# Book of Abstracts

# 9th IFAC Workshop on Time Delay Systems

*Faculty of Mechanical Engineering,*
*Czech Technical University in Prague,*
*and Centre for Applied Cybernetics*

**Prague, Czech Republic**

**June 7-9, 2010**

# Contents

# Preface

As the organizers of the 9th IFAC Workshop on Time-Delay Systems in Prague, we endeavoured to keep the successful tradition and high standard of all the preceding workshops held in Grenoble (France, 1998), Ancona (Italy, 2000), Santa Fe (USA, 2001), Rocquencourt (France, 2003), Leuven (Belgium, 2004), L'Aquila (Italy, 2006), Nantes (France, 2007) and Sinaia (Romania, 2009). The main objective was to bring together the specialists in the area of *Time Delay Systems* and to create a joint forum for researchers in the field ranging from control theory, modelling, identification, filtering and estimation, algebraic and numerical methods, to applications in engineering, physics, biology and economics. Looking at the final program we believe that the goal of the Workshop will be reached in proving that the time delay issues represent a significant problem area in the contemporary large scale integration of control and monitoring systems and that worldwide extensive research is exerted in this field.

An *Opening lecture* of the workshop, given by Miroslav Krstic (University of California), will celebrate the memory of Professor Otto J. M. Smith and highlight some of the new developments in the area of predictor feedback. The first *Invited lecture* will be given by Wim Michiels (K.U. Leuven) who will address a challenging topic of fixed order controller design via eigenvalue optimization approach. The second *Invited lecture* given by Nejat Olgac (University of Connecticut) will be devoted to bridging between theory and realistic applications of Time Delay Systems. In the third *Invited lecture*, Lotfi Belkoura (Universite Lille) will address the theoretically demanding topic of identifiability and identification of time delay systems.

In workshop sessions, sixty five high quality regular papers are to be presented, selected from ninety submitted manuscripts after a careful review process. Each paper has been reviewed by two reviewers at least - the average number of reviews per paper was 2.9 - so that the International Program Committee was in a condition to perform fair and effective selection of the papers. A distinguished aspect of the Prague TDS workshop is the relatively large number of invited sessions in the workshop program, which has contributed to its compactness and integrity.

The workshop is organized by the Faculty of Mechanical Engineering, Czech Technical University in Prague (CTU) and by the Centre for Applied Cybernetics (CAK). CTU is one of the largest universities in the Czech Re-

public and the oldest institute of technology in Central Europe - established in 1707 by the Emperor Joseph I. It consists of eight faculties and two higher education institutes. CAK is a research institution funded by the Czech Government since 2000 and lead by Vladimír Kučera. CAK unifies leading research groups in the fields of control and information science in the country - five universities, two institutes of the Czech Academy of Sciences and seven hi-tech companies are involved in the project.

The 9th IFAC TDS Workshop is held in Prague, the capital of the Czech Republic and former centre of the Kingdom of Bohemia. The history of this city ranges over eleven centuries and you see monuments of the past when walking through the old centre of the city - recognized as a UNESCO World Heritage since 1992. The well-known and most famous Wenceslas square reminds of one of the Czech Saints, St. Wenceslas (907 - 935), which with the St. Ludmila and St. Vojtech (Adalbert) established the spiritual image of the millennium of Bohemian State. Moreover St. Wenceslas is known as an eternal guardian of the Premyslids Bohemian king dynasty. Even the most famous king of Bohemia, and Holy Roman Emperor Charles (Karel) IV. (1316 - 1378) acknowledged the continuity of St. Wenceslas tradition. The monuments from his reign, e.g. Charles bridge, St. Vitus Cathedral and Charles University, are still the most attractive sights in Prague.

In the occasion of opening the workshop, we would like to commemorate Professor Jack K. Hale - a leader and a pioneer in many areas of dynamical systems including Time Delay Systems, a regular IPC member of TDS workshops, *teacher, mentor and friend* - who regrettably passed away on December 9, 2009. Our special thanks go to Erik Verriest for commemoration of Professor Hale in the following note.

Pavel Zítek, NOC Chairman,
Tomáš Vyhlídal, Program Editor.

# Jack K. Hale
## teacher, mentor and friend

Erik I. VERRIEST

It was with great sadness that I reported to this community the demise of Professor Jack Hale on December 9, 2009 at the age of 81. Who is not familiar with his book "Introduction to Functional Differential Equations" with S. M. Verduyn Lunel, which has been cited over and over by most authors in our workgroup and elsewhere. Many of us were fortunate to attend his plenary talk, "Stability, Control and Small Delays," at the 3rd IFAC Workshop on Time Delays Systems (TDS 2001) in Santa Fe, New Mexico, and/or his presentation on synchronization at the CNRS-NSF Workshop on Time Delay Systems in Paris, France, (January 2003). Hazel, his lifetime companion since 1949, came along for this visit to Paris. Jack's enthusiasm in explaining fundamental issues in delay differential equations is legendary. He could make complex topics look astonishingly simple, dissolving theorems into sonnets. He was also fascinated by the work of engineers in combatting systems with delays, and enjoyed discussing and interacting with them.

It was shortly after he left Brown University in 1988, for the Georgia Institute of Technology that I became acquainted with him, and played the role of a grad student once again when I attended his lectures on Infinite Dimensional Systems during the Fall 1989 and Winter 1990. In fact, this greatly influenced my own career by directing my research interest to time delay systems. I consider myself fortunate to have co-advised a doctoral dissertation with Jack, and served on the doctoral committee for two more of his students. But I am only one of the many people who were influenced by Jack. For decades, Jack has inspired many researchers, far exceeding the 47 doctoral students he supervised. In fact, he was among the few taking the helm in modern dynamical systems. Even after he retired in 1998, he continued work unabatedly, attended the weekly dynamics seminar at Georgia Tech, interacted with speakers and students, and in his own unselfish way helped where he could. Jack submitted his last paper, with Geneviève Raugel, just one week before he died. The manuscript was first submitted to the Journal of Dynamics and Differential Equations in the autumn of 2009, but Jack had found a way to improve on it. It was resubmitted December 2, 2009.

Without doubt, Jack was one of the most influential and inspirational professors in dynamical systems. But what made him very special also was his boundless enthusiasm, vision of life and thoughtfulness when interacting with people. He truly was a gentle giant. He will sorely be missed.

Jack received multiple awards: the Chauvenet Prize, Guggenheim Fellowship, British Carnegie Fellowship, Sigma Xi sustained Research Award. He was a Corresponding Member of the Brazilian Academy of Science. Honorary Fellow of Royal Society of Edinburgh and Foreign Member Polish Academy of Science. He received honorary degrees from Ghent, Belgium; Stuttgart, Germany; University Tecnia of Lisboa, Portugal; Rostock, Germany and Clark University, Worcester, MA.

A short biography of Jack [1] was published on the occasion of his 70th birthday and retirement, and an interview was written up by Yingfei Yi [2].

[1] N. Chafee (2000). Jack K. Hale: A Brief Biography. *Journal of Differential Equations*, 168, 3-9.
[2] Y. Yi (2003). An Interview with Jack K. Hale. *Dynamical Systems Magazine*, January 2004.
http://www.dynamicalsystems.org/ma/ma/display?item=55

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# Technical Program

## Otto J.M. Smith Memorial Lecture

*Chairman:*
Michael ŠEBEK
*Monday, June 7, 9:00-10:00*
*Room: Congress Hall*

**From Classical Delay Compensation to Delay-Adaptive Predictor Feedback and PDE-ODE Cascades**

KRSTIC, Miroslav (University of California, San Diego, US)

On its golden anniversary, the Smith predictor (1959), a feedback tool for compensation of long dead-time, remains as widely used as ever in industrial applications in process control, and is increasingly relevant in modern applications such as teleoperation and networked systems. Professor Miroslav Krstic will highlight some of the new developments in the area of predictor feedback, such as adaptive control in the presence of long unknown delays and the generalizations of predictor tools from delay-ODE cascades to PDE-ODE cascades. These problems, as well as extensions to nonlinear and PDE plants, are introduced in his new book Delay Compensation for Nonlinear, Adaptive and PDE Systems (Birkhauser, Oct. 2009). The lecture will celebrate the memory of Professor Otto J. M. Smith (1917-2009) and his invention, a precursor to the modern infinite-dimensional feedback design.

**Biography**

Miroslav Krstic is the Daniel L. Alspach Professor at UC San Diego and the founding director of the Cymer Center for Control Systems and Dynamics. He is a co-author of eight books, including Nonlinear and Adaptive Control Design (1995), which is one of the two most cited research monographs in the history of control engineering, the new single-authored Delay Compensation for Nonlinear, Adaptive, and PDE Systems (2009), and six other books on control of turbulent fluid flows, stochastic nonlinear systems, and extremum seeking.

