TIAGO ROUX OLIVEIRA

Q. How did your education and early career lead to your initial and continuing interest in the control field?

***Tiago*:** I began my career on a popular topic in my academic environment in Rio de Janeiro—adaptive and sliding mode control (SMC). I was advised by Prof. Liu Hsu at the Federal University of Rio de Janeiro/Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia, an eminent leader in control theory in Brazil. He was ranked number four in the field of electronics and electrical engineering among top scientists in a national rank for 2022.

Digital Object Identifier 10.1109/MCS.2022.3187356
Date of current version: 15 September 2022

Under his supervision, I completed my master's dissertation and doctoral thesis on the topic of feedback systems with unknown control directions (or unknown high-frequency gains). This was a long-standing problem proposed by Monopoli-Morse in the adaptive control literature and solved a couple of years later by Nussbaum. However, the existing solution did not ensure robustness or guaranteed transient performance. Together with Prof. Liu Hsu, we found an improved solution based on a new switching-based monitoring function associated with the sliding mode framework. After that, the monitoring function ingredient was also successfully tested in the robust adaptive control recipe.

Tiago Roux Oliveira with his beloved wife, Deborah Roux, and his little French bulldogs (Polenguinho and Trufa) at his parents' house in Rio de Janeiro.

Tiago Roux Oliveira and Deborah enjoying one more sunny day at the famous Ipanema Beach in Rio.

Our contributions were not restricted to the theoretical material. In terms of applications, we made experimental tests with visual servoing robotics for unstructured scenarios and connected the unknown control direction problem to another very exciting area: extremum seeking. With this research, I received from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) the National Award for Best Doctoral Thesis in Engineering in 2011.

Our advances started to receive attention from the SMC community. On one occasion, I met Prof. Leonid Fridman for the first time in Mexico City, when he was organizing the 11th International Workshop on Variable Structure Systems (VSS 2010). After that, I had the opportunity to discuss with him several times at different engineering conferences and scientific events we both attended. We have published many papers on adaptive and higher-order SMC schemes since 2015. We were also the guest editors of the *International Journal of Adaptive Control and Signal Processing* for the special issue "From Adaptive Control to Variable Structure Systems—Seeking Harmony."

Since 2016, I have been an elected member of the Technical Committee on Variable Structure and Sliding Mode Control of the IEEE Control Systems Society, of which he was the chair for four years. It is a great pleasure (12 years late!) to share the general chair position with him for a special upcoming event: the 16th International Workshop on Variable Structure Systems and Sliding Mode Control (VSS 2022). This workshop will occur for the first time in Brazil (Rio de Janeiro) on September 11–14, 2022.

At this point, I would like to pause the SMC story and go back to the extremum-seeking link I noted earlier. The concrete realization I had with the mentioned CAPES Award was a fellowship for a visiting scholar position outside Brazil. Eight years ago, I spent one year with Prof. Miroslav Krstic at the University of California (UC), San Diego, one of the foremost experts on extremum seeking and the boundary control of partial differential equations (PDEs). He

suggested a difficult topic: extremum seeking in the presence of large delays. Never before was extremum seeking undertaken in an infinite-dimensional context. With some fortune, I did succeed. Our first result, conceived in San Diego, was our 2017 *IEEE Transactions on Automatic Control* paper, "Extremum Seeking for Static Maps With Delays."

Following this first success, I returned from San Diego to Rio in 2015, and I grasped how many other research hurdles I could topple with such a powerful research machinery. I was emboldened to go after extremum-seeking problems with even bigger challenges, particularly with PDEs and in a multiagent, game-theoretic, model-free optimization context. In fact, as mentioned by Prof. Krstic in his 2017 interview for *IEEE Control Systems*, "Control of delay systems is a small island in a vast PDE ocean."

Recently, I had the opportunity to collaborate with two other eminent figures in our field: Prof. Tamer Basar (an extraordinary leader in game theory from the University of Illinois Urbana-Champaign, United States) and Prof. Emilia Fridman (one of the pioneers on the delayed and sampled-data control of ordinary differential equations and PDEs from Tel Aviv University, Israel). The contributions with both of them in "Nash Seeking for Noncooperative Games Under PDEs" and "Sampled-Data Extremum Seeking With Delays" sprouted from the seeds planted at UC San Diego with Prof. Krstic.

Q. What are some of your research interests?

***Tiago*:** My current research interests are totally oriented to the topic of extremum seeking through delays and PDEs as well as its potential applications. Indeed, this is the title of my recent book, coauthored with Prof. Krstic, which will appear in the prestigious series of the Society for Industrial and Applied Mathematics (SIAM), *Advances in Design and Control*.

