REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final Technical 10/1/92 - 9/30/95

4. TITLE AND SUBTITLE
Adaptive Control of Systems with Uncertain Nonlinearities

5. FUNDING NUMBERS
Proj./task 2304/AS
Grant: 949620-92-J-0495

6. AUTHOR(S)
Petar V. Kokotovic

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Control Engineering and Computation (CCEC)
Department of Electrical & Computer Engineering
University of California
Santa Barbara, CA 93106-9560

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR-96-0026

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Marc Q. Jacobs
AFOSR/NM
110 Duncan Avenue, Suite B-115
Bolling AFB, DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19960202 008

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Our broad research program in robust and adaptive control has culminated in the development of three new design methodologies presented in two books totaling 850 pages, four book chapters, 26 major journal publications, and more numerous conference papers.

Our new inverse optimality approach to robust nonlinear control avoids the need to solve the HJI equation, but still achieves the desirable properties of optimal systems. A systematically constructed robust Lyapunov function is at the same time the upper value function of a meaningful differential game. For systems with unknown nonsmooth nonlinearities in actuators and sensors - hysteresis, dead-zone and backlash - we have developed an adaptive inverse approach. Adaptive controllers of this type compensate for the undesirable effects of the nonlinearities and with imperfect components achieve high tracking performance.

Modular adaptive designs lead to new controllers applicable to larger classes of nonlinear systems. In the linear case, when other adaptive schemes are also applicable, our designs result in superior transientt and steady-state performance.

The results of this research have been well received by the research community and industrial applications are beginning to appear.

14. SUBJECT TERMS

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298
Prescribed by ANSI
298-102

DTIC QUALITY INSPECTED 1

AFOSR Grant 92-J-0495

Adaptive Control of Systems with Uncertain Nonlinearities

Petar V. Kokotovic
Principal Investigator
Center for Control Engineering and Computation (CCEC)
Department of Electrical & Computer Engineering
University of California
Santa Barbara, CA 93106-9560
Tel: (805) 893-7011
Fax: (805) 893-3262

e-mail: petar@ece.ucsb.edu

FINAL TECHNICAL REPORT

For the period: October 1, 1992 - September 30, 1995

TABLE OF CONTENTS

6 Publications

1 INTRODUCTION

During the three-year period of this grant we have pursued a broad research program in control of nonlinear systems with uncertainties.

For systems with functional uncertainties and/or bounded disturbances we have initiated the development of a radically new *robust inverse optimal design,* in which a *robust control Lyapunov function* is shown to be the value function for a meaningful differential game. A book summarizing this approach is in preparation.

For systems with parametric nonlinearities we have developed systematic *adaptive backstepping designs* of two types: with tuning functions and estimation-based modular designs. This methodology is presented in our comprehensive 550-page book [B1].

Adaptive compensation of dead-zone, backlash and hysteresis nonlinearities, which are common in actuators and sensors, was the third major direction of our research which resulted in a systematic design methodology, summarized in our 300-page book [B2].

Details of our results are documented in 26 major journal publications and more numerous conference papers. They are briefly reviewed in this report.

2 ROBUST NONLINEAR CONTROL

Our new approach to the design of robust controllers for nonlinear systems addresses the fundamental problems left open by the two current nonlinear theories: geometric and H-infinity. The tools of the geometric theory provide the needed insight into the structural properties of ideal models, but are unable to cope with imperfections of real life models. Nonlinear analogs of some linear H-infinity results are aimed at dealing with uncertainty, but have so far remained local and computationally complex. Our robust control Lyapunov function and the related concept of inverse optimality, make use of the system geometric properties and, without an excessive computational burden, achieve a form of robust optimality.

2.1 Robust Control Lyapunov Function [BC1, BC3, J1, J23, J24, C9, C18, C22, C23, C24, C27, C30, C33]

The robust control Lyapunov function (rclf) is a unifying concept for the feedback design of nonlinear systems with uncertainties characterized by set-valued maps. For each fixed state outside some bounded set, the negativity of the time derivative of rclf can be satisfied robustly by choice of a control. In [BC3, C9, C20, C21] it is shown that the existence of an rclf is equivalent to robust stabilizability and recursive methods (robust backstepping) are developed for constructing rclf's for wide classes of uncertain systems.

