2013 EUROPEAN CONTROL CONFERENCE, ZURICH, SWITZERLAND

WORKSHOP ON
TIME DELAY SYSTEMS – Stability & Control in Applications
July 16, 2013 – 9.00 am – 5.30 pm

Lecturers:

- Fatihcan M. Atay, GERMANY – fatay at mis.mpg.de
- Dimitri Breda, ITALY - dimitri.breda at uniud.it
- Wim Michiels, BELGIUM - Wim.Michiels at cs.kuleuven.be
- Silviu-Iulian Niculescu, FRANCE – Silviu.NICULESCU at lss.supelec.fr
- Hitay Ozbay, TURKEY – hitay at bilkent.edu.tr
- Rifat Sipahi, USA – rifat at coe.neu.edu

Synopsis: Time delays are ubiquitous in dynamical systems around us, as found in mechatronics systems, energy management systems, traffic flow dynamics, tele-operation and remote control systems, synchronization of agent-based dynamics, population dynamics, HIV infection dynamics, financial investment and stock trading strategies, and supply chain management. Delays bring about significant effects on the evolution of such systems, causing instability, poor performance, and limitation on the ability to control, which ultimately result in poorly functioning and inefficient dynamical behavior. On the other hand, there are also situations where delays have beneficial effects and can be used as controller parameters.

In this one day workshop, the lecturers will cover both the theory and relevant applications, starting from the fundamentals and developing toward complex problems. Discussions include stability theory, stabilization, delay-dependent and delay-independent stability, structured control design, utilization of advanced numerical tools, spectrum calculations, H infinity control, existing capabilities, limitations and open research problems. Application examples in particular include network systems, biological systems, engineering problems, resource-competition dynamics, and supply chains.

Lecture Format and Audience: The lecturers will utilize fundamentals tools, such as eigenvalue problems, state space representations, root locus, frequency domain analysis and control design, from classical and modern control theory, to present the workshop materials. The lecturers will mainly focus on Linear Time-Invariant Time Delay Systems, and will use PowerPoint slides as well as Matlab demonstrations via projector to deliver their lectures. The audience is welcome to bring their laptops to actively participate. Lecturers will also provide hand outs to the audience regarding presentation material as well as key references. Demo files will be available for upload after the workshop.

Registration & Policies: Attendance to the Workshop is limited to ECC 2013 participants.

Student registration: CHF 50
Full registration: CHF 150

Details about the workshop can be downloaded from www.coe.neu.edu/~rifat

For any questions regarding the Workshop coverage, please contact the lecturers via email.

In case a web link listed above does not work, please copy and paste it in your browser address line.
SCHEDULE

Part 1: 9.00 am – 10.30 am
Stability Theory of Time Delay Systems and Applications from Engineering to Biology
S.-I. Niculescu & W. Michiels

Coffee Break (10.30 am – 11.00 am)

Part 2: 11.00 am – 12.20 pm
Cooperative Dynamics on Networks with Time Delays
F.M. Atay

LUNCH 12.30 pm – 1.20 pm

Part 3: 1.30 pm – 3.00 pm
Delays in Control Loops: Analysis and Optimization-based Control Design
W. Michiels

Delay-Dependent & Delay-Independent Stability in Connection with Algebraic Tools
R. Sipahi

Coffee Break (3.00 pm– 3.30 pm)

Part 4: 3.30 pm – 5.30 pm
Computational Methods for H-infinity Control of Time Delay Systems
H. Ozbay

From Delay Differential Equations to Ordinary Differential Equations
D. Breda
DETAILS on WORKSHOP COVERAGE

In this Workshop, the instructors will primarily concentrate on Linear Time-Invariant Time Delay Systems in connection with illustrative examples. The coverage will link delays to various applications, approaches and methodologies, also showing the rationale behind how mathematical models are derived, for what reasons delays arise, and how mathematically one models various delay effects, all within a unified “frequency domain analysis” framework, while discussing stability, practical ways of designing effective controllers, delay effects on network systems, and demonstrating the techniques to convert PDEs to delay systems, to convert delay differential equations to ODEs, how one utilizes existing numerical packages to perform stability analysis and control design, as well as the capabilities and limitations in numerical analysis.

Focusing on LTI systems will also allow a practical way of communicating with the audience who are expected to have background in eigenvalue concepts, poles/zeros, stability theory, frequency response, complex analysis, and state space.

