AFRL-SR-AR-TR-09-0188

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*: 05/06/2009

2. REPORT TYPE: final

3. DATES COVERED *(From - To)*: 03/01/2008-111/30/2008

4. TITLE AND SUBTITLE
Robust Adaptive Control of Multivariable Nonlinear Systems

5a. CONTRACT NUMBER: FA9550-08-1-0135

5b. GRANT NUMBER: FA9550-08-1-0135

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Naira Hovakimyan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Virginia Tech, AOE, 215 Randolph Hall, Blacksburg, VA 24061-02023

UIUC, MechSE Department, 1206 West Green street, Urbana, IL 61801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NL
875 N Randolph St
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Our research is focused on development of reconfigurable robust adaptive control architectures that can be designed with systematic methods to have guaranteed performance specifications and robustness/stability margins. Research in this direction over the past three years has led to a powerful set of tools shaping The Theory of Fast and Robust Adaptation. This new paradigm for design of adaptive control systems embeds the robustness specifications explicitly into the control problem formulation (control objective) and enables to predict the closed-loop system performance a priori based on the conservative bounds of uncertainty. The time-delay margin of these architectures can be systematically tuned using methods from classical and robust control.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include eree code)*

ROBUST ADAPTIVE CONTROL OF MULTIVARIABLE NONLINEAR SYSTEMS

FA9550-08-1-0135 (March - November, 2008)

Naira Hovakimyan
Department of Aerospace and Ocean Engineering
Virginia Tech, Blacksburg, VA
and
Mechanical Science and Engineering
University of Illinois at Urbana-Champaign, IL

Abstract
Our research is focused on development of reconfigurable robust adaptive control architectures that can be designed with systematic methods to have guaranteed performance specifications and robustness/stability margins. Research in this direction over the past several years has led to a powerful set of tools shaping *The Theory of Fast and Robust Adaptation.* This new paradigm for design of adaptive control systems embeds the hardware specification explicitly into the control problem formulation (control objective) and enables to predict the closed-loop system performance *a priori* based on the conservative bounds of uncertainty. Moreover, it leads to analytically provable robustness/stability margins. The performance limitations are proved to be consistent with the hardware limitations: the available CPU sets the adaptation rate, while the control channel specifications define the limits of the achievable performance. Similar to linear systems, the time-histories of system's input/output signals scale with the change of reference inputs, uncertain parameters and initial conditions. Various architectures of this theory have been flight tested by our collaborators, which include design of autopilots for MAVs, augmentation of off-the-shelf autopilots for flight test validation of robustness metrics in the presence of control surface failures[1], and time-critical coordination of UAVs within spatial constraints in the presence of time-varying communication network topology[2]. Other applications, verified in mid-to-high fidelity simulation environments, include design of control laws for validation of time-delay margins for unmanned unstable tailless aircraft and aerial refueling autopilot design[3], development of vision-based guidance laws, control of hypersonic vehicles, missile longitudinal autopilot design, control of CLV vehicle and control of flexible aircraft[4]. The key concepts and tools of this framework can be extended to a broader class of nonlinear controllers with an objective to quantify uniform performance bounds and guaranteed robustness metrics.

Status of effort

---

[1] Leveraged by NASA LaRC IRAC Flight program
[2] Leveraged by ARO, and transitioned to NPS for further use in USSOCOM supported TNT exercises
[3] Leveraged by AFRL WP/Boeing under CerTA FCS program
[4] Leveraged by NASA LaRC under *Sensorcraft* project of Air Force

During this time period we worked on extension of L_1 adaptive controller to output feedback and its application to Boeing's missile longitudinal autopilot design and NASA's CLV model.

Output feedback solution [10]: The key contribution of the past year was the output feedback solution for the class of systems

$$y(s) = A(s)(u(s) + d(s)),$$

where $A(s)$ is strictly proper unknown transfer function, while $d(s)$ is the Laplace transform of unknown nonlinearities $f(t, y(t))$, subject to $|f(t, y_1) - f(t, y)| \le L|y_1 - y_2|$. The control objective is to design an adaptive output feedback controller to ensure that y follows that output of a given transfer function $y_m(s) = M(s)r(s)$ for the reference input $r(s)$, where $M(s)$ is <u>**not**</u> necessarily strictly positive real (SPR). The main result is given by the following theorem.

