ROBUST NONLINEAR CONTROL THEORY WITH APPLICATIONS TO AEROSPACE VEHICLES

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1 Objectives

The focus of this program is fundamental research in general methods of analysis and design of complex uncertain nonlinear systems. Our approach builds on our recent success in blending robust and nonlinear control methods with a much greater emphasis on the use of local and global techniques in nonlinear dynamical systems theory. Specific areas of interest include real-time trajectory generation for unmanned aerial vehicles, geometric mechanics and nonlinear stabilization, and unified techniques for stabilization of nonlinear systems that combine model predictive control techniques with control Lyapunov function techniques.

2 Status of Effort

Research conducted under this proposal has continued to make progress in the area of nonlinear control of mechanical systems, linear parameter varying (LPV) control and its applications, and new approaches to nonlinear control that combine model predictive and control Lyapunov techniques.

3 Accomplishments

Linear Parameter Varying Control and Its Applications

ICE The past year our research at the University of Minnesota under the AFOSR PRET program has focused on applying linear-parameter varying (LPV) control design methods to flight control, active flutter attenuation and turbofan engines. We are working closely with researchers at the Air Force Research Laboratory, Wright

Patterson AFB to apply LPV techniques to a tailless fighter aircraft model developed under the Innovative Control Effectors (ICE) program. The aircraft is a 65 degree sweep delta wing, single engine multi-role supersonic fighter with internal weapons carriage with no vertical tail. The ICE aircraft has a large suite of conventional and innovative control effectors that provide forces and moments in multiple axis. The objective is to use the innovative, stealth effectors a majority of the time. This imposes hard constraints on the actuator deflections.

To date, we have successfully implemented a LPV controller in pilot-in-the-loop simulations at WPAFB. The simulations were performed in the Large Amplitude MultiMode Aerospace Research Simulator (LAMARS) at WPAFB. The simulator consists of a 20-foot diameter do me with 6 image projectors providing a full front 180 degree field of view. The cockpit is a reconfigurable F-15/F-16 cockpit. For these simulations, it is configured in F-16 mode, with an F-16 side-stick and throttle. For the discrete HUD tracking task, the HUD includes a time-varying command bar and a bracket fixed to the airframe coordinates, in which the pilot attempts to center the command bar.

The LPV controller for the ICE was compared with a reference aircraft with its standard flight control system. In comparisons of Cooper-Harper ratings, the reference aircraft was generally rated slightly better than the ICE aircraft with the LPV controller for the tasks considered. Both configurations exhibit level 2 flying qualities for the majority of the tasks (6 of 10 for the ICE configuration, and 5 of 10 for the reference configuration) and were judged to have level 3 flying qualities for task for several more difficult tasks. Both configurations were deemed to give relatively better performance in the pitch tracking tasks, indicating that the poorer ratings for roll are probably at least partially due to a more difficult task. The PIO ratings in general follow the same trends, with lower ratings given to the LPV controller during the roll tasks. Based on these results, we are redesigning the LPV controllers for the ICE vehicle and plan on testing them in LAMARS at WPAFB at the end of July.

Active Vehicle Suspension Active vehicle suspensions is a topic slightly outside of Aerospace Vehicles, though one can imagine the importance of the suspension system on aircraft during taxiing for takeoff and landing. It has been shown in the literature that nonlinear active control laws have the potential to achieve superior suspension system performance compared to their linear counterparts. A nonlinear controller can focus on maximizing passenger comfort when the suspension deflection is small compared to it's structural limit. As the deflection limit is approached, the controller can shift focus to prevent the suspension deflection from exceeding this limit. This results in superior ride quality over the range of road surfaces, as well as reduced wear of suspension components. We used linear parameter-varying (LPV) control techniques to design active suspensions that stiffen as the suspension limits are reached. The controllers use only suspension deflection as the feedback signal. Nonlinear simulations of the linear parameter-varying controllers show excellent performance of the controllers on both smooth and rough roads.