The workshop program is planned as follows (please see abstracts below for further details):

**Part 1 by S.-I. Niculescu & W. Michiels – (9.00 am – 10.30 am):** This part will be primarily summarized from the article “Stability and Stabilization of Systems with Time Delay, Limitations and Opportunities” (IEEE Control System Magazine, 2011, by R. Sipahi, S.-I. Niculescu, C.T. Abdallah, W. Michiels, K. Gu) and the book “Stability and stabilization of time-delay systems. An eigenvalue based approach” (Advances in Design and Control, vol. 12, SIAM Publications, 2007, by W. Michiels & S.-I. Niculescu), introducing the problem and relevant applications from various fields. The instructors will discuss the underlying stability theory and the arising eigenvalue problems; show step-by-step the derivations of mathematical models and incorporation of delays into models; and present the essence of stability analysis from simpler to more complicated problems. Authors will also discuss NP hard nature of the stability analysis, and overview the principles of existing Matlab-based computational techniques.

**Coffee Break (10.30 am – 11.00 am)**

**Part 2 by F.M. Atay – (11.00 am – 12.20 pm):** This part is dedicated to understanding the effects of networks and the behavior of coupled dynamical systems that communicate under delays. Delays, network behavior, and stability become intertwined in such settings, all three parameters affecting each other. The instructor will primarily discuss cooperative dynamics on networks, with examples from traffic flow dynamics, and consensus of autonomous agents. Particular attention will be given to the relationship of stability theory and the respective graph by which interaction patterns among dynamical systems is described, while considering both discrete-type and distributed-type delay models.

**LUNCH 12.30 – 1.20 pm**

**Part 3 by W. Michiels & R. Sipahi – (1.30 pm – 3 pm):** In this part, the instructors will discuss the ability to control and how presence of delay in control loop adds limitations to control design, including maximum achievable delay margin, optimization-based control, predictor design, low-order controllers, and the principles of solving associated nonlinear eigenvalue problems for designing structured controllers. Instructors will also present recent results on designing controllers for creating closed-loop systems that are delay-independent stable, and discuss computational issues, and some inherent limitations in computational approaches, summarizing primarily from the book “Stability and stabilization of time-delay systems. An eigenvalue based approach” (Advances in Design and Control 12, SIAM Publications, Philadelphia, 2007, by W. Michiels & S.-I. Niculescu), and the article “Delay-Independent Stability Test for Systems with Multiple Time Delays” (IEEE Transactions on Automatic Control, 57(4), 2012, by I.I. Delice & R. Sipahi).

**Coffee Break (3 – 3.30 pm)**

**Part 4 by H. Ozbay & D. Breda – (3.30 pm – 5.30 pm):** In this part, the instructors will present H-infinity control design techniques for various classes of time delay systems, demonstrating controller
implementation in different feedback connections, and discussing efficient numerical implementation of the control design. Moreover, from numerical perspective, the instructors will discuss techniques and the underlying mathematics to discretize delay-differential equations, converting them to ordinary differential equations, without losing the essence of the stability of the original problem. These techniques, which are especially important for stability and control design of delay systems, are presented over several examples, and limitations in computational approaches are highlighted.

Cooperative Dynamics on Networks with Time Delays
Fatihcan M. Atay
Max Planck Institute for Mathematics in the Sciences, Leipzig, GERMANY

This talk will focus on a class of closely related problems arising in coupled networks of dynamical systems, where the information flow is subject to time delays. Examples include the stability of traffic flows, synchronization of coupled oscillators, and consensus problems in networks of autonomous agents, among others. The spatial structure naturally invites notions from graph theory into the analysis of the dynamical behavior. We will discuss the effects of graph structure and time delays on the dynamics. The differences between information transmission delays and information processing delays will be emphasized and discrete as well as distributed delays will be considered.

From Delay Differential Equations to Ordinary Differential Equations
Dimitri Breda
University of Udine, Udine, ITALY

Differential equations with delay in time identify dynamical systems on an infinite-dimensional state space. Numerical methods developed to either approximate solutions or detect stability of equilibria and cycles represent, soon or later, a form of reduction to finite dimension, read ordinary differential equations. We are interested in analyzing the dynamical implications of this discretization when pseudospectral methods are applied to nonlinear problems, focusing on the step from infinite to finite rather than on its later use. We will particularly look at example cases coming from population dynamics that can be modeled as delay integro-differential systems, as found for instance in resource-consumer dynamics and cannibalism.