2.2 Inverse Optimality
[J20, C21, D4]

Once an rclf is known, a robust control law is chosen which renders negative the worst-case derivative of the rclf along trajectories of the closed-loop system. By construction, every such control law guarantees the robust stability of the closed-loop system. The choice for such a control law is usually made by inspection, and herein lies one potential pitfall of these designs: not every such control law will necessarily provide adequate closed-loop performance. In fact, the simplest choices for the control law will indeed guarantee robust stability but may result in poor closed-loop performance. How, then, should one choose a good control law?

Our most important result in this direction is that every rclf solves the Hamilton-Jacobi-Isaacs partial differential equation associated with a meaningful game. This is proven in [J20] where also a formula is given for the construction of the optimal worst-case controllers. This formula generates a family of controllers which guarantee not only robust stability but also some level of performance. Robust control Lyapunov functions can thus be used to obtain candidates for good controllers without the burden of having to compute solutions to the Isaacs equation.

2.3 Flattened RCLF for Softer Controls
[J4, C29]

In [J4] *flattened* rclf's are introduced which lead to softer controls and greatly improve performance over the standard quadratic-like rclf's. In a typical system, the positive and negative sections of the control activity set (the ones corresponding to positive and negative values for the stabilizing control) are separated by the uncontrollability set. If the gap between these sections is narrow, high gain in the feedback law is necessary for the transition from positive to negative control values. This may cause chattering and other forms of undesirable behavior.

A flattened rclf is an rclf for which the uncontrollability set is "thick" so that the gap between the positive and negative sections of the control activity set is wide. A flattened rclf therefore requires much lower gain for the transition from positive to negative control values, and this results in softer controls and greatly improved performance. With a flattening technique, we have also been able to extend the backstepping method to systems with nonsmooth nonlinearities [C29].

2.4 Robustness to Measurement Uncertainty [J19, C11, C20]

The flattened rclf is a crucial ingredient in our solution [C11] of a long-standing open problem of achieving robustness of nonlinear feedback to errors in the state measurement. Such errors are difficult to accommodate in nonlinear systems, especially when strongly nonlinear control is required for stabilization. It is shown in [C11] that a large and practically important class of nonlinear systems can be made globally input-to-state stable with respect to disturbances affecting the state measurement. A key result here is the construction of an rclf which is so flat that, for sufficiently large signals, the uncontrollability set is "thick" enough to encompass the uncertainty set. Consequently, one can design a control law so that the state remains bounded no matter how large the bound on the disturbance. An extension of these results to the output feedback case is possible as illustrated by an example in [C20]. The fundamental limitations in this problem are examined in [J19].

3 ADAPTIVE NONLINEAR CONTROL

Our most intensive research effort has been dedicated to, and our most significant results have been obtained in, the development of systematic design methods for adaptive control of nonlinear systems. The theory and design of our new adaptive controllers are comprehensively documented in some 30 papers and presented in a tutorial fashion in our most recent 550-page monograph [B1]. Here we only highlight some properties of the newly designed controllers.

3.1 Adaptive Backstepping Design [B1, BC4, J2, J9, J10, J18, J25, C1, C2, R1]

Our method of *adaptive backstepping with tuning functions*, radically changed the adaptive controller design. The adaptive controller, which cannot be a certainty equivalence controller for the original nonlinear system, is designed as a certainty equivalence controller for a modified system. In this framework, the tuning functions are a technique for recursively generating adaptive control Lyapunov functions [J18, C32].

An important feature of the tuning functions design is that the control law incorporates the parameter update law [J7, J10, C1, C2]. This is another departure from the certainty equivalence principle because, instead of treating the parameter estimates as constants, the controller compensates for the parameter estimation transients.

3.2 Output Feedback and Modular Designs [B1, BC2, J8, J15, J17, J21, J22, C3, C6, C13, C15, C16, C19, C26, C31, C32]

A modular approach to adaptive control is to separately design the controller and the identifier. Until recently this was possible only for linear systems. Now we have developed modular designs which employ new controllers that are stronger than the certainty equivalence controllers and are applicable to nonlinear systems [J8, J15].

For full modularity, adaptive controllers for nonlinear systems have to be strong enough to withstand the destabilizing effects of parameter estimation transients. Controllers in [J8, J15, C16] are designed to achieve input-to-state stability (ISS) with respect to the parameter estimation error and its derivative as the inputs.