For instance, my student Paulo Paz and I achieved one significant result in extremum seeking applications on neuromuscular electrical stimulation for stroke patients. This publication was the winner of the 2021 Outstanding Paper Award of *IEEE Transactions on Control Systems Technology*. We demonstrated this work in a laboratory experimental and clinical setting.

Of course, besides extremum seeking and the boundary control of PDEs, research on nonlinear adaptive control and SMC is still very active in my academic life. Indeed, most of my students are fascinated by the beauty of concepts involving robustness and adaptation. They open avenues for new ideas and serve the needs for future challenges.

I am also very grateful to all of the talented students I have advised. Most of the research objectives that were achieved in this journey were because of their help. I must cite and thank one in particular: Victor Hugo Pereira Rodrigues, for his constant support and desire to learn.

Q. What courses do you teach relating to control? Do you have a favorite course? How would you describe your teaching style?

***Tiago*:** I have taught "Classic Control" and "Digital Control" for undergraduate students. For graduate courses, I have also been teaching a series of control-related courses, such as "Linear Systems," "Computer-Controlled Systems," "Nonlinear Systems," and "Nonlinear Control."

Due to my research and administrative duties, I was forced to choose just two courses per semester. My favorite ones are "Digital Control" and "Nonlinear Systems." In the former, I can keep exploring engineering since I am strongly connected to the laboratory experiments. In the latter, I can exercise my mathematical instincts and skills since it is a more theoretical environment with graduate students.

Q. What are some of the most promising opportunities you see in the control field?

***Tiago*:** My experience as the current chair of the *International Federation of Automatic Control (IFAC) Technical Committee on Adaptive and Learning Systems* leads me to say that I can see many opportunities in this field with extremum seeking. With the explosion of interest in learning algorithms (for all sorts of purposes, including optimization and control), it would be regrettable if it were overlooked that extremum seeking is also a learning-based approach (in the minimalistic, most efficient sense of learning), a model-free approach, and a data-based approach.

Tiago Roux Oliveira with Miroslav Krstic during his stay as a visiting scholar at the University of California, San Diego, La Jolla.

The real-time capabilities as well as the rigorous convergence guarantees and convergence rate assignment capabilities (which extremum seeking possesses) are what machine learning and reinforcement learning algorithms have yet to achieve. It is my hope that some of the researchers and students who are pursuing learning-based capabilities will take note of what this may offer, especially in terms of the possibility of blending model-free learning and optimization with the model-based compensation of physical (and social) processes, such as transport and diffusion.

In addition, my recent accomplishment is not only an extension of extremum seeking to delay and PDE systems. It is also—and conversely—an extension of the control of delay systems and PDEs to extremum seeking. The PDE control community is rapidly growing as a result of the emergence of PDE backstepping, which supplies the user with controllers with explicit gains for PDEs whose levels of open-loop instability are unrestricted. The delay systems community is even larger and has a much longer history. From now on, many of these researchers can deploy their experiences in model-free and online optimization problems through the extremum-seeking approach, suitably integrated with their techniques.

Profile of Tiago Roux Oliveira

- *Current position*: associate professor, State University of Rio de Janeiro.
- *Visiting and research positions*: University of California, San Diego.
- *Contact information*: State University of Rio de Janeiro, Department of Electronics and Telecommunication Engineering, Office 5018E, Rua São Francisco Xavier 524, Rio de Janeiro, RJ 20550-900, Brazil, tiagoroux@uerj.br, https://tiagoroux.com/.
- *Experience highlights*: member roster, Technical Committee on Variable Structure and Sliding Mode Control, IEEE Control Systems Society (2016–2022); affiliate member, Brazilian Academy of Sciences (2017–2021); Board of Directors–Engineering Council, Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) (2018–2022); chair, Technical Committee on Adaptive and Learning Systems, International Federation on Automatic Control (IFAC) (2020–2023); president of the Superior Council, Brazilian Society of Automatics (2021–2023); associate editor and member of the International Program Committee, 13th and 14th IFAC Workshop on Adaptive and Learning Control Systems (ALCOS 2019 and 2022); associate editor of the Conference Editorial Board for the 18th–20th European Control Conferences (ECC 2020–2022); technical associate editor and member of the International Program Committee for the 21st IFAC World Congress (2020); general chair, 16th IEEE International Workshop on Variable Structure Systems and Sliding Mode Control (2022); associate editor, *Journal of The Franklin Institute* (2017–2022); associate editor, *IEEE Latin America Transactions* (2018–2020); associate editor, *International Journal of Robust and Nonlinear Control* (2020–2022); associate editor, *Systems & Control Letters* (2020–2022).
- *Notable awards*: IEEE Transactions on Control Systems Technology Outstanding Paper Award (2021); Rio de Janeiro Researcher Award, FAPERJ (2021); Semiplenary Lecture, Third IFAC Conference on Modeling, Identification and Control of Nonlinear Systems, Tokyo, Japan (2021); Top Downloaded Paper 2018–2019, *Asian Journal of Control*, Wiley (2020); Senior Member of IEEE (2018); Outstanding Reviewer in *Systems & Control Letters*, Elsevier (2018); Outstanding Reviewer in *Expert Systems With Applications*, Elsevier (2017); Readers' Award winner for *International Journal of Control*, 3.579 downloads, Taylor & Francis (2016); Rio de Janeiro Young Researcher Award, FAPERJ (2012, 2015, and 2018); Brazilian PQ Investigator Award, Conselho Nacional de Desenvolvimento Científico e Tecnológico (2013, 2016, and 2019); Best National Doctoral Thesis Award, CAPES (2011).