Krstic has held the Russell Severance Springer Distinguished Visiting Professorship at UC Berkeley and the Harold W. Sorenson Distinguished Professorship at UC San Diego. He is a recipient of the ONR Young Investigator, PECASE, and NSF Career Awards, as well as the Axelby and Schuck Paper Prizes. Krstic was the first recipient of the UCSD Research Award in Engineering. He is a Fellow of IEEE and IFAC. Krstic serves as Senior Editor in IEEE Transactions on Automatic Control and Automatica and as Editor of the Springer-Verlag book series Communications and Control Engineering.

# Nonlinear and adaptive control of Delay Systems

***Invited Session***

*Organisers:*

Miroslav KRSTIC, Andrey SMYSHLYAEV

*Monday, June 7, 10:20-12:20*

*Room: Congress Hall*

10:20-10:40

**Stabilization By Means of Approximate Predictors for Systems with Delayed Input**

KARAFYLLIS, Iasson (Technical University of Crete, Greece)

Sufficient conditions for global stabilization of nonlinear systems with delayed input by means of approximate predictors are presented. An approximate predictor is a mapping which approximates the exact values of the stabilizing input for the corresponding system with no delay. A systematic procedure for the construction of approximate predictors is provided for globally Lipschitz systems. The resulting stabilizing feedback can be implemented by means of a dynamic distributed delay feedback law.

10:40-11:00

**Stabilizing Controllers for Delay Systems subject to Positivity Constraints**

MAZENC, Frédéric (INRIA, CNRS-Supélec, Gif-sur-Yvette, France)
NICULESCU, Silviu-Iulian (CNRS-Supélec, Gif-sur-Yvette, France)

For time-varying forward-complete nonlinear systems with delay in the input, a new reduction model approach is proposed. It presents three advantages. First, the derived control laws have no distributed terms. Second, it yields closed-loop systems with positive solutions that can be easily found. Third, the stabilized systems possess some robustness properties that can be estimated.

11:00-11:20

**Separation Theorems for a Class of Retarded Nonlinear Systems**

GERMANI, Alfredo (University of L'Aquila, Italy)
MANES, Costanzo (University of L'Aquila, Italy)
PEPE, Pierdomenico (University of L'Aquila, Italy)

In this paper global and local separation theorems for a class of retarded nonlinear systems are investigated.

11:20-11:40

**Time delay resistant adaptive control of mini-UAVs**

DYDEK, Zachary T. (MIT, Cambridge, USA)
ANNASWAMY, Anuradha M. (MIT, Cambridge, USA)
SLOTINE, Jean-Jacques E. (MIT, Cambridge, USA)
LAVRETSKY, Eugene (The Boeing Company, Huntington Beach, USA)

Many potential applications of adaptive control, such as adaptive flight control systems, require that the controller have high performance, stability guarantees, and robustness to time delays. These requirements typically lead to engineering trade-offs, such as a tradeoff between performance and robustness. In this paper, a new Time Delay Resistant (TDR) adaptive control framework is proposed using a combination of several modifications to the typical direct model reference adaptive control (MRAC) approach. The benefits of the TDR approach are explored with a simulation of the longitudinal dynamics of a fixed-wing aircraft. Flight tests of a 4 rotor mini-UAV were also performed using a subset of the TDR adaptive control features.

11:40-12:00

**Lyapunov-based Adaptive Output-Feedback Control of MIMO Nonlinear Plants with Unknown, Time-varying State Delays**

MIRKIN, Boris (Technion, Haifa, Israel)
GUTMAN, Per-Olof (Technion, Haifa, Israel)

In this paper, we develop a model reference adaptive control (MRAC) scheme for a class of multi-input-multi-output (MIMO) non-linear dynamic systems with unknown time-varying state delay which is also robust with respect to an external disturbance with unknown bound. An output feedback adaptive control scheme uses feedback actions only, and thus does not require a direct measurement of the command or disturbance signals. A suitable Lyapunov-Krasovskii type functional is introduced to design the adaptation algorithms and to prove stability.

12:00-12:20

**Output Control Algorithm for Unstable Plant with Input Delay and Cancellation of Unknown Biased Harmonic Disturbance**

PYRKIN, Anton (SPbSU ITMO, St. Petersburg, Russia)
SMYSHLYAEV, Andrey (University of California, San Diego, USA)
BEKIARIS-LIBERIS, Nikolaos (University of California, San Diego, USA)
KRSTIC, Miroslav (University of California, San Diego, USA)

We present a new stabilization approach for a linear plant with input delay, parametric uncertainties, and an unknown harmonic disturbance. To solve this problem, we combine the well-known predictor feedback approach with the state observer and adaptive scheme that identifies the frequency of the disturbance. Compared to the existing approaches, the dynamic order of our adaptive scheme is low (equal to three) and the results apply to plants that are unstable, non-minimum phase, and have an arbitrary relative degree.

## Lyapunov Techniques

*Chairpersons:*
Sabine MONDIÉ, Andreas OTTO
*Monday, June 7, 10:20-12:00*
*Room: Gallery*

10:20-10:40
**Lyapunov Spectrum of Linear Delay Differential Equations with Time-Varying Delay**
OTTO , Andreas (Univ. of Technology Chemnitz, Germany)
RADONS, Günter (Univ. of Technology Chemnitz, Germany)

To understand the dynamics of systems with fluctuations in the retarded argument, the Lyapunov spectra of a scalar, linear delay differential equation (DDE) are studied. Depending on the structure of the deviated argument some Lyapunov exponents can be equal to minus infinity, which indicate the difference between the dimension of the state space and the asymptotic solution space. In order to validate the results of this dimensional collapse in systems with time-varying delay, the continuous DDE is analyzed by the *method of steps*. The iterated map of the stepwise retarded access by the deviated argument up to values of the initial function can characterize the dimensional behavior of DDE with time-varying delay.

10:40-11:00

**Robust Delay-Dependent Stabilizing Control of Time-Delay Systems with State and Input Delays: Augmented L.K. Functional Approach**

PARLAKCI, Mehmet Nur Alpaslan (Istanbul Bilgi University, Turkey)
KÜCÜKDEMIRAL, Ibrahim Beklan (Yildiz Technical Univ., Istanbul, Turkey)

In this paper, we investigate the design problem of a stabilizing control for a class of linear uncertain time-delay systems with time-varying state and input delays. The control law is selected to be a state-feedback controller. Adopting to employ an augmented type of Lyapunov-Krasovskii functional, for the nominal case, we first derive some sufficient delay-dependent stabilization criteria which can be solved using a convex optimization technique with interior-point algorithms. The stabilization synthesis is then extended to the case when the time-delay system is subject to the norm-bounded uncertainties which affect state and input matrices. Several numerical examples are presented to demonstrate the application of the proposed synthesis of a stabilizing controller. The numerical results on the maximum allowable delay bound and the uncertainty bound seem to be quite less conservative in comparison to the existing methods from the literature.

11:00-11:20

**$H_\infty$ control of time-delay switched linear systems by state-dependent switching**

GALBUSERA, Luca (Politecnico di Milano, Italy)
BOLZERN, Paolo (Politecnico di Milano, Italy)

In this paper we propose contributions on the $\mathcal{H}_\infty$ control of switched linear systems subject to time-delays through the assignment of the switching law. Based on previous results related to switched linear systems with no delays and exploiting the concept of piecewise-quadratic Lyapunov-Krasovskii functionals, we formulate the problem of finding suitable switching laws as the solution of a set of $N$ matrix inequalities, where $N$ is the number of modes. In this way, both delay-independent and delay-dependent criteria are derived.

11:20-11:40

**Instability conditions for systems with distributed time delays via functionals of complete type**

OCHOA, Blanca M. (ESIME, IPN, Mexico)
MONDIÉ, Sabine (CINVESTAV, Mexico)

Instability conditions for single delay systems of retarded type are given. The approach is based on using the converse results on the existence of special quadratics lower bounds for the Lyapunov Krasovskii functional of complete type associated to these systems.

11:40-12:00

**Adaptive Mamdani fuzzy backstepping control for a class of strict-feedback nonlinear time-varying delay systems**

HAMDY, Mohamed (Menoufia University, Egypt)
EL-GHAZALY, Gamal (Menoufia University, Egypt)
IBRAHIM, M. (Menoufia University, Egypt)

This paper presents an adaptive Mamdani fuzzy control scheme for a class of uncertain strict-feedback nonlinear systems with unknown time-varying delays. Within this scheme, fuzzy logic systems are used to approximate nonlinear functions and the developed adaptive fuzzy controller is recursively designed via backstepping technique and Lyapunov-Krasovskii functionals, which not only significantly compensate for the unknown time-varying delays but also, avoids controller singularity problem. The proposed adaptive fuzzy controller guarantees that all signals in the closed-loop system are uniformly ultimately bounded, while tracking error converges to a small neighborhood of the origin. The main advantages of the proposed controller are that the designed control law is time-delay independent and only one adaptive parameter is required to be updated online. Simulation results are presented to verify the effectiveness of the proposed scheme.