With a controller module which achieves the above ISS property, one needs an identifier module which is able to guarantee boundedness of the parameter estimation error and its derivative. Two types of such identifiers have been developed. The 'swapping' identifiers [J15] employ filters to convert a dynamic parametric model into a static one. The 'passive' identifiers [J8] employ observers which exploit passivity of the observer error system. Identifiers of both types employ stability strengthening to counteract the effect of parameter estimation transients.

3.3 Transient Performance Improvement [B1, J5, C4, C7, C12, C28]

Transient performance has been a major open problem in adaptive control because the certainty equivalence designs neglect the time-varying nature of the parameter estimates. In our new adaptive backstepping designs we are able to quantify the transient behavior through computable performance bounds [J5, C4]. Their dependence on design parameters provides guidelines for systematic improvement of transient responses. This analysis has also provided the first quantitative comparison of adaptive and nonadaptive controllers. Adaptation was shown to improve both the transient and asymptotic performance relative to a nonadaptive design.

4 ADAPTIVE CONTROL OF SYSTEMS WITH ACTUATOR AND SENSOR NONLINEARITIES

Actuator and sensor nonlinearities are among the key factors severely limiting the achievable performance of feedback control systems. Harmful effects of backlash in gears are well known. Backlash prevents accurate positioning and may lead to chattering and limit-cycle type instabilities.

Examples of more complex hysteresis are magnetic and piezoelectric phenomena in solenoid actuated valves and micro-motion scanners. As a rule, materials with low hysteresis are costly. Can inexpensive magnetic and piezoelectric materials be used, but with their hysteresis effects removed by real-time computations? An analogous question can be raised for actuators and sensors with "dead-zones", that is with insensitivity to small magnitude signals.

In this research we have answered these questions for piece-wise linear models of unknown dead-zone, backlash and hysteresis. Our approach is to cancel the harmful effects of actuator and sensor nonlinearities by implementing their inverses inside the controller. Our first concern is that such inverses, possibly discontinuous, indeed exist. Our second concern is that they also be parametrized as linear functions of the unknown parameters. Having passed these two hurdles, we look for an adaptive implementation of the linearly parametrized inverses, continuously adjusted by adaptive update laws. When they converge to the true inverses of the unknown nonlinearities, the ideal goal of canceling the nonlinear effects is achieved: the control loops perform as if their inexpensive actuators and sensors are perfect. We have shown that this is the case for plants with input (actuator) nonlinearities, plants with output (sensor) nonlinearities, and plants with both input and output nonlinearities.

When implemented with parameter estimates our inverses result in a control error which can be expressed in two parts, one of which is parametrizable. The unparametrizable part due to the nonsmoothness of the nonlinearities is treated as an unknown disturbance. It is crucial that this disturbance is always bounded. The control error expression is instrumental in the development of an adaptive law which updates the estimates of the unknown parameters.

4.1 Compensation of Actuator Nonlinearities [B2, J3, J6, J11, J12, J16, C5, C10, C14, C25]

Two types of adaptive control problems with actuator nonlinearities have been investigated: when only the nonlinear part of the plant is unknown, and when the whole plant is unknown. The adaptive inverse controller consists of a linear controller structure with an adaptive dead-zone, backlash or hysteresis inverse. When only the nonlinear part is unknown, the adaptive inverse controller contains an adaptive inverse and a fixed linear structure. When the whole plant is unknown, the adaptive inverse controller has a new adaptive linear structure which results in a linearly parametrized closed-loop system suitable for the development of an adaptive law. For both problems, the linear controller structure generates the input signal to the adaptive inverse whose output is then applied to the plant with an unknown input nonlinearity. The adaptive inverse parameters are updated by adaptive laws with modifications for robustness with respect to a bounded "disturbance" - an unparametrizable error due to the nonsmoothness of the dead-zone, backlash and hysteresis nonlinearities. In addition, parameter projection is employed to ensure that the parameter estimates stay in a prespecified region. Extensive simulation results show significant improvements of the system tracking performance.

4.2 Compensation of Sensor Nonlinearities [B2, J13, J14, C8, C17]

For sensor nonlinearities, that is, the nonlinearities at the plant output, a continuous-time design is practically infeasible and only the discrete-time designs are developed. The difficulty with the sensor dead-zone or backlash is that they make the sensor input unobservable from its output. Despite this difficulty, when both the linear part and the nonlinear part are known, an inverse control scheme is developed for achieving the output tracking of a given reference signal. When the nonlinear part is unknown, an adaptive inverse controller is designed which consists of a linear part and two adaptive inverses: one to invert the plant output and the other to invert a given reference output. Two designs are presented: one for a known linear part and the other for an unknown linear part. In simulations the designed adaptive output inverse controllers lead to significant improvements of the tracking performance. Finally, discrete-time inverse control schemes for plants with both input (actuator) and output (sensor) nonlinearities.