Theorem: Consider the following reference system dynamics:

$$y_{ref}(s) = M(s)(u_{ref}(s) + \sigma_{ref}(s)),\ \ u_{ref}(s) = C(s)(r(s) - \sigma_{ref}(s))$$
$$\sigma_{ref}(s) = ((A(s) - M(s))u_{ref}(s) + A(s)d_{ref}(s)) / M(s)$$

where $d_{ref}(s)$ is the Laplace transform of $f(t, y_{ref}(t))$, while $C(s)$ is strictly proper low-pass filter with DC gain 1, verifying stability of $H(s) = \dfrac{A(s)M(s)}{C(s)A(s) + (1 - C(s))M(s)}$ and ensuring that the 1-norm of the cascaded system $H(s)(1 - C(s))$ verifies the following upper bound $\|H(s)(1 - C(s))\|_{L_1} L \le 1$. Then the reference system is BIBO stable. Moreover, the following adaptive output feedback controller

$$u(s) = C(s)r(s) - C(s)\frac{c_m^T(sI - A_m)^{-1}}{c_m^T(sI - A_m)^{-1}b_m}\hat{\sigma}(s)$$

where $(A_m \in R^{n\times n}, b_m \in R^n, c_m \in R^n)$ is the minimal realization of $M(s)$, while the piece-wise constant adaptive law for $\hat{\sigma}(t)$ is given by[5].

---

[5] The parameter T is the sampling rate of the CPU.

$$\hat{\sigma}(t) = \hat{\sigma}(iT), \quad t \in [iT, (i+1)T)$$

$$\hat{\sigma}(iT) = -\Phi^{-1}(T)\mu(iT), \quad i = 1,2,3,...$$

$$\Phi(T) = \int_0^T e^{\Lambda A_m \Lambda^{-1}(T-\tau)} \Lambda d\tau, \quad \Lambda = \begin{bmatrix} c_m^T \\ D\sqrt{P} \end{bmatrix}, \quad A_m^T P + P A_m = -Q$$

$$\mu(iT) = e^{\Lambda A_m \Lambda^{-1} T} 1_1 \tilde{y}(iT), \quad \tilde{y}(t) = \hat{y}(t) - y(t)$$

with D being the null-space of $c_m^T\left(\sqrt{P}\right)^{-1}$, $1_1 = [10...0]^T \in R^n$ and $\hat{y}(t)$ being the output of the following estimator dynamics (with unmatched estimation)

$$\dot{\hat{x}}(t) = A_m \hat{x}(t) + b_m u(t) + \hat{\sigma}(t)$$

$$\hat{y}(t) = c_m^T \hat{x}(t)$$

ensures that there exist constants γ_1, γ_2, proportional to T, such that

$$\left\| y - y_{ref} \right\|_{L_\infty} \le \gamma_1, \quad \left\| u - u_{ref} \right\|_{L_\infty} \le \gamma_2$$

Acknowledgment/Disclaimer

This work was sponsored (in part) by the Air Force Office of Scientific Research, USAF, under grants FA9550-05-1-0157, FA9550-08-1-0135. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the AFOSR or the U.S. Government.

References

1. P. Aguiar, I. Kaminer, R. Ghabcheloo, A. Pascoal, E. Xargay, N. Hovakimyan, C. Cao, V. Dobrokhodov, Time-Coordinated Path Following for Multiple UAVs using Dynamic Networking and L_1 Adaptation, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
2. P. Aguiar, I. Kaminer, R. Ghabcheloo, A. Pascoal, E. Xargay, N. Hovakimyan, C. Cao, Coordinated Path Following of Multiple UAVs for Time-Critical Missions in the Presence of Time-Varying Communication Topologies, IFAC Congress, Seoul, South Korea, 2008.
3. K. Wise, E. Lavretsky, N. Hovakimyan, C. Cao, J. Wang, Verifiable Adaptive Flight Control: UCAV and Aerial Refueling, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
4. Y. Lei, C. Cao, E. Cliff, N. Hovakimyan, A. Kurdila, K. Wise, Design of an L_1 Adaptive Controller for Air-breathing Hypersonic Vehicle Model in the Presence of Dynamic Coupling Between Fuselage Bending and Elevator Motion, AIAA-2008-7446, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
5. C. Cao, N. Hovakimyan, I. Gregory, L_1 Adaptive Output Feedback Controller for a Flexible Wing Application, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
6. I. Gregory, E. Kharisov, C. Cao, N. Hovakimyan, L_1 Adaptive Control Laws for Flexible Space Lunch Vehicle and Proposed Plan for Flight Test Validation, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.

