Tutorial on time-delay and sampled-data systems

Alexandre Seuret [*] **Emilia Fridman** [**]

[*] *LAAS - CNRS, Université de Toulouse, CNRS, Toulouse, France, e-mail: aseuret@laas.fr*
[**] *Tel Aviv University, Tel Aviv, Israel, e-mail: emilia@eng.tau.ac.il*

Abstract: Time-delay naturally appears in many control systems and applications. It is frequently a source of instability. However, for some systems, the presence of delay can have a stabilizing effect. Therefore, stability and control of time-delay systems is of theoretical and practical importance. Modern control systems usually employ digital technology for controller implementation, i.e. sampled-data control. A time-delay approach to sampled-data control, where the system is modeled as a continuous-time system with the delayed control input became popular in the networked control systems, where the plant and the controller exchange data via communication network. In the present tutorial, introduction to time-delay and sampled-data systems will be given together with some advanced results on the topic.

Keywords: Time-delay systems, sampled-data systems, linear matrix inequality, nonlinear systems, model reduction predictor control.

1. OBJECTIVES OF THE TUTORIAL

The objective of this tutorial is to provide to the attendees an overview of the recent achievements and developments regarding the analysis and control of time-delay systems and sampled-data systems. The stability analysis and control of such classes of systems has attracted many researchers as pointed out in the survey papers Richard (2003); Hespanha et al. (2007); Sipahi et al. (2011); Hetel et al. (2017); Xu and Lam (2008); Gu and Niculescu (2003); Heemels et al. (2012) or monograph Fridman (2014); Niculescu (2001) These classes of systems appears naturally in many applications fields such as in Biology, Traffic control, Engineering among many other. A particular attention is also paid to Networked Control Systems (NCS) where the classical control loop studied in Automatic Control is closed via some communication links. Since these links unavoidably induce delays and samplings, the stability of the resulting networked control systems requires a particular attention.

This tutorial aims at providing a large view of the recent trends in the fields of delayed and sampled data systems. After a general introduction pointing out the various problems appearing when studying these systems, several aspects will be covered by various experts and young researchers.

The problem addresses in this tutorial are concerned with several aspects of the stability analysis of time-delay and sampled-data systems. A first presentation emphasizes the use of integral inequalities and their application to the derivation to Linear Matrix inequalities for time-delay systems. A second aspect is concerned with a survey of various methods to assess stability of sampled-data systems including the input delay approach. Then stability analysis of delayed and sampled-data nonlinear systems using control Lyapunov-Krasovskii functionals will be addressed Pepe (2014, 2016). The problem of model reduction and predictor controller will be also considered. Finally two applications of the previous method to treat stability and control of NCS with on a first hand a robust stability of controller with scheduled protocols and, on a second hand, to event-triggered control, which means that the sampling instants are computed online depending on some particular event.

2. ORGANIZATION

The tutorial consists of two sessions of 2 hours, in which 3 and 4 presentations will be given. The talks and speakers are provided below.

3. DESIRED PREREQUISITE KNOWLEDGE OF THE AUDIENCE

The objectives of this tutorial is to present basics as well as recent achievements to the fields of time-delay and sampled-data systems. The presentations require basic knowledge on (delay) differential equations, Lyapunov functions and functionals, and Linear Matrix inequalities.

The objectives of this tutorial are to provide to the attendees the basic knowledge to address stability and control problems related to delay and sampled-data systems. Through the proposed lectures, the speakers will present both basic concepts of the fields as well as some recent advances.

4. DESCRIPTION OF THE PRESENTATIONS AND TIME-TABLE

This tutorial is scheduled on Sunday, the 9th of July, from 9:00 to 12:30. The presentations of this tutorial are scheduled as follows.

