Recent Advances in Extremum Seeking Control and its Applications

Names and Affiliations of Speakers

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Abstract

Extremum seeking control (ESC) is a real time optimization method for steady-state optimization of engineered systems. It is an enabling technology that is used in a range of important engineering applications; ranging from power generation, to environmental monitoring and economics.
The main objective of this tutorial is to present the recent advances in the ESC, covering both theoretical developments as well as applications for a broad audience of interested control engineers. A number of ongoing research directions will be touched upon.

Intended Audience

The expected audience includes engineers, scientists, postgraduate students, and academics; not necessarily familiar with ESC, as the basic principles will be covered.

Description

Design of engineered systems whose operation is in some sense optimal is increasingly important due to the range of socio-economic and environmental problems we are facing at the dawn of the 21st century. Increased demand for energy and other limited resources, climate change and an increased competition in the global market exert pressure on engineered systems to be more efficient, cheaper, and cleaner and of better overall quality than existing systems. Optimal control engineering is an enabling technology that provides methods for the systematic design of engineered systems that exhibit optimal behaviour, such as maximal productivity, best efficiency, minimal cost and best quality.

While still attracting considerable research attention, optimal control methods can be regarded as classical and in certain areas, such as linear quadratic control, they are very well developed and understood. An underlying assumption in the classical control literature is that both the plant model and the cost to optimize are known to the engineer designing the system. However, many engineering systems do not satisfy this basic assumption and, hence, classical optimization methods are often not directly applicable.

Extremum seeking control (ESC) is an optimal control approach that deals with situations when the plant model and/or the cost to optimize are not available to the designer but the plant input and output signals may be measured. Using only these available signals, an extremum seeking controller

dynamically searches for the optimizing inputs in real time. The modern idea of extremum seeking dates back to the 1950s. However, a deep understanding of the behaviour of extremum seeking systems, and design guidelines required significant research and development work. Major breakthroughs were made just in the last two decades.

Engineers have implemented ESC in biochemical reactors, in automotive brakes, variable cam timing, electromechanical valves, axial compressors, mobile robots, mobile sensor networks, optical fibre amplifiers, the Frascati Tokamak Upgrade, bluff-body drag reduction, human exercise machines, tidal energy harvesting and thermoacoustic instability. All these applications indicate the power of ESC as a paradigm and its power to address real applications.

Outline

This tutorial will consist of 3 sessions (6 hours altogether)

Session 1 (50 mins): Introductory Session (by Prof. Iven Mareels)
The Introduction Session focuses on the basic principles of ESC, in particularly the adaptive ESC. A simplest possible ESC will be presented into details. The attendee will come to understand

- The basic problem formulation of ESC;
- The link of ESC to optimization algorithms;
- The performance of ESC;
- The design trade-off of ESC;

Session 2 (100mins) – Overview of Recent Theoretic Developments
Session 2a (50 mins) Deterministic Systems (by Professor Dragan Nešić)
This section introduces some recent developed frameworks which make systematic analysis and design of ESC possible. These frameworks include

- A unifying framework of adaptive ESC based on estimation of derivatives;
- A systematic approach to ESC based on parameter estimation;
- A global sampled-data based ESC framework.

With the knowledge of these design frameworks, it is possible to combine an algorithm from a large class of discrete or continuous (on-line) optimization algorithms with appropriate estimators to design various ESCs. This provides a much needed design flexibility as the designer can tailor the ESC to the problem at hand.
Session 2b (50 mins) Stochastic Systems (by Professor Miroslav Krstic)
Stochastic ES is inspired by the stochastic gradient estimation that bacteria employ when seeking nutrients (chemotaxis). The following topics will be covered:

- Stochastic averaging for analyzing stability of stochastic ES algorithms
- Gradient-based stochastic ES
- Non-cooperative games with stochastic ES
- Newton-based stochastic ES
- Source seeking for mobile robots using stochastic ES

Session 3 (200 mins) Implementation issues and Applications

1) (50min) Applications tuning and implementation of ESC (by Professor Martin Guay)
2) (50 min) Anti-windup ESC (by Dr. Ying Tan)
3) (50 min) Applications of ESC in Automobile industry (Associate Professor Chris Manzie)
4) (50min) Applications of ESC in Robotic System (Dr. Nicholas R. Gans).

This section will introduce real world examples that motivate the need for extremum seeking solutions, and discuss aspects of practical application of extremum seeking.

We will have half an hour for dialogue, diagnosis and brainstorm thinking. Attendees are encouraged to bring and present for discussion, their own research experience, and problems encountered in applying ESC to various applications.

The attendees will find course slides and annotated bibliography on the conference website.

Bio-sketches:

BIOGRAPHY of Professor Iven Mareels

Iven Mareels is Professor of Electrical and Electronic Engineering and Dean of the Melbourne School of Engineering. He is a leading expert in the area of control engineering, with seminal contributions to adaptive control and ESC. Professor Mareels is a Vice-President of the International Federation of Automatic Control (IFAC) and Chair of the IFAC Technical Board (2008-2014). He is a Fellow of the IEEE, Fellow of the Australian Academy of Technological Sciences and a Fellow of the Flemish Royal Belgian Academy of Sciences and Humanities. He was the Chair of the National Committee for Automation Control and Instrumentation, Engineers Australia, (2004 - 2009), and Chair of the Australian Research Council College of Experts for Mathematics, Information and Communication Sciences, 2002 - 2004. Iven Mareels has published 5 books, 120 journal publications, 16 book chapters and 230 conference publications. He holds 15 international patents.

