

Into the Second Century of Extremum Seeking Control

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GRAPHIC CREATED FROM AUTHOR-GENERATED ARTWORK USING OPENAI CHATGPT. FOR IMAGE CREDITS, PLEASE SEE THE "ACKNOWLEDGMENT" SECTION OF THIS ARTICLE.

The early promise of extremum seeking control (ESC) was alarmingly simple: perturb, observe, and adjust. Yet, behind this simplicity lay a subtle question that would occupy the community for decades: *Why does it work?* The emergence of rigorous stability and convergence proofs around the turn of

the millennium transformed ESC from an ingenious trick into a reliable method. With that transformation came confidence, and with confidence came adoption. Today, ESC is deployed across chip manufacturing, wind and photovoltaic energy systems, mobile robotics, bioengineering, acoustic control, noncooperative games, neuromuscular electrical stimulation, biological reactors, oil drilling, additive manufacturing, and traffic flow optimization for urban mobility, among many others.

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In an era captivated by machine learning, ESC reminds us that learning, optimization, and stability need not be traded off against one another.

What distinguishes ESC from many contemporary data-driven and learning-based approaches is not merely its model-free character but the nature of its guarantees. ESC does not rely on large offline datasets nor does it defer performance assurances until after extensive retraining. Instead, it operates online, in a closed loop, and comes equipped with quantifiable convergence and robustness properties that speak directly to the language of control. In an era captivated by machine learning, ESC reminds us that learning, optimization, and stability need not be traded off against one another.

Recent years have witnessed an acceleration of theoretical and practical developments that have expanded the scope of ESC far beyond its original formulations. Extensions to systems with delays, infinite-dimensional dynamics governed by partial differential equations, stochastic and nonsmooth dynamics, and hybrid architectures combining continuous-time physics with discrete-time decision making have opened new territories for real-time model-free optimization. These advances are not incremental; they represent qualitative shifts that position ESC as a central tool for complex cyberphysical systems.

Against this backdrop, the present special issue has an ambitious but deliberately focused goal: to provide the *IEEE Control Systems* readership with a coherent snapshot of high-momentum directions in extremum seeking research and application. Rather than attempting a comprehensive survey—a task that would be both monumental and quickly outdated—we have curated a set of tutorial-style contributions that emphasize insight, perspective, and connection. Our hope is that readers new to ESC will find clear entry points into the field, while experts will discover resonances across theory and practice.

The first two articles in this special issue focus on theory. The first [A1], by Tiago Roux Oliveira, Miroslav Krstić, and Tamer Başar, surveys extremum and Nash equilibrium seeking for systems with delays and partial differential equations, tracing the evolution of ESC from finite-dimensional settings to networks of distributed infinite-dimensional agents. The second [A2], by Jorge I. Poveda and Andrew R. Teel, addresses extremum seeking in hybrid dynamical systems, where continuous-time dynamics intertwine with discrete events, logic, and decision making.

Complementing these theoretical contributions are two application-oriented articles. One [A3], by Mouhacine Benosman, illustrates how ESC has been translated into robust industrial solutions, from electromagnetic brakes to fluid dynamic systems, demonstrating the

method's ability to survive—and thrive—in demanding operational environments. The other [A4], by Alexander Scheinker, explores the emerging synergy between extremum seeking and deep generative learning, showing how ESC can enhance the robustness of machine learning-based controllers for time-varying systems, with particle accelerators providing a compelling case study.

Mirroring the four technical articles, the cover artwork of this special issue follows a Warhol-meets-Kurosawa (Rashomon) rationale: four colorful variations of a single image, symbolizing four distinct perspectives on ESC—different viewpoints on the same underlying idea. In essence, extremum seeking is not about knowing the mountain but about learning how to climb to its peak.

Taken together, the articles in this special issue portray a field that is both mature and restless: mature in its analytical foundations yet restless in its pursuit of new problem classes and technological frontiers. If the first century of extremum seeking was devoted to discovering and justifying its core ideas, the second century promises integration, with hybrid systems, games, infinite-dimensional dynamics, and modern learning architectures.

We hope that this special issue will serve not only as a reference but also as a catalyst. By gathering diverse perspectives in one place, we aim to encourage cross fertilization among communities and inspire new collaborations across disciplines and continents. Extremum seeking began as a practical response to uncertainty. Its future, we believe, lies in embracing complexity without relinquishing the rigor that has brought it this far.

ACKNOWLEDGMENT

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A century after its invention and a quarter century after the first rigorous convergence proofs, ESC stands as one of the most enduring and quietly transformative ideas in control. Born from the practical need to optimize systems whose models are uncertain, incomplete, or altogether unavailable, ESC has matured from heuristic beginnings into a principled framework for real-time optimization of *dynamic* systems. This special issue of *IEEE Control Systems* marks not only a historical milestone but also a turning point: an invitation to look forward, into the second century of extremum seeking.

The emergence of rigorous stability and convergence proofs around the turn of the millennium transformed ESC from an ingenious trick into a reliable method.

They are also grateful for the support of the current and former editors-in-chief, Anuradha Annaswamy and Rodolphe Sepulchre, as well as associate editors Mihailo Jovanovic and Alexandre Bazanella. The opening artwork was generated using ChatGPT. Prompt by Tiago Roux Oliveira: “Provide a mosaic of four images with a goat searching for the peak of a mountain. The aesthetic must follow Andy Warhol’s art style.”