Turbofan Engine Controllers Our research under this AFOSR PRET has lead to a contract with NASA Lewis to synthesize multivariable, inner-loop LPV controllers for the Pratt & Whitney 952 engine that accurately tracks overall pressure ratio, engine pressure ratio and the high rotor speed across power code and the flight envelope. An LPV controller has been synthesized for a a fixed altitude which achieves excellent tracking of the desired values across large variations in power code. This work is being expanded to include the entire flight envelope.

Unified Approach to Nonlinear Stabilization

We continue to explore the use of Model Predictive Control (MPC) strategies for the stabilization and maneuvering of flight vehicles. Model based approaches hold forth the possibility of higher performance operations through the understanding and exploitation of system nonlinearities including control saturations.

Most MPC strategies derive from the fact that stabilizing controllers may be constructed through the use of optimal control. In a number of interesting cases, e.g., the linear quadratic regulator, "solutions" to optimal problems of interest can be found and implemented—the calculations are practicable and the solution has a manageable representation. Unfortunately, the curse of dimensionality adversely impacts the calculation *and* representation of optimal feedbacks when significant nonlinearities are present.

One way to resolve the representation problem is to use on-line calculations (rather than off-line) to provide the necessary optimal feedback. A typical strategy is to solve, at each time (or in sampled data fashion), a finite horizon trajectory optimization problem to obtain the desired control as a function of the current state. Of course, one must ensure that the resulting Receding Horizon (RH) control strategy results in a stable closed loop system. This is especially important in the control of high performance flight vehicles which are often designed with maneuvering, and not stability, in mind. (In contrast, stability has not been a primary issue in the successful application of MPC to a number of open loop stable industrial chemical processes.)

In order to better understand the important issues, we have performed substantial numerical investigations into the use of receding horizon/model predictive control techniques for stabilization and maneuvering of flight vehicles, using the Caltech Ducted Fan as model vehicle. These results were presented in a CDC Workshop on Nonlinear Control.

We have developed an unconstrained receding horizon control strategy [13, 11, 12, 5] that retains the desired stability and performance properties of an effective infinite horizon optimal control strategy. The key idea is to approximate the tail of the infinite horizon cost-to-go using, as terminal cost, an appropriate control Lyapunov function (CLF).

In [5], we provide a complete analysis of the stability and region of attraction properties of receding horizon control strategies that utilize finite horizon approximations in the proposed class. It is shown that the guaranteed region of operation contains that of the CLF controller and may be made as large as desired by increasing the optimization horizon (restricted, of course, to the infinite horizon domain). The choice of horizon T provides a continuous transformation of a CLF based controller into an infinite horizon optimal controller.

Dynamics and Control of Mechanical Systems

Marsden and coworkers have characterized a class of mechanical systems for which the "method of controlled Lagrangians" provides a family of control laws that stabilize an unstable (relative) equilibrium [6]. The controlled Lagrangian approach involves making modifications to the Lagrangian for the uncontrolled system such that the Euler-Lagrange equations derived from the modified or "controlled" Lagrangian describe the closed-loop system. For the closed-loop equations to be consistent with available control inputs, the modifications to the Lagrangian must satisfy "matching" conditions. Our matching and stabilizability conditions are constructive; they provide the form of the controlled Lagrangian, the control law and, in some cases, conditions on the control gain(s) to ensure stability. The method is applied to stabilization of an inverted spherical pendulum on a cart and to stabilization of steady rotation of a rigid spacecraft about its unstable intermediate axis using an internal rotor. An expanded and more complete version of this work is given in [4]. The procedure may be viewed as a symmetry preserving *kinetic shaping* technique as opposed to *potential shaping* developed by Jalnapurkar and Marsden]citeJM99-tac,JM99-rcd, building on the well known work of van der Shaft. The controlled Lagrangian approach is appropriate for underactuated *balance systems* whereas potential shaping is not. Accordingly, it is expected that the procedure can be combined with control methods that manage instabilities and use potential techniques for tracking.