5 RESEARCH TEAM AND IMPACT

In addition to the principal investigator Petar Kokotovic, the research team included postdoctoral researchers M. Jankovic, J. Sun, R. Ghanadan, P. Martin and R. Sepulchre, and graduate students P. C. Yeh, M. Krstic, R. Freeman, G. Johnstone, K. Ezal, D. Fontaine, and C. Barbu. During this research period Yeh, Krstic and Freeman have completed their PhD degrees and obtained academic positions. Krstic received two Student Best Paper Awards: at 1994 CDC and 1995 ACC. Kokotovic is the recipient of the 1995 IEEE Control Systems Award.

The results reported here have already had a significant impact on the research community. Many other researchers have began to extend and apply methods developed by this research team.

Some of the results are being applied in industry: Ford, Rockwell and TSI. The main nonlinear design methodology is being applied to jet engine control problems within a new PRET project in cooperation with UTRC and Pratt & Whitney.

6 Publications

Books

[B1] M. Krstic, I. Kanellakopoulos and P. Kokotovic, *"Nonlinear and Adaptive Control Design,"* 550 pages, John Wiley & Sons, Inc., 1995.

[B2] G. Tao and P. V. Kokotovic, *"Adaptive Control of Systems with Actuator and Sensor Nonlinearities,"* 300 pages to appear John Wiley & Sons, Inc., 1996.

Book Chapters

[BC1] R. A. Freeman and P. V. Kokotovic, "Design and Comparison of Globally Stabilizing Controllers for an Uncertain Nonlinear System" in *Systems, Models, and Feedback: Theory and Applications*, A. Isidori and T. J. Tarn, (Eds.), 249-264, Birkhauser, 1992.

[BC2] M. Krstic and P. V. Kokotovic, "Estimation-Based Schemes for Adaptive Nonlinear State-Feedback Control," in *Adaptive Control, Filtering, and Signal Processing*, K. J. Åström, G.C. Goodwin and P.R. Kumar, (Eds.), 165-198, Springer-Verlag, 1995.

[BC3] R. A. Freeman and P. V. Kokotovic, "Lyapunov Design" *The Control Handbook*, 109-116, CRC Press, Inc., to appear in 1995.

[BC4] M. Krstic and P. V. Kokotovic, "Adaptive Nonlinear Control" *The Control Handbook*, 99-112, CRC Press, Inc., to appear in 1995.

Journal Publications

[J1] A. Isidori, S. S. Sastry, P. V. Kokotovic and C. I. Byrnes, "Singularly Perturbed Zero Dynamics of Nonlinear Systems," *IEEE Trans. Automatic Control*, AC-37:1625-1631, October 1992.

[J2] I. Kanellakopoulos, P. V. Kokotovic and A. S. Morse, "Adaptive Output-Feedback Control of Systems with Output Nonlinearities," *IEEE Trans. Automatic Control*, AC-37:1666-1682, November 1992.

[J3] G. Tao and P. V. Kokotovic, "Adaptive Control of Systems with Backlash," *Automatica*, 29:323-335, March 1993.

[J4] R. A. Freeman and P. V. Kokotovic, "Design of "Softer" Robust Nonlinear Control Laws," *Automatica*, 29:1425-1437, November 1993.

[J5] M. Krstic, P. V. Kokotovic and I. Kanellakopoulos, "Transient Performance Improvement with a New Class of Adaptive Controllers," *Systems & Control Letters*, 21:451-461, December 1993.

[J6] G. Tao and P. V. Kokotovic, "Adaptive Control of Plants with Unknown Dead-Zones," *IEEE Trans. Automatic Control*, AC-39:59-68, January 1994.

[J7] M. Krstic, I. Kanellakopoulos, and P. V. Kokotovic, "Nonlinear Design of Adaptive Controllers for Linear Systems," *IEEE Trans. Automatic Control*, AC-39:738-752, April 1994.

[J8] M. Krstic and P. V. Kokotovic, "Observer-Based Schemes for Adaptive Nonlinear State-Feedback Control," *Int. J. Control*, AC-59:1373-1381, June 1994.