# Plenary Session I

*Chairman:*
Vladimír KUČERA
*Monday, June 7, 14:00-15:00*
*Room: Congress Hall*

**Design of fixed-order stabilizing and $H_2/H_\infty$ optimal controllers: an eigenvalue optimization approach**
MICHIELS, Wim (K.U. Leuven, Belgium)

In the context of $H_2$ and $H_\infty$ control of time-delay systems two mainstream approaches can be distinguished. The first approach is based on applying a generalization of the classical systems and control theory to infinite-dimensional systems. It mostly results in infinite-dimensional or distributed controllers which may be hard to implement in practical applications where the controller structure is fixed or restricted (hence, an approximation is necessary), or in controllers that include observers requiring an on-line numerical simulation of the systems equations. The second approach consists of identifying approximate finite-dimensional models of low order, and applying the existing design methods that typically yield controllers whose dimensions are larger or equal than the dimension of the plant model. As a drawback the properties of the resulting closed-loop system may heavily depend on the accuracy of the approximation, and the design involves a trade-off between accuracy and reliability on the one hand and the feasibility of the controller implementation on the other hand. In my presentation I will give an overview of the ongoing work in my group on control design methods that aim at bridging the gap between the two types of approaches described above, by designing directly controllers for a large class of linear time-delay systems (without starting from a low-order approximation), where the controller structure or order is a priori specified (e.g. imposed from practical considerations). These methods are based on a direct optimization of appropriately defined cost functions and inspired by recent work on low-order control design for finite-dimensional systems within an eigenvalue optimization framework. The analysis and design problems under consideration include the stabilization problem and the computation and optimization of $H_2$ and $H_\infty$ type cost functions.

**Biography**

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 has been research Fellow of the Research Foundation Flanders (2002-2008) and 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. Among other published work, he has authored the monograph *Stability and Stabilization* of Time-Delay Systems. An Eigenvalue Based Approach (SIAM Publications, 2007, with S.-I. Niculescu), over 40 articles in international scientific journals, and he has been co-editor of three books. 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 14nt Belgian-French-German Conference on Optimization (Leuven, 2009). He is member of the IFAC Technical Committee on Linear Control Systems. 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 life sciences.

# Analysis and numerics of the spectrum of time delay system, Part I - Analysis and computation

***Invited Session***

*Organisers:*

Dimitri BREDA, Wim MICHIELS, Rossana VERMIGLIO

*Monday, June 7, 15:20-17:20*

*Room: Congress Hall*

15:20-15:40

**On roots and charts of delay equations with complex coefficients**

BREDA, Dimitri (University of Udine, Italy)

This work is devoted to the analytic study of the characteristic roots of scalar autonomous Delay Differential Equations (DDEs) with complex coefficients. The focus is placed on the robust analysis of the position of the roots in $\mathbb{C}$ with respect to the variation of the coefficients, with the final aim of obtaining suitable representations for the relevant stability boundaries and charts. The investigation benefits from a preliminary shift of the coefficients which reduces the number of free parameters allowing for useful graphical visualizations. The present research is motivated on the base of studying the stability of *systems* of DDEs.

15:40-16:00

**A New Method for Delay-Independent Stability of Time-Delayed Systems**

ERGENC, Ali Fuat (Istanbul Technical University, Turkey)

A new method is presented for determining delay-independent stability zones of the general LTI dynamics with multiple delays against parametric uncertainties. This method utilizes extended Kronecker summation and unique properties of self-inversive polynomials. Self- inversive polynomials are special polynomials which exert useful tools for examination of the distribution of its zeros. A sufficient condition for delay-independent stability is presented. The main focus in this paper is a novel approach to the robustness of the time-delayed systems. Anew sufficient condition for delay-independent stability is introduced. These new concepts are also demonstrated via some example case studies.

16:00-16:20

**An Arnoldi method with structured starting vectors for the delay eigenvalue problem**

JARLEBRING, Elias (K.U. Leuven, Belgium)
MEERBERGEN, Karl (K.U. Leuven, Belgium)
MICHIELS, Wim (K.U. Leuven, Belgium)

The method called *Arnoldi* is currently a very popular method to solve large-scale eigenvalue problems. The general purpose of this paper is to generalize Arnoldi to the characteristic equation of a *time-delay system*, here called a *delay eigenvalue problem*. The presented generalization is mathematically equivalent to Arnoldi applied to the problem corresponding to a Taylor approximation of the exponential. Even though the derivation of the result is with a Taylor approximation, the constructed method can be implemented in such a way that it is independent of the Taylor truncation paramater $N$. This is achieved by exploiting properties of vectors with a special structure, the vectorization of a rank one matrix plus the vectorization of a matrix which right-most columns are zero. It turns out that this set of vectors is closed under the matrix vector product as well as orthogonalization. Moreover, both operations can be efficiently computed. Since Arnoldi only consists of these operations, if Arnoldi is started with the special vector structure, the method can be efficiently executed. The presented numerical experiments indicate that the method is very efficient in comparison to methods in the literature.

16:20-16:40

**Fast-Lifting Approach to the Computation of the Spectral Radius of Neutral Time-Delay Systems**

HAGIWARA, Tomomichi (Kyoto University, Japan)
FUJINAMI, Tokuya (Kyoto University, Japan)

This paper discusses a further development of the lifting-based method for continuous-time time-delay systems (TDSs), in which the state transition is viewed in discrete-time and described by the monodromy operator. The method deals with only infinite-dimensional bounded operators without taking any process that directly reduces the infinite-dimensionality to finite-dimensionality, and only uses 'pseudo-discretization' induced by the fast-lifting technique. A key role of fast-lifting lies in facilitating an appropriate approximation of the monodromy operator with a tractable one that is still infinite-dimensional, where the latter eventually leads to the reduction to finite-dimensionality. The method is thus purely operator-theoretic and also system-theoretic. Under such a framework, a finite-dimensional computation method of the spectrum of the monodromy operator was derived in a preceding paper, which is ensured to be asymptotically exact as the fast-lifting parameter $N$ tends to infinity but was restricted to retarded time-delay systems. This paper shows that a similar method can be established also for neutral TDSs as far as the spectral radius computation is concerned.

16:40-17:00

**Comparison Between Collocation Methods and Spectral Element Approach for the Stability of Periodic Delay Systems**

KHASAWNEH, Firas A. (Duke University, Durham, USA)
MANN, Brian P. (Duke University, Durham, USA)
BUTCHER, Eric A. (New Mexico State University, Las Cruces, USA)

This paper compares two methods that are commonly used to study the stability of delay systems. The first is a collocation technique while the second is a spectral element approach which uses the weighted residual method. Two distributions of the collocation points are compared: the first uses the extrema of Chebyshev polynomials of the first kind whereas the second uses the Legendre-Gauss-Lobatto points. The spectral element approach uses the Legendre-Gauss-Lobatto points and higher-order trial functions to discretize the delay equations while Gauss quadrature rules are used to evaluate the resulting weighted residual integrals. Two case studies are used to compare the different methods. The first case study is a 3rd order autonomous DDE while the second is a DDE describing the midspan deflections of an unbalanced rotating shaft with feedback gain (nonautonomous DDE). Convergence plots that compare the different rates of convergence of the described methods are also provided.

17:00-17:20

**On discretizing the semigroup of solution operators for linear time invariant - time delay systems**

BREDA, Dimitri (University of Udine, Italy)
MASET, Stefano (University of Trieste, Italy)
VERMIGLIO, Rossana (University of Udine, Italy)

In this paper we give an account of the basic facts to be considered when one attempts to discretize the semigroup of solution operators for Linear Time Invariant - Time Delay Systems (LTI-TDS). Two main approaches are presented, namely *pseudospectral* and *spectral*, based respectively on *classic interpolation* when the state space is $\mathcal{C} = C(-\tau, 0; \mathbb{C})$ and *generalized Fourier projection* when the state space is $\mathcal{X} = \mathbb{C} \times L^2(-\tau, 0; \mathbb{C})$. Full discretization details for constructing the approximation matrices are given. Moreover, concise, yet fundamental, convergence results are discussed, with particular attention to their similarities and differences as well as pros and cons with regards to solution approximation and asymptotic stability detection.