7. J. Wang, C. Cao, N. Hovakimyan, R. Hindman, B. Ridgely, L_1 Adaptive Output Feedback Controller for a Missile Longitudinal Autopilot Design, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
8. D. Li, N. Hovakimyan, C. Cao, K. Wise, Filter Design for Feedback-loop Trade-off of L_1 Adaptive Controller: A Linear Matrix Inequality Approach, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
9. I. Kitsiois, V. Dobrokhodov, I. Kaminer, M. Lizarraga, E. Xargay, C. Cao, N. Hovakimyan, I. Gregory, Flight Test Validation of Metrics Driven L_1 Adaptive Controller, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
10. C. Cao, N. Hovakimyan, L_1 Adaptive Output Feedback Controller for Non-Strictly Positive Real Reference Systems, *Submitted to* 47th IEEE Conference on Decision and Control, Cancun, Mexico, 2008.

Personnel supported partially during duration of grant

Jiang Wang (Graduate Student), Chengyu Cao (Research Scientist), Naira Hovakimyan (Professor) Virginia Tech, Blacksburg, VA, and (Professor) UIUC, IL

Selected publications complementing references mentioned above

1. C. Cao, N. Hovakimyan, L_1 Adaptive Controller for Systems with Unknown Time-varying Parameters and Disturbances in the Presence of Non-zero Trajectory Initialization Error, International Journal of Control, vol. 81, No. 7, pp. 1148-1162, 2008.
2. C. Cao, N. Hovakimyan, L_1 Adaptive Output Feedback Controller for Systems of Unknown Dimension, IEEE Transactions on Automatic Control, vol. 53, No. 3, pp. 815-821, 2008.
3. C. Cao, N. Hovakimyan, Design and Analysis of a Novel L_1 Adaptive Control Architecture with Guaranteed Transient Performance, IEEE Transactions on Automatic Control, vol.53, No.2, pp. 586-591, 2008.
4. J. Wang, V. Patel, C. Cao, N. Hovakimyan, E. Lavretsky, Novel L_1 Adaptive Control Methodology for Aerial Refueling with Guaranteed Transient Performance, AIAA Journal of Guidance, Control and Dynamics, vol. 18, No. 1, pp. 182-193, 2008.
5. V. Stepanyan, N. Hovakimyan, Visual Tracking of a Maneuvering Target, AIAA Journal of Guidance, Control and Dynamics, vol. 18, No. 1, pp. 66-80, 2008.
6. D. M. Stipanović, A. Melikyan, N. Hovakimyan, Some Sufficient Conditions for Multi-Player Pursuit-Evasion Games with Continuous and Discrete Observations, Annals of the International Society of Dynamic Games, Vol. 9, 2008.
7. E. Lavretsky, N. Hovakimyan, Adaptive Dynamic Inversion for Nonaffine in Control Uncertain Systems via Time-Scale Separation: Part 2, Journal of Dynamical Systems and Control, vol. 14, No. 1, pp. 33-41, 2008.
8. N. Hovakimyan, E. Lavretsky, A. Sasane, Approximate Dynamic Inversion for Nonaffine in Control Systems via Time-Scale Separation: Part 1, Journal of Dynamical Systems and Control, vol. 13, No. 4, pp. 451-465, 2007.
9. A. Young, C. Cao, V. Patel, N. Hovakimyan, E. Lavretsky, An Adaptive Approach to Nonaffine Control Design for Aircraft Applications, AIAA Journal of Guidance, Control and Dynamics, vol. 18, No. 6, pp. 1770-1782, 2007.
10. A. Melikyan, A. Akhmetzhanov and N. Hovakimyan, On Initial Value and Terminal Value Problems for Hamilton-Jacobi Equation, Systems and Control Letters, vol. 56, No.11-12, pp. 714-721, 2007.