The procedure is demonstrated for several problems, including the stabilization of an inverted pendulum on a cart (both a planar and a spherical pendulum), and the problem of stabilization of rotation of a rigid spacecraft about its unstable intermediate axis using a single internal rotor, stabilizing the dynamics of an underwater vehicle and finally, stabilization of an inverted pendulum on a rotating arm.

We have also extended the method of controlled Lagrangians to include potential shaping for complete state-space stabilization of mechanical systems [6]. The method of controlled Lagrangians deals with mechanical systems with symmetry and provides symmetry-preserving kinetic shaping and feedback-controlled dissipation for state-space stabilization in all but the symmetry variables. Potential shaping complements the kinetic shaping by breaking symmetry and stabilizing the remaining state variables. The approach also extends the method of controlled Lagrangians to include a class of mechanical systems without symmetry such as the inverted pendulum on a cart that travels along an incline.

Feedback laws to asymptotically stabilize relative equilibria of mechanical systems with symmetry have been reported in [3, 1]. It uses a notion of stability 'modulo the group action' and deals with both *internal* instability and with instability of the rigid motion. The methodology is that of *potential shaping*, but the system is allowed to be internally underactuated, i.e., have fewer internal actuators than the dimension of the shape space. We intend to merge these methods with the kinetic shaping techniqes described earlier.

An alternative formulation of the rigid body equations, their relationship with the discrete rigid body equations of Moser–Veselov and their formulation as an optimal control problem have been analyzed [4]. In addition we discuss a general class of discrete optimal control problems. There are interesting connections with the theory of variational symplectic integrators.

4 Personnel Supported

Faculty	Gary Balas, UMN John Doyle, Caltech Jerrold Marsden, Caltech Richard Murray, Caltech
Postdoctoral fellows	Ian Fialho, UMN B. N. Shashikanth, Caltech
Graduate students	Raktim Bhattacharya, UMN Dong Eui Chang, Caltech Alex Fax, Caltech Martha Gallivan, Caltech Suvo Ganguli, UMN Yun Huang, Caltech Sameer Jalnapurkar, Caltech/UCB James Primbs, Caltech Matthew West, Caltech Jie Yu, Caltech Xiaoyun Zhu, Caltech
Others	John Hauser, U. Colorado (visiting professor at Caltech) David Chichka, Caltech (staff researcher) Sanjay Lall, Caltech (staff researcher)

5 Publications

Journal Publications

Appeared

[J1] S. M. Jalnapurkar and J. E. Marsden. Stabilization of relative equilibria ii. *Reg. and Chaotic Dyn.*, 3:161–179, 1999.

[J2] J. A. Primbs, V. Nevistić, and J. C. Doyle. Nonlinear Optimal Control: A

Control Lyapunov Function and Receding Horizon Perspective. *Asian Journal of Control*, 1(1):1–11, 1999.

Accepted

[J3] S. M. Jalnapurkar and J. E. Marsden. Stabilization of relative equilibria. *IEEE Transactions on Automatic Control*, 1999. To appear.

Submitted

[J4] A. M. Bloch, N. Leonard, and J. E. Marsden. Controlled lagrangians and the stabilization of mechanical systems i: The first matching theorem. *IEEE Transactions on Automatic Control*, 1999.

[J5] A. Jadbabaie, J. Yu, and J. E. Hauser. Unconstrained receding horizon control of nonlinear systems. *IEEE Transactions on Automatic Control*, 1999. Submitted.

Conference Proceedings

[C1] G. J. Balas, A. Packard, and E. Wemhoff. Cone-bounded analysis of interconnections of identical, but uncertain lipschitz nonlinearities. In *Proc. IEEE Control and Decision Conference*, 1998.