# Applications

*Chairmen:*
Miloš SCHLEGEL, Artem S. KREMLEV
*Monday, June 7, 15:20-17:20*
*Room: Gallery*

15:20-15:40
**Control of a Vacuum Coating Process with Long Dead-Time and an Integrator: a Case Study**
DEMENTJEV, Alexander (Dresden University of Technology, Germany)
HENSEL, Burkhard (Dresden University of Technology, Germany)
KUBIN, Hellmuth (Dresden University of Technology, Germany)
RIBBECKE, Heinz-Dieter (Dresden University of Technology, Germany)
KABITZSCH, Klaus (Dresden University of Technology, Germany)

This paper presents the comparative analysis of different methods for the control of a characteristic industrial process with a long dead-time. Not only traditional control strategies (Smith predictor, Model-Following Controller and Generalized Predictive Control) are considered, but also an alternative approach - the use of virtual sensors.

15:40-16:00
**Rejection of Unknown Biased Harmonic Disturbance for Nonlinear System with Input Delay**
PYRKIN, Anton A. (SPbSU ITMO, St. Petersburg, Russia)
BOBTSOV, Alexey A. (SPbSU ITMO, St. Petersburg, Russia)
KREMLEV, Artem S. (SPbSU ITMO, St. Petersburg, Russia)

In this paper a new approach for cancellation of a biased harmonic disturbance is proposed. Compared with a number of known results in this paper the disturbance compensation problem is solved when the output variable is measured only, a relative degree of the plant is arbitrary and the control channel has delay. The reaction wheel pendulum on a movable platform is considered as the plant to demonstrate how proposed approach can be plugged. Created by hand disturbance moves the platform in horizontal surface and the pendulum is oscillating. The second goal of this work is the development of mechatronic applications using in education.

16:00-16:20

**Feature-based Parametrization of Input Shaping Filters with Time Delays**

SCHLEGEL, Miloš (University of West Bohemia, Czech Republic)
GOUBEJ, Martin (University of West Bohemia, Czech Republic)

This paper deals with signal shaping filters in form of sum of weighted time delays. The filter can be used to solve various control problems. The first important application is a control of flexible mechanical systems with respect to minimization of excited residual vibrations. The second interesting field is feedback control design using open loop frequency response shaping. The paper presents an algorithm for parametrization of all equidistant four-pulse shaping filters with minimum set of chosen parameters.

16:20-16:40

**Predictive Control Strategy with Online Time Delay Estimation Applied in General Anaesthesia**

HODREA, Ramona (Ghent University, Belgium)
IONESCU, Clara (Ghent University, Belgium)
DE KEYSER, Robin (Ghent University, Belgium)

General anaesthesia refers to the state of total unconsciousness resulted from the administration of several drugs. The depth of anaesthesia can be monitored with a device called BIS (Bispectral index) monitor. A manifold of artifacts corrupt the signals measured with this monitor, e.g. coughing, movement of feet and arms, face washing, etc., which challenge the correct estimation of the bispectral index. As such, estimation techniques evaluate the signal to noise ratio and if insufficient information is available, data from the past measurements is used to evaluate the current state of the patient. In this manner, instrumental time delay is introduced in the closed loop regulation of general anaesthesia. This paper evaluates whether or not an incorrect estimation of the time delay has an influence on the stability and robustness of the closed loop control. The performance of the EPSAC (Extended Prediction Self-Adaptive Control) controller was tested using different scenarios. Under- and over-estimations of the real time delay were considered in the prediction. The online time delay estimation was added to the control algorithm and the performance was evaluated.

16:40-17:00

**Delay Variability Compensation for Combating the Bullwhip Effect in Periodic-Review Inventory Systems with Multiple Suppliers**

IGNACIUK Przemyslaw (Technical University of Lódź, Poland)
BARTOSZEWICZ Andrzej (Technical University of Lódź, Poland)

In this paper we provide a control-theoretic methodology for combating the bullwhip effect (amplification of demand variations in order quantities) in supply chain, where multiple supply alternatives are used for acquiring the stock at a goods distribution center. We propose a new policy which effectively combines the benefits of linear-quadratic (LQ) optimal control and disturbance compensation techniques for providing a smooth ordering signal. In addition, the designed policy ensures that demand is entirely satisfied from the on-hand stock (yielding zero lost-sales cost) and the warehouse capacity at the distribution center is not exceeded (which eliminates the risk of costly emergency storage). Robustness to time-varying delay and unknown, variable demand is strictly proved and verified numerically.

17:00-17:20

**Controlling the bifurcation in friction induced vibrations using delayed feedback**

SAHA, Ashesh (Indian Institute of Technology, Kanpur, India)
WAHI, Pankaj (Indian Institute of Technology, Kanpur, India)

We analyse the control of friction induced vibrations using linear time-delayed displacement feedback applied in a direction normal to the friction force. Linear analysis reveals that the steady state looses stability via a Hopf bifurcation. The nature of the bifurcation is either subcritical or supercritical depending on the choice of control parameters. Hence, with a linear delayed feedback we are able to both stabilize the system by completely quenching the vibrations as well as control the nature of the bifurcation which is important for cases with partial quenching.

# Analysis and numerics of the spectrum of time delay system, Part II - Synthesis and parametric studies

***Invited Session***

*Organisers:*

Dimitri BREDA, Wim MICHIELS, Rossana VERMIGLIO

*Monday, June 7, 17:40-19:00*

*Room: Congress Hall*

17:40-18:00

**Continuation Based Computation of Root-Locus for SISO Dead-Time Systems**

GUMUSSOY, Suat (K.U. Leuven, Belgium)
MICHIELS, Wim (K.U. Leuven, Belgium)

We present a numerical method to plot the root-locus of Single-Input-Single-Output (SISO) dead-time systems on a given right half-plane up to a predefined controller gain. We compute the starting and intersection points of root-locus inside the region and we obtain the root-loci of each root based on a predictor-corrector type continuation method. The method is effective for high-order SISO dead-time systems.

18:00-18:20

**Ultimate-Frequency based Dominant Pole Placement**

ZÍTEK, Pavel (CTU in Prague, Czech Republic)
FIŠER, Jaromír (CTU in Prague, Czech Republic)
VYHLÍDAL, Tomáš (CTU in Prague, Czech Republic)

A dominant pole placement method for PID control of time delay plant is dealt with in the paper. To select suitable candidate values of poles to be prescribed for tuning the PID parameters the ultimate frequency assessment is utilized and the phase margin specification is the additional design requirement. The over-determined problem is solved by means of repeated least-square approach selecting the crossover frequency best satisfying the design requirements.

18:20-18:40

**Dependence of Delay Margin on Network Topology: Single Delay Case**

QIAO, Wei (Northeastern University, Boston, USA)
SIPAHI, Rifat (Northeastern University, Boston, USA)

The main objective in this paper is to capture the indirect relationship between the delay margin $\tau^*$ of coupled systems and different graphs $\mathcal{G}$ these systems form via their different topologies, $\tau^* = \tau^*(\mathcal{G})$. A four-agent linear time invariant (LTI) consensus dynamics is taken as a benchmark problem with a single delay $\tau$ and second-order agent dynamics. In this problem, six possible topologies with graphs $\mathcal{G}_1, \ldots, \mathcal{G}_6$ exist without disconnecting an agent from all others. To achieve the objectives of the paper, we start with a recently introduced stability analysis technique called Advanced Clustering with Frequency Sweeping (ACFS) and reveal the delay margin $\tau^*$, that is, the largest delay that the consensus dynamics can withstand without loosing stability. We next investigate how $\tau^*$ is affected as one graph transitions to another when some links between the agents weaken and eventually vanish. Finally, the damping effects to $\tau^*$ and the graph transitions are studied and discussed with comparisons. This line of research has been recently growing and new results along these lines promise delay-independent, robust and delay-tolerant topology design for coupled delayed dynamical systems.

18:40-19:00

**Stability Conditions for a System Modeling Cell Dynamics in Leukemia**

ÖZBAY, Hitay (Bilkent University, Ankara, Turkey)
BENJELLOUN, Houda (INRIA Rocquencourt, France)
BONNET, Catherine (INRIA Rocquencourt, France)
CLAIRAMBAULT, Jean (INRIA Rocquencourt, France)

In a series of recent publications a dynamical system with distributed delays has been proposed for modeling hematopoietic cell maturation dynamics in acute myelogenous leukemia. Sufficient conditions for stability of the linearized system have been obtained earlier. In this paper we discuss the level of conservatism in these conditions by studying stability crossing roots and the gain margin of the system.

# Networks

*Chairmen:*
Silviu-Iulian NICULESCU, Harold J. KUSHNER
*Monday, June 7, 17:40-19:00*
*Room: Gallery*

17:40-18:00
**Suboptimal state estimation under communication delays**
PACHNER, Daniel (Honeywell, Prague, Czech Republic)
BARAMOV , Lubomír (Honeywell, Prague, Czech Republic)
HAVLENA, Vladimír (Honeywell, Prague, Czech Republic)

We present a suboptimal state estimation method under communication delays. The missing measurements are replaced with model predictions and these predictions are put into memory. When the delayed measurements arrive, the effect of using prediction as fictitious measurements is removed. The optimality is recovered, which this is the key property of the method. The algorithm complexity is low compared to the optimal solution. The method requires the measurements to be time stamped. The plant model must be linear, time invariant.

