Meeting on Nonlinear Control Theory and its Applications

May 5–6, 2004
Queen's University
Kingston, ON

Long programme (last revised: 23/04/2004)

May 5:

8:59:45-9:00:
Opening remarks
Andrew Lewis, Queen's University

9:00-10:00:
Speaker: Manfredi Maggiore, University of Toronto
Title: *A separation principle for nonlinear systems*
Abstract: This talk introduces a "state-variable approach" to output feedback stabilization of nonlinear systems which, unlike other recently developed techniques, does not work in input-output coordinates and does not rely on input saturation to achieve separation between the state feedback and observer designs. Rather, we show that by using nonlinear high-gain observers working in state coordinates, together with a dynamic projection algorithm, the same kind of separation principle is achieved for a larger class of systems which are not uniformly completely observable. By working in state coordinates, this approach avoids using knowledge of the inverse of the observability mapping to estimate the state of the plant, which is otherwise needed when using high-gain observers to estimate the output time derivatives.

10:00-10:30:
Speaker: Chris Nielsen, University of Toronto
Title: *Maneuver regulation, transverse feedback linearization and zero dynamics*
Abstract: The maneuver regulation (or path following) problem has received considerable attention in the control literature and feedback linearization has proven an effective approach to solving this problem. This talk presents a general synthesis method for designing path following controllers for a class of systems using the concept of transverse feedback linearization. The relationship between maneuver regulation, transverse feedback linearization and zero dynamics is also discussed.

10:30-10:45: Break

10:45-11:45
Speaker: Martin Guay, Queen's University
Title: *Observer linearization by generalized transformations*
Abstract: In this presentation, we explore the problem of observer linearization for single output dynamical systems in the presence of an output-dependent time-scaling

transformation and a output diffeomorphism. Our approach, based on an exterior calculus method, provides a constructive approach to the problem of equivalence of a locally observable nonlinear system to a linear observer form that easily incorporates output dependent time-scale transformations, output diffeomorphisms and state-space diffeomorphisms. A generalization of existing results is obtained which allows the treatment of a larger class of locally observable nonlinear systems.

11:45-12:15:

Speaker: Darryl DeHaan, Queen's University

Title: *Extremum-seeking control of nonlinear, state-constrained systems*

Abstract: We pose and solve a type of extremum seeking control problem for a class of convex state-constrained nonlinear systems with unknown parameters. The controller is derived to drive the system states to the (unknown) "set-points" which maximize the value of an objective function depending upon unknown parameters. Feasibility of the trajectory and its limit point are ensuring using an interior-point approach.

12:15-1:30: Lunch

1:30-2:00:

Speaker: Meg Gao, University of Waterloo

Title: *Design of robust gain-scheduled model predictive controllers for nonlinear processes*

Abstract: Gain-scheduling has proven to be a successful design methodology for nonlinear systems. However, in the absence of a sound theoretical analysis, these designs have no guarantees of robust stability, performance or even nominal stability of the overall gain-scheduled deign. In this talk, we will present such an analysis for one type of nonlinear gain-scheduled control system where scheduling is based on the process input. Conditions which guarantee robust stability and performance of the closed-loop systems are formulated as a finite set of Linear Matrix Inequalities (LMI) and hence, the resulting problem is numerically tractable. Based on these conditions, robust gain-scheduled MPC's (Model Predictive Controllers) are designed. A simulation study of a nonlinear continuous stirred tank reactor (CSTR) process indicates that this approach can lead to the design of efficient robust gain-scheduled controllers.

2:00-3:00:

Speaker: Ron Hirschorn, Queen's University

Title: *Hybrid sliding mode control for multi-input nonlinear systems*

Abstract: The purpose of this talk is to present a framework for the design of multi-input hybrid sliding mode controllers. In this framework the control effort goes to zero as the state approaches the sliding surface, a key feature for practical implementation. The sliding surface is a submanifold with codimension equal to the dimension of the involutive distribution G generated by the controlled vector fields rather than the dimension of their linear span. We also allow nonzero vectors in G to be tangent to the sliding surface, the singular case in sliding mode control.

3:00-3:30:

Speaker: Dmitry Voytsekhovsky, Queen's University

Title: *Stabilization of single-input nonlinear systems with sliding mode control*
Abstract: In this talk we will investigate approaches of stabilizing single-input nonlinear systems using sliding mode control. The idea is based on defining a local coordinate transformation for the system with given robust relative degree, and then finding a control law, in the new coordinates, which steers the system to the origin.

