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This report briefly describes research results on the analysis and design of nonlinear control systems obtained by the author and his students over the three-year period of support. The main focus of the research has been on a new approach for designing nonlinear control laws that is called design by extended linearization. Results reported include a method for designing nonlinear controllers of proportional-integral-derivative type, a method for designing nonlinear control laws that achieve asymptotic tracking of reference signals and rejection of disturbance signals for nonlinear plants, and a method for achieving approximate noninteraction with stability in cases where exact noninteraction with stability cannot be achieved. Technical publications describing these and other results are listed.

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ANALYSIS AND DESIGN METHODS FOR NONLINEAR CONTROL SYSTEMS

Wilson J. Rugh

Department of Electrical and Computer Engineering
The Johns Hopkins University
Baltimore, Maryland 21218

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1. Research Objectives

The overall goal of this research program was to formulate analysis and design approaches for nonlinear control systems in aerospace applications. A major part of the program was to further develop the method of extended linearization for the design of nonlinear control laws. Specific tasks included investigation of a frequency domain formulation of the method, exploration of the use of extended linearization in the setting of nonconstant nominal trajectories, and the determination of quantitative measures of the performance of designs resulting from the extended-linearization approach. A second part of the research program involved further investigation of aspects of the differential-geometric theory of control with the aim of deducing concrete design approaches.

2. Research Accomplishments

The underlying theme of our research activities for this grant was the extended-linearization design method, which we developed under previous AFOSR support. This approach can be described briefly as follows. The nonlinear plant to be controlled is represented by its family of linearizations about a family of constant operating points (equilibrium points). Then a family of linear control laws, parameterized by the operating points, is designed so that the design objectives are satisfied by the closed-loop linearization family at each operating point. Finally, a nonlinear control law is computed from the parameterized linear law and applied to the original nonlinear system. The resulting closed-loop system has the designed closed-loop linearization at each operating point. Relying on the accuracy of the linearized model, this nonlinear closed-loop system should satisfy the design objectives in a neighborhood of the family of closed-loop constant operating points. (Indeed, we discuss below stability results that support this intuition.)

An initial part of our effort toward the objectives in Section 1 involved completing certain studies of the basis for the extended-linearization method. The most important of these is reported in [1] *, entitled "Feedback Linearization Families for Nonlinear Systems." In this paper we have presented characterizations for those parameterized linear control laws that can arise as the linearization of a nonlinear control law. This issue emerged as basic to the application of extended linearization to control problems other than the linearized eigenvalue placement problem that was the first problem studied. As an illustration, the noninteracting control problem for nonlinear systems is considered in the paper (though only in a preliminary way compared to work reported below). The characterizations presented in the paper form the foundation for our subsequent work on different types of nonlinear control problems.

We completed an investigation of the nonuniqueness of nonlinear control laws that arise in the extended linearization approach. The idea was to add further constraints involving the higher-order terms in the nonlinear feedback gains that would effectively zero higher-order terms in the resulting closed-loop system. Our conclusion was reported in publication [2], entitled "K^{th}-Order Extended Linearization." Conditions were derived for the existence of a nonlinear feedback law that satisfies requirements on the higher-order terms, in addition to the linear terms. This work was successful in the sense that rather simple existence conditions were obtained. However the conditions are restrictive, and they indicate that a different

*Square-bracketed citations refer to the publication list in Section 3.

approach is needed. That is, general methods of profitably reducing the nonuniqueness by imposing additional requirements on the design process remain to be discovered.

We completed work on publication [3], entitled "Design of Nonlinear PID Controllers." In this paper it is demonstrated that the extended linearization approach can be applied to standard, classical, linear design methods in the frequency domain. To illustrate, a typical class of nonlinear process control problems was considered, and the extended linearization method was used to construct what could be called a nonlinear Zeigler-Nichols proportional-integral-derivative (PID) controller. While this is a rather simple application of the method, it was a first step in a major new direction in our subsequent work - namely, the use of robust linear servomechanism design techniques in the context of the extended linearization approach to nonlinear servomechanism design.