AUTHOR INFORMATION

Tiago Roux Oliveira (tiagoroux@uerj.br) joined the State University of Rio de Janeiro, Rio de Janeiro-RJ 20550-900, Brazil, as an associate professor in the Department of Electronics and Telecommunication Engineering in 2010. In 2014, he was a visiting scholar with the University of California, San Diego, USA. He has published about 300 refereed journal articles, book chapters, and conference papers. In 2017, he was nominated as an affiliate member of the Brazilian Academy of Sciences. He has served as an associate editor on the editorial boards of *IEEE Transactions on Automatic Control*, *IEEE Open Journal of Control Systems*, *IEEE Control Systems Letters*, *Automatica*, and *Systems & Control Letters*, among others. In 2020, he was elected and nominated chair of Technical Committee Adaptive and Learning Systems of the International Federation of Automatic Control for the triennium 2020–2023 (being reelected to the triennium 2023–2026). In 2021, he received the IEEE Transactions on Control Systems Technology Outstanding Paper Award from the IEEE Control Systems Society. In 2022, he was elected president of the Brazilian Society of Automatics for the biennial 2023–2025. He is a coauthor of the book *Extremum Seeking Through Delays and PDEs*, published by the Society for Industrial and Applied Mathematics in 2022. He is a Senior Member of IEEE.

Jorge I. Poveda received dual B.S. degrees in electronics and mechanical engineering from the University of Los Andes, Colombia, as well as the M.S. degree in electrical engineering from the same institution. He then received M.Sc. and Ph.D. degrees in electrical and computer engineering from the University of California (UC), Santa Barbara. He is an associate professor in the Department of Electrical and Computer Engineering at UC San Diego, La Jolla, CA 92093 USA. After receiving the Ph.D. degree, he was a postdoctoral scholar at Harvard University and an assistant professor at the University of Colorado Boulder. He is the recipient of the Computer and Information Science and Engineering Research Initiation Initiative and CAREER Awards from the National Science Foundation, Young Investigator

Awards from the Air Force Office of Scientific Research and Society of Hispanic Professional Engineers, the American Automatic Control Council Donald P. Eckman Award, the CCSD Outstanding Scholar Fellowship and Best Ph.D. Dissertation Awards from UC Santa Barbara, and the UC San Diego Engineering Early Career Faculty Development Award. He has also received several best paper and best paper finalist awards with his students and colleagues, including recognitions from *IEEE Transactions on Control of Network Systems* (2023), the American Control Conference (2024), the IEEE Conference on Decision and Control (2017 and 2021), and the IFAC Conference on Analysis and Design of Hybrid Systems (2024). His group develops foundational frameworks and algorithms for the design, control, and operation of autonomous and cyberphysical systems, with an emphasis on hybrid dynamics, adaptation, game theory, artificial intelligence, and real-time decision making across multiagent engineering, societal, and biological domains.

Martin Guay is a professor in the Department of Chemical Engineering, Queen’s University, Kingston, ON K7L 4V1, Canada. He received the Queen’s University Chancellor Research Award and the Premier Research Excellence Award. He also received the Syncrude Innovation Award and the D. G. Fisher Award from the Canadian Society of Chemical Engineers. In 2011, he received, with Dr. Veronica Adetola, the Best Paper Award (Theory) from *Journal of Process Control* (2008–2011). He is the editor-in-chief of *Journal of Process Control* and a senior editor of *IEEE Control Systems Letters*. He is an associate editor of *Automatica* and *IEEE Transactions on Automatic Control*. He is also a review editor for *Canadian Chemical Engineering Journal*. His research interests include process control, control theory, and applied statistics. He is a Senior Member of IEEE and a fellow of the Chemical Institute of Canada.

APPENDIX: RELATED ARTICLES

- [A1] T. R. Oliveira, M. Krstić, and T. Başar, “Extremum and Nash equilibrium seeking with delays and PDEs: Designs & applications: Into the second century of extremum-seeking control,” *IEEE Control Syst.*, vol. 46, no. 2, pp. 39–87, Apr. 2026, doi: [10.1109/MCS.2025.3647235](https://doi.org/10.1109/MCS.2025.3647235).
- [A2] J. I. Poveda and A. R. Teel, “Hybrid set-seeking systems: Model-free feedback optimization via hybrid inclusions,” *IEEE Control Syst.*, vol. 46, no. 2, pp. 88–129, Apr. 2026, doi: [10.1109/MCS.2025.3646104](https://doi.org/10.1109/MCS.2025.3646104).
- [A3] M. Benosman, “Examples of extremum seeking control in industry: Auto-tuning applications from electromagnetic brakes to fluid dynamics,” *IEEE Control Syst.*, vol. 46, no. 2, pp. 130–149, Apr. 2026, doi: [10.1109/MCS.2025.3646338](https://doi.org/10.1109/MCS.2025.3646338).
- [A4] A. Scheinker, “Adaptive control meets deep learning: Extremum seeking in latent space with particle accelerator applications,” *IEEE Control Syst.*, vol. 46, no. 2, pp. 150–176, Apr. 2026, doi: [10.1109/MCS.2025.3646850](https://doi.org/10.1109/MCS.2025.3646850).