[C2] J. Barker and G. J. Balas. Flight control of a tailless aircraft via linear parameter-varying techniques. In *AIAA Conference on Guidance, Navigation, and Control*, 1999.

[C3] J. M. Barker, G. J. Balas, and P. A. Blue. Gain-scheduled linear fractional control for active flutter suppression. In *Proc. American Control Conference*, 1999.

[C4] A. M. Bloch, P. Crouch, J. E. Marsden, and T. S. Ratiu. Discrete rigid body dynamics and optimal control. In *Proc. IEEE Control and Decision Conference*, pages 2249–2254, 1998.

[C5] A. M. Bloch, N. Leonard, and J. E. Marsden. Matching and stabilization by the method of controlled lagrangians. In *Proc. IEEE Control and Decision Conference*, pages 1446–1451, 1998.

[C6] A. M. Bloch, N. Leonard, and J. E. Marsden. Potential shaping and the method of controlled lagrangians. In *Proc. IEEE Control and Decision Conference*, 1999.

[C7] A. M. Bloch, N. Leonard, and J. E. Marsden. Stabilization of the pendulum on a rotor arm by the method of controlled lagrangians. In *Proc. IEEE International Conference on Robotics and Automation*, 1999. To appear.

[C8] J. A. Fax, D. A. Hill, and R. M. Murray. Robustness analysis of accelerometry using an electrostatically suspended gyroscope. In *Proc. IEEE International Conference on Control and Applications*, 1999.

[C9] S. Ganguli and G. J. Balas. Application of robust control techniques to the actex-i flight experiment. In *AIAA Conference on Guidance, Navigation, and Control*, 1999.

[C10] S. Glavaski, J. E. Marsden, and R. M. Murray. Model reduction via centering and karhunen loeve expansion. In *Proc. IEEE Control and Decision Conference*, 1998.

[C11] A. Jadbabaie, J. Yu, and J. E. Hauser. Receding horizon control of the caltech ducted fan: A control lyapunov function approach. In *Proc. IEEE International Conference on Control and Applications*, 1999.

[C12] A. Jadbabaie, J. Yu, and J. E. Hauser. The region of attraction of receding horizon control strategies with control lyapunov functions. In *Proc. IEEE Control and Decision Conference*, 1999. Submitted.

[C13] A. Jadbabaie, J. Yu, and J. E. Hauser. Stabilizing receding horizon control of nonlinear systems: A control lyapunov function approach. In *Proc. American Control Conference*, 1999.

[C14] M. Milam and R.M. Murray. A testbed for nonlinear control techniques: The caltech ducted fan. In *Proc. IEEE International Conference on Control and Applications*, 1999.

[C15] J. A. Primbs. The Analysis of Optimization Based Controllers. In *Proc. American Control Conference*, San Diego, CA, 1999.

[C16] J. A. Primbs and M. Giannelli. Control Lyapunov Function Based Receding Horizon Control for Time-Varying Systems. In *37th Conference on Decision and Control*, Tampa, Florida, Dec 1998.

[C17] J. A. Primbs and M. Giannelli. A Control Lyapunov Function Based Receding Horizon Methodology for Input Constrained Nonlinear Systems. In *International Federation of Automatic Control, 14th World Congress*, Beijing, China, 1999.

[C18] M. Rathinam and R. Murray. Discrete function approximation: Numerical tools for nonlinear control. In *Proc. IEEE Control and Decision Conference*, 1998.

[C19] J. Yu, A. Jadbabaie, J. Primbs, and Y. Huang. Comparison of Nonlinear Control Designs for a Ducted Fan Model. In *International Federation of Automatic Control, 14th World Congress*, Beijing, China, 1999.

Theses

None.

6 Interactions and Transitions

Meetings and conferences

All personnel have attended a variety of conferences including CDC, ACC, and GNC.

Consulting and advisory functions

- Doyle is a current member of the Air Force Scientific Advisory Board.
- Murray is a member of the Defense Science Study Group, a DARPA supported program designed to introduce young scientists and engineers to the Department of Defense.

