Real-time Optimization of Nonlinear Dynamical Systems by Extremum-seeking control

M. Guay and D. Dochain

1 Introduction

Increased demands imposed by global market pressures, environmental constraints and energy costs have had a dramatic impact on the management and operation of processing systems in many sectors including chemical and petrochemical production plants. There is a signicant thrust in North American companies to integrate science and technology into strategies for producing services and products for a dynamic world market. These changes in operating culture have led to an emphasis on the development of integrated strategies that offer the flexibility required to respond to economic pressures while satisfying emission restrictions and reducing energy costs.

Most adaptive control schemes documented in the literature [15]-[17],[20] are developed for regulation to known set-points or tracking known reference trajectories. In some applications, however, the control objective could be to optimize an objective function which can be a function of unknown parameters, or to select the desired states to keep a performance function at its extremum value. Self-optimizing control and extremum seeking control are two methods to handle these kinds of optimization problems. The goal of self-optimizing control is to find a set of controller variables which, when kept at constant set-points, indirectly lead to near-optimal operation with acceptable loss [8][25][29]. The task of extremum seeking is to find the operating set-points that maximize or minimize an objective function. Since the early research work on extremum control in the 1920's [21], many successful applications of extremum control approaches have been reported, for example, fuel flow control to achieve maximum pressure [32], combustion process control for IC engines and gas furnaces [1][28], and anti-lock braking system control [6].

Real-time optimization has seen a resurgence of interest in the recent years. The traditional approach is the model-based repeated optimization where the model is adapted using the available measurements and numerical optimization is performed on the updated model [24][37]. An alternative approach to real-time optimization

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

is known extremum seeking. Extremum seeking control allows the solution of the optimization problem as a *control problem* with the advantages related to sensitivity reduction and disturbance rejection.

In the past few years, Krstic et al. [18][19][33] have presented several schemes for extremum-seeking control of nonlinear systems. First the system is perturbed using an external excitation signal in order to numerically compute the gradient [3][19]. The excitation can also be possibly generated internally by sliding mode control [36]. Their framework allows the use of black-box objective functions with the restriction that the objective value to be minimized is measured on line. Although this technique has been proven useful for some applications [34], the lack of guaranteed transient performance of the black-box schemes remains a significant drawback in its application. Alternatively an adapted model of the system is used for analytical evaluation of the gradient [9]. The extremum seeking framework proposed by Guay and Zhang [9] assumes that the objective function is explicitly known as a function of the system states and uncertain parameters from the system dynamic equations. Parametric uncertainties make the on-line reconstruction of the true cost impossible such that only an estimated value based on parameter estimates is available. The control objective is to simultaneously identify and regulate the system to the lowest cost operating point, which depends on the uncertain parameters. The main advantage of this approach is that one can guarantee some degree of transient performance while achieving the optimization objectives when a reasonable functional approximation of the objective function is available.

In this workshop, we provide an introduction to the problem of real-time optimization (RTO) and control of nonlinear dynamical systems. Real-time optimization (RTO) has become a leading technology for steady-state process optimization in the process industry. RTO is used as a supervisory control technique to compute, in real-time, optimal setpoints (with respect to e.g. cost, quality, etc...) to be tracked by the process operation. Unfortunately, the objective of RTO, which seeks to explore new operating regimes, cannot be done effectively without an appropriate design of the enabling process control system. In this workshop, we formalize the integrated design of RTO and control systems as a model-based adaptive extremum-seeking control (AESC) task. The main idea advocated is to integrate the competing tasks by using the objective function of the AESC system to formulate a suitable Lyapunov function for the control system. The resulting integrated control system achieves the steady-state optimization objectives with guaranteed transient performance. AESC has proven to be an effective technology in a number of areas including bioprocess control, chemical reactor control, building systems control and fuel-cell control. We will provide a comprehensive introduction to leading solutions of the AESC problem. In doing so, we establish a number of new results in the area of nonlinear adaptive control, constrained

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

system control, periodic system control, nonlinear model predictive control and dynamic real-time optimization.

The workshop targets practicing control engineers, graduate students and researchers interested in extremum-seeking control and real-time optimization of dynamical systems.