Another project is reported in [4], entitled "Linearized Model Matching for Single-Input Nonlinear Systems." The motivation for this problem is that in many circumstances the desired closed-loop system behavior cannot be achieved by placement of the eigenvalues of the linearized closed-loop system alone. In fact, this was the case in our earlier work with the fourth-order nonlinear flight control model for the F-8C at high angle of attack. While the designed nonlinear control law behaved well with regard to placing the linearized closed-loop eigenvalues at each operating point, the input-output responses varied considerably over the range of operating points (flight conditions) that was simulated. This was due to variations in the gain and the zero locations of the input-output transfer function of the linearized system about different operating points. The model matching approach deals with obtaining a desired linearized system transfer function, and thus can be used to control this variation by specifying a constant gain and fixed zero (as well as pole) locations. Of course, to address this problem requires a frequency domain version of the extended linearization method - one of the research objectives mentioned above. This has proved to be relatively straightforward for single-input, single-output systems, though the multivariable case is much more difficult. Another reason that we have not pursued the model matching problem further is that the sensitivity properties of the resulting closed-loop system can be rather poor.

Motivated by the techniques used in the model matching problem, we have developed an alternate treatment of the original pseudo-linearization results of Champetier and Reboulet. This work is reported in [5], entitled "On the Pseudo-Linearization Problem for Nonlinear Systems." The original treatment of this problem was differential-geometric in character. However, we have been able to give a simpler, more explicit solution of the problem for systems with one or two inputs. In particular we believe our solution is much more suitable in terms of the possible application of the pseudo-linearization theory in the design of nonlinear control laws, and illustrates our objective of making use of recent results in geometric control theory to develop direct design methods.

We have made significant progress on a general, multi-input, multi-output servomechanism design problem. [6] In this problem the goal is to provide, using output feedback control, asymptotic tracking of constant reference inputs while rejecting unmeasured, constant disturbance signals. Even for quite general nonlinear plants, it turns out that this problem has an elegant solution. For linear plants the control law design reduces to the well known linear servomechanism theory developed in the 1970's. Our formulation of the problem includes both measured and unmeasured disturbance signals, and our design approach is constructive. We regard this as one of the major accomplishments of our research effort.

In order to better understand the performance of systems designed by the extended-linearization method when time-varying inputs and/or disturbances are applied, we have been very interested in a recent (1986) stability result by M. Kelemen. In fact, this result is used in the analysis of the performance of the servomechanism problem discussed above when the reference input and disturbance signals are time-varying. While the stability result is innovative, the proof is quite involved, and does not provide explicit performance bounds, so we have developed an alternate proof that we believe is more explicit, and simpler. [7] This stability result is a main tool for investigating the performance of closed-loop control systems designed using our approach, and we currently are exploring extensions of the basic result, and additional applications to our design method.

Another major accomplishment is the work reported in [8], entitled "Approximate Noninteracting Control with Stability for Nonlinear Systems." In this paper we show that under certain conditions the recently-discovered geometric obstruction to achieving exact nonlinear noninteraction with stability can be overcome in the context of a weaker notion of noninteraction. This weaker notion arises naturally from considerations in the extended-linearization approach, and appears to be quite appropriate for practical problems. For some systems for which exact noninteraction with stability cannot be obtained with static feedback, approximate noninteraction with stability can be obtained with static feedback. Also, for some systems for which exact noninteraction with stability cannot be obtained with either static or dynamic feedback, approximate noninteraction with stability can be obtained with dynamic feedback.

Initial results on the third major accomplishment of our research effort are reported in [9]. This paper essentially shows how the extended linearization design approach can be generalized to problems involving classes of time-varying nominal trajectories, rather than the families of constant equilibria considered up to now. Phrased in the context of the servomechanism problem again, these results show how to design control laws to achieve, for example, asymptotic tracking of ramp reference inputs with asymptotic rejection of a sinusoidal disturbance. It appears that this more general formulation will have a number of important implications in our future work.

Finally, publication [10], entitled "Analytical Framework for Gain Scheduling" is the first step in exploiting the close association between the extended-linearization approach and the typical practice of gain scheduling on exogenous signals to shed light on the design process for gain-scheduled control systems.

3. Publications

(Cumulative, from March 1, 1987.)

