of the feedback matrices which exercises the available degrees of freedom.

We have established a relationship between high gain feedback systems and VSS. We find that in sliding mode, VSS enjoy the same insensitivity property as high gain feedback systems. This motivated us to develop observers with variable structure feedback as well as high gain observers. We then examined the behavior of variable structure feedback systems with variable structure observers. The same degrees of freedom in the design of variable structure feedback is discovered as in high gain systems.

We addressed an important consideration in application: the robustness property of these classes of feedback systems with respect to model reduction. As a step in this direction, we considered the most common model reduction in practice, the neglection of actuator and sensor dynamics. This robustness property differentiates VSS and high gain feedback systems. As a reward for the added complexity, VSS are more robust with respect to the neglected small time constants. This is due to the fact that variable structure control does not force the motion to be fast. The design procedures are applied to the control of the longitudinal motions of an aircraft. For details see [A36,C15].

III. Publications

A. Journal Articles

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2. A. Thowsen and W. R. Perkins, "Optimal Discrete-Time Feedback Control of Mixed Distributed and Lumped Parameter Systems," International Journal of Control, Vol. 18, No. 3, pp. 657-665, 1973.

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17. A. Thowsen and W. R. Perkins, "On the Controllability of Linear Time-Delay Systems with Piecewise-Constant Inputs," Int. J. System Science, Vol. 7, No. 3, pp. 347-360, 1976.

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27. J. H. Chow, "Preservation of Controllability in Linear Time-Invariant Perturbed Systems," Int. J. Control, Vol. 25, pp. 697-704, 1977.

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B. Meeting Papers

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2. J. B. Cruz, Jr., "Survey of Nash and Stackelberg Equilibrium Strategies in Dynamic Games," Third NBER Stochastic Control Conf., Washington, D. C., May 1974.

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C. Laboratory Reports

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4. B. F. Gardner, Jr., "Discrete-Time Dynamic Games," R-691, September 1975.

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