18:00-18:20
**Consensus in networks under transmission delays and the normalized Laplacian**
ATAY, Fatihcan M. (Max Planck Institute, Leipzig, Germany)

We study discrete and continuous time consensus problems on directed and weighted networks in the presence of time delays. We focus on information transmission delays, as opposed to information processing delays, so that each node of the network compares its current state to the past states of its neighbors. Furthermore, we allow both fixed and distributed time delays. The connection structure of the network is described by a normalized Laplacian matrix. We show that consensus is achieved if and only if the underlying graph contains a spanning tree. Furthermore, this statement holds independently of the value of the delay, in contrast to the case of processing delays. We also calculate the consensus value and show that, unlike the case of processing delays, the consensus value is determined not just by the initial states of the nodes at time zero, but also on their past history over an interval of time.

18:20-18:40

**Feedback stabilization and motion synchronization of systems with time-delay in the communication network**

LOMBARDI, Warody (SUPELEC System Sci., Gif-sur-Yvette, France)
LUCA Anamaria (SUPELEC System Sci., Gif-sur-Yvette, France)
OLARU Sorin (SUPELEC System Sci., Gif-sur-Yvette, France)
NICULESCU, Silviu-Iulian (SUPELEC-CNRS, Gif-sur-Yvette, France)
CHEONG, Joono (Korea University, Jochiwon, Korea)

This paper is dedicated to the stabilization problem of dynamical systems in the presence of variable time-delay in the communication channel which is handled at the discretization stage by means of a guaranteed uncertainty approximation technique. In this context, the proposed stabilization methodology will be based on a Lyapunov-Krasovskii candidate leading finally to Linear Matrix Inequalities formulations for the controller synthesis. The motion synchronization control of two interconnected subsystems linked by a network is considered a possible application of these techniques.

18:40-19:00

**Numerical Methods for Optimal Controls for Nonlinear Stochastic Systems With Delays and Applications to Internet Regulation**

KUSHNER, J. Harold (Brown University, USA)

The Markov chain approximation method, a primary approach for computing optimal values and controls for stochastic systems, was extended to nonlinear diffusions with delays in a recent book. The convergence of many forms of algorithms was proved. The path, control and/or reflection terms can all be delayed. Reflection terms occur in communications models, where they correspond to buffer overflows. If the control and/or reflection terms are delayed, the memory requirements can make the problem intractable. Recasting the problem in terms of a wave equation yields practical algorithms with much reduced computational needs. We outline the approach, concentrating on forms motivated by applications to communications, and give data illustrating the potential.

## Plenary Session II

*Chairman:*
Pavel ZÍTEK
*Tuesday, June 8, 9:00-10:00*
*Room: Congress Hall*

**Time Delayed Systems, Bridging Between Theory and Realistic Applications**
OLGAC, Nejat (University of Connecticut, USA)

Practically motivated investigations have been conducted for over four decades in the machine tools regenerative chatter area bringing the time delayed dynamics into question. These efforts went on almost completely decoupled from the theoretical developments in mathematics, almost in the same chronological time span. In this presentation we wish to take a journey bridging variety of application-based research studies to the theory. Some industrial problems that await solution and corresponding theoretical developments will be revisited. Missed opportunities of cross-breeding between the two groups of researchers and potentially fertile new venues are also reviewed. Interwoven nature of knowledge creation between the practice to theory will be displayed with video clips and numerical simulations.

Several focus points in the talk are: (a) A concept of actively tuned vibration absorbers, the *Delayed Resonator*, which is inspired from machine tool chatter phenomenon, (b) Neutral class of TDS in practice, (c) Cluster Treatment of Characteristic Roots (CTCR) paradigm and its impact on single and multiple delay systems, (d) Chatter stabilization in Simultaneous Machining using *Delay Scheduling* method, (e) *Spectral Delay* and *Building Block* concepts for multiple and rationally independent delay cases, (f) Stability of multi-agent swarm control.

**Biography**

Nejat Olgac, Dr. Eng. Sci. Columbia Univ 1976, M.Sc. Technical Univ. of Istanbul, Turkey 1972, both in Mechanical Engineering. He managed industrial groups in Europe between 1976-81. He joined the University of Connecticut in 1981, in the Mechanical Engineering Department where he is a professor today. His research interests are in robust nonlinear controls, active vibration absorption, time-delayed systems, micromanipulation in cellular biology applications, control of autonomous swarms. Dr . Olgac holds three patents (1995-1996-1999) on the Delayed Resonator active vibration suppression technique. He is the director of Advanced Laboratory for Robotics, Automation and Manufacturing (ALARM) at UConn. Dr. Olgac was Visiting Professor at INRIA (Sophia Antipolis, France) 1988-89, SEW Eurodrive Fellow - Guest Professor at Technical Univ. of Munich, Germany in 1995-96 and Visiting Professor at Harvard University 2002-03). He was on the editorial board of the ASME Trans. of Dynamic Systems, Measurement and Control (1996-2004), and the guest editor of the Special Issue of JDSMC on Time Delayed Systems (June, 2003), is presently on the Editorial Boards of J. Vibration and Control, Int. J. of Mechatronics and Manufacturing Systems. He was a member and the Chairman of the Executive Committee of the ASME Dynamic Systems and Control Division (2001-6). Prof. Olgac is a member of the Connecticut Academy of Science and Engineering, Fellow of ASME and Senior Member of IEEE.

# Time delay systems in Mechanical engineering applications

***Invited Session***

*Organisers:*

Tomáš VYHLÍDAL, Tamás INSPERGER

*Tuesday, June 8, 10:20-12:20*

*Room: Congress Hall*

10:20-10:40

**Balancing using accelerometers and equations with advanced arguments**

INSPERGER, Tamás (Budapest Univ. of Technology and Economics, Hungary)
WOHLFART, Richard (Budapest Univ. of Technology and Economics, Hungary)
TURI, Janos (University of Texas in Dallas, USA)
STÉPÁN, Gábor (Budapest Univ. of Technology and Economics, Hungary)

The stick balancing problem is considered, where the vertical direction is measured using a single accelerometer attached to the stick. It is shown that the output is a linear combination of the angular position and the angular acceleration of the stick. If this output is fed back in a PD controller with feedback delay, then the governing equation of motion is an advanced functional differential equation, since the highest derivative, the jerk, appears with delayed argument through the derivative term. Autonomous equations with advanced arguments are typically non-causal and are unstable with infinitely many unstable poles. However, if the sampling effect of the digital controller is modeled, then the argument of the delayed highest derivative term is piecewise constant. In this case, the non-causality does not arise, and the system can also be stabilized by tuning the control parameters properly. In the paper, different models for stick balancing are considered and discussed by analyzing the corresponding stability diagrams.

10:40-11:00

**Experimental and Theoretical Study of Distributed Delay in Machining**

DOMBOVARI, Zoltan (Budapest Univ. of Technology and Economics, Hungary)
STÉPÁN, Gábor (Budapest Univ. of Technology and Economics, Hungary)

In this work, an experimental and theoretical studies are given for the well-known process damping effect arisen in turning processes. This effect generally pushes the stability chart (lobes) to higher depth of cuts in low spindle speed domain and causes difficulties to predict the stability of stationary cutting (equilibrium of the process). The orthogonal cutting model presented and investigated here contains distributed delays due to the cutting force distribution on the rake face. The paper presents measurement set up to create and to track the oscillating cutting force for the identification of the model parameters. An extended model also investigated that explains the experimental observations.

11:00-11:20

**Comparison of Time Delayed Tyre Models**

TAKÁCS, Dénes (Budapest Univ. of Technology and Economics, Hungary)
STÉPÁN, Gábor (Budapest Univ. of Technology and Economics, Hungary)

This paper investigates a low degree-of-freedom mechanical model of the well-known phenomenon wheel shimmy. The applied model considers the elasticity of the tyre and describes the motion of the towed tyre by time delay differential equation, where the memory effect is originated in the contact patch. The stability charts of the towed tyre are presented for different types of tyre models.

11:20-11:40

**An iterative method for the multipliers of periodic delay-differential equations and the analysis of a PDE milling model**

ROTT, Oliver (WIAS, Berlin, Germany )
JARLEBRING, Elias (K.U. Leuven, Belgium)

Locally convergent iterative schemes have turned out to be very useful in the analysis of the characteristic roots of delay-differential equations (DDEs) with constant coefficients. In this work we present a locally convergent iterative scheme for the characteristic multipliers of periodic-coefficient DDEs. The method is an adaption of an iterative method called *residual inverse iteration*. The possibility to use this method stems from an observation that the characteristic matrix can be expressed with the fundamental solution of a differential equation. We apply the method to a coupled milling model containing a partial and an ordinary differential equation. The conclusion of the numerical results is that the stability diagram of the coupled model differs significantly from the combined stability diagrams for each subsystem.