11. E. Lavretsky, N. Hovakimyan, Positive μ -modification for Stable Adaptation in the Presence of Input Constraints, Systems and Control Letters, vol. 56, No.11-12, pp. 722-729, 2007.
12. V. Stepanyan, N. Hovakimyan, Robust Adaptive Observer Design for Uncertain Systems with Bounded Disturbances, IEEE Transactions on Neural Networks, vol. 18, No. 5, pp. 1392-1403, 2007.
13. C. Cao, N. Hovakimyan, J. Wang, Intelligent Excitation for Adaptive Control with Unknown Parameters in Reference Input, IEEE Transactions on Automatic Control, vol. 52, No.8, pp. 1525-1532, 2007.
14. C. Cao, N. Hovakimyan, Novel L_1 Neural Network Adaptive Control Architecture with Guaranteed Transient Performance, Special Issue on Feedback Control of IEEE Transactions on Neural Networks, vol. 18, No. 4, pp. 1160-1171, 2007.
15. V. Stepanyan, N. Hovakimyan, An Adaptive Disturbance Rejection Controller for Visual Tracking of a Maneuvering Target, AIAA Journal of Guidance, Control and Dynamics, vol. 30, No. 4, pp. 1090-1106, 2007.
16. E. Lavretsky, N. Hovakimyan, Stable Adaptation in the Presence of Multiple Actuator Constraints with Applications to Flight Control, AIAA Journal of Guidance, Control and Dynamics, vol. 30, No. 2, pp. 337-345, 2007.
17. M. C. Cotting, C. Cao, N. Hovakimyan, R. Kraus, W. Durham, Simulator Testing of Longitudinal Flying Qualities with L_1 Adaptive Controller, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
18. L. Ma, C. Cao, N. Hovakimyan, V. Dobrokhodov, I. Kaminer, Adaptive Vision-Based Guidance Law with Guaranteed Performance Bounds for Tracking a Ground Target with Time-Varying Velocity, AIAA-2008-7445, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.
19. D. M. Stipanović, A. Melikyan, N. Hovakimyan, Guaranteed Strategies for Nonholonomic Players in Pursuit-Evasion Games, *In Proceedings of* XIII International Symposium on Dynamic Games and Applications, Warsaw, Poland, 2008.
20. C. Cao, N. Hovakimyan, L_1 Adaptive Controller for Multi-Input Multi-Output Systems in the Presence of Unmatched Disturbances, American Control Conference, Seattle, WA, 2008.
21. C. Cao, N. Hovakimyan, L_1 Adaptive Controller for a Class of Systems with Unknown Nonlinearities: Part I, American Control Conference, Seattle, WA, 2008.
22. C. Cao, N. Hovakimyan, L_1 Adaptive Controller for Nonlinear Systems in the Presence of Unmodelled Dynamics: Part II, American Control Conference, Seattle, WA, 2008.
23. C. Cao, N. Hovakimyan, L_1 Adaptive Controller for Systems in the Presence of Unmodeled Actuator Dynamics, *In Proc. of* 46^{th} IEEE Conference on Decision and Control, New Orleans, LA, 2007.

Honors & Awards Received

- College of Engineering Faculty Fellow of Virginia Tech, 2006-2009
- Promoted to professor in 2007
- Moved to UIUC as Professor and Schaller Faculty Scholar of MechSE, 2008
- Invited Plenary Speaker at SIAM Conf. Contr. and Its Applications, 2007, San Francisco, CA
- Associate Fellow of AIAA, 2006
- Associate Editor of IEEE Transactions on Neural Networks, 2004 – 2008
- Associate Editor of IEEE Transactions on Control Systems Technology, 2005 – present
- Outstanding reviewer of AIAA Journal of Guidance, Control and Dynamics

AFRL Points of Contact

Johnny Evers, AFRL, Eglin AFB, FL, e-mail: johnny.evers@eglin.af.mil
Siva Banda, WP AFRL, e-mail: Siva.Banda@wpafb.af.mil
Dave Doman, WP AFRL, e-mail: David.Doman@wpafb.af.mil

Transitions

- The theory has been transitioned to NASA LaRC for wind-tunnel testing of *Sensorcraft* and also for flight control law design for a CLV model. POC: I. Gregory, NASA LaRC, Hampton, VA 23681, Ph: 757-864-4075.
- The theory has been used to augment an existing autopilot (Piccolo) for accurate path following in the problem of time-critical cooperation of UAVs with spatial constraints in the presence of time-varying communication network topology. POC: Isaac Kaminer, MAE, NPS, Monterey, CA 93943, Phone: 831-656-3459 (further transition to USSOCOM in TNT exercises).
- The theory has been implemented for AAR (Autonomous Aerial Refueling) problem in collaboration with The Boeing Co., under CerTA FCS program from WP AFRL. The UAV model was provided by The Boeing Co., while the ICE vortex data were obtained from WP AFRL. POC: E. Lavretsky (Boeing), Technical Fellow, 5301 Bolsa Ave. MC H013-b318, Huntington Beach, CA 92647, Ph: 714-235-7736, D. Homan (WP AFRL).
- The theory has been implemented for hypersonic vehicle model of WP AFRL. POC: D. Doman, WP AFRL, e-mail: David.Doman@WPAFB.AF.MIL
- The theory has been implemented for missile longitudinal autopilot design, the model being provided by Raytheon. POC: R. Hindman, e-mail: Rick.Hindman@raytheon.com, B. Ridgely, e-mail: dbridgely@raytheon.com

New Discoveries

2008 Provisional Patent filed "Adaptive Control Devices and Methods for Systems of Unknown Relative Degree" (with C. Cao)