ROBUST NONLINEAR CONTROL THEORY WITH APPLICATIONS TO AEROSPACE VEHICLES

AFOSR-PRET GRANT F49620-95-1-0419

Richard Murray
Control and Dynamical Systems
California Institute of Technology
Pasadena, CA 91125

John Doyle Jerry Marsden
Caltech Control and Dynamical Systems

Gary Balas
University of Minnesota

Annual Report
1 July 1999 to 14 June 2000

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. In addition, we are exploring techniques for modeling and control of chemically reacting systems, with applications to gas turbine engines and materials growth.

2 Status of Effort

This was the final year of the PRET program, which ended in June 2000. Research conducted in this last year 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. In addition, we have begun to develop new insights and techniques for modeling of chemically reacting systems, motivated by applications in materials processing. A variety of new programs have been initiated as a result of the basic research conducted under this program.

3 Accomplishments

In this section we give a brief summary of some of the work performed in the last year. Additional details can be found in the references.

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 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.)

Over the past several years, we have developed provably stable techniques that combine receding horizon control with control Lyapunov functions and allow excellent performance even when very short horizons are used for the online optimization. Over the past year, we have focused on providing theoretical and algorithmic improvements required to implement these systems on engineering platforms, using the Caltech ducted fan as a prototype.

A key element of the approach, developed under prior PRET funding, was to show that the end point constraints that are typically present in MPC approaches can be converted to a terminal cost that is based on the value of a CLF. This greatly simplifies the finite time optimization problem to be solved and is a key element in enabling real-time implementation.

In work jointly sponsored by DARPA, we have derived new theoretical results that demonstrate that incremental improvements during iterations of the algorithm are sufficient to guarantee stability for receding horizon control techniques [C7]. This provides a solid framework for implementing algorithms that use a finite number of iterations at each step of the algorithm.

We have also implemented a real-time algorithm for trajectory generation in the presence of state and input constraints, based on combining ideas from differential flatness and collocation to obtain high performance algorithms. This approach has been demonstrated on simulations of the Caltech ducted fan and timing results indicate they can be implemented on the experimental system [C9].

This work is being continued as part of the DARPA-sponsored Software Enabled Control (SEC) program and involves several industrial partners.

Linear Parameter Varying Control and Its Applications (UMN)

In work initiated under the PRET program in 1998, UMN has been 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. In past years, we have developed a model of the ACTEX structure based on experiment data from space tests and have developed controllers for our model.

The vibration attenuation controllers we designed for the ACTEX satellite have been tested in space by TRW. These controllers performed better than open-loop in parts of the frequency domain and worse than open-loop in other frequency ranges. Our analysis indicates that these controllers were implemented with an incorrect sign. Therefore, TRW plans to re-uplinked these controllers with the correct sign to the ACTEX satellite and send us the on-orbit experimental results.

In the area of linear parameter varying systems, the results of our research under the AFOSR PRET program has led to three new research programs at UMN. A direct out growth of our work under the AFOSR PRET program is funding from NASA Dryden to synthesize a LPV controller for the F-18 Systems Research Aircraft (SRA) in the up-and-away flight regime. The objective is take this design from nonlinear simulations to pilot-in-the-loop simulations and then to flight test.

To date we have synthesized longitudinal and lateral-axis LPV controllers for the Class B flight envelope of the F/A-18 SRA. Pilot in the loop simulations are scheduled for August 2000. Upon a successful completion of piloted simulation, the next stage is to code these LPV controllers in Ada and implement them in the PSFCC research computer and test them in hardware in the loop simulations. Flight tests are planned for Spring 2001.

A second program which has started as an outgrowth of our PRET research is part of the NASA Aviation Safety Program, entitled "Application of Linear Parameter-Varying Techniques to Safety Critical Aircraft Flight Systems." It is being funded by NASA Langley under the NASA Safety Program. Under this program we plan to develop a unified approach to health management and control under adverse flight conditions using linear, parameter-varying (LPV) system theory.