11:40-12:00

**Stability Analysis for a Consensus System of a Group of Second Order Dynamics with Time Delays**

CEPEDA-GOMEZ, Rudy (Univ. of Connecticut, USA)
OLGAC, Nejat (Univ. of Connecticut, USA)

This study addresses the consensus problem for a group of agents with second order dynamics and time delays. It is assumed that all the agents in the group communicate with each other, and that the time delay incurred is constant and equal for all the communication channels. An efficient control structure of PD type is proposed to create consensus in the position and velocity of the agents. The proposed control law introduces a particular construction into the characteristic equation of the system, which is exploited to simplify the stability analysis in the delay space. A complete stability picture, taking into account the variations in the control parameters and the communication delay, is obtained. Case studies and simulations results are presented to verify the analytical derivations.

12:00-12:20

**Generalized $H_2$-Preview Control and its Application to Car Lateral Steering**

SALEH, Louay (IRCCyN, Nantes, France)
CHEVREL, Philippe (IRCCyN, Nantes, France)
LAFAY, Jean-Francois (IRCCyN, Nantes, France)

This paper is dedicated to studying the characteristics of the optimal preview control for lateral steering of a passenger vehicle. This synthesis of control law has proved through many applications its ability to guarantee improved performance. The success of this advanced control strategy lies mainly in its ability to include knowledge of a path to follow in the future on a finite horizon, and its ability to moderate the effect of potential delays in the control loop through the advanced information.

## Stability and Stabilization

*Chairmen:*
Jean-Pierre RICHARD, Alexandre SEURET
*Tuesday, June 8, 10:20-12:20*
*Room: Gallery*

10:20-10:40
**Characteristic equation and stability analysis of linear periodic systems with delay**
LAMPE, Bernhard P. (University of Rostock, Germany)
ROSENWASSER, Efim N. (State Univ. of Marine Techn., St. Petersburg, Russia)

For a linear continuous periodic system with several delays, a characteristic equation is defined in such a way, that for its stability it is necessary and sufficient that all its roots are outside the closed unit disc. By applying the theory of Fredholm integral equations of the second kind, an approximate characteristic equation is derived in polynomial form. Conditions are given, under which the exact and the approximate equation yield the same stability statement. An example illustrates how this method could be applied.

10:40-11:00
**Exponential stability and stabilization of sampled-data systems with time-varying period**
SEURET, Alexandre (GIPSA-LAB, Saint Martin d'Héres - FRANCE.)

This article proposes a novel approach to assess the exponential stability of linear systems with sampled-data inputs. The paper considers both uncertainties in the model parameters and in the sampling period. Inspired by the input-delay approach and the stability of impulsive systems, the proposed method provides easy tractable stability conditions. Sufficient stability and stabilization conditions are provided to deal with both cases of constant and time- varying sampling periods. The period-dependent conditions are expressed using computable linear matrix inequalities. Several examples show the efficiency and the limitation of such stability criteria.

11:00-11:20

**Adaptive Output Stabilization of Time-Delay Nonlinear System**

BOBTSOV, Alexey A. (SPbSU ITMO, St. Petersburg, Russia)
PYRKIN, Anton A. (SPbSU ITMO, St. Petersburg, Russia)

This paper deals with the output stabilization of time-delay systems with sector-bounded nonlinearity. In this paper we will consider the problem of absolute stability for a class of time-delay systems which can be represented as a feedback connection of a linear dynamical system with unknown parameters and a uncertainty nonlinearity satisfying a sector constraint. For a class of output control algorithms a controller providing output asymptotic stability of equilibrium position is designed.

11:20-11:40

**Delay dependent stability analysis of interval time-delay systems**

JIANG, Wenjuan (GIPSA-lab, Saint Martin d'Héres, France)
KRUSZEWSKI, Alexandre (Ecole Centrale de Lille, France)
FRIDMAN, Emilia (Tel Aviv University, Israel)
RICHARD, Jean-Pierre (LAGIS CNRS, Ecole Centrale de Lille, France)

This paper considers interval time-varying delay systems. The time-delay interval is divided into several zones and the systems switch among the different zones. Based on Lyapunov-Krasovskii functional methods and linear matrix inequality (LMI) techniques, Exponential stability is exploited for every time-delay zone. The global stability of the switched system is guaranteed if some minimum average dwell time conditions are satisfied. Some numerical examples and comparisons with other works show that the methods greatly enlarge the value of maximum upper-bound of time-delay for the systems.

11:40-12:00

**A Necessary and Sufficient First Delay-Interval Stability Condition**

SOUZA, Fernando O. (Federal Univ. of Sao Joao del-Rei, Brazil)
DE OLIVEIRA, Maurício C. (Univ. of California San Diego, USA)
PALHARES, Reinaldo M. (Federal Univ. of Minas Gerais, Brazil)

This paper is concerned with stability of the first delay-interval of linear delay systems. Stability analysis of linear delay systems is complicated by the presence of exponential transcendental terms in the characteristic equation. The main result consists in showing that first delay-interval stability can be assessed by verifying the stability of an associated rational characteristic equation. A single real parameter on this associated rational characteristic equation plays the role of the time-delay in the original transcendental characteristic equation.

12:00-12:20

**Stability Analysis and Controller Design for Discrete-Time Fuzzy Systems With Time-Varying Delay**

VIANA, Dimitri C. (CEFET-MG, Belo Horizonte, Brazil)
LEITE, Valter J. S.(CEFET-MG, Divinópolis, Brazil)
MIRANDA, Márcio F. (UFMG / Coltec, Belo Horizonte, Brazil)

Convex conditions for stability analysis and control synthesis for discrete-time fuzzy systems with time-varying delay are proposed in this paper. The conditions depend on the variation rate of the time-delay and are obtained by considering a parameter dependent Lyapunov-Krasovskii functional. To reduce the conservatism, besides the standard techniques to include extra matrix variables, some extra equations related to the control signal are also added. It is shown that this approach leads to a less expensive convex formulation that the standard way. In all cases, the conditions are formulated as an LMI (linear matrix inequality) feasibility test, that can be efficiently solved in polynomial time by specialized numerical solvers. Numerical examples are presented to compare and illustrate the efficiency of the proposed conditions.

# Algebraic tools

***Invited Session***

*Organisers:*

Michael DI LORETO, Jean-Francois LAFAY

*Tuesday, June 8, 14:00-16:00*

*Room: Congress Hall*

14:00-14:20

**Accelerating Convergence of Sum-of-Square Stability Analysis of Coupled Differential-Difference Equations**

GU, Keqin (Southern Illinois Univ., Eduardsville, USA)
ZHANG, Yashun (Nanjing Univ. of Science and Technology, China)
PEET, Matthew (Illinois Inst. of Technology, USA)

This article aims at accelerating the convergence of the Lyapunov-Krasovskii stability analysis of coupled differential-difference equations using the sum-of-squares formulation. Under the assumption that the single integral and double integral terms are both positive definite, a necessary and sufficient condition for the positivity of the quadratic integral expression is obtained. This result is applied to the Lyapunov-Krasovskii functional and derivative conditions. The method seems to be less conservative than previous results using sums-of-squares with the same degree of polynomials. The method is illustrated via numerical examples.

14:20-14:40

**Controller Design for Delay-Independent Stability of Multiple Time-Delay Systems via Déscartes's Rule of Signs**

DELICE, Ismail Ilker (Northeastern University, Boston, USA)
SIPAHI, Rifat (Northeastern University, Boston, USA)

A general class of multi-input linear time-invariant (LTI) multiple time-delay system (MTDS) is investigated in order to obtain a control law which stabilizes the LTI-MTDS independently of all the delays. The method commences by reformulating the infinite-dimensional analysis as a finite-dimensional algebraic one without any sacrifice of accuracy and exactness. After this step, iterated discriminant allows one to construct a single-variable polynomial, coefficients of which are the controller gains. This crucial step succinctly formulates the delay-independent stability (DIS) condition of the controlled MTDS based on the roots of the single-variable polynomial. Implementation of the Déscartes rule of signs then reveals, without computing these roots, the sufficient conditions on the controller gains to make the LTI-MTDS delay-independent stable. Case studies are provided to demonstrate the effectiveness of the proposed methodology.

14:40-15:00

**Consensus with constrained convergence rate and time-delays**

MORĂRESCU, Irinel-Constantin (J. Fourier Univ., St. Martin d'Héres, France)
NICULESCU, Silviu-Iulian (L2S (UMR CNRS 8506), CNRS-Supélec, France)
GIRARD, Antoine (J. Fourier Univ., St. Martin d'Héres, France)

In this paper we discuss consensus problems for networks of dynamic agents with fixed and switching topologies in presence of delay in the communication channels. The study provides sufficient agreement conditions in terms of delay and the second largest eigenvalue of the Perron matrices defining the collective dynamics. We found an exact delay bound assuring the initial network topology preservation. We also present an analysis of the agreement speed when the asymptotic consensus is achieved. Some numerical examples complete the presentation.