[J9] R. Marino, P. Tomei, I. Kanellakopoulos and P. V. Kokotovic, "Adaptive Tracking for a Class of Feedback Linearizable Systems," *IEEE Trans. Automatic Control*, AC-39:1314-1319, July 1994.

[J10] M. Krstic, I. Kanellakopoulos and P. V. Kokotovic, "Passivity and Parametric Robustness of a New Class of Adaptive Systems," *Automatica*, 30:1703-1716, November 1994.

[J11] G. Tao and P. V. Kokotovic, "Discrete-Time Adaptive Control of Systems with Unknown Deadzones," *Int. J. Control*, 61:1-17, January 1995.

[J12] G. Tao and P. V. Kokotovic, "Adaptive Control of Plants with Unknown Hystereses," *IEEE Trans. Automatic Control*, AC-40:200-212, February 1995.

[J13] G. Tao and P. V. Kokotovic, "Adaptive Control of Systems with Unknown Output Backlash," *IEEE Trans. Automatic Control*, AC-40:326-330, February 1995.

[J14] G. Tao and P. V. Kokotovic, "Discrete-Time Adaptive Control of Plants with Unknown Output Dead-Zones," *Automatica*, 31:287-291, February 1995.

[J15] M. Krstic and P. V. Kokotovic, "Adaptive Nonlinear Design with Controller-Identifier Separation and Swapping," *IEEE Trans. Automatic Control*, AC-40:426-440, March 1995.

[J16] G. Tao and P. V. Kokotovic, "Continuous-Time Adaptive Control of Systems with Unknown Backlash," *IEEE Trans. Automatic Control*, AC-40:1083-1087, June 1995.

[J17] P. C. Yeh and P. V. Kokotovic, "Adaptive Output-Feedback Design for a Class of Nonlinear Discrete-Time Systems," *IEEE Trans. Automatic Control*, AC-62:303-324, August 1995.

[J18] M. Krstic and P. V. Kokotovic, "Control Lyapunov Functions for Adaptive Nonlinear Stabilization," *Systems & Control Letters*, 26:17-23, September 1995.

[J19] R. A. Freeman and P. V. Kokotovic, "Global Internal Stabilizability Does Not Imply Global External Stabilizability for Small Sensor Disturbances," to appear in *IEEE Trans. Automatic Control*, 1995.

[J20] R. A. Freeman and P. V. Kokotovic, "Inverse Optimality in Robust Stabilization," to appear in *SIAM J. Contr. Optimiz.*, July 1996.

[J21] M. Jankovic, "Adaptive Output Feedback Control of Nonlinear Feedback Linearizable Systems," to appear in *Int. J. Adaptive Control and Signal Processing*.

[J22] M. Jankovic, "Adaptive Nonlinear Output Feedback Tracking with a Partial High-Gain Observer and Backstepping," to appear in *IEEE Trans. Automatic Control*.

[J23] M. Jankovic, D. Fontaine and P.V. Kokotovic, "Tora Example: Cascade and Passivity Based Control Designs," to appear in *IEEE Trans. on Control Systems Technology.*

[J24] R. Sepulchre and D. Aeyels, "Stabilization does not imply homogeneous stabilization for controllable systems," to appear in *SIAM Journal of Control and Optimization.*

[J25] P. C. Yeh and P. V. Kokotovic, "Adaptive Control of a Class of Nonlinear Discrete-Time Systems," to appear in *Intl. J. Control.*

[J26] P. C. Yeh and P. V. Kokotovic, "Stability Enhancement in Adaptive Neural Control of Nonlinear Systems," to appear in *Intl. J. Control.*

Conference Papers

[C1] P. V. Kokotovic, M. Krstic and I. Kanellakopoulos, "Backstepping to Passivity: Recursive Design of Adaptive Systems," *Proc. 31st IEEE Conf. Decision and Control,* Tucson, AZ, 3276-3280 December 16-18, 1992.

[C2] M. Krstic, I. Kanellakopoulos and P. V. Kokotovic, "A New Generation of Adaptive Controllers for Linear Systems," *Proc. 31st IEEE Conf. Decision and Control,* Tucson, AZ, 3644-3650, December 16-18, 1992.