3:30-4:00: Break

4:00-5:00:
Speaker: Daniel Miller, University of Waterloo
Title: *Nonlinear and linear approaches to adaptive control*
Abstract: In classical model reference adaptive control, the goal is to design a controller to make the closed loop system act like a prespecifed reference model in the face of significant plant uncertainty. Typically the controller consists of an identifier (or tuner) which is used to adjust the parameters of an LTI compensator, and under suitable assumptions on the plant model uncertainty it is proven that asymptotic matching is achieved. However, the controller is highly nonlinear, and the closed loop system can exhibit undesirable behaviour, such as large transients, expecially if the initial parameter estimates are poor.

After providing an overview of the classical approach, we discuss an alternative approach, which yields a linear periodic controller. Rather than estimating the plant or compensator parameters, instead we estimate what the control signal would be if the plant parameters were known; we are able to do so in a linear fashion. We explore the benefits and limitations of the approach and compare it to the classical one.

5:00-6:00:
Speaker: Mireille Broucke, University of Toronto
Title: *Hybrid optimal synthesis and geometric time optimal control*
Abstract: In the last five years a new paradigm has emerged for solving static Hamilton-Jacobi-Bellman equations. This paradigm uses fast shortest path algorithms rather than the traditional finite element, fixed-point approach and results in a vast speedup to obtain the numerical solution. The key idea in these new algorithms is an observation due to Tsitskilis that if a triangulation of the state space can be constructed so that the value function V evaluated on the grid points can be ordered along level sets of V, then a shortest path algorithm can be used.

In this talk I will discuss one such algorithm for solving HJB equations numerically. This algorithm exploits the geometry of certain relevant vector fields, in the spirit of numerical solvers that preserve geometric invariants of a flow. Two small examples will demonstrate the performance of the algorithm.

Next, I will discuss preliminary results on the application of this algorithm to one of the open problems in time optimal control: time optimal swing up of the 2D pendulum on a cart. Results from the geometric theory of time optimal control for 2D control affine systems due to Sussmann and Piccoli will be briefly reviewed and it will be shown how a combination of analytical and numerical analyses gives a convincing picture of the global structure of the time optimal trajectories.

6:00-6:30

Speaker: Gino Labinaz, Queen's University

Title: *Viability of hybrid systems*

Abstract: The problem of viability of hybrid systems is considered in this work. A model for a hybrid system is developed including three forms of uncertainty, transition dynamics, structural uncertainty and parametric uncertainty. A computational basis for viability of hybrid systems is developed and applied to three control law classes. An approach is developed for robust viability based on two extensions of the controllability operator. The three-tank example is examined for both the viability problem and the robust viability problem.

May 6:

9:00-10:00:

Speaker: Brian Ingalls, University of Waterloo

Title: *System biology: Control theoretic analysis of biochemical networks*

Abstract: The tools of systems and control theory are finding new application in the field of molecular biology. Laboratory experiments are revealing interconnected networks of biochemicals which are responsible for a cell's primary functions. These systems are responsible for regulating cellular growth and activity, for processing intra- and extra-cellular information, and for controlling genetic expression. These networks have evolved to perform these tasks in a robust manner, allowing the cell to function under a wide variety of intra- and extra-cellular conditions.

The reductionist approach of molecular biology is not well suited to the reverse-engineering of these complex networks. Control and systems theory may provide the best approach to uncovering their structure and function. In this talk we will discuss the role of control theory in systems biology, taking a recent analysis of glycolytic oscillations as an example.

10:00-10:30:

Speaker: Leonard Vu, University of Waterloo

Title: *IOSS for singularly perturbed systems*

Abstract: This talk will review the notion of detectability for linear systems, extending this concept to nonlinear systems. A robust definition of zero-detectability given by Krichman (2001), called Input-Output-to-State stability will be presented. An issue that has not been addressed is the Input-Output-to-State stability for singularly perturbed systems. Such systems will be described and a result will be presented in this regard.

10:30-10:45: Break

10:45-11:45:

Speaker: Kirsten Morris, University of Waterloo

Title: *Dissipative controller design*

Abstract: Dissipative systems theory has a long history in the field of control. It can be motivated in terms of energy: the energy stored in a dissipative system will be no greater than the stored energy at an initial time plus the work done on the system. However, this concept can be defined abstractly and the storage function does not always have an interpretation as the energy of the system. The major input-output stability results can be obtained a special cases of results using dissipative systems.