15:00-15:20

**On the structure at infinity for linear time-delay systems**

DI LORETO, Michael (Univ. de Lyon, INSA-Lyon, CNRS UMR5005, France)
LAFAY, Jean-Francois (IRCCyN, Ecole Centrale de Nantes, France)
LOISEAU, Jean-Jacques (IRCCyN, Ecole Centrale de Nantes, France)
LU, Hao (Universite de Lyon, INSA-Lyon, France)

In this paper, we generalize the notion of structure at infinity for general linear time-delay systems. From realization theory, we introduce various non-equivalent notions of proper and biproper fractions. Hence, we characterize the structure at infinity for general time-delay systems and we analyze some particular cases.

15:20-15:40

**Affine parameterization design of cascade control for time delay plants**

ZÍTEK, Pavel (CTU in Prague, Czech Republic)
KUČERA, Vladimír (CTU in Prague, Czech Republic)
VYHLÍDAL, Tomáš (CTU in Prague, Czech Republic)

The cascade control architecture is a standard solution in control engineering practice for industrial plants with considerable time delays. In this paper, an affine parameterization based design of cascade controllers for time delay plants is presented. The design rests on the use of the so-called quasi-integrating meromorphic function used to prescribe the desired open-loop behaviour. Due to the parameterization approach both the slave and master controllers are obtained as time delay systems. Unlike most of relevant papers on the subject, the primary controlled output is not considered to be directly dependent on the secondary one. The only property required from the secondary output is its markedly faster response to disturbances to be compensated for.

15:40-16:00

**Efficient inversion of matrices over a non-commutative ring**

MÁRQUEZ-MARTÍNEZ, Luis Alejandro (CICESE, Ensenada, Mexico)
BRIZUELA-RODRIGUES, Carlos Alberto (CICESE, Ensenada, Mexico)

When using algebraic tools for analysis and control of nonlinear time-delay systems, it is necessary to deal with a non-commutative ring of polynomials on the delay operator, with coefficients in the field of meromorphic functions. An efficient inversion method, valid for matrices over this ring, is presented. Numerical tests on randomly generated instances show that the proposed algorithm is far more efficient than the standard adaptation of the Gauss-Jordan method.

# PID control

*Chairmen:*
Antonín VÍTEČEK, Roman PROKOP
*Tuesday, June 8, 14:00-15:40*
*Room: Gallery*

14:00-14:20
**Autotuning for delay systems using meromorphic functions**
PROKOP, Roman (Tomas Bata Univ. in Zlín, Czech Republic)
PEKAŘ, Libor (Tomas Bata Univ. in Zlín, Czech Republic)
KORBEL, Jiří (Tomas Bat'a Univ. in Zlín, Czech Republic)

The paper presents an autotuning method for time delay systems. The novelty in principles is a new combination of biased-relay feedback identification and an algebraic control design method for time-delay systems. The estimation of the controlled process is based on an asymmetrical limit cycle data experiment. Then, a stable transfer function with a dead-time term is identified. The controller is designed through solutions of Diophantine equations in the ring of stable and proper retarded quasipolynomial meromorphic functions. Controller parameters are tuned through a pole-placement problem as a desired multiple root of the characteristic closed loop equation. First and second order identification gives Smith-like feedback controllers with the realistic PI and PID structure. The design principle also offers a scalar tuning parameter $m_0 > 0$ which can be adjusted by a suitable principle or an optimization method. The developed approach is illustrated by examples in the Matlab + Simulink environment.

14:20-14:40
**Tuning the leading roots of a second order DCservomotor with proportional retarded control**
VILLAFUERTE, Raul (Papaloapan Univ., Mexico)
MONDIÉ, Sabine (CINVESTAV, Mexico)

The stabilization of a second order system through a proportional delay controller insuring a specified closed loop exponential decay $\sigma$ is studied. The analysis in the frequency domain allows the determination of the $\sigma$-stabilizability regions of the controller. The locus of the dominant roots is analyzed in detail and the characterization of some key loci, including the maximum achievable decay is obtained. The tuning of a DC servomotor experimental setup illustrates the results.

14:40-15:00

**2DOF PI and PID Controllers Tuning**

VÍTEČKOVÁ, Miluše (VŠB Technical Univ. of Ostrava, Czech Republic)
VÍTEČEK, Antonín (VŠB Technical Univ. of Ostrava, Czech Republic)

This paper is devoted to the tuning of the PI and PID controllers with two degrees of freedom by the multiple dominant pole method for first order plants with a time delay and integrating plants with a time delay. It is shown that by the corresponding tuning of the controllers with two degrees of freedom it is possible to obtain the non-oscillatory servo and regulatory step responses without overshoots. The cases that are used are demonstrated in the examples.

15:00-15:20

**PI Controller design for time delay systems**

BAKOŠOVÁ, Monika (Slovak Univ. of Technology in Bratislava, Slovakia)
VANEKOVÁ, Katarina (Slovak Univ. of Technology in Bratislava, Slovakia)
ZÁVACKÁ, Jana (Slovak Univ. of Technology in Bratislava, Slovakia)

The paper presents an approach to PI controller design for systems with varying time delay, which can be interpreted as systems with interval parametric uncertainty. The transfer function of the controlled system is modified by approximation of the time delay term by its Pade expansion or Taylor expansion in the numerator. PI controllers, that are able to assure robust stability of the feedback closed loop with the modified controlled system are found by the graphical method. Then the pole-placement method is used to specify those controller parameters, which assure certain quality of the control performance. Designed PI controllers are implemented using PLC SIMATIC S7-300 and tested by experiments on a laboratory electronic equipment with varying time delay.

15:20-15:40

**Design of PI and PID Controllers for Fractional Order Time Delay Systems**

ÖZYETKIN, M. Mine (Inonu University, Malatya, Turkey)
YEROĞLU, Celaleddin (Inonu University, Malatya, Turkey)
TAN, Nusret (Inonu University, Malatya, Turkey)
TAĞLUK, M. Emin (Inonu University, Malatya, Turkey)

This paper deals with the computation of rational approximations of fractional derivatives and/or integrals. All rational approximations for fractional order of 0.1, 0.2,, 0.9 are obtained using continued fraction expansion (CFE) method. Extension of the stability boundary locus approach to control systems with a fractional order transfer function is given for the computation of stabilizing PI and PID controllers using continuous approximations of fractional orders. Numerical examples are provided to illustrate the results and to show the effect of the order of approximation on the stability region.

# Plenary Session III

*Wednesday, June 9, 9:00-10:00*
*Chairman:*
Jean-Francois LAFAY
*Room: Congress Hall*

**Identifiability and algebraic identification of time delay systems**
BELKOURA, Lotfi (Universite des Sciences et Technologies de Lille, France)

The first part is devoted to the identifiability of Time Delay Systems described by convolution equations. The notion of sufficiently rich input which enforces identifiability is also addressed and the results are obtained assuming knowledge of solutions on a bounded time interval. The second part deals with an algebraic approach for parameters and delay identification. The identification procedure mainly consists in differentiation, multiplication with appropriate smooth functions, and integrations. The open loop approach is tackled by means of annihilations of structured entries, while the closed loop case is based on the properties of the convolution products and on the supports in a distributional framework. Based on these non-asymptotic techniques, the identification approach reduces to solving polynomials or eigenvalue problems.

**Biography**
Lotfi Belkoura is currently an Associate Professor at the University Lille 1, Sciences and Technology, France. He received the Ph.D. Degree in Automatic Control from the same University in 1993. In 1999, he joined the team SyNeR (Non Linear Systems and Delays) of the Laboratory of Automatic control, Computer Sciences and Signal of Lille (LAGIS, CNRS FRE 3303), and in 2006 the INRIA project-team ALIEN (Algebra for Identification and Numerical Estimation). He has defended his *Habilitation a Diriger des Recherches* in 2006. Since 2008 he has been Director of the SMaRT Research Master degree program of University Lille 1.

His main research interests include the analysis of time delay systems, and more particularly the questions of parameters and delays identifiability and identification. The developed methodology turned out to go beyond the scope of delay systems and his research activities also progressively tended to estimation problems for Hybrid systems. The developed distributional approach offers a large potential of applications and particularly in the domain of detection of abrupt changes. Theses aspects are illustrated in recent papers in which a unified framework is presented for dealing with both delays and parameters estimation of Time lag and Hybrid systems.