Delays in Control Loops: Analysis and Optimization-based Control Design
Wim Michiels
Department of Computer Science, K.U. Leuven, Leuven, BELGIUM

In the first part of the talk the qualitative effects of delays in control loops are briefly discussed. Not only limitations induced by delays are addressed, including fundamental limitations, but also opportunities to use delays in the construction of controllers. The latter include the use of delays to generate predictions and to stabilize predictors, time-delayed feedback, stabilizing oscillatory systems by means of phase synchronization, and the use of delays to approximate missing derivatives or in state reconstruction. In the second part of the talk quantitative analysis tools are presented as well as methods for the design of controllers, whose structure or order is a-priori specified, and which may be of simpler low-order form yet still effective to achieve control. These methods, which we demonstrate on control design of heat exchangers, are mainly based on a direct optimization of appropriately defined cost functions as a function of the controller parameters. They are inspired by recent work on low-order control design for finite-dimensional systems and rely on solving eigenvalue optimization problems. The design problems under consideration include the stabilization problem and the computation and optimization of H-2 and H-infinity type cost functions, which we again test on the aforementioned control design for heat exchangers. These new methods not only demonstrate the many potential in real-world control problems, but they also bridge theoretically the gap between the two mainstream approaches for controlling linear time-delay systems,
which are based on applying the systems theory for infinite-dimensional systems, and based on a finite-dimensional approximation of the system, respectively.

**Stability Theory of Time Delay Systems and Applications from Engineering to Biology**

Silviu-Iulian Niculescu  
CNRS LSS – SUPELECE, Gif sur Yvette, FRANCE

Many control systems are affected by the presence of delays, mainly because it takes time to acquire the information needed for decision-making, to create control actions, and to execute them. Such systems with delays are all around us, as found in engineering, biology, physics, operations research, and economics. For instance, in traffic-flow models, the drivers’ delayed reactions must be considered to better understand the evolution of traffic flow, to predict traffic jams, and to possibly re-route traffic using advanced signalizations to improve traffic flow throughput on highways and in city traffic. In this talk, the instructor will cover such application examples, summarizing from “Stability and Stabilization of Systems with Time Delay, Limitations and Opportunities” (IEEE Control System Magazine, 2011, by R Sipahı, S-I Niculescu, CT Abdallah, W Michiels, K Gu). Next, principles of stability theory of time delay systems will be covered, and several case studies will be studied to analyze the effects of delays to stability. It will be of particular interest to discuss the dual effects of delays, that is, delays often times may cause instability, however in some cases delays may also favor stability in dynamical systems.

**Computational Methods for H-infinity Control of Time Delay Systems**

Hitay Ozbay  
Dept. of Electrical & Electronics Eng., Bilkent University, Ankara, TURKEY

In this lecture we consider robust control (H-infinity) problems for various classes of time delay systems with low order performance and robustness weights. We demonstrate a special type of factorization on the plant transfer function. This relies on finding the right half plane roots of quasi-polynomials (a topic discussed in earlier lectures). With the help of this factorization, we can employ an operator theoretic method known as the skew-Toeplitz theory that reduces the computation of the optimal performance level and the optimal controller to solving a set of finitely many linear equations. We also discuss reliable implementation of this controller (in terms of series, parallel and feedback connections of stable transfer functions) in various application areas including mechatronics and networked control systems.

**Delay-Dependent & Delay-Independent Stability in Connection with Algebraic Tools**

Rifat Sipahi  
Mechanical and Industrial Engineering, Northeastern University, Boston, USA.

In this lecture, we expand on the well-known concepts of delay-dependent and delay-independent stability of time delay systems, exploring how these concepts apply to stability and control problems of delay systems with multiple delays arising especially in mechatronics and network systems applications, and present how algebraic tools can be connected to such concepts to perform stability analysis with respect to delays, and synthesize structured controllers such that closed loop systems can be rendered delay-independent stable. We also show how low-order controllers and delay-adaptation in control design could be used to render effective control in LTI systems in a class of synchronization networks.
BIOGRAPHICAL SKETCHES OF THE LECTURERS

Fatihcan M. Atay has received his B.S. in Mechanical Engineering in 1985 and M.S. in Systems and Control Engineering in 1989, both from Bogazici University, Istanbul, and his Ph.D. in Applied Mathematics in 1994 from Brown University, Providence, Ri. He has worked both in academia and industry before joining the Max Planck Institute for Mathematics in the Sciences, Leipzig, as a Principal Investigator in 2002, where he is currently the coordinator of the group “Dynamical Systems and Network Analysis”. He has also been actively involved in several committees of the Complex Systems Society and is the coordinator of a large European FP7 project on the dynamics of complex multi-level systems. His research interests include delay differential equations, dynamical systems, complex networks and graph theory, mathematical neuroscience, and industrial applications. URL: http://personal-homepages.mis.mpg.de/fatay/

Dimitri Breda graduated in Mechanical Engineering in 1998 (Univ. Udine) and received a Ph.D. in Computational Mathematics in 2004 (Univ. Padova). Assistant Professor of Numerical Analysis at the Department of Mathematics and Computer Science of the University of Udine, his main research interests are in the field of numerical and applied mathematical analysis, in particular numerical methods for the stability analysis of (delay and functional) differential and integral equations with applications in control as well as in population dynamics. Authors of publications in international journals (Numerische Mathematik, SIAM Journal on Numerical Analysis, IEEE), he served as a member of the International Program Committee of the IFAC workshops on Time Delay Systems in 2010 and 2012. URL: http://users.dimi.uniud.it/~dimitri.breda/