[1] J. Wang, W.J. Rugh, "Feedback Linearization Families for Nonlinear Systems," *IEEE Transactions on Automatic Control*, Vol. AC-32, No. 10, pp. 935-940, 1987.

[2] J. Wang, W.J. Rugh, "K^{th}-Order Extended Linearization," *Proceedings of the Twenty-first Conference on Information Sciences and Systems*, Baltimore, Maryland, pp. 675-680, 1987.

[3] W.J. Rugh, "Design of Nonlinear PID Controllers," *AIChE Journal*, Vol. 33, No. 10, pp. 1738-1742, 1987.

[4] J. Wang, W.J. Rugh, "Linearized Model Matching for Single-Input Nonlinear Systems," *IEEE Transactions on Automatic Control*, Vol. AC-33, No. 9, pp.793-796, 1988.

[5] J. Wang, W.J. Rugh,"On the Pseudo-Linearization Problem for Nonlinear Systems," *Systems & Control Letters*, Vol. 12, pp. 161-167, 1989.

[6] J. Huang, W.J. Rugh, "On a Nonlinear Multivariable Servomechanism Problem," *Automatica*, accepted for publication, 1990.

[7] D. Lawrence, W.J. Rugh, "On a Stability Theorem for Nonlinear Systems with Slowly-Varying Inputs," *IEEE Transactions on Automatic Control*, accepted for publication, 1990.

[8] J. Huang, W.J. Rugh, "Approximate Noninteracting Control with Stability for Nonlinear Systems," *IEEE Transactions on Automatic Control*, submitted for publication, 1990.

[9] J. Huang, W.J. Rugh, "Stabilization of Zero-Error Manifolds and the Nonlinear Servomechanism Problem," *Proceedings of the Conference on Information Sciences and Systems*, accepted for publication, 1990. (To be submitted for journal publication.)

[10] W.J. Rugh, "Analytical Framework for Gain Scheduling," *Proceedings of the American Control Conference*, accepted for publication, 1990. (To be submitted for journal publication.)

4. Personnel

Principal Investigator:

Wilson J. Rugh

Research Assistants (Graduate Students):

J. Wang: PhD completed, December 1987. Dissertation title: "On Linearization Families of Nonlinear Systems and Nonlinear Control Laws."

J. Huang: current PhD student, estimated completion in Summer, 1990.

D. Lawrence: current PhD student, estimated completion in Spring, 1991.

5. Interactions

Publication [2] was presented at the Conference on Information Sciences and Systems, Baltimore, MD, March, 1987.

Publication [5] was presented at the Conference on Information Sciences and Systems, Princeton, NJ, March, 1988.

A seminar on publication [6] was presented at the Electrical Engineering Department, Michigan State University, East Lansing, MI, in February, 1989.

A lecture on the extended-linearization method in general was presented at the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, in February, 1989.

Publication [7] was presented at the Conference on Information Sciences and Systems, Baltimore Maryland, in March, 1989.

In April, 1989, the PI visited Dr. James Cloutier and other personnel at the Guidance and Control Branch, AF Armament Laboratory, Eglin AFB, FL, for discussions on nonlinear control aspects of missile autopilots, and related issues such as gain scheduling.

A lecture on publication [6] was presented at the IFAC Symposium on Nonlinear Control Design, Capri, Italy, in June, 1989.

A lecture on publication [10] was presented at the NASA Ames - UC Berkeley Workshop on Nonlinear Flight Control, University of California, Berkeley, CA, in August, 1989.

Publication [9] was presented at the Conference on Information Sciences and Systems, Princeton, NJ, in March, 1990.

Lectures on publications [8] and [10], the latter an invited presentation, will be presented at the American Control Conference, San Diego, CA, in May, 1990.

Discussions with personnel at the Johns Hopkins Applied Physics Laboratory have led to a joint project on the application of the design approach developed under this grant to the autopilot design for a high-performance tactical missile. Initial results indicate that our nonlinear control approach can be much more effective than modern robust linear design approaches for this project. Our continuing plan is both to comparatively evaluate these two approaches, and to carry the nonlinear design approach through to completion of a practical, high-performance autopilot design.