# Advances in neutral systems

***Invited Session***

*Organisers:*

Michael DI LORETO, Jean-Francois LAFAY

*Wednesday, June 9, 10:20-12:20*

*Room: Congress Hall*

10:20-10:40

**The Exact Controllability Property of Neutral Type Systems by the Moment Problem Approach Revisited**

RABAH, Rabah (IRCCyN/Ecole des Mines de Nantes, France)
SKLYAR, Grigory M. (University of Szczecin, Poland)
BARKHAYEV, Pavel Yu. (Kharkov National University, Ukraine)

In a recent paper authors gave an analysis of the exact controllability problem via the moment problem approach. Namely, the steering conditions of controllable states are formulated as a vectorial moment problem using some Riesz basis. One of the main difficulties was the choice of the basis as, in general, a basis of eigenvectors does not exist. In this contribution we use a change of control by a feedback law and modify the structure of the system in such a way that there exists a basis of eigenvectors which allows a simpler expression of the moment problem. Hence, one obtains the result on exact controllability and on the time of exact controllability.

10:40-11:00

**Computation of critical parameters for neutral type time delay systems**

OCHOA, Gilberto (CINVESTAV-IPN, Mexico)
MONDIÉ, Sabine (CINVESTAV-IPN, Mexico)
KHARITONOV, Vladimir (St.-Petersburg State Univ., Russia)

In this paper, a procedure for the computation of the Lyapunov matrix of neutral type systems, with delays multiple of a basic one, is recalled: It consists in solving a boundary value problem for a delay free system of matrix equations. The important property that the elements of the spectrum of the delay system that are symmetric with respect to the imaginary axis belong to the spectrum of the delay free system is also established. This property is exploited for the determination of the critical values of the time delay system.

11:00-11:20

**A numerical method to find stability windows and unstable poles for linear neutral time-delay systems**

FIORAVANTI, André Ricardo (INRIA Rocquencourt, France)
BONNET, Catherine (INRIA Rocquencourt, France)
ÖZBAY, Hitay (Bilkent University, Ankara, Turkey)
NICULESCU, Silviu-Iulian (L2S (UMR CNRS 8506), CNRS-Supélec, France)

This paper focuses on a numerical procedure to stability analysis of neutral time-delay systems with multiple commensurate delays. First, we give the asymptotic location of chains of poles, and conditions for their stability, for an arbitrary small delay. In this case, we can continue by using the root continuity argument, and by means of a simple substitution, find the location where roots cross the imaginary axis through numerical integration. Similarly, we can adapt the same technique to provide the location of all unstable poles (and eventually some stable ones). Several examples are presented and discussed.

11:20-11:40

**Global asymptotic stability for a class of nonlinear systems which are equivalent to neutral higher order Functional Differential Equations**

RĂSVAN, Vladimir (Univ.of Craiova, Romania)
POPESCU, Dan (Univ. of Craiova, Romania)
DANCIU, Daniela (Univ. of Craiova, Romania)

This paper has a strong motivation in the models occurring in the problem of PIO (Pilot In-the-Loop Oscillations) where any pilot model contains at least one pure delay; at the same time in the so-called PIO II category all dynamics are assumed linear except the position and rate limiters whose models include the saturation nonlinearity - a typical bounded nonlinear function. Interesting enough, an equally motivating application arises from neural networks dynamics where both delays and bounded sigmoids are to be met. In this paper we start from some classical results for integral equations concerning boundedness and asymptotic behavior and extend them to an interesting class of systems whose structure incorporates those described by input/output neutral functional differential equations of higher order.

11:40-12:00

**Liapunov Criteria for Stability in $L_p$ Norm of Special Neutral Systems**

PEPE, Pierdomenico (University of L'Aquila, Italy)
VERRIEST, Erik I. (Georgia Institute of Technology, USA)

In this paper we present further results concerning the Lyapunov-Krasovskii methodology for checking the global asymptotic stability and the input-to-state stability of systems described by retarded functional differential equations coupled with continuous time difference equations, often referred to as special neutral systems. The methodology provides results in terms of the $L_p$ norm for the non differentiated variable and does not require the preliminary check of the difference system part input-to-state stability. The initial conditions are allowed to be un-matched and piece-wise continuous. The Liapunov conditions are given without involving, not even formally, the solution.

12:00-12:20

**When classical nonlinear time-delay state-space systems admit an input-output equation of neutral type**

ANGUELOVA, Milena (Chalmers Univ. of Techn., Gothenburg Univ., Sweden)
HALÁS, Miroslav (Slovak Univ. of Technology, Bratislava, Slovakia)

This paper deals with nonlinear retarded time-delay systems that surprisingly admit an input-output representation of neutral type. It is shown that such an unexpected behaviour represents a strictly nonlinear phenomenon, for it cannot happen in the linear time-delay case where retarded systems always admit an input-output representation of retarded type. A necessary and sufficient condition under which the nonlinear systems admit a neutral input-output representation is given and strategies for finding an input-output representation of retarded type are briefly outlined. Some open problems that arise, like minimality and system transformations, are discussed as well.

# Robust, predictive and adaptive control

*Chairmen:*
Antonio GONZALEZ, Daniel LIMON
*Wednesday, June 9, 10:20-12:00*
*Room: Gallery*

10:20-10:40
**Stabilizing design parameters for model predictive control of constrained nonlinear time-delay systems**
REBLE, Marcus (University of Stuttgart, Germany)
ALLGÖWER, Frank (University of Stuttgart, Germany)

In this work a novel procedure for the calculation of stabilizing design parameters for model predictive control of nonlinear time-delay systems is presented. In contrast to previous results, the conditions derived for the local control law and the terminal region are based only on Lyapunov Krasovskii arguments and do not require any Lyapunov Razumikhin arguments. Therefore, the conditions are less restrictive, however a more complicated terminal region is obtained. The applicability of the proposed scheme is demonstrated for the numerical model of a continuous stirred tank reactor with recycle stream.

10:40-11:00
**Robustness of a discrete-time predictor-based controller for time-varying measurement delay**
GARCIA, Pedro (Polytechnic Univ. of Valencia, Spain )
GONZALEZ, Antonio (Polytechnic Univ. of Valencia, Spain )
CASTILLO, Pedro (Univ. of Technology of Compiégne, France)
LOZANO, Rogelio (Univ. of Technology of Compiégne, France)
ALBERTOS, Pedro (Polytechnic Univ. of Valencia, Spain)

Robustness properties for different uncertainties of a predictor-based control of time-delay systems are analyzed in this paper. First, a time-varying delay dependent stability condition is expressed in terms of LMIs. Then, uncertainties in the knowledge of the plant parameters and the sampling time period are considered. In addition, the resulting closed-loop system is shown to be robust with respect to these uncertainties. Moreover, this scheme has been tested in a real-time application to control the roll angle of a quad-rotor mini-helicopter. The experimental results have demonstrated the good performance of the proposed scheme and the robustness even in presence of long delays uncertainties.

11:00-11:20

**Robust Simple Adaptive Control for Delayed Measurements Systems**

BEN YAMIN, Rabin (Tel-Aviv University, Israel)
YAESH, Issac (I.M.I, Israel)
SHAKED, Uri (Tel-Aviv University, Israel)

In this paper an output-feedback problem is solved for a class of linear time delayed measurements systems with polytopic-type parameter uncertainties. The objective is to make the system output follow the output of a system model. The time-delay is either constant (known) or time-varying. In both cases, the problem is tackled by applying a combination of a simple direct adaptive control scheme, a Smith-predictor, and a low-pass filter. Sufficient conditions for closed-loop stability of the proposed control scheme are given, in terms of bilinear matrix inequalities. Two numerical examples are given, which demonstrate the applicability of the proposed methods and the simplicity of their implementation.

11:20-11:40

**Simple Robust Controllers for Delayed Systems**

DLAPA, Marek (Tomas Bata Univ. in Zlín, Czech Republic)

A way for treating general delayed systems with uncertain delays in both the numerator and denominator is shown. The proposed procedure is demonstrated by an example. A simple controller is derived via algebraic theory and the structured singular value, which treats uncertain time delay in both the numerator and denominator of an anisochronic system. The overall performance is verified by simulations and compared with standard tool for robust control design.

11:40-12:00

**Explicit input-delay compensation for robustness improvement in MPC**

SANTOS, Tito Luís Maia (Federal Univ. of Santa Catarina, Brasil)
NORMEY-RICO, Julio Elias (Federal Univ. of Santa Catarina, Brasil)
LIMÓN, Daniel (Univ. of Seville, Spain)

This paper proposes a filtered Smith predictor (FSP) delay compensation strategy for model predictive control (MPC) robustness improvement. The intrinsic MPC delay compensation is analyzed for a class of systems with a common input-delay to show that robustness can be enhanced by using a different predictor structure. Moreover, FSP robust compensation scheme is applied in a tube based MPC strategy in order to guarantee robust stability. Finally, a simulation example is presented to illustrate the usefulness of the proposed approach.

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