Q. You are the author of four books in the control field. What topics do these books cover?

***Tiago*:** Two of them are thesis-books related to my findings during my M.Sc. and D.Sc. studies on feedback systems with unknown control directions (in Portuguese):

- T. R. Oliveira, "Tracking Control for Uncertain Systems With Strong Nonlinearities and Unknown Control Direction," D.Sc. thesis, Programa de Pós-Graduação em Engenharia Elétrica, 2010. Available: http://www.pee.ufrj.br/index.php/pt/producao-academica/teses-de-doutorado/2010/2010012501-2010012501/file. This won the Best Doctoral Thesis Award.
- T. R. Oliveira, "Sliding Mode Control of Uncertain Systems with Unknown Control Direction," M.Sc. thesis, Programa de Pós-Graduação em Engenharia Elétrica, 2006. Available: http://www.pee.ufrj.br/index.php/pt/producao-academica/dissertacoes-de-mestrado/2006-1/2006072101-2006072101/file.

The third one is a coedited book, *Sliding-Mode Control and Variable-Structure Systems: The State of the Art* (with L. Fridman and L. Hsu) for the Springer series *Studies in Systems, Decision, and Control*, 2022. The book covers the latest theoretical results and sophisticated applications of SMC and VSS from renowned authors in the field, which include both theoretical results and in-hardware implementations of the algorithms.

The great success of this book is reflected by 20 chapters, all of them presenting the cutting-edge results of diverse groups representing distinct countries around the world. The topics cover new SMC algorithms; observers for state and disturbance estimation; discretization; adaptation; chattering analysis; and engineering applications, from

biological systems to robotics and intelligent transportation. This clear and deep exposition helps readers understand one of the most efficient tools for addressing uncertain systems due to the robustness and insensitivity properties to perturbations of the SMC–VSS methodology.

The most recent one is a research monograph covering the topics of extremum seeking for infinite-dimensional systems: *Extremum Seeking Through Delays and PDEs*. This SIAM book (2022) is coauthored by Prof. Miroslav Krstic. The book begins with systems of infinite dimension, which are arguably the most common in control practice: delays at the input or due to computation (sometimes also referred to as "dead time"). With predictor feedback designs for input delays, we compensate for delays of arbitrary length in extremum-seeking feedback loops and ensure the convergence of the algorithms.

We then extend such results, using PDE backstepping, to various PDEs in the actuation or sensing pathways of unknown input–output maps. Finally, we study the use of delay-compensated and PDE-compensated extremum-seeking algorithms by multiple players in noncooperative game settings and prove that the users of such algorithms are assured that their actions will converge to a Nash equilibrium (namely, to the best possible strategy in the presence of other rational players, even though the players employing extremum-seeking algorithms may not even be aware of the presence of the competing players, let alone know the competing players' actions or payoffs). It is the exhaustive consideration of these three problems and various extensions (such as multivariable maps, dynamical plants, nonconstant and uncertain delays, and distributed delays) that make up the three parts of this book and its approximately 500 pages.

Q. What are some of your interests and activities outside of your professional career?

***Tiago*:** I love traveling, watching soccer, and listening to music. My wife and I make plans to visit all of the countries we can. My favorite kind of music is *música popular Brasileira*, the Brazilian old school. I root for *Vasco da Gama*, my favorite soccer team. I also like to take my dogs for a pleasant walk and love playing beach tennis. The latter entered my life recently, and it was a joyful surprise!

Q. Thank you for your comments.

***Tiago*:** Thank you very much for the opportunity.