09:00-09/30 : General introduction to time-delay and sampled-data systems
by *Emilia Fridman*, University of Tel Aviv, Israel.
Emilia Fridman received the M.Sc. degree from Kuibyshev State University, USSR, in 1981 and the Ph.D. degree from Voronezh State University, USSR, in 1986, all in mathematics. From 1986 to 1992 she was an Assistant and Associate Professor in the Department of Mathematics at Kuibyshev Institute of Railway Engineers, USSR. Since 1993 she has been at Tel-Aviv University, where she is currently Professor of Electrical Engineering Systems. She is the author of the monograph 'Introduction to Time-Delay Systems: Analysis and Control' (Birkhauser, 2014). In 2014 she was Nominated as a Highly Cited Researcher by Thomson ISI. She serves/served as Associate Editor in Automatica, SIAM Journal on Control and Optimization and IMA Journal of Mathematical Control and Information.
Her research interests include time-delay systems, networked control systems, distributed parameter systems, robust control and singular perturbations. She has published more than 100 articles in international scientific journals.

09:30-10:00 : Advances methods for time-delay systems
by *Alexandre Seuret*, LAAS - CNRS, Toulouse, France.
A. Seuret was born in 1980, in France. He earned the Engineer's degree from the 'Ecole Centrale de Lille' (Lille, France) and the Master's Degree from the University of Science and Technology of Lille (France) in 2003. He received the Ph.D. degree in Automatic Control from the 'Ecole Centrale de Lille' and the University of Science and Technology of Lille in 2006. From 2006 to 2008, he held one-year postdoctoral positions at the University of Leicester (UK) and the Royal Institute of Technology (KTH, Stockholm, Sweden). From 2008 to 2012, he was a junior CNRS researcher (Chargé de Recherche) at GIPSA-Lab in Grenoble, France. Since 2012, he has been with the 'Laboratoire d'Architecture et d'analyse des Systèmes' (LAAS), in Toulouse, France as a junior CNRS researcher. He serves as associate editor for the International Journal of Control and for the Conference on Decision and Control and the American Control Conference as a member of the CSS editorial board. He is also a member of the technical committee TC.1.5 on Networked Control Systems in IFAC.
His research interests include time-delay systems, networked control systems and multi-agent systems.

10:00-10:30 : Survey on Sampled-data systems
by *Laurentiu Hetel*, CRIStAL - CNRS, Lille, France.
Laurentiu Hetel is a Researcher (Chargé de Recherche) at the Centre National de la Recherche Scientifique (CNRS). He works with CRIStAL (UMR CNRS 9189), Lille, France. He received the PhD Degree in Automatic Control from the Institut National Polytechnique de Lorraine, Nancy University, France, in 2007. He was a postdoctoral fellow at the Eindhoven University of Technology (April to October 2008). His research interests are in hybrid dynamical systems and sampled-data control. He is currently an Associate Editor for Systems and Control Letters.
His major Interests are related to Hybrid Systems, Sampled - data control and Networked or Embedded Control Systems.

10:30-10:50 : Break

10:50-11:20 : Nonlinear time-delay and sampled-data systems
by *Pierdomenico Pepe*, Univeristà degli studi dell'Aquila, Italy.
Pierdomenico Pepe was born in 1965 in Sant'Omero, in 1990 received the Laurea in Electronic Engineering summa cum laude from the University of Ancona, and in 1996 received the Ph.D. in Electronic Engineering from the University of L'Aquila, Italy. He served in 1991-1992 as second lieutenant in the Technical Corp of the Italian Army, Rome, in 1992-1993 as a member of the Technical and Scientific Division of Roland DG, Martinsicuro, in 1997-2000 as the Technician in the Laboratory of Automatics and Robotics, and in 2001-2013 as tenured assistant professor, at the University of L'Aquila, where he is currently serving as associate professor. In 2000, 2001 and 2004 he held one-semester visiting scholar positions at the University of California, Berkeley, at the Georgia Institute of Technology, Atlanta, and at the Polytechnic University, New York, respectively. He has authored or co-authored over 140 technical papers and is co-editor of a book in the Springer series LNCIS and a book in Springer series ADD. In 2006 he was Chairman and co-Editor of the 6th IFAC Workshop on Time-Delay Systems, held in L'Aquila. He has served as IPC member in several IFAC and IEEE international conferences. He served as AE in the IEEE Transactions on Automatic Control (2011-2014), and is currently serving as AE in Systems & Control Letters, SIAM Journal on Control and Optimization,Taylor & Francis Journal on Control and Decision.
His main research interests include stability theory, nonlinear control, observers, optimal control, with special emphasis to systems with time-delays, and applications to biomedical, chemical, electrical and mechanical engineering.