The key ideas in dissipative systems and some important stability theorems will be presented. The approach will be illustrated with examples, including some recent results on robust control of smart materials.

11:45-1:15: Lunch

1:15-2:15:

Speaker: Andrew Lewis, Queen's University
Title: *Musings on controllability and stabilisability*
Abstract: The problem of determining whether a given system is locally controllable and/or locally stabilisable is difficult. In this talk, an approach for characterising the geometric structure of these problems will be outlined. Specifically, the problems will be reduced to questions involving affine subbundles. Once this reduction is accomplished, some existing results in controllability and stabilisation, probably familiar to most, will be expressed in this geometric language, as a warmup. Then some not so well-known (i.e., new) results will be given. The idea will be to illustrate some apparent (but not proved) connections between controllability from a point and stabilisability to a point.

2:15-2:45:

Speaker: David Tyner, Queen's University
Title: *Controllability and motion planning for mechanical systems*
Abstract: Path planning for underactuated mechanical systems using the notion of kinematic controllability will be introduced and illustrated via example of a planar rigid body. The planar rigid body is modelled as a simple mechanical system. We shall define a simple mechanical system as a triple $\Sigma = (Q, g, V)$ where Q is an n-dimensional configuration manifold, g is the Riemannian metric, and V the potential energy. In particular we are interested in the case when $V = 0$ and the system is underactuated. Such systems do not yield a controllable linearisation. Thus more sophisticated methods are required to deal with the full non-linear case. One approach is to relate Σ to an associated driftless system via the notion of kinematic controllability. To do so, one must first find a set of decoupling vector fields for Σ. That is, vector fields whose integral curves are controlled trajectories for Σ up to arbitrary reparameterisation. This has a clear advantage for path planning; one can pick a reparameterisation such that the end points of the integral curves have zero velocity. Then the path planning algorithms amount to piecing the end points of these curves together to obtain the desired final configuration.

2:45-3:15:

Speaker: Joshua Marshall, University of Toronto
Title: *Exploring the collective behaviour of wheeled-vehicles in cyclic pursuit*
Abstract: Multiple agent systems are nowadays becoming a research topic of increasing popularity, especially within the systems and control community. In this talk, we'll

explore how certain networks of interacting dynamical systems (e.g., wheeled vehicles) collectively behave. In particular, results from an analysis of the geometric formations for multiple unicycle systems in cyclic pursuit will be presented. Our primary motivation is to follow the historical development of cyclic pursuit problems found in the mathematics literature, while at the same time viewing these ideas as a potential distributed control strategy for multiple vehicle systems.

3:15-3:45:

Speaker: Zhiyun Lin, University of Toronto

Title: *Feasibility for formation stabilization of multiple unicycles*

Abstract: The problem of coordinated control of a group of autonomous wheeled vehicles is of recent interest in control and robotics due to the broad range of applications of multi-vehicle systems. Individual vehicles in a distributed system must be capable of collectively accomplishing tasks using only locally sensed information and little or no direct communication. Coordinated control of multi-vehicle systems includes many aspects, one of the most important and fundamental being formation control. In this talk, the feasibility problem is studied of achieving a specified formation among a group of autonomous unicycles by local distributed control. The directed graph defined by the information flow plays a key role. Necessary and sufficient conditions are presented for formation stabilization of multiple unicycles to a point and a line. A similar result is given for formation stabilization to more general geometric arrangements with the condition that a group of unicycles have a common sense of direction.

3:45-4:15:

Speaker: Sehjung Kim, University of Waterloo

Title: *Stability of linear switching system with delayed feedback control*

Abstract: We consider a switching system consisting of a finite number of linear systems with delayed feedback. It has been shown that the stability of a switching system composed of linear ODE systems may be achieved by using a "Single Lyapunov Function Method" switching rule. Here we extend this result to a class of delayed systems.

In our model there are N subsystems, each having an unstable ODE part and a delayed feedback control. We modify the switching rule for ODE systems to a "Single Lyapunov Functional Method" switching rule for DDE systems and show that it stabilizes our model. Our result uses a Riccati type Lyapunov functional under a condition on the time delay.