Wim Michiels (1974) obtained a MSc degree in Electrical Engineering and a PhD degree in Computer Science from the K.U.Leuven, Belgium, in 1997 and 2002, respectively. He was a fellow of the Research Foundation Flanders (2002-2008) and a postdoctoral research associate at the Eindhoven University of Technology, the Netherlands (2007). In October 2008 he was appointed associate professor at the K.U. Leuven, Belgium, where he leads a research team within the Numerical Analysis and Applied Mathematics Division. He has authored the monograph "Stability and Stabilization of Time-Delay Systems. An Eigenvalue Based Approach" (SIAM Publications, 2007, with S.-I. Niculescu), more than 60 articles in scientific journals in the area of control and numerical mathematics, and he has been co-organizer of several workshops and conferences in the area of numerical analysis, control and optimization, including the 5th IFAC Workshop on Time-Delay Systems (Leuven, 2004) and the 14nd Belgian-French-German Conference on Optimization (Leuven, 2009). He is member of the IFAC Technical Committee on Linear Control Systems and associate editor of the journal Systems and Control Letters. His research interests include control and optimization, dynamical systems, numerical linear algebra, and scientific computing. His work has focused on the analysis and control of systems described by functional differential equations and on large-scale linear algebra problems, with applications in engineering and the bio-sciences. URL http://people.cs.kuleuven.be/~wim.michiels/

Silviu-Iulian Niculescu is senior researcher at CNRS at the Laboratory of Signals and Systems (L2S), CNRS-Supélec, Gif-sur-Yvette, France. He received the B.S. from IPB, Bucharest, Romania, the M.Sc. and Ph.D. from INPG, Grenoble, and the "Habilitation à Diriger des Recherches" (HDR) in Automatic Control from UTC, Compiégne, France in 1992, 1993, 1996, and 2003, respectively. In 2006, he joined the L2S, where, he has been the head since January 2010. He is the author of three books, coeditor of five multi-author volumes, and the coauthor of more than 350 book chapters, journal papers, and communications in international conferences. He was an associate editor for IEEE Transactions on Automatic Control from 2003 to 2005. He was awarded the CNRS Bronze and Silver Medals for scientific research in 2001 and 2011, respectively. His research interests include delay systems, robust control, operator theory, and numerical methods in optimization and their applications to the design of engineering systems. URL: http://silviu.niculescu.lss.supelec.fr

Hitay Ozbay is a Professor of Electrical and Electronics Engineering at Bilkent University in Ankara, Turkey. He received his B.S., MEng. and PhD, degrees from Middle East Technical University (Ankara, Turkey, 1985), McGill University (Montreal, Canada, 1987) and University of Minnesota, (Minneapolis, USA, 1989), respectively. He worked at the University of Rhode Island (1989-1990), and at The Ohio State University (1991-2006) where he was a Professor of Electrical and Computer Engineering, prior to joining Bilkent University in 2002, on leave from OSU. He served as an Associate Editor for IEEE Transactions on Automatic Control (1997-1999), and Automatica, (2001-2007). He was an appointed member of the Board of Governors of IEEE Control Systems Society (1999) and a vice-chair of the IFAC Technical Committee on Networked Control Systems (2005-2011). Currently, he is an Associate Editor for SIAM Journal on Control and Optimization. URL: http://www.ee.bilkent.edu.tr/~ozbay/

Rifat Sipahi is an Associate Professor at Northeastern University, Boston, USA (BSc in 2000 (Istanbul Technical University Turkey); MSc in 2002 & PhD in 2005 (University of Connecticut USA); postdoc in 2005-2006 at Heudiasyc CNRS at Université de Technologie de Compiègne, France; 2006-2012: Assistant Professor at Northeastern University). Dr. Sipahi works on the stability analysis of LTI systems with single and multiple delays; is one of the recipients of 2011 DARPA Young Faculty Award and of 2005 Chateauariand Postdoctoral Scholarship of the French Government; and he is the lead author of the article “Stability and Stabilization of Systems with Time Delay, Limitations and Opportunities” published in IEEE Control Systems Magazine in 2011. Prof. Sipahi is a member of IEEE and ASME Dynamic Systems and Control (DSC) Division; was the editor/co-organizer of 2012 IFAC Workshop on Time Delays Systems; is an Associate Editor on the editorial board of IEEE Transactions on Circuits and Systems (TCAS) – I. URL: www.coe.neu.edu/~rifiant