ACTEX

In addition to UMN's work on linear-parameter varying control designs, they are working on the design of vibration attenuation controllers for the ACTEX satellite. ACTEX is cooperative program between AFRL/Space Vehicles Technology Directorate, Ballistic Missile Defense Organization (BMDO) and TRW Inc., to demonstrated vibration suppression of a pointing platform in space. The main objective of the ACTEX flight experiment is to demonstrate the space-readiness of embedded PZT sensors and actuators for system identification and structural control. To date, we have developed a model of the ACTEX structure based on experiment data from space tests and have developed controllers for our model. We have supplied TRW with our controllers for the ACTEX structure and we hope to have them uplinked to the satellite.

Transitions

1. **Performer:** Prof Jerrold Marsden, CDS, Caltech; marsden@cds.caltech.edu

   Customer: JPL mission design community

   Contact: Dr. Martin Lo, mwl@trantor.Jpl.Nasa.Gov

   Results: A prior partially supported AFOSR postdoc, Wang-Sang Koon in collaboration with Jerrold Marsden, Shane Ross and Martin Lo, building on their recently discovered heteroclinic connection in the three body problem have applied the ideas to the design of some new mission trajectories beyond the now well known Genesis trajectory.

Application: These new trajectories are to a "petit grand tour" of the moons of Jupiter. These new dynamical systems techniques allow one to create orbits that require only half the fuel of the traditional Hohmann transfer methods.

2. **Performer:** Prof Gary Balas, University of Minnesota Telephone 612.625.6857

   Customer: MUSYN Inc. and NASA Langley Research Center

   Contact: Dr. Chris Belcastro, 757.864.4035

   Results: Application of LPV techniques to the design of the longitudinal axis of the NASA High Speed Civil Transport (HSCT). The difficulty is that the HSCT is an extremely flexible aircraft which will require the active attenuation of flexible body modes as well as a standard flight controller. The LPV control designs will be compared with the current Boeing flight controller and augmented structural mode control system. The LPV designs will be tested in pilot-in-the-loop simulation at NASA Langley and NASA Dryden.

   Application: The robust, gain-scheduled multivariable controllers perform as well as the current designs. These results lend support to these techniques to design current and future flight control systems. As systems become more highly coupled, robust, gain-scheduled multivariable techniques offer a major benefit over classical methods in terms of achievable performance, robustness and overall safety.

3. **Performer:** Prof Gary Balas, University of Minnesota, (612) 625-6857

   Customer: MUSYN Inc, Johns Hopkins Applied Physics Laboratory

   Contact: Tom Urban, 240.228.7605

   Results: Application of LPV techniques to the design of aggressive, high performance missile autopilots. The objective is to fly the missile at higher angles-of-attack and sideslip than previously possible with standard techniques. We have successfully synthesized autopilots for aggressive acceleration maneuvers at high mach numbers.

   Application: Future missile systems and unmanned air vehicle can expand their operating range with these advanced, gain-scheduled multivariable techniques. In addition, the automated nature of these dynamics will minimize the time between design cycles.

4. **Performer:** Richard M. Murray, Caltech, murray@indra.caltech.edu

   Customer: United Technologies Research Center

   Contact: Robert Hobbs, (860) 610-7421

   Results: Murray hired by UTRC as Director, Mechatronics Systems. Effective 7/1/98.

Application: Nonlinear dynamics and control problems in gas turbine engines (Pratt & Whitney), rotorcraft and UAVs (Sikorsky), HVAC/R (Carrier), and elevators (Otis).

7 Honors and Awards

Richard Murray

June 1999	Plenary lecture, American Control Conference

Jerrold Marsden

1990	AMS-SIAM Norbert Wiener Prize
1993	Fellow, Royal Society of Canada
1997	Member, American Academy of Arts and Science

New Discoveries, Inventions, or Patent Disclosures

None.