2 Workshop Organization

The workshop is organized as follows:

1. Real-time optimization problem description with examples
    - Chemical and bioreactor control problems
    - Polymerization systems
    - Building systems control
2. Real-time optimization using extremum-seeking control
    - Extremum-seeking control: Performance enhancement and limitations
    - Local versus global considerations
3. Model-based adaptive extremum-seeking control
    - Real-time optimization of nonlinear systems
    - Constrained RTO of nonlinear systems
    - Input signal design for guaranteed convergence
    - Improved performance in adaptive nonlinear systems
4. Dynamic real-time optimization
    - Trajectory generation
    - Periodic system control
    - Predictive control
5. Real-time optimization control
    - Bioreactor control
    - Polymerization reactor control
    - Building systems applications

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

3 Worshop participants

- M. Guay, Queen's University, Kingston, Ontario Canada
- D. Dochain, Université catholique de Louvain, Louvain-la-Neuve, Belgium

References

[1] Astrom K. J. and B. Wittenmark (1995). *Adaptive Control*, Addison-Wesley, 2nd edition, Reading, MA: Addison-Wesley.

[2] Bastin G. and D. Dochain (1990). *On-line Estimation and Adaptive Control of Bioreactors*, Elsevier, Amsterdam.

[3] Blackman P.F. (1962). Extremum-seeking regulators. In *An Exposition of Adaptive Control*, J.H. Westcott (ed.), The Macmillan Company, New York.

[4] Chioua M., B. Srinivasan, M. Guay and M. Perrier (2008). Dependence of the error in the optimal solution of perturbation-based extremum-seeking methods on the excitation frequency. Submitted for publication.

[5] CougnonP., D. Dochain, M. Guay and M. Perrier (2006). Real-time optimization of a tubular reactor with distributed feed. *AIChE Journal*, 52(6), 2120–2128.

[6] Drkunov S., U. Ozguner, P. Dix and B. Ashrafi (1995). ABS control using optimum search via sliding modes. *IEEE Trans. Control Syst. Technol.*, 3, 79-85.

[7] Favache A., D. Dochain M. Perrier AND M. Guay (2008). Extremum seeking control of retention for a microparticulate system. To appear in *Can. J. Chem. Eng.*.

[8] Findeisen W., F.N. Bailey, M. Brdys, K. Malinowski, P. Tatjewski and A. Wozniak (1980). *Control and coordination in Hierarchical Systems,* John Wiley, New York.

[9] Guay M. and T. Zhang (2003). Adaptive Extremum Seeking Control of Nonlinear Dynamic Systems with Parametric Uncertainties. *Automatica*, 39(7), 1283-1293.

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

[10] Guay M., D. Dochain and M. Perrier (2004). Adaptive Extremum Seeking Control of Continuous Stirred Tank Bioreactors with Unknown Growth Kinetics. *Automatica*, 40, 881-888.

[11] Guay M., D. Dochain and M. Perrier (2005). Adaptive extremum seeking control of nonisothermal *CSTR. Chem. Eng. Science*, 60(13), 3671-3681.

[12] Guay M., D. Dochain, M. Perrier and N. Hudon (2007). Flatness-Based Extremum Seeking Control Over Periodic Orbits. IEEE Trans. Aut. Control, 52 (10), 2005-2012.

[13] Hudon N., M. Perrier, M. Guay and D. Dochain (2004). Adaptive Extremum Seeking Control of a Non-Isothermal Tubular Reactor With Unknown Kinetics. *Comp. Chem. Eng.*, 29 (4), 839-849.

[14] Hudon N., M. Guay, M. Perrier and D. Dochain (2008). Adaptive Extremum-Seeking Control of Convection-Reaction Distributed Reactor with Limited Actuation. To appear in *Comp. Chem. Eng.*.

[15] Ioannou P. A. and J. Sun (1996). *Robust Adaptive Control,* Englewood Cliffs, NJ: Prentice-Hall.

[16] Khalil H.K. (2002). *Nonlinear Systems.* Prentice-Hall, Upper Saddle River, NJ.

[17] Krstic M., I. Kanellakopoulos, and P. Kokotovic (1995). *Nonlinear and Adaptive Control Design,* New York: Wiley and Sons.