11:20-11:50 : Model reduction and predictor control
by *Frédéric Mazenc*, Inria Disco, L2S France.
Frédéric Mazenc received his Ph.D. in Automatic Control and Mathematics from the CAS at Ecole des Mines de Paris in 1996. He was a Postdoctoral Fellow at CESAME at the University of Louvain in 1997. From 1998 to 1999, he was a Postdoctoral Fellow at the Centre for Process Systems Engineering at Imperial College. He was a CR at INRIA Lorraine from October 1999 to January 2004. From 2004 to 2009, he was a CR1 at INRIA Sophia-Antipolis. From 2010, he was a CR1 at INRIA Saclay. He received a best paper award from the IEEE Transactions on Control Systems Technology at the 2006 IEEE Conference on Decision and Control.

His current research interests include nonlinear control theory, differential equations with delay, robust control, and microbial ecology. He has more than 200 peer reviewed publications. Together with Michael Malisoff, he authored a research monograph entitled 'Constructions of Strict Lyapunov Functions in the Springer Communications and Control Engineering Series'. Currently he serves as Associate Editor in IEEE Transactions on Automatic Control, European Journal of Control, the Asian Journal of Control, the Journal of Control and Decision and Mathematical Control and Related Fields.

11:50-12:10 : A time-delay approach to Networked Control Systems (20min)
by *Kun Liu*, Beijing Institute of Technology, China.
Kun Liu received the M.Sc. degree in Operational Research and Cybernetics from University of Science and Technology Beijing, China, in 2007. He received PhD in 2012 in the Department of Electrical Engineering and Systems at Tel-Aviv University, Israel, and was post-doc in KTH, Stockholm, Sweden from 2012 to 2014. Since 2015 he is associate professor at BIT, Beijing, China.
His research interests include time-delay systems and networked control systems.

12:10-12:30 : Event-triggered control for systems driven by delayed and Partial differential equations (20min)
by *Anton Selivanov*, University of Tel Aviv, Israel.
Anton Selivanov received the M.Sc. degree in 2011 (summa cum laude) and the Ph.D. degree in 2014, both in math and both from St. Petersburg State University, Russia. Currently he is a Postdoctoral Fellow at the School of Electrical Engineering, Tel Aviv University, Israel.
His research interests include adaptive control, event-triggered control, distributed parameter systems, and time-delay systems.

REFERENCES

Fridman, E. (2014). *Introduction to time-delay systems: Analysis and control*. Springer.

Gu, K. and Niculescu, S.I. (2003). Survey on recent results in the stability and control of time-delay systems. *Journal of Dynamic Systems, Measurement, and Control*, 125(2), 158–165.

Heemels, W., Johansson, K., and Tabuada, P. (2012). An introduction to event-triggered and self-triggered control. In *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, 3270–3285. IEEE.

Hespanha, J., Naghshtabrizi, P., and Xu, Y. (2007). A survey of recent results in networked control systems. *Proceedings of the IEEE*, 95(1), 138–162.

Hetel, L., Fiter, C., Omran, H., Seuret, A., Fridman, E., Richard, J.P., and Niculescu, S.I. (2017). Recent developments on the stability of systems with aperiodic sampling: an overview. *to appear in Automatica*.

Niculescu, S.I. (2001). *Delay Effects on Stability. A Robust Control Approach*. Springer-Verlag.

Pepe, P. (2014). Stabilization in the sample-and-hold sense of nonlinear retarded systems. *SIAM Journal on Control and Optimization*, 52(5), 3053–3077.

Pepe, P. (2016). On stability preservation under sampling and approximation of feedbacks for retarded systems. *SIAM Journal on Control and Optimization*, 54(4), 1895–1918.

Richard, J.P. (2003). Time delay systems: an overview of some recent advances and open problems. *Automatica*, 39, 1667–1694.

Sipahi, R., Niculescu, S., Abdallah, C., Michiels, W., and Gu, K. (2011). Stability and stabilization of systems with time delay. *Control Systems, IEEE*, 31(1), 38 –65.

Xu, S. and Lam, J. (2008). A survey of linear matrix inequality techniques in stability analysis of delay systems. *International Journal of Systems Science*, 39(12), 1095–1113.