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Robust Nonlinear Control Theory with Applications to Aerospace Vehicles

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Progress Report

1 August 1997 to 31 July 1998

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 strong progress in the area of nonlinear control of mechanical systems, robustness analysis for nonlinear systems, real-time trajectory generation, and linear parameter varying (LPV) control. An increased emphasis is being placed on computational methods in nonlinear control as well as fundamental theory of nonlinear control of mechanical systems.

3 Accomplishments

Linear Parameter Varying Control and Its Applications

The research at the University of Minnesota (G. Balas, PI) is focused on application of linear-parameter varying (LPV) H_∞ control design methods to aerospace vehicles. LPV methods have been successfully applied to design autopilots for a high performance, highly coupled missile, and are currently being applied to the design of longitudinal and lateral-directional axis flight and structural mode control for the high speed civil transport. Pilot-in-the-loop simulations are planned for this year.

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. We have developed and applied LPV techniques that successfully account for these saturations in the control design process.

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. A model matching LPV controller was 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.

Based on the success of our work on LPV systems, these techniques are currently being applied to design autopilots for a high performance, highly coupled missile and design flight controllers for the High Speed Civil Transport.

Unified Approach to Nonlinear Stabilization

Two well known approaches to nonlinear control involve the use of control Lyapunov functions (CLFs) and receding horizon control (RHC), also known as model predictive control (MPC).

We have developed a new framework for the nonlinear optimal control design process that recognizes and exploits the complementary nature of CLF and RHC techniques. CLF based pointwise min-norm controllers, which provide guarantees of stability, can be viewed as the limiting case of a receding horizon control scheme. This receding horizon scheme inherits stability properties from the CLF, while at the same time taking advantage of the performance properties of receding horizon control. Not only does this yield a more unified view of the competing approaches to optimal control, but it results in a more flexible use of on-line computing power, facilitating practical implementation as well.

We have implemented and tested this technique on a variety of simple examples and it shows very good performance characteristics compared with other linear and nonlinear stabilization techniques. We are in the process of implementing this control methodology on the Caltech ducted fan to demonstrate the feasibility of implementing this computational intensive approach using modern computational hardware.

Trajectory Generation and Tracking Using Differential Flatness

Murray and his coworkers have been investigating techniques for online trajectory generation for flight control applications, motivated by problems in uninhabited aerial vehicles. The role of trajectory generation is important in these systems since the pilot is not in the plane and therefore cannot provide feasible guidance commands in highly aggressive flight situations. We are investigating techniques for generating state and input trajectories which satisfy the equations of motion and trade off tracking performance for internal stability.

Over the past year, we have begun to focus on the role of magnitude and rate constraints in both trajectory tracking and trajectory generation. For trajectory tracking, we have derived several ad-hoc algorithms for nonlinearly rescaling the gains of a linear control law that perform extremely well on our flight control experiment. These ad-hoc control laws are supported by theoretical work on a related stabilization problem that gives insight into the way in which the rescaling is done. The basic techniques employed are based on Lyapunov design and are similar to other results that are beginning to appear in the literature.

The problem of trajectory generation in the presence of magnitude and rate constraints is much less studied. We have made recent progress on this problem in the context of linear systems in joint work with Prof. Sunil Agrawal (U. Delaware). Making use of flatness-based concepts, we have devised a method for solving point to point motion control problems in the presence of constraints on the input magnitudes and rates. These techniques are being implemented on a couple mass system at U. Delaware to demonstrate the efficacy of the approach. The basic approach should be extendable to nonlinear systems that are differentially flat, although some of the tricks used in the linear case may no longer apply, leading to increased computational requirements.

Dynamics and Control of Mechanical Systems

In joint work with Tony Bloch and Naomi Leonard, Marsden is investigating a structured approach to stabilization of Lagrangian systems. The first step involves making certain admissible modifications to the Lagrangian for the uncontrolled system, thereby constructing what we call the *controlled Lagrangian*. The Euler-Lagrange equations derived from the controlled Lagrangian describe the closed-loop system where the new terms introduced by the modifications of the Lagrangian are identified with control forces. Since the controlled system is Lagrangian by construction, energy methods can be used to find control gains that yield closed-loop stability. These results are currently being generalized to include examples such as a spacecraft with a robotic arm and other underactuated mechanical systems.

Additional work on mechanical systems includes extension of previous results on nonholonomic mechanics (with W. S. Koon) and generalization of the energy-momentum method to systems with nonholonomic constraints (with D. Zenkov and A. Bloch).

