Robust Nonlinear Control Theory with Applications to Aerospace Vehicles

AFOSR Partnership for Research, Excellence, and Transition (PRET)

Richard M. Murray, John C. Doyle, Jerrold E. Marsden, Stephen Wiggins
California Institute of Technology

Gary Balas
University of Minnesota

Blaise Morton
Honeywell Technology Center

April 1997

Stabilization of Mechanical Systems with Euclidean Motion Symmetry

(joint project with N. Leonard, Princeton)

Motivating Problems

- Stabilizing satellite attitude with internal rotors using energy methods
- Stability analysis and stabalization of streamlined motion of underwater vehicles

Objectives

- Design stabilizing feedback control laws for mechanical systems of this type
- Exploit mechanical (or Lagrangian) structure and knowledge of symmetry groups

Techniques

- Generalization of nonlinear stability method of Arnold (to allow noncompact group, nongeneric equlibria)
- Continued development of theory for controlled Lagrangians; resulting control laws do not destroy mechanical structure

Results to Date

- Generation of classes of stabilizing feedbacks
- Stablity theorems and stabilization verified numerically and experimentally

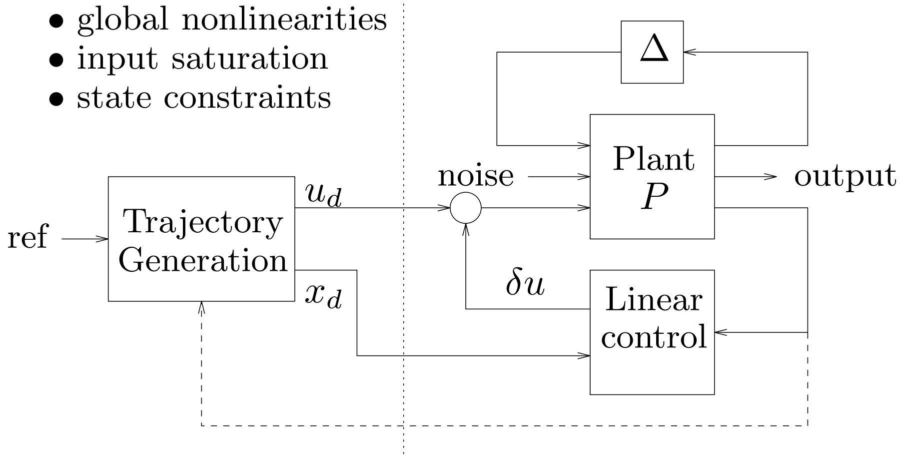
Significance

- Vehicle controllers use rotors rather than thrusters, propellers, or fins (possible noise and/or energy advantages)
- Links with path planning, trajectory generation, and locomotion problems for a variety of motion control systems
- Starting point for exploration of more general uses of symmetry of mechanical systems, relative equilibria, and stabilization

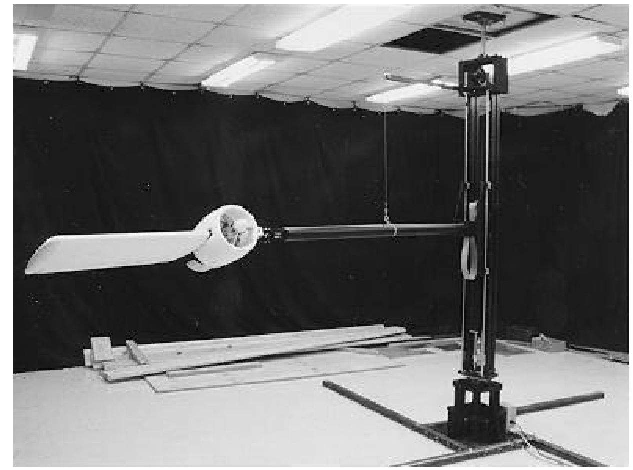
Trajectory Tracking Generation and Tracking Using Differential Flatness

Nonlinear design
- global nonlinearities
- input saturation
- state constraints

Linear design



Caltech Ducted Fan



Approach: Two Degree of Freedom Design

- Use online trajectory generation to construct feasible trajectories
- Use (scheduled) linear control for local performance
- For many flight vehicles, system is *differentially flat* $\Longrightarrow$ reduce dynamic system to algebraic equivalent and generate feasible trajectories in real-time
- Validatation on Caltech ducted fan experiment

Results

- Real-time algorithms developed and tested on Caltech ducted fan (van Nieuwstadt and Murray, 1996)
- Necessary and sufficient conditions for flatness of a class of underactuated mechanical systems (Rathinam and Murray, 1996)
- Current focus: using flatness for improved surface allocation in presence of actuator limits

Control of Compression System Instabilities

Compression System Instabilities

- Surge: compressor $\leftrightarrow$ plenum; axisymmetric
- Stall: rotating disturbance in rotor/stator
- Flutter: blade vibrations, coupled by fluid

Control of Stall Using Air Injection

- Use (pulsed) air injection at rotor face to modify inlet flow field
- Experiments show that non-axisymmetric injection has much better performance characteristics

Reduction of Bleed Valve Requirements

- Use *steady* air injection to modify rate requirements for stabilization using downstream bleed valves
- Shift in compressor characteristic map (unstead loss dynamics) responsible for significant changes in system dynamics and control properties

Stabilization of Flutter by Mistuning

- Mistune blades to affect stability boundary; breaks circumferential symmetry
- Exploit remaining system symmetry in dynamics to develop efficient algorithms for computing optimal mistuning

Technology Transfer

- Strong interaction with United Technologies Research Center + Pratt and Whitney
- Patent disclosure filed on modification of compressor characteristic to reduce actuator requirements
- Patent disclosure filed on variations of mistuning algorithm