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14. ABSTRACT

During this grant period, we have enhanced robustness of our backstepping designs and thus increased their ability to accommodate disturbances and unmodeled dynamics. We have also broadened the class of systems to which these methods are applicable. In a different direction, we have developed structure specific methods to analyze boundedness properties of systems with "stiffening" nonlinearities, as in micro-electromechanical probes. A major advance has been made on difficult output feedback problem with a novel nonlinear observer design, achieving robustness to modeling errors. Explicit necessary and sufficient conditions have been derived for coordinated passivation designs. A new maneuvering design has been developed. Further progress was made in MIMO adaptive control. We now briefly summarize our main results.

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CONSTRUCTIVE NONLINEAR CONTROL

Final Report

AFOSR - Grant 49620-00-1-0358

08/15/2000 - 09/30/2003

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OBJECTIVES

Research topics under this grant evolved from the AFOSR-PRET five-year program 'Robust Nonlinear Control of Stall and Flutter in Aeroengines'. This PRET program has demonstrated that constructive nonlinear methods, further developed under this grant, are highly relevant to several key technologies, including aero and auto engines and micro-electromechanical devices. To be reliable and of reasonable cost, a nonlinear controller must act in harmony with system nonlinearities, rather than try to override them. Starting with this premise, constructive nonlinear control methods combine structure-specific analytical and computational tools into systematic procedures which exploit inherent system properties. Most fundamental system properties – stability, passivity, dissipativity, optimality, etc. were analyzed earlier, but have not been fully activated as design tools. Their activation has been the main objective of this research effort.

ACCOMPLISHMENTS

During this grant period, we have enhanced robustness of our backstepping designs and thus increased their ability to accommodate disturbances and unmodeled dynamics. We have also broadened the class of systems to which these methods are applicable. In a different direction, we have developed structure specific methods to analyze boundedness properties of systems with "stiffening" nonlinearities, as in micro-electromechanical probes. A major advance has been made on difficult output feedback problem with a novel nonlinear observer design, achieving robustness to modeling errors. Explicit necessary and sufficient conditions have been derived for coordinated passivation designs. A new maneuvering design has been developed. Further progress was made in MIMO adaptive control. We now briefly summarize our main results.

Jet Engine Compressor Experiments [J6, J16, C2, C3]
Our major survey of nonlinear control theory shows that many fundamental descriptive results are still 'inactive' as design tools. It then describes the current efforts at their 'activation' for constructive feedback design. Among these is our application of the control Lyapunov function concept to a jet engine compressor model in which the two-dimensional control is achieved with a ring of four bleed valves. To maintain the pressure rise near the peak value, a linear controller was first designed, but it resulted in an unacceptably small region of attraction. When the optimal value function of this linear design was used as a control Lyapunov function for the nonlinear compressor model, simulations predicted significant improvements of performance. Our subsequent experiments have confirmed this prediction. The stability region of the optimal operating point has been enlarged to the limit set by the bleed valve constraints.

Locally Optimal Backstepping [J12, C11]
Backstepping procedures provide a systematic construction of control Lyapunov functions, but do not explicitly address the performance of the designed nonlinear system. This drawback has been removed in our recent work. The constructed Lyapunov function is now an approximation, to a desired order, of the optimal value function of the given optimal control (or differential game) problem. In this way the designed nonlinear system is optimal locally, while it also possesses other desired global properties. Most recently backstepping has been extended to a wider class of systems.

Robust Nonlinear Control [J1, J2]
A significant part of our research is aimed at robustification of earlier constructive design procedures with respect to unmodeled dynamics, especially the most common ones appearing at the system input ('actuator dynamics'). For backstepping, our result is based on a robust stability property of the zero dynamics. Our redesign of the nested saturation method for feedforward systems is applicable to actuators that change the relative degree of the system.

Nonlinear Output Feedback Design [J7, C1]
One of our major advances during this period is in the area of output feedback design. For a class of nonlinear systems, we have been able to extend our state feedback locally optimal designs to output feedback in the presence of unknown input disturbance. The new constructive design blends worst-case filtering with

backstepping and results in a disturbance attenuating dynamic feedback controller that achieves global stability and local optimality.

Passivation Designs [J3, J4, J8, J13, J14, C7]]
Systems with (bounded or unbounded) sector nonlinearities are suitable for application of various passivation tools, including numerical solution of linear matrix inequalities. Our contributions to dynamic output feedback passivation clarify structural conditions for passivation and algebraic feasibility conditions for circle criterion designs. A more general use of the passivation idea is to allow any pair of signals to play the role of the 'input' and 'output' for which the passivation is to be achieved by employing (possibly dynamic) feedback from the actual measured output to the actual control input. This problem is addressed as 'coordinated passivation'. A situation of this kind is when the selected 'indirect' input-output pair represents the ports of a conic (scalar or vector) nonlinearity in an otherwise linear system. The problem is then to find a feedback law between the actual output and input to achieve passivity for the 'indirect' pair. By either the Circle or Popov criterion, this results in a stable closed loop system. We have also derived explicit algebraic conditions which are necessary and sufficient for each of these two designs to be feasible. These conditions reveal new structural properties of systems consisting of linear and nonlinear blocks.

Observer-Based Designs [J5, J9, J11, C5]
Using our recently developed observer for systems with monotonic nonlinearities, we have developed an output feedback design robust to a class of unmodeled dynamics. When, in addition, the nonlinearities are with restricted slope, the design is further simplified in and applied to Euler-Lagrange systems in. A novel feature in the observer design is the use of nonlinear injection and LMI calculations based on the circle criterion.

Output Maneuvering via Backstepping [J17, C8, C9, C10]]

The distinction between 'tracking' and 'maneuvering' is that in the first problem the output is the follow a given function of time, while in the second it follows a geometric path with time assignment left free. The contribution is a maneuvering design that is applicable to systems in vectorial strict feedback form of any relative degree. In the *n* recursive steps, the design solves the geometric part of the problem. It then proceeds to construct an update law that ties together the geometric design with the speed assignment. And extra degree of freedom is provided for an operator to select the speed of the maneuver variable.

Boundedness Without Absolute Stability [J10]

There are problems in which the stability of an equilibrium is either not required or is impossible to achieve, and the desired property is boundedness. For systems containing a linear block of relative degree one or two in feedback with a nonlinearity, our results give conditions for achieving boundedness. One of the examples is boundedness in a system consisting of an unstable Mathieu equation in feedback with stiffening nonlinearity. This phenomenon is observed experimentally in microelectromechanical systems.

MIMO Adaptive Control [J15, C4, C6]]

An intricate problem in MIMO adaptive control is the characterization of the 'infinite frequency gain' matrix, which would allow stable adaptive update laws to be designed by Lyapunov and backstepping methods. Such advances are made for linear and a class of nonlinear systems.

PERSONNEL SUPPORTED

<u>Faculty</u>
P. Kokotovic, PI

<u>Post-Doctoral Researcher</u>
M. Arcak
R. Goebel

<u>Graduate Students</u>
N. Petrovacki
S. Tuna
D. Dacic
M. Larsen
D. Fontaine

<u>Visiting Faculty</u>
R. Costa

TRANSITIONS

The impact of our research has been primarily through the current work of our recent Ph D's and postdoctoral fellows, in particular: Dr. Ezal, Toyon, Santa Barbara; Dr. Michael Larsen, Information Systems Laboratories, San Diego; and Dr. Mrdjan Jankovic, Ford Research Laboratories. Their projects hold promise for rapid industrial application of some of our constructive methods. An excellent example is the extension of backstepping and passivation to systems with delays, recently achieved by Dr. Jankovic, mjankov1@ford.com, and applied to a turbocharged diesel engine.

HONORS/AWARDS

During the period of this grant, Petar Kokotovic received two prestigious recognitions: the AACC Richard E. Bellman Control Heritage Award for "Pioneering contributions to control theory and engineering, and for inspirational leadership as mentor, advisor, and lecturer over a period spanning four decades." and the IEEE James H. Mulligan Jr. Education Medal for "Leadership in control engineering theory and engineering education as an inspirational teacher and mentor." In the International Citation Index his name is consistently among the top hundred most frequently cited authors in all fields of engineering. He was a plenary speaker at the IEEE Decision and Control Conference, December 2000, Sydney, Australia, and at the Mediterranean Control Conference, June 2001, Dubrovnik, Croatia, where he also presented the Best Student Paper Award. He also presented a plenary talk at the IFAC Robust Control Workshop, June 2003, Milano, Italy, and at the IEEE International Conference on Control Applications, Istanbul, Turkey, June 2003.

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[J17] R. Skjetne, T. Fossen, P.V. Kokotovic, "Robust Output maneuvering for a Class of Nonlinear Systems," to appear in *Automatica*, 2004

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[C1] M. Arcak and P. Kokotovic, "Robust Output-Feedback Design Using A New Class of Nonlinear Observers," *Proc. 39th IEEE Conference on Decision and Control*, 778-783, Sydney, Australia, December 2000.

[C2] D. Fontaine, S. Liao, J. Paduano, P. Kokotovic, "Nonlinear Control Experiments on an Axial Flow Compressor," *Proc. 39th IEEE Conference on Decision and Control*, 1329-1334, Sydney, Australia, December 2000.

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