Finally, we have funding from DARPA under the Software Enabled Control program to develop theory, algorithms and software modules required to perform inner-loop vehicle control, trajectory generation for rapid tactical response and vehicle system management for an unmanned combat air vehicle. The goal is a complete, unified design framework to synthesize and simulate individual vehicle management systems. All of these research programs build on the LPV control foundation developed under the AFOSR PRET program.

Dynamics and Control of Mechanical Systems

Motivated by problems in formation flight for micro-satellite clusters, we have continued our work in nonlinear control of mechanical systems by exploring the use of geometric structure in optimal control problems. This is relevant for satellites since their dynamics are dominated by Lagrangian structure and there is a critical need to exploit this structure to minimize fuel usage.

Over the past year, we have investigated the optimal control of affine connection control systems and achieved some initial results [C1]. The formalism of the affine connection can be used to describe geometrically the dynamics of mechanical systems, including those with nonholonomic constraints. In the standard variational approach to such problems, one converts an n dimensional second order system into a $2n$ dimensional first order system, and uses these equations as constraints on the optimization. An alternative approach, which we develop in the referenced paper, is to include the system dynamics as second order constraints of the optimization, and optimize relative to variations in the configuration space. Using the affine connection, its associated tensors, and the notion of covariant differentiation, we show how variations in the configuration space induce variations in the tangent space. In this setting, we derive second order equations have a geometric formulation parallel to that of the system dynamics. They also specialize to results found in the literature.

We have also considered the optimal control of time-scalable systems [C2]. The time-scaling property is shown to convert the PDE associated with the Hamilton-Jacobi-Bellman (HJB) equation to a purely spatial PDE. Solution of this PDE yields the value function at a fixed time, and that solution can be scaled to find the value function at any point in time. Furthermore, in certain cases the unscaled control law stabilizes the system, and the unscaled value function acts as a Lyapunov function for that system. For the example of the nonholonomic integrator, this PDE is solved, and the resulting optimal trajectories coincide with the known solution to that problem.

Past theoretical work that has been performed in this area forms a central part of a variety of new programs. Under AFOSR funding, we have a program to explore specific problems associated with the dynamics and control of micro-satellite clusters (see report in this volume) and we have also developed several collaborative efforts with the Jet Propulsion Laboratory (JPL) for deep space missions. In addition, the work in nonlinear control of mechanical systems is part of two new MURI proposals that are based on some of the fundamental work performed under this program.

Dynamics and Control of Chemically Reacting Systems

For several years, in conjunction with the AFOSR PRET on Aeroengines, we have been exploring the use of dynamics and control techniques for modeling and control of chemically reacting systems. The primary application in past work has been combustion instabilities, which was pursued in collaboration with United Technologies Research Center. Over the past year, we have shifted the focus to a different chemically reacting system, namely materials processing and growth of thin films. This work is jointly sponsored by DARPA and NSF as part of the Virtual Integrated Prototyping (VIP) program, with the emphasis in this program being on developing new control-oriented modeling techniques.

The system that we are studying is a MOCVD reactor for growth of YBCO super-conducting thin films. We have developed a Monte Carlo model of the system and have been using this model to explore the response of the system to time-varying growth conditions. We vary temperature and partial pressure sinusoidally and identify behavior typical of low-dimensional nonlinear systems. In particular, the frequency content of the roughness response is sensitive to the presence of steps in the surface, indicating some low dimensional nonlinear effects might be present [C4].

For closed-loop control of thin film deposition, one would like to directly control film properties such as roughness, stress, or composition, rather than process parameters like temperatures and flow rates. This requires a model of the dynamic response of film properties to changes in process conditions. Direct atomistic simulation is far too slow to be used in this capacity, but a promising approach we explore here is to derive reduced-order dynamic models from atomistic simulations.

In [C3] we consider film growth on a vicinal surface using a kinetic Monte Carlo model. The temperature range spans the transition from smooth step flow to rough island growth. Proper Orthogonal Decomposition is used to extract the dominant spatial modes from the KMC simulations. Only five spatial modes adequately represent the roughness dynamics for all simulated times and temperatures, indicating that a 5-state model may be sufficient for real-time roughness control.