[C3] M. Krstic and P. V. Kokotovic, "Estimation-Based Schemes for Adaptive Nonlinear State-Feedback Control," *Proc. IMA Workshop Adap. Control, Filtering, and Signal Proc.,* Minneapolis, Minnesota, April 12-16, 1993.

[C4] M. Krstic, P. V. Kokotovic and I. Kanellakopoulos, "Performance Analysis for Recursive Passive Adaptive Controllers," *IEEE Conf. Aerospace Control Systems,* Westlake Village, CA, 195-199, May 25-27, 1993.

[C5] G. Tao, P. V. Kokotovic and G. Ianculescu, "Adaptive Friction Compensation Applied to Positioning of a Space Station Solar Array," *Proc. IEEE Conf. Aerospace Control Systems,* Westlake Village, CA, 80-84, May 25-27, 1993.

[C6] M. Krstic, P. V. Kokotovic and I. Kanellakopoulos, "Adaptive Nonlinear Output-Feedback Control with an Observer-Based Identifier," *Proc. American Control Conf.,* San Francisco, CA, 2821-2825, June 2-4, 1993.

[C7] I. Kanellakopoulos, M. Krstic and P. V. Kokotovic, "Trajectory Initialization in Adaptive Nonlinear Control," *Proc. IEEE Mediterranean Symp. on New Directions in Control Theory & Applic.,* Chania, Greece, June 21-23, 1993.

[C8] G. Tao and P. V. Kokotovic,"Adaptive Control of Plants with Unknown Output Dead-Zones," *Proc. IFAC 12th World Congress,* Sydney, Australia, 6:7-10, July 18-23, 1993.

[C9] R. Freeman and P. V. Kokotovic, "Design of Robust Nonlinear Feedback Controls: Concepts, Tools, and Procedures," *Proc. 31st Allerton Conf. on Comm., Control, and Computing,* Monticello, IL., 791-800, September 1993

[C10] G. Tao and P. V. Kokotovic, "Adaptive Inverses of Nonsmooth Nonlinearities with Applications," *Proc. of the Intl. Conf. on Contr. Theory & its Applications,* Kibbutz Maale HaChamisha, Israel, October 18-21, 1993.

[C11] R. A. Freeman and P. V. Kokotovic, "Global Robustness of Nonlinear Systems to State Measurement Disturbances," *Proc. 32nd IEEE Conf. Decision and Control,* San Antonio, TX, 1507-1512, December 15-17, 1993.

[C12] I. Kanellakopoulos, M. Krstic and P. V. Kokotovic, "k-Adaptive Control of Output-Feedback Nonlinear Systems," *Proc. 32nd Conf. Decision and Control,* San Antonio, TX, 1061-1066, December 15-17, 1993.

[C13] M. Krstic and P. V. Kokotovic, "Adaptive Nonlinear Control with Nonlinear Swapping," *Proc. 32nd Conf. Decision and Control,* San Antonio, TX, 1073-1080, December 15-17, 1993 **(1993 Best Student Paper Award to M. Krstic).**

[C14] D. A. Recker and P. V. Kokotovic, "Indirect Adaptive Nonlinear Control of Discrete-Time Systems Containing a Deadzone," *Proc. 32nd Conf. Decision and Control,* San Antonio, TX, 2647-2653, December 15-17, 1993.

[C15] M. Jankovic, "Adaptive Nonlinear Output Feedback Tracking with a Reduced Order High-Gain Observer," *Proc. American Control Conf.,* Baltimore, MD, 875-879, June 29-July 1, 1994.

[C16] M. Krstic and P. V. Kokotovic, "Adaptive Nonlinear Output-Feedback Schemes with Marino-Tomei Controller," *Proc. American Control Conf.,* Baltimore, MD, 861-866, June 29-July 1, 1994. Also submitted to *IEEE Trans. Automatic Control.*

[C17] G. Tao and P. V. Kokotovic, "Discrete-Time Adaptive Control of Systems with Unknown Output Hystereses," *Proc. American Control Conf.,* Baltimore, MD, 870-874, June 29-July 1, 1994.

[C18] P. V. Kokotovic and R. A. Freeman, "Promises and Pitfalls of Recursive Lyapunov Techniques," presented at the *VSLT 94 Workshop,* Benevento, Italy, September 1994.

[C19] P.V. Kokotovic, R. Freeman and M. Krstic, "Robust and Adaptive Nonlinear Control," Invited Plenary Talk, *Hong Kong Int. Workshop on New Directions of Control and Manufacturing.* November 7-9, 1994.