[18] Krstic M. (2000). Performance Improvement and Limitation in Extremum Seeking Control. *Systems & Control Letters*, 39 (5), 313-326.

[19] Krstic M. and H.H. Wang (2000). Stability of Extremum Seeking Feedback for General Dynamic Systems. *Automatica*, 36 (4), 595-601.

[20] Landau Y. D. (1979) *Adaptive Control*, New York: Marcel Dekker.

[21] Leblanc M. (1922). Sur l'életrification des chemins de fer au moyen de courants alternatifs de fréquence élevée. *Revue Générale de l'Electricité.*

[22] Marcos N., M. Guay, D. Dochain and T. Zhang (2003). Adaptive extremum seeking control of a continuous bioreactor. *J. Proc. Control*, 14 (3), 317-328.

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

[23] Marcos N., M. Guay and D. Dochain (2004). Output feedback adaptive extremum seeking control of a continuous stirred tank bioreactor with Monods kinetics. *J. Proc. Control*, Special issue on Dynamics, Monitoring, Control and Optimization of Biological Systems, 14(7), 807-818.

[24] Marlin T.E. and A.N. Hrymak (1997). Real-time operations optimization of continuous processes. In *5th Int. Conf. Chemical Process Control*, J.C. Kantor, C. Garcia & B. Carnahan (Eds.), AIChE Symp. Series 316, Vol. 93, 156-164.

[25] Morari M. , G. Stephanopoulos and Y. Arkun (1980). Studies in the synthesis of control structures for chemical processes. Part I: Formulation of the problem. Process decomposition and the classification of the control task. Analysis of the optimizing control structures. *AIChE J.*, 26(2), 220-232.

[26] Sanner R.M. and J.J. E. Slotine (1992). Gaussian networks for direct adaptive control. *EEE Trans. Neural Networks*, 3(6), 837-863.

[27] Seshagiri S. and H.K. Khalil (2000). Output feedback control of nonlinear systems using RBF neural networks. *IEEE Trans. Neural Networks*, 11(1),69-79.

[28] Sternby J. (1980). Extremum control systems: An area for adaptive control?" Preprints of the *Joint American Control Conference,* San Fancisco, CA, WA2-A.

[29] Skogestad S. (2000). Plantwide control: the search for the self-optimizing control structure. *J. Proc. Control*, 10, 487-507.

[30] Titica M., D. Dochain and M. Guay (2003). Adaptive extremum seeking control of fedbatch bioreactors. *Eur. J. Control*, 9(6), 618-631.

[31] Titica M., D. Dochain and M. Guay (2003). Real-time Optimisation of fedbatch bioreactors via adaptive extremum seeking control. *Chem. Eng. Res. Des.*, 81 (A9): 1289-1295.

[32] Vasu G. (1957). Experiments with optimizing controls applied to rapid control of engine presses with high amplitude noise signals. *Trans. ASME,* 481-488.

[33] Wang H.H., S. Yeung and M. Krstic (1998). Experimental Application of Extremum Seeking on an Axial Flow Compressor. *Proc. ACC*,1989-1993.

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.

[34] Wang H.H., M. Krstic and G. Bastin (1999). Optimizing bioreactors by extremum seeking. *Int. J. Adaptive Control & Signal Processing*, 13(8),651-669.

[35] Wittenmark B. and J. Evans (2001). Extremal control of Wiener model processes. *Dept Aut. Control, Lund Inst. Technol., Int. rep.*, ISRN LUTFD2 TFRT7599SE.

[36] Yaodong P., U. Ozguner U and T. Acarman (2003). Stability and performance improvement of extremum seeking control with sliding mode. *Int. J. Control*, 76(9-10), 968–985.

[37] Zhang Y., D. Monder and J.F. Forbes (2002). Real-time optimization under parametric uncertainty: A probability constrained approach. *J. Proc. Control*,12(3), 373-389.

[38] Zhang T., M. Guay and D. Dochain (2003). Adaptive extremum seeking control of continuous stirred tank bioreactors. *AIChE J.*, 49 (1), 113-123.

Preprint submitted to 2010 American Control Conference.
Received September 22, 2009.