4 Personnel Supported

Faculty

- Gary Balas, UMN
- John Doyle, Caltech
- Jerrold Marsden, Caltech
- Richard Murray, Caltech

Postdoctoral fellows

- B. N. Shashikanth, Caltech
- Sameer Jalnapurkar, Caltech/UCB

Graduate students

- Raktim Bhattacharya, UMN
- Alex Fax, Caltech
- Martha Gallivan, Caltech
- Suvo Ganguli, UMN
- Mark Milam, 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] W. S. Koon, M. Lo, J. E. Marsden, and S. Ross. Heteroclinic connections between periodic orbits and resonance transitions in celestial mechanics. *Chaos*, 10:427–469, 2000.

Accepted

[J2] N. Faiz, S. Agrawal, and R. M. Murray. Differentially flat systems with inequality constraints: An approach to real-time feasible trajectory generation. *Journal of Guidance, Control, and Dynamics*, 2000. To Appear.

[J3] C. Kane, J. E. Marsden, M. Ortiz, and M. West. Variational integrators and the newmark algorithm for conservative and dissipative mechanical systems. *Int. J. Num. Math. Eng*, 2000. To Appear.

Submitted

[J5] 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.

[J6] 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] A. Fax and R. M. Murray. Optimal control of affine connection control systems: A variational approach. In *Proc. IEEE Control and Decision Conference*, 2000. To Appear.

[C2] A. Fax and R. M. Murray. Finite-horizon optimal control and stabilization of time-scalable systems. In *Proc. IEEE Control and Decision Conference*, 2000. To Appear.

[C3] M. A. Gallivan, R. M. Murray, and D. G. Goodwin. The dynamics of thin film growth: A modeling study. In *Proc. Electrochemical Society*, 2000.

[C4] M. A. Gallivan, R. M. Murray, and D. G. Goodwin. Kinetic monte carlo simulation of dynamic phenomena in thin film growth. In *Materials Research Society Spring Meeting*, 2000.

[C5] A. Jadbabaie, M. Giannelli, J. Yu, and J. E. Hauser. Unconstrained receding horizon control with magnitude saturation. In *Proc. American Control Conference*, 2000.

[C6] J. E. Hauser and A. Jadbabaie. Aggressive maneuvering of a thrust vectored flying wing: A receding horizon approach. In *Proc. IEEE Control and Decision Conference*, 2000. Submitted.

[C7] A. Jadbabaie and J. E. Hauser. Relaxing the optimality condition in receding horizon control. In *Proc. IEEE Control and Decision Conference*, 2000.

[C8] M. B. Milam and R. M. Murray. A testbed for nonlinear flight control techniques: The Caltech ducted fan. In *Proc. IEEE International Conference on Control and Applications*, 1999.

[C9] M. B. Milam, K. Mushambi, and R. M. Murray. A computational approach to real-time trajectory generation for constrained mechanical systems. In *Proc. IEEE Control and Decision Conference*, 2000. Submitted.

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 was a member of the Air Force Scientific Advisory Board.
- Murray served as 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 chairing a panel on Future Directions in Control and Dynamical Systems. Doyle and Marsden are members of the panel.

Transitions

1. **Performer:** Richard M. Murray, Caltech, murray@cds.caltech.edu

   Customer: United Technologies Research Center

   Contact: Robert Hobbs, (860) 610-7421

   Results: Murray worked at UTRC as Director, Mechatronics Systems through 15 March 2000.

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

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

   Customer: MUSYN Inc., Lockheed Martin Aero, NASA Langley

   Contact: Dr. Christine Belcastro 757.864.4035, Dr. Rowena Eberhardt, 817.935.1071

   Results/Application: Synthesize a flight controller for the Gulfstream V using the LPV techniques developed under the AFOSR PRET program as part of the NASA Aviation Safety Control and Upset Management Program. This work is being performed under the Lockheed-Martin AIMSAFE program. NASA and Lockheed-Martin view parameter dependent system theory as a potential unifying approach to on-line health monitoring and identification, fault detection, reconfiguration or adaptation and flight control.