[C20] R. A. Freeman and P. V. Kokotovic, "Robust Control Lyapunov Functions: The Measurement Feedback Case," *Proc. 33rd Conf. Decision and Control,* Lake Buena Vista, FL, 3533-3538, December 14-16, 1994.

[C21] R. A. Freeman and P. V. Kokotovic, "Tools and Procedures for Robust Control of Nonlinear Systems," *Proc. 33rd IEEE Conf. Decision and Control,* Lake Buena Vista, FL, 3458-3463, December 14-16, 1994.

[C22] R. Ghanadan, "Nonlinear Control System Design via Dynamic Order Reduction," *Proc. 33rd IEEE Conf. Decision and Control,* Lake Buena Vista, FL, 3752-3757, December 14-16, 1994.

[C23] M. Krstic, J. Sun and P. V. Kokotovic, "Control of Feedback Linearizable Systems with Input Unmodeled Dynamics," *Proc. 33rd IEEE Conf. Decision and Control,* Lake Buena Vista, FL, 1633-1638, December 14-16, 1994.

[C24] P. Martin, S. Devasia and B. Paden, "A Different Look at Output Tracking: Control of a VTOL Aircraft," *Proc. 33rd IEEE Conf. Decision and Control,* Lake Buena Vista, FL, 2376-2381, December 14-16, 1994.

[C25] G. Tao and P. V. Kokotovic, "Discrete-time Adaptive Control of Systems with Unknown Nonsmooth Input Nonlinearities," *Proc. 33rd IEEE Conf. Decision and Control,* Lake Buena Vista, FL, 1171-1176, December 14-16, 1994.

[C26] M. Krstic and P. V. Kokotovic, "Modular Approach to Adaptive Nonlinear Stabilization," *Proc. ACASP,* Budapest, Hungary, June 14-16, 1995.

[C27] M. Jankovic, D. Fontaine and P. V. Kokotovic, "TORA Example: Cascade and Passivity Based Control Designs," *Proc. American Control Conference,* Seattle, WA, 4347-4351, June 21-23, 1995.

[C28] M. Krstic, "Asymptotic Properties of Adaptive Nonlinear Stabilizers, *Proc. American Control Conference,* Seattle, WA, 576-581, June 21-23, 1995 **(1995 Best Student Paper Award).**

[C29] P. C. Yeh and P. V. Kokotovic, "Adaptive Tracking Designs for Input-Constrained Linear Systems Using Backstepping," *Proc. American Control Conference,* Seattle, WA, 1590-1593, June 21-23, 1995.

[C30] R. A. Freeman and P. V. Kokotovic, "Backstepping Design with Nonsmooth Nonlinearities," *Proc. NOLCOS,* Tahoe City, CA, 483-488, June 25-28, 1995.

[C31] R. A. Freeman and P. V. Kokotovic, "Tracking Controllers for Systems Linear in the Unmeasured States," *Proc. NOLCOS,* Tahoe City, CA, 620-625, June 25-28, 1995. Also to appear in *Automatica.*

[C32] M. Jankovic and B. K. Ghosh, "Multistage Nonlinear Observer with Application to Vision Based Estimation," *Proc. NOLCOS,* Tahoe City, CA, 64-68, June 25-28, 1995.

[C33] M. Krstic and P. V. Kokotovic, "Lyapunov and ISS Frameworks for Adaptive Nonlinear Stabilization," *Proc. NOLCOS,* Tahoe City, CA, 119-124, June 25-28, 1995.

[C34] R. Sepulchre and D. Aeyels, "Adding an Integrator to a Non Stabilizable Planar Homogeneous System," *Proc. NOLCOS,* Tahoe City, CA, 170-175, June 25-28, 1995.

Doctoral Dissertations and Reports

[D1] P. C. Yeh, PhD Dissertation: "Adaptive Control of Nonlinear Discrete-Time Systems," February 1994.

[D2] M. Krstic, PhD Dissertation: "Adaptive Nonlinear Control," March 1995.

[D3] R. Freeman, PhD Dissertation: "Robust Control of Nonlinear Systems," September 1995.

[R1] R. Ghanadan, "Computer Algebra Tools for Recursive Design of Robust and Adaptive Nonlinear Controllers," Technical Report CCEC-06-09-94, University of California, Santa Barbara, June 1994.