BIOGRAPHY of Professor Dragan Nešić

Dragan Nešić is a Professor in the Department of Electrical and Electronic Engineering (DEEE) at The University of Melbourne, Australia. He received his B.E. degree in Mechanical Engineering from The University of Belgrade, Yugoslavia, in 1990, and his Ph.D. degree from Systems Engineering, RSISE, Australian National University, Canberra, Australia, in 1997. Since February 1999 he has been with The University of Melbourne. His research interests include networked control systems, discrete-time, sampled-data and continuous-time nonlinear control systems, input-to-state stability, extremum seeking control, applications of symbolic computation in control theory, hybrid control systems, and so on. He was awarded a Humboldt Research Fellowship (2003) by the Alexander von Humboldt Foundation, an Australian Professorial Fellowship (2004–2009) and Future Fellowship (2010–2014) by the Australian Research Council. He is a Fellow of IEEE and a Fellow of IEAust. He is currently a Distinguished Lecturer of CSS, IEEE (2008–). He served as an Associate Editor for the journals Automatica, IEEE Transactions on Automatic Control, Systems and Control Letters and European Journal of Control.

BIOGRAPHY of Dr. Ying Tan

Dr. Ying Tan received her Bachelor from Tianjin University, China in 1995. In 1998, she joined the National University of Singapore and finished her PhD study in 2002. She joined McMaster University in 2002 as a postdoctoral fellow in the Department of Chemical Engineering. She has started her work in the Department of Electrical and Electronic Engineering, the University of Melbourne since 2004. Currently Dr. Ying Tan is Future Fellow (2010--2013), which is a research position funded by the Australian Research Council. Her research interests are in intelligent systems, nonlinear control systems, extremum seeking control, sampled-data distributed parameter systems and formation control. Dr. Ying Tan is IEEE Senior member and a Steering Committee member of the Asian Control Association (ACA).

BIOGRAPHY of Associate Prof. Chris Manzie

Chris Manzie received the B.S. degree in physics and the B.E. degree (with honours) in electrical and electronic engineering and the Ph.D. degree from the University of Melbourne, Melbourne, Australia, in 1996 and 2001, respectively. Since 2003, he has been affiliated with the Department of Mechanical Engineering, University of Melbourne, where he is currently an Associate Professor and an Australian Research Council Future Fellow. He was a Visiting Scholar with the University of

California, San Diego in 2007, and a Visiteur Scientifique at IFP Energies Nouvelles, Paris in 2012. He has industry collaborations with companies including Ford Australia, BAE Systems, ANCA Motion and Virtual Sailing. His research interests lie in applications of model-based and extremum-seeking control in fields including mechatronics and energy systems. Associate Professor Manzie is a member of the IEEE and IFAC Technical Committees on Automotive Control.

BIOGRAPHY of Professor Miroslav Krstic

Miroslav Krstic holds the Daniel L. Alspach endowed chair and is the founding director of the Cymer Center for Control Systems and Dynamics at UC San Diego. He also serves as Associate Vice Chancellor for Research at UCSD. Krstic is a recipient of the PECASE, NSF Career, and ONR Young Investigator Awards, as well as the Axelby and Schuck Paper Prizes. Krstic was the first recipient of the UCSD Research Award in the area of engineering (immediately following the Nobel laureate in Chemistry Roger Tsien) and has held the Russell Severance Springer Distinguished Visiting Professorship at UC Berkeley and the Distinguished Visiting Professorship of the Royal Academy of Engineering. He is a Fellow of IEEE and IFAC and serves as Senior Editor in IEEE Transactions on Automatic Control and Automatica. He has served as Vice President of the IEEE Control Systems Society and chair of the IEEE CSS Fellow Committee. Krstic has co-authored ten books on adaptive, nonlinear, and stochastic control, extremum seeking, and control of PDE and delay systems.

BIOGRAPHY of Professor Martin Guay

Martin Guay received his Ph.D. in Chemical Engineering from Queen's University in Kingston, Ontario, Canada. He is currently an associate professor in the Department of Chemical Engineering at Queen's University. His research interests are in nonlinear control theory, particularly in the areas of differential geometric control, constructive controller design of nonlinear systems and hybrid systems. Current research is focused on hybrid systems control, adaptive learning control and extremum-seeking control

BIOGRAPHY of Dr. Nicholas Gans

Dr. Gans is an Assistant Professor at The University of Texas at Dallas. His research interests include nonlinear and adaptive control, with focus on vision-based control and estimation, robotics and autonomous vehicles. Current research includes control of self-optimizing autonomous sensors to maximize sensor information, human-machine interfaces, vision-based control of autonomous ground and air vehicles, and use of novel vision sensors such as thermal and range cameras. Dr. Gans has published over forty peer-reviewed conference and journal papers, and he holds two patents in these areas. Dr. Gans earned his M.S. in electrical and computer engineering and his Ph.D. in systems and entrepreneurial engineering from the University of Illinois at Urbana-Champaign in December 2005. Prior to joining UT Dallas, he worked as a postdoctoral researcher with the Mechanical and Aerospace Engineering Department at the University of Florida and as a postdoctoral associate with the National Research Council, where he conducted research on control of autonomous aircraft for the Air Force Research Laboratory Munitions Directorate and developed the Visualization Laboratory for simulation of vision-based control systems.