Vibration attenuation for flexible structures

The University of Minnesota is also working on the design of vibration attenuation controllers for the ACTEX satellite and developing shape memory alloys (SMAs) for vibration attenuation in flexible structures. 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 implemented the TRW controllers in our model. We are currently synthesizing active controllers for the ACTEX structure to be supplied to TRW and then up linked to the satellite. We have been involved in the ACTEX Guest Investigator (GI) program for the last three months and hope to out controllers in space by the end of the year. we have designed and are developing an actuator for structural vibration attenuation using shape memory alloys (SMAs).

Our past research has shown that SMAs can be successfully used as passive vibration attenuation devices. To extend this work, we have design an active SMA actuator for vibration attenuation. We are able to achieve a bandwidth of approximately 10 Hz, though the force levels are very small (on the order of 0.1 - 0.4 Newtons). The SMA actuator weights less than 1 gram not including the mounting structure. We were able to achieve a factor of 6 attenuation of resonant mode on our experimental structure. This level of performance is on the same order as achieved using our 1.8 lb voice coil actuators. We are able to achieve a bandwidth of approximately 10 Hz which is quite significant for SMA wire.

Active Control of Fluids

In cooperation with the AFOSR PRET Center on Nonlinear Robust Control of Stall and Flutter in Aerospace Engines, we have been investigating a variety of problems in active control of fluid systems. Work on active control of compression systems is described in the summary report for the aeroengines PRET. In addition, we are also beginning to investigate problems in combustion instabilities and cavity flow instabilities.

Combustion instabilities in gas turbine engines involve an interaction between the acoustic modes of the combustion chamber and the unsteady heat release. Most of the work to date has focused on system modeling and identification. The most recent results were reported in a paper to appear in the 1998 American Control Conference as well as a workshop held at Caltech in November, 1997. The work in combustion instabilities is joint work with Prof. Fred Culick at Caltech and researchers at the United Technologies Research Center.

Cavity flow instabilities occur in certain high speed flight situations and can generate large pressure oscillations in bomb bays and wheel wells. We have begun to build a small experiment, using the hydrodynamic analogy between acoustic flow fields and shallow water flows, to demonstrate and test active control techniques for minimizing the size of the oscillations. This is joint work with Prof. Tim Colonius at Caltech and involves numerical computation, date-driven reduced order modeling, and nonlinear analysis.

4 Personnel Supported

Faculty	Gary Balas, UMN John Doyle, Caltech Jerrold Marsden, Caltech Richard Murray, Caltech
Postdoctoral fellows	Ian Fialho, UMN Wang Sang Koon, Caltech B. N. Shashikanth, Caltech
Graduate students	Raktim Bhattacharya, UMN Anthony Blaom, Caltech Francesco Bullo, Caltech Jeremy Dillon, Caltech Alex Fax, Caltech Martha Gallivan, Caltech Sonja Glavaski, Caltech Yun Huang, Caltech Sameer Jalnapurkar, Caltech/UCB Volkan Nalbantoglu, UMN Pablo Parrilo, Caltech James Primbs, Caltech Jong-Yeob Shin, UMN Matthew West, Caltech Jie Yu, Caltech Xiaoyun Zhu, Caltech
Others	Sunil Agrawal, U. Delaware (visiting professor at Caltech) David Chichka, Caltech (staff researcher) Sanjay Lall, Caltech (staff researcher)

5 Publications

Journal Publications

Appeared

[J1] M. Rathinam and R. Murray. Configuration flatness of Lagrangian systems underactuated by one control. *SIAM Journal of Control and Optimization*, 36(1):164–179, 1998.

[J2] M. van Nieuwstadt, M. Rathinam, and R. M. Murray. Differential flatness and absolute equivalence. *SIAM Journal of Control and Optimization*, 36(4):1225–1239, 1998.

[J3] M. J. van Nieuwstadt. Rapid hover to forward flight transitions for a thrust vectored aircraft. *Journal of Guidance, Control, and Dynamics*, 21(1):93–100, 1998.

[J4] D. V. Zenkov, A. M. Block, and J. E. Marsden. The energy momentum method for the stability of nonholonomic systems. *Dyn. Stab. of Systems*, 13:123–166, 1998.

Accepted

[J5] G. J. Balas. Synthesis of controllers for the active mass driver system in in the presence of uncertainty. *Earthquake Engineering and Structural Dynamics*, 1998. To appear.

[J6] G. J. Balas, A. K. Packard, R. M'Closkey, J. Renfrow, and C. Mullaney. Design of controllers for the f-14 aircraft lateral-directional axis during powered approach. *Journal of Guidance, Control, and Dynamics*, 1998. To appear.

[J7] G. J. Balas and P. M. Young. Sensor selection via closed-loop control objectives. *IEEE Transations on Control Systems Technology*, 1998. To appear.

[J8] W. S. Koon and J. E. Marsden. The poisson reduction of nonholonomic mechanical systems. *Reports on Mathematical Physics*, 1998. To appear.

[J9] J. S. Vipperman, J. M. Barker, R. L. Clark, and G. J. Balas. Comparison of μ and h_2 -synthesized controllers on an experimental typical section. *Journal of Guidance, Control, and Dynamics*, 1998. To appear.

Submitted

[J10] J. M. Barker, G. J. Balas, and P. Blue. Gain-scheduled linear fractional control for active flutter suppression. *Journal of Guidance, Control, and Dynamics*, 1998. Submitted.

[J11] I. Fialho and G. J. Balas. Design of nonlinear controllers for active vehicle suspensions using parameter-varying control synthesis. *Vehicle System Dynamics*, 1997. Submitted.

[J12] I. Fialho and G. J. Balas. Road adaptive active suspension design using linear parameter-varying gain-scheduling. *ASME Transations on Vehicle Dynamics*, 1998. Submitted.

[J13] W. Lu, G. J. Balas, and E. B. Lee. A variational approach to $\langle_\infty$ control with transients. *IEEE Transactions on Automatic Control*, 1997. Submitted.

[J14] J. Primbs, V. Nevistic, and J. Doyle. On receding horizon extensions and control lyapunov functions, part i: Background. *IEEE Transactions on Automatic Control*, 1998. Submitted.

[J15] J. Primbs, V. Nevistic, and J. Doyle. On receding horizon extensions and control lyapunov functions, part ii: a receding horizon generalization of pointwise min-norm controllers. *IEEE Transactions on Automatic Control*, 1998. Submitted.

Conference Proceedings

[C1] R. M. Murray, C. A. Jacobson, R. Casas, A. I. Khibnik, C. R. Johnson, R. Bitmead, A. A. Peracchio, and W. M. Proscia. System identification for limit cycling systems: A case study for combustion instabilities. In *Proc. American Control Conference*, 1998.

[C2] J. Primbs and V. Nevistic. Constrained finite receding horizon linear quadratic control. In *Proc. IEEE Control and Decision Conference*, 1997.

[C3] J. Primbs and V. Nevistic. A framework for robustness analysis of constrained finite receding horizon control. In *Proc. American Control Conference*, 1998.

[C4] J. Primbs, V. Nevistic, and J. Doyle. On receding horizon extensions and control lyapunov functions. In *Proc. American Control Conference*, 1998.

6 Interactions and Transitions

Meetings and conferences

All personnel have attended a variety of conferences including CDC, ACC, and GNC. In addition, the following specific activities were performed:

- Murray attended a RESTORE program review in March, 1998.
- Balas attended the ACTEX kickoff meeting in June, 1998.

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.
- Murray is consulting for United Technologies Research Center in the area of nonlinear control of combustion instabilities (Jan-Jul).

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 partially supported AFOSR postdoc, Wang-Sang Koon in collaboration with Jerrold Marsden and Martin Lo, discovered numerically an important heteroclinic connection in the three body problem. This heteroclinic connection (in the sense of dynamical systems) is between two halo orbits with the same Jacobi constant; one is around the libration point L1 and the other around L2. In solar system dynamics such as the Earth-Sun system, these orbits are widely separated (by several diameters of the moon's orbit). This connection will lead to a deeper understanding of the important phenomenon of resonant transitions (studied by, eg, Belbruno and B. Marsden) between the inner and outer Hill's region.

   Application: This connection is important in the computation of the dynamics of specific missions such as the upcoming Genesis mission as well as the planning of future missions (eg, to Europa) and for the understanding of phenomena that are important in astrodynamics such as the capture of comets and asteroid impacts.

2. **Performer:** Prof Gary Balas, University of Minnesota, (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, California Institute of Technology, (626) 395-6460

   Customer: Boeing North American

   Contact: Daniel Hill, (714) 762-1151

   Results: A collaborative project has been established between Boeing North American (formerly Rockwell) and Caltech to apply modern robust control techniques to stabilization of an electrostatic gyro (ESG) and to evaluate performance enhancements due to use of modern, multi-variable control techniques. A control law has been designed and implemented on the ESG using a PC-based real-time control system. Robust analysis tools have been used to estimate the achievable performance and these results are being compared to alternative navigation technologies.

   Application: High performance control of an electrostatic gyro, an inertial guidance sensor marketed by Boeing and currently used for ship and submarine applications.

7 Honors and Awards

Richard Murray

June 1998 Plenary lecture, SIAM Conference on Control and Its Applications,

New Discoveries, Inventions, or Patent Disclosures

None.