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13. ABSTRACT *(Maximum 200 words)*

The research completed has established connections between systematic methods of nonlinear stabilization and nonlinear optimal control. The redesigns of adaptive and robust nonlinear controllers developed under this grant are inverse optimal, and thus use less control effort and possess a certain margin of robustness to some uncertainties. This grant has also produced the first methods for stabilization for stochastic nonlinear systems. The most significant among the results is disturbance attenuation and adaptive stabilization for systems with noise of unknown covariance. Finally, the grant has revived a whole research area called extremum seeking control which deals with non-model-based on-line optimization. The PI and the group obtained the first stability guarantees for etremum seeking schemes and proposed techniques for their application to much more general classes of systems than previously possible.

The ultimate goal of the theoretical research was an application to nonlinear instabilities arising in aeroengines. The PI has advanced the state of the art in this area in three directions. First, he developed the first nonlinear control laws with guaranteed regions of attraction and robustness to some modeling errors. Second, he pioneererd the methods for seeking of the maximum of the compressor pressure rise characteristic. Third, he designed the first model-based adaptive controllers for thermoacoustic instabilities in combustion chambers.

The results of the work have been published (or submitted for publication) in 1 book, 22 journal papers, a number of conference papers, and four book chapters.

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Contents

ABSTRACT

The state of the art in nonlinear control at the beginning of this research was such that control schemes were available for stabilization of certain classes of nonlinear systems but these schemes were often too complex to synthesize, required a high control effort, and their robustness was not guaranteed. This research was concerned with establishing connections between systematic methods of nonlinear stabilization and optimal control. As our main result, we provide redesigns of adaptive and robust nonlinear controllers which are inverse optimal, and thus use less control effort and possess a certain margin of robustness to some uncertainties.

Additionally, prior to this grant nonlinear stabilization methods were available only for deterministic systems. Our most significant results in the area of stochastic nonlinear control are the development of methods of disturbance attenuation and adaptive stabilization for systems with noise of *unknown covariance*. The novelty of these results is twofold: (1) this is the first time a stochastic problem is considered with no a priori knowledge on the noise intensity; (2) this is the first set of *constructive* results on stochastic stabilization.

Finally, this grant has revived a whole research area called extremum seeking control which deals with nor-model-based on line optimization. Under this grant we obtained the first stability guarantees for extremum seeking schemes and proposed techniques for their application to much more general classes of systems than previously possible.

The objective of the theoretical research was an application to nonlinear instabilities arising in aeroengines. We have advanced the state of the art in this area in three directions. First, we have developed the first nonlinear control laws with guaranteed regions of attraction and robustness to some modeling errors. Second, we have pioneered the methods for seeking of the maximum of the compressor pressure rise characteristic. Third, we have designed the first model-based adaptive controllers for thermoacoustic instabilities in combustion chambers.

The results of our work have been published (or submitted for publication) in 1 book, 22 journal papers, a number of conference papers, and four book chapters. They are discussed in two major sections of this technical report, Section 2 which discusses our theoretical accomplishments, and Section 3 which discusses our applications.

1 THEORY

During the grant period the PI's research has resulted in 15 journal articles and one book [K1]. These publications are listed at the end of this section.

1.1 Inverse Optimal Controllers for Systems with Deterministic Uncertainties

Nonlinear optimal control problems reduce to Hamilton-Jacobi pde's which are difficult to solve. We have provided analytical solutions to HJ pde's for nonlinear systems affine in disturbances or parametric uncertainties.

- **Disturbances—Differential Game Approach.** In [K3] we proved that input-to-state stabilizability is both *necessary and sufficient* for the solvability of an Isaacs equation associated with a meaningful differential game problem. Our cost functional is more general than in the "nonlinear $\mathcal{H}_\infty$" problem and the penalties on the disturbance and the control in general become non-quadratic (rather than completion of squares, our main technical tools are Legendre-Fenchel transforms), which allows an analytical solution to the pde.

- **Parametric Uncertainties—Adaptive Approach.** In [K2] we proved that an inverse optimal adaptive tracking problem is solvable if and only if an "adaptive control Lyapunov function" exists for the system. The adaptive controller that we present is the first adaptive controller that is truly optimal (previous pointwise-Riccati-based adaptive controllers do not actually minimize any meaningful cost functional). Optimality is achieved by including a terminal penalty on the parameter estimation error in the cost functional, which forces the controller to compensate parameter adaptation transients.

1.2 Stochastic Nonlinear Control

Stabilization of stochastic nonlinear continuous-time systems is a problem whose difficulty is well known. In [K4] we present a systematic global solution for a class of nonlinear systems driven by white noise (without growth or matching restrictions on the nonlinearities). The main technical difficulty with a Hessian term in the Lyapunov analysis (arising from the Ito differential) is dealt with by replacing the usual quadratic-like choice of a Lyapunov function with *quartic* Lyapunov functions. In [K5] we provide general results for optimal global stabilization in probability using "stochastic control Lyapunov functions."

In [K7] we extend the above results to the general case of *unknown covariance* for which we present two solutions: one based on disturbance attenuation, and the other based on adaptation. Our work includes the development of a new set of Lyapunov theorems for stochastic nonlinear systems. In the disturbance attenuation setting the problem is solved by introducing an innovation of treating the covariance as an opposing player in a differential game. In the linear case with "multiplicative noise", our adaptive design extends the results by Wonham and by Willems and Willems to a larger class of systems. In [K6,K8] the results are extended to the output-feedback case.

1.3 Extremum Seeking

This feedback method has been used widely in applications since the 1940's for finding an extremum of an *uncertain* reference-to-output equilibrium map. In [K9] we provide the first proof of its stability. We employ the tools of averaging and singular perturbation analysis and allow the plant to be a general (non-affine) dynamical system. In [K10] we extend the extremum seeking method to the problem of minimizing the amplitude of limit cycles.

1.4 Asymptotic Properties of Adaptive Nonlinear Systems

A fundamental unanswered question in adaptive control has been whether the parameter estimates always converge to stabilizing values. In fact, except for the case of persistent excitation or least-squares estimation, it was not even known if the parameter estimates converge at all. In [K11], we provided an affirmative answer to the question of convergence to constant estimates, and then, using center manifold and invariant manifold theorems, showed that, for the problem of regulation to zero, (1) the parameter estimates may not always converge to stabilizing values, and (2) the set of initial conditions that lead to exponentially destabilizing estimates is of measure zero. In a subsequent study [K12] we construct a simple example of adaptive regulation to a non-zero equilibrium where the controller converges to exponentially destabilizing estimates from initial conditions of *positive measure*.

1.5 Robust Redesigns of Adaptive Nonlinear Controllers.

Even for linear plants, benign-looking disturbances and unmodeled dynamics can cause unbounded solutions of adaptive systems. We have addressed some of these problems for adaptive *nonlinear* systems. In [K13,K14] we showed that the standard robustification tool - dynamic normalization—is not necessary in tuning functions schemes. Instead, we employ only leakage or parameter projection to prevent the drift of the estimates. In addition to unmodeled dynamics, we have also addressed the problem of bounded uncertainties in [K15]. For each of the previously developed adaptive nonlinear designs, we presented a redesign which guarantees *global* boundedness of solutions and arbitrarily small $\mathcal{L}_2$ and $\mathcal{L}_\infty$ gains with respect to the disturbances.

2 APPLICATIONS

The output of PI's applied activity during the grant period is 7 journal articles.

2.1 Rotating Stall and Surge in Jet Engine Compressors

In [K17] we designed a feedback controller that globally stabilizes a broad range of possible equilibria in a nonlinear compressor model of Moore and Greitzer. This is achieved with a novel type of backstepping design which avoids cancellation of the system's useful nonlinearities—those that would be cancelled in a feedback linearizing design. While stability analysis is involved, the resulting control law is simple, requires minimal modeling information, simpler sensing, and changes the character of the bifurcation from subcritical to supercritical globally (since we do not use bifurcation normal forms but Lyapunov tools, our results are more than local). In the article [K18] we have also proposed controllers (a) for compressors with a "deep-hysteresis" characteristic, (b) with actuators of limited bandwidth, and (c) with a high value of Greitzer's B parameter.

In [K19] we apply the extremum seeking scheme to the Moore-Greitzer model of an aeroengine compressor and maximize the steady-state pressure rise, while also stabilizing rotating stall and surge. Then we also present an *experimental* validation of the method performed on a compressor rig at Caltech through the PRET program on aeroengine control. We use a combined actuation via a slow bleed valve and fast air injection.

2.2 Acoustic Instabilities in Combustion Chambers

When a combustion system is operated with a lean fuel/air mixture (for example, in order to reduce the NO_x emission) or at high power, it becomes more prone to limit cycling thermoacoustic waves. In [K20] we developed an adaptive PI controller which is the first compensator that drives to zero more than just the first mode of pressure oscillations. Our adaptation scheme employs only one pressure sensor, thus avoiding requirements for sophisticated sensing of higher mode amplitudes. We show that our adaptation mechanism is robust to pure delay, which is the first such theoretical result.

2.3 Other Aerospace Applications

- **Aircraft Wing Rock.** Wing rock is a nonlinear oscillation in the roll angle caused by asymmetric leading-edge vortices in fighter aircraft flying at high angle-of-attack. We developed an adaptive nonlinear controller [K21] which achieves attenuation of oscillations on a wing-rock model with uncertain aerodynamic parameters and "rolling-moment derivative."

- **Optimal Control of Spacecraft.** Optimal regulation of attitude and velocity in spacecraft models is a problem that has been open since the 1960's. We have recently solved it in [K22] via inverse optimality combined with backstepping. Our cost functional puts a nonquadratic penalty on the angular velocity, orientation, and control torque to account for the nonlinearity of the system.

- **Helicopter blade vortex interaction.** The interaction of a helicopter rotor blade with the vortices shed by the preceding blade(s) is the primary determinant of the helicopter's far-field acoustic signature. Motivated by efforts to incorporate flap actuation into the rotor blade using active ("smart") structure technology, and associated modeling efforts, we developed and numerically tested two control designs for BVI suppression [K23]: (a) robust feedback controllers for BVI *suppression* and (b) adaptive feedforward controllers for BVI *cancellation*.

3 PI'S SELECTED PUBLICATIONS FROM THE GRANT PERIOD

Book

[K1] M. Krstic and H. Deng, *Stabilization of Nonlinear Uncertain Systems*. New York. Springer, 1998.

Journal Papers

(inverse optimal adaptive and robust nonlinear control)

[K2] Z. H. Li and M. Krstic, "Optimal design of adaptive tracking controllers for nonlinear systems," *Automatica,* vol. 33, pp. 1459-1473, 1997.[1]

[K3] M. Krstic and Z. H. Li, "Inverse optimal design of input-to-state stabilizing nonlinear controllers," *IEEE Transactions on Automatic Control,* vol. 43, pp. 336-351, 1998.

(stochastic nonlinear control)

[K4] H. Deng and M. Krstic, "Stochastic nonlinear stabilization—Part I: A backstepping design," *Systems and Control Letters*, vol. 32, pp. 143-150, 1997.

[K5] H. Deng and M. Krstic, "Stochastic nonlinear stabilization—Part II: Inverse optimality," *Systems and Control Letters,* vol. 32, pp. 151-159, 1997.

[K6] H. Deng and M. Krstic, "Output-feedback stochastic nonlinear stabilization," *IEEE Transactions on Automatic Control*, vol.44, pp.328-33, 1999.

[K7] H. Deng and M. Krstic, "Stabilization of stochastic nonlinear systems driven by noise of unknown covariance," submitted to *IEEE Transactions on Automatic Control*, 1997.[2]

[K8] H. Deng and M. Krstic, "Output-feedback stabilization of stochastic nonlinear systems driven by noise of unknown covariance," *Systems and Control Letters*, to appear, 2000.

(extremum seeking)

[K9] M. Krstic and H. H. Wang, "Stability of extremum seeking feedback for general nonlinear dynamic systems," *Automatica,* to appear, 2000.

[K10] H.-H. Wang and M. Krstic,"Extremum seeking for limit cycle minimization," *IEEE Transactions on Automatic Control,* to appear, 2000.

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[1] Best Student Paper Award, 1997 American Control Conference (for conf. version of the paper).

[2] Finalist for the Best Student Paper Award, 1998 American Control Conference (ranked best among theoretical papers).

(asymptotic properties of adaptive nonlinear systems)

[K11] M. Krstic, "Invariant manifolds and asymptotic properties of adaptive nonlinear stabilizers," *IEEE Transactions on Automatic Control*, vol. 41, pp. 817-829, 1996.[3,4,5]

[K12] Z.-H. Li and M. Krstic, "Geometric/asymptotic properties of adaptive nonlinear systems with partial excitation," *IEEE Transactions on Automatic Control*, vol. 43, pp. 419-425, 1998.

(robustness of nonlinear control designs)

[K13] F. Ikhouane and M. Krstic, "Robustness of the tuning functions adaptive backstepping design for linear systems," *IEEE Transactions on Automatic Control*, vol. 43, pp. 431-437, 1998.

[K14] F. Ikhouane and M. Krstic, "Adaptive backstepping with parameter projection: robustness and asymptotic performance," *Automatica*, vol. 34, pp. 429-435, 1998.

[K15] R. A. Freeman, M. Krstic, and P. V. Kokotovic, "Robustness of adaptive nonlinear control to bounded uncertainties," *Automatica*, vol.34, pp.1227-30, 1998.

[K16] Z.-H. Li and M. Krstic, "Maximizing regions of attraction via backstepping and CLFs with singularities," *Systems and Control Letters*, vol. 30, pp. 195-207, 1997.

(compressor control)

[K17] M. Krstic, D. Fontaine, P. V. Kokotovic, and J. Paduano, "Useful nonlinearities and global bifurcation control of jet engine surge and stall," *IEEE Transactions on Automatic Control*, vol.43, pp.1739-45, 1998.

[K18] H.-H. Wang, M. Krstic, and M. Larsen, "Control of deep hysteresis aeroengine compressors," *Journal of Dynamic Systems, Measurement, and Control*, to appear, 2000.

[K19] H.-H. Wang, S. Yeung, and M. Krstic, "Experimental application of extremum seeking on an axial-flow compressor," *IEEE Transactions on Control Systems Technology*, to appear, 1999.

(combustion control)

[K20] M. Krstic, A. S. Krupadanam, and C. A. Jacobson, "Self-tuning control of a nonlinear model of combustion instabilities," *IEEE Transactions on Control Systems Technology*, vol. 7, pp. 424-436, 1999.

[3] Best Student Paper Award, 1995 American Control Conference (for conf. version of the paper).

[4] O. Hugo Schuck Best Paper Award, American Automatic Control Council, 1996 (conf. version).

[5] George S. Axelby Outstanding Paper Award of IEEE Trans. Automatic Control, 1998.

(other aerospace applications)

[K21] M. M. Monahemi and M. Krstic, "Control of wing rock motion using adaptive feedback linearization," *Journal of Guidance, Control, and Dynamics,* vol 19, pp. 905 912, 1996.

[K22] M. Krstic and P. Tsiotras, "Inverse optimality results for the attitude motion of a rigid spacecraft," *IEEE Transactions on Automatic Control,* vol. 44, pp. 1042-1049, 1999.

[K23] K.B.Ariyur and M. Krstic, "Feedback attenuation and adaptive cancellation of blade-vortex interaction noise on a helicopter blade element," *IEEE Transactions on Control Systems Technology,* vol. 7, pp. 596-605, 1999.

4 ADDITIONAL DATA

4.1 Personnel Supported

- Dr. Miroslav Krstic, Associate Professor, Principal Investigator
- Dr. Andras Balogh, postdoctoral researcher
- Dr. Weijiu Liu, postdoctoral researcher
- Hsin-hsiung Wang, Graduate Student Researcher
- Kartik Ariyur, Graduate Student Researcher
- Hua Deng, Graduate Student Researcher
- Dejan Boskovic, Graduate Student Researcher

4.2 Doctoral Dissertations Completed

- Z.-H. Li, *Optimal Lyapunov Design of Robust and Adaptive Nonlinear Controllers*, University of Maryland, 1998.
- H.-H. Wang, *Bifurcation Control and Extremu Seeking for Aeroengine Compressors and Bioreactors*, University of Maryland, 1998.

4.3 Transitions

Our extremum seeking algorithms are under consideration for the use in compressor and combustion control systems for gas turbines at the *United Technologies Research Center*. Our PhD student Kartik Ariyur has spent Summer 1998 as an intern in UTRC working on problems of identification, model validation, and control of combustion instabilities under the direction of Dr. Andrzej Banaszuk (phone: 860 610-7381).

4.4 Awards

- Axelby Outstanding Paper Award of IEEE Transactions on Automatic Control.
- Presidential Early Career Award for Scientists and Engineers (PECASE).
- Finalist for the Young Author Prize at the 1999 IFAC World Congress.
- Finalist for Best Student Paper Award at the American Control Conference 1998, student author: Hua Deng, co-